The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

ICTP Experts Meeting on "Science & Renewable Energy"
January 15 - 18, 2007

Venue: ICTP Adriatico Guest House - Lundqvist Lecture Hall

310/1905

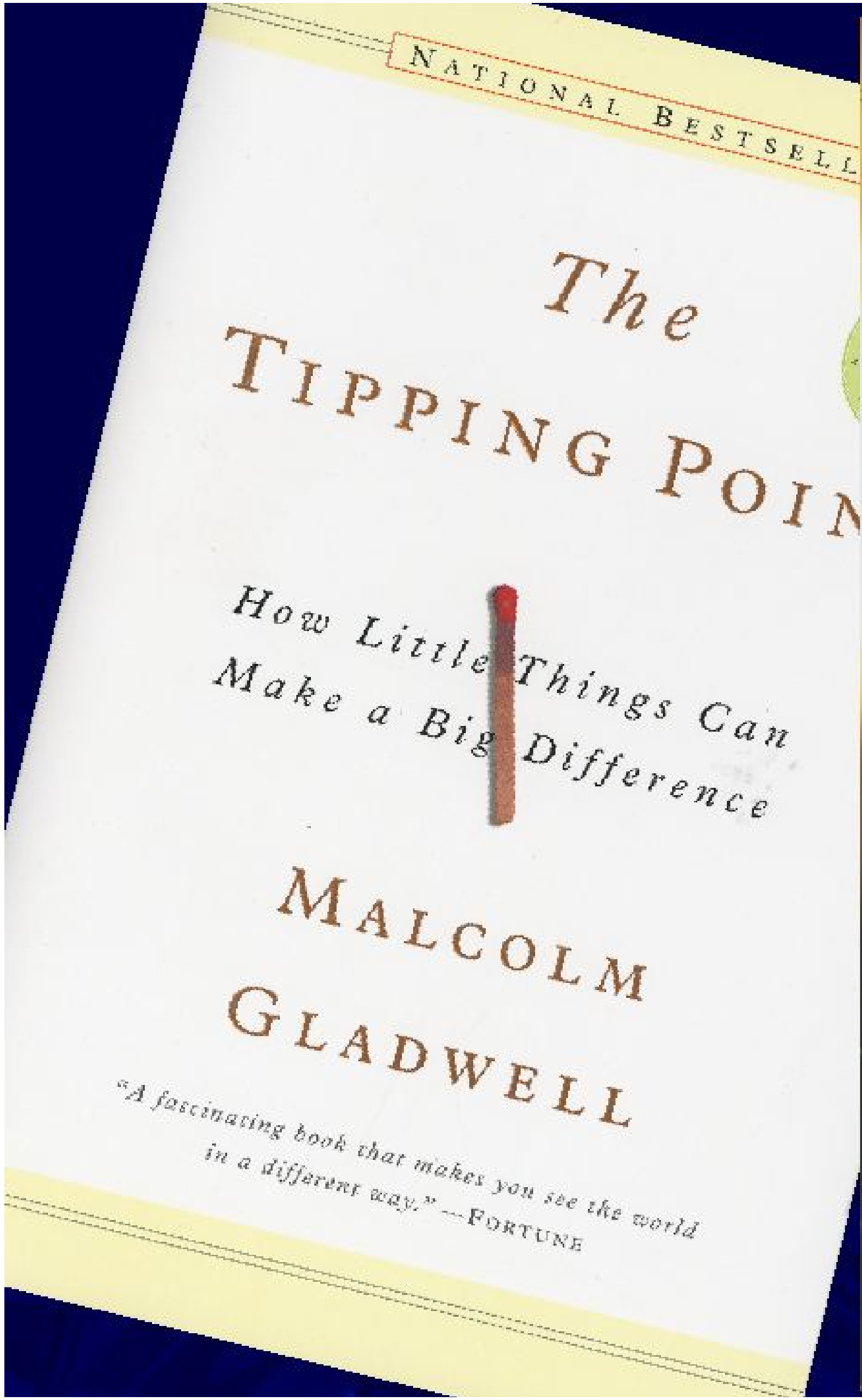
"Photovoltaics Technology: Evoluntionary, Disruptive & Revolutionary"
(……At the Tipping Point)

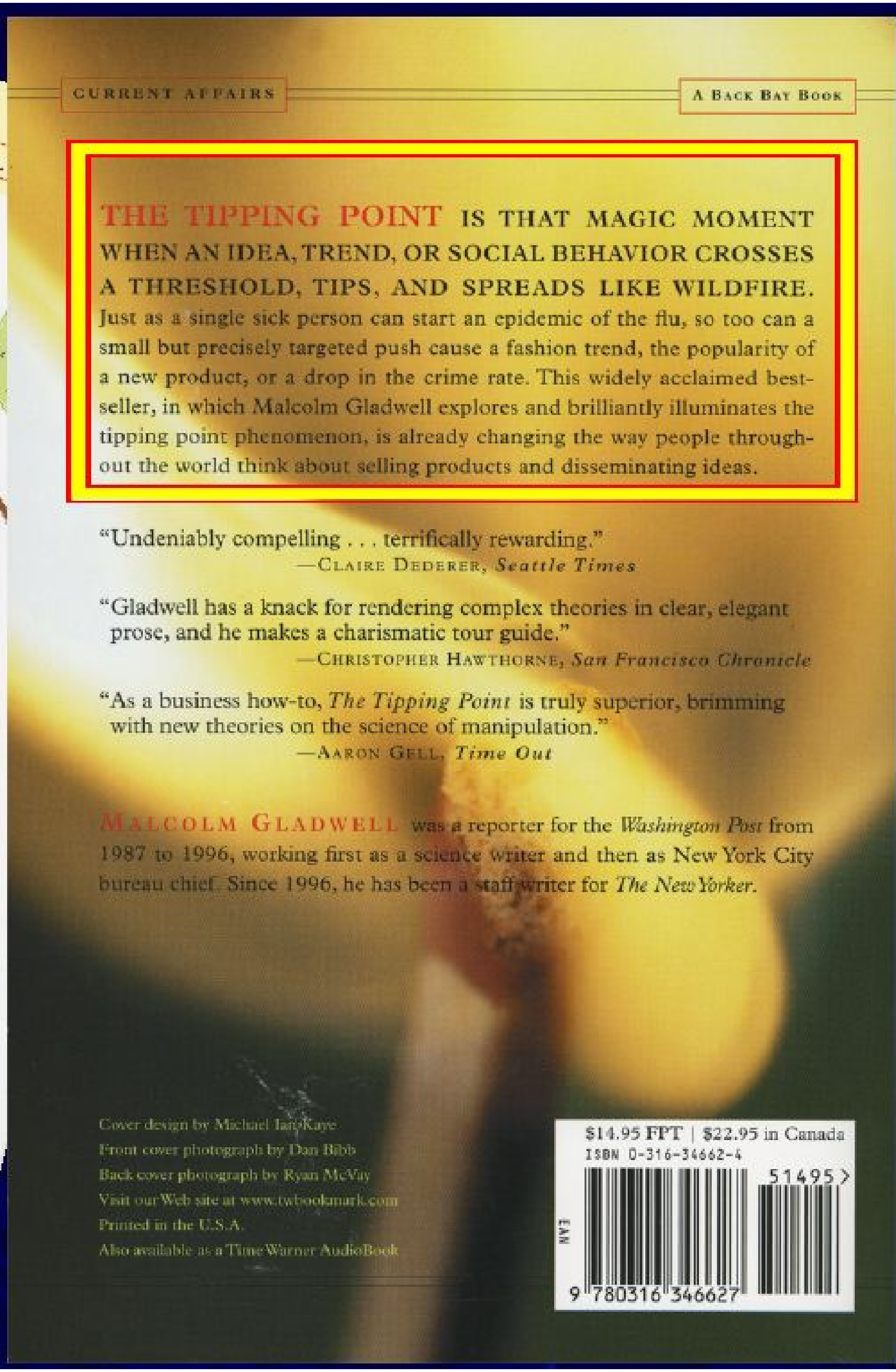
L. Kazmerski
NREL
USA

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

Photovoltaics Technology:
Evolutionary, Disruptive & Revolutionary
(. . . At the Tipping Point)

Lawrence L. Kazmerski
National Center for Photovoltaics
National Renewable Energy Laboratory
Golden, Colorado 80401 USA


National Bestsell
The
Tipping Poin
How Little Things Can
Make a Big Difference
Malcolm
Gladwell
"A fascinating book that makes you see the world
in a different way." —Fortune


Current Affairs
A Back Bay Book
THE TIPPING POINT IS THAT MAGIC MOMENT WHEN AN IDEA, TREND, OR SOCIAL BEHAVIOR CROSSES A THRESHOLD, TIPS, AND SPREADS LIKE WILDFIRE. Just as a single sick person can start an epidemic of the flu, so too can a small but precisely targeted push cause a fashion trend, the popularity of a new product, or a drop in the crime rate. This widely acclaimed best-seller, in which Malcolm Gladwell explores and brilliantly illuminates the tipping point phenomenon, is already changing the way people throughout the world think about selling products and disseminating ideas.
"Undeniably compelling . . . terrifically rewarding."
—Claire Dederer, Seattle Times
"Gladwell has a knack for rendering complex theories in clear, elegant prose, and he makes a charismatic tour guide."
—Christopher Hawthorne, San Francisco Chronicle
"As a business how-to, The Tipping Point is truly superior, brimming with new theories on the science of manipulation."
—Aaron Gell, Time Out
Malcolm Gladwell was a reporter for the Washington Post from 1987 to 1996, working first as a science writer and then as New York City bureau chief. Since 1996, he has been a staff writer for The New Yorker.
Cover design by Michael Ian Kaye
Front cover photograph by Dan Bibb
Back cover photograph by Ryan McVay
Visit our Web site at www.twbookmark.com
Printed in the U.S.A.
Also available as a Time Warner AudioBook
$14.95 FPT | $22.95 in Canada
ISBN 0-316-34662-4
51495
9 780316 346627

"Regretfully, I have come to conclude that the world has missed the boat on evolving a good working plan on global energy for 2020."

Policy
Technology

K.R. Sreenivasan
Abdus Salam Research Professor
Director, ICTP

"Regretfully, I have come to conclude that the world has missed the boat on evolving a good working plan on global energy for 2020."

"In 2050 . . . where is this energy going to come from?"

"Oil . . . fission . . . fusion . . . hydrogen . . . renewable energy . . . "

" . . . reasonable goal for 2050 . . a three way mix of renewable energy, fossil fuels and nuclear fission . . . "

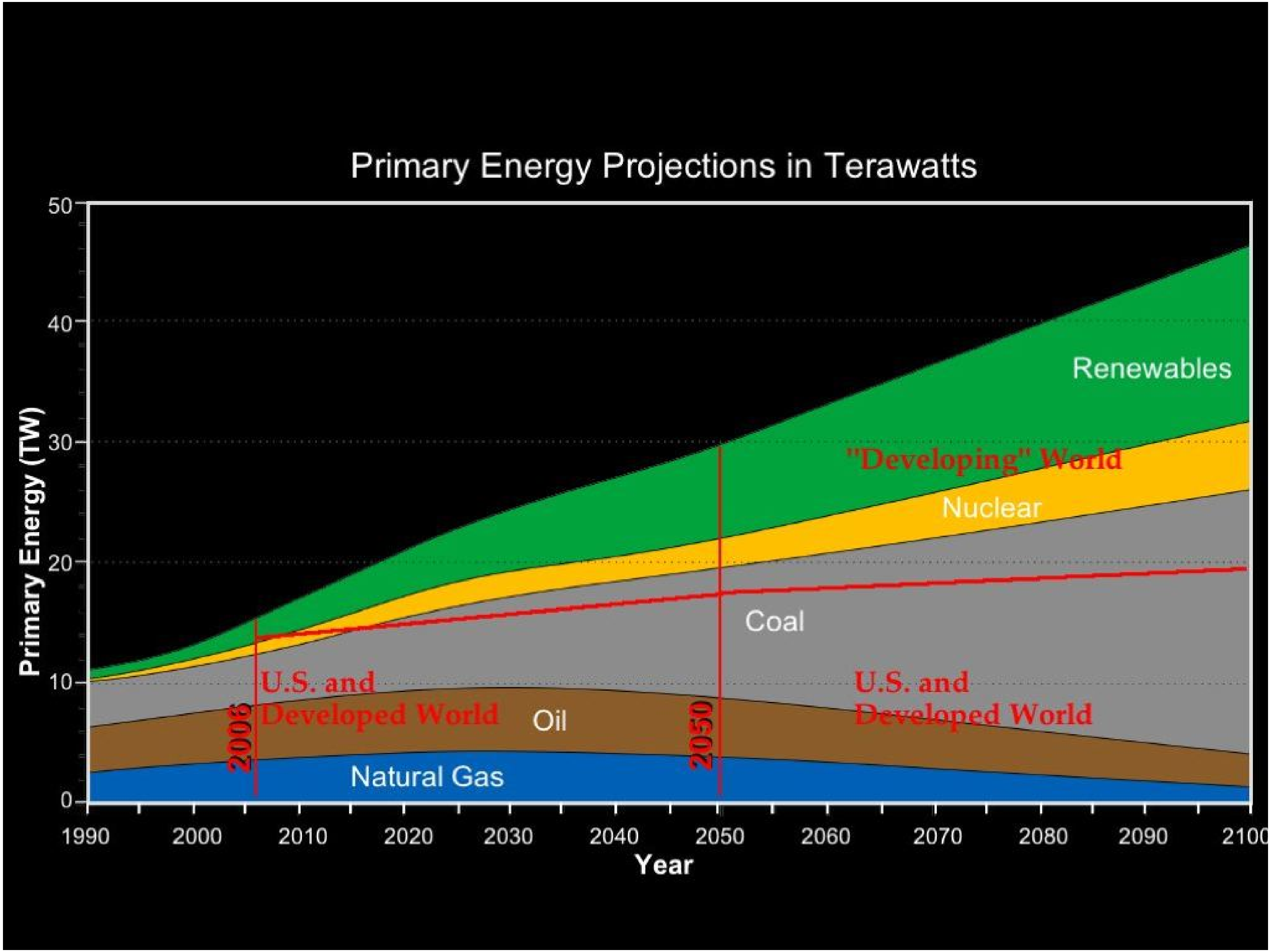
"By 2050, we will surely know more about . . . fusion, hydorgen and large-scale harvesting of renewable energy, and we will have to readapt ourselves to a new equilibrium point for 2100."

K.R. Sreenivasan
Abdus Salam Research Professor
Director, ICTP

Energy Issues . . .

Now and short term

	U.S.	Developed World	Developing World
Growth			XXX
Security	XXX	XXX	
Environment	X-	XX	X



Primary Energy Projections in Terawatts
Primary Energy (TW)
0
10
20
30
40
50
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Renewables
"Developing" World
Nuclear
Coal
U.S. and
Developed World
Oil
Natural Gas
U.S. and
Developed World
2006
2050

Energy Issues . . .

Long term (toward 2050 & beyond)

	U.S.	Developed World	Developing World
Growth			XX
Security	XXX	XXX	XXX
Environment	XXX	XXX	XXX

The Challenges *(The Terawatt Dilemma . . .)*

Worldwide Energy Consumption (now to the future):

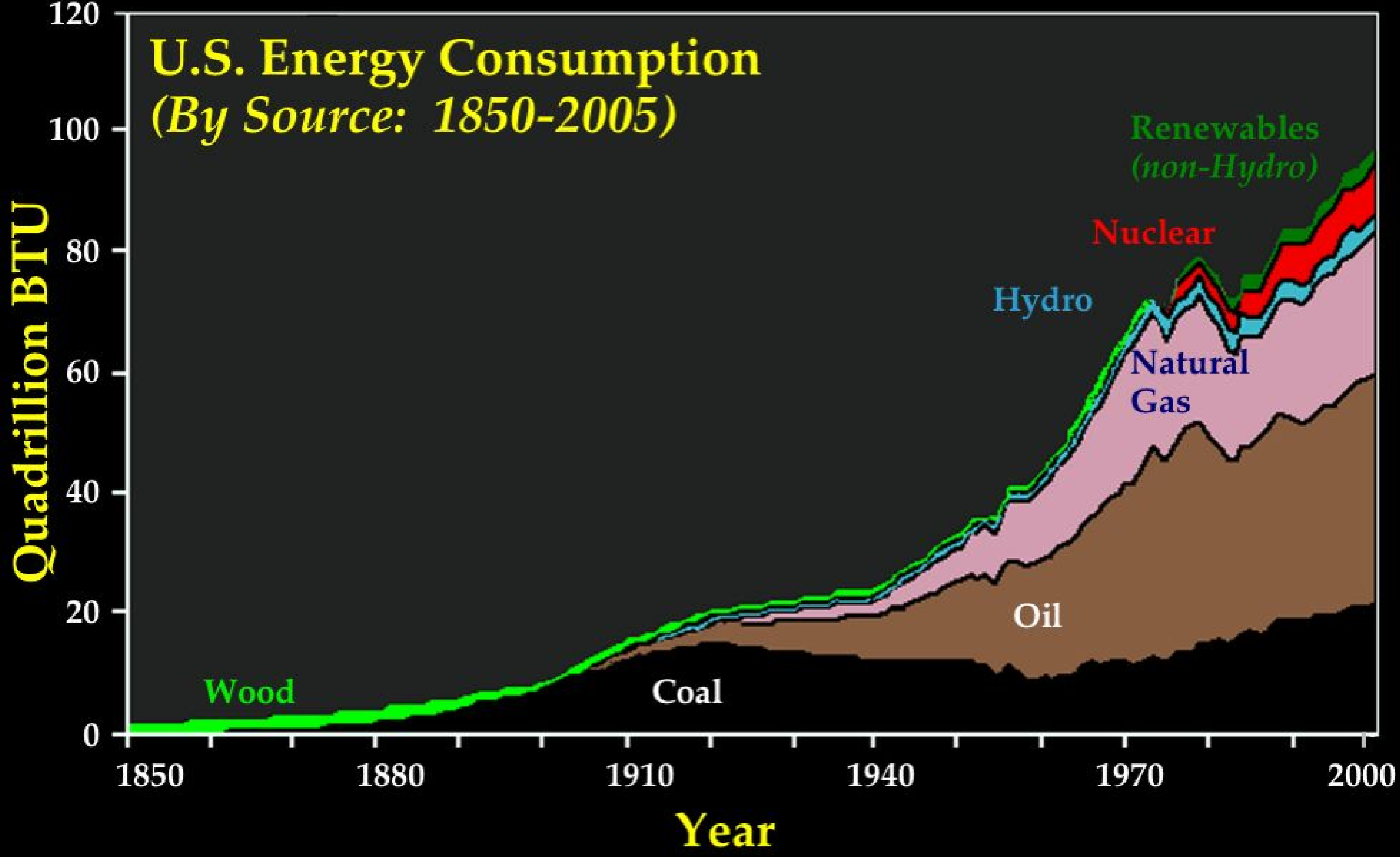
2005: About 14 TW total primary energy
By 2050, *we will need an additional 10-15 TW!*

Energy to meet this future?

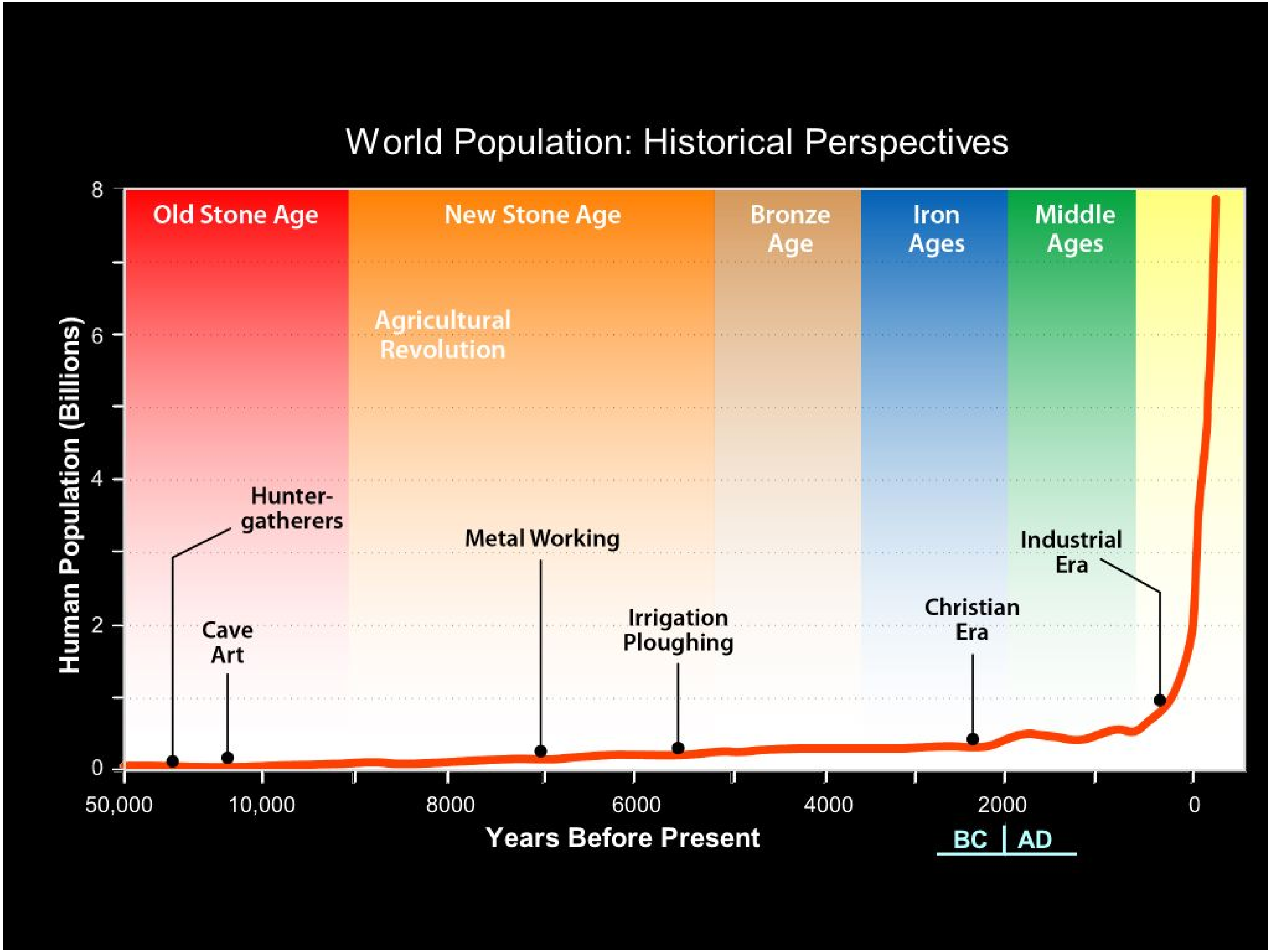
Electricity: ***Solar, Wind, Bioenergy, . . . Nuclear, Renewables?***

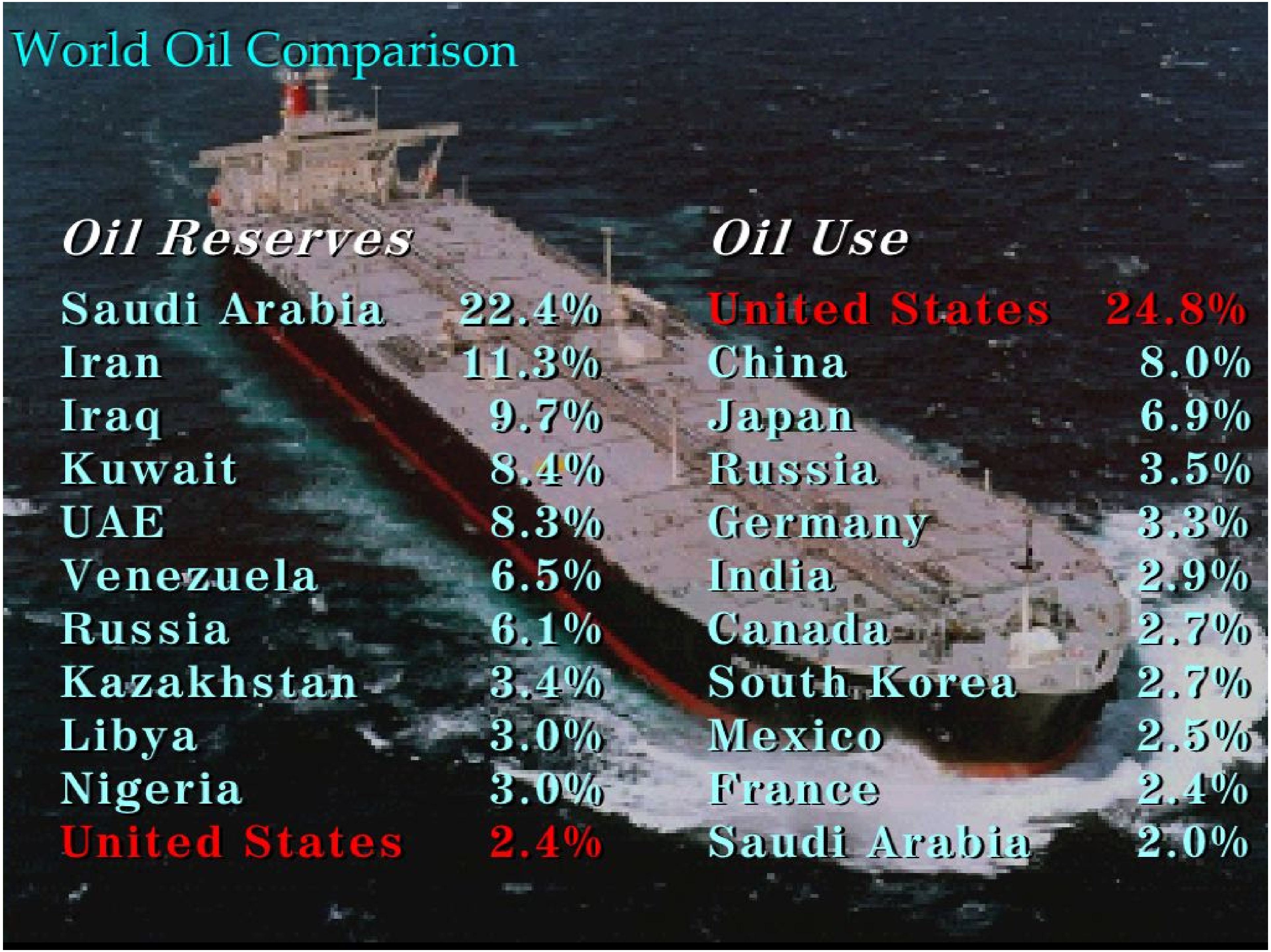
Fuels: ***Hydrogen, methanol, ethanol, others?***

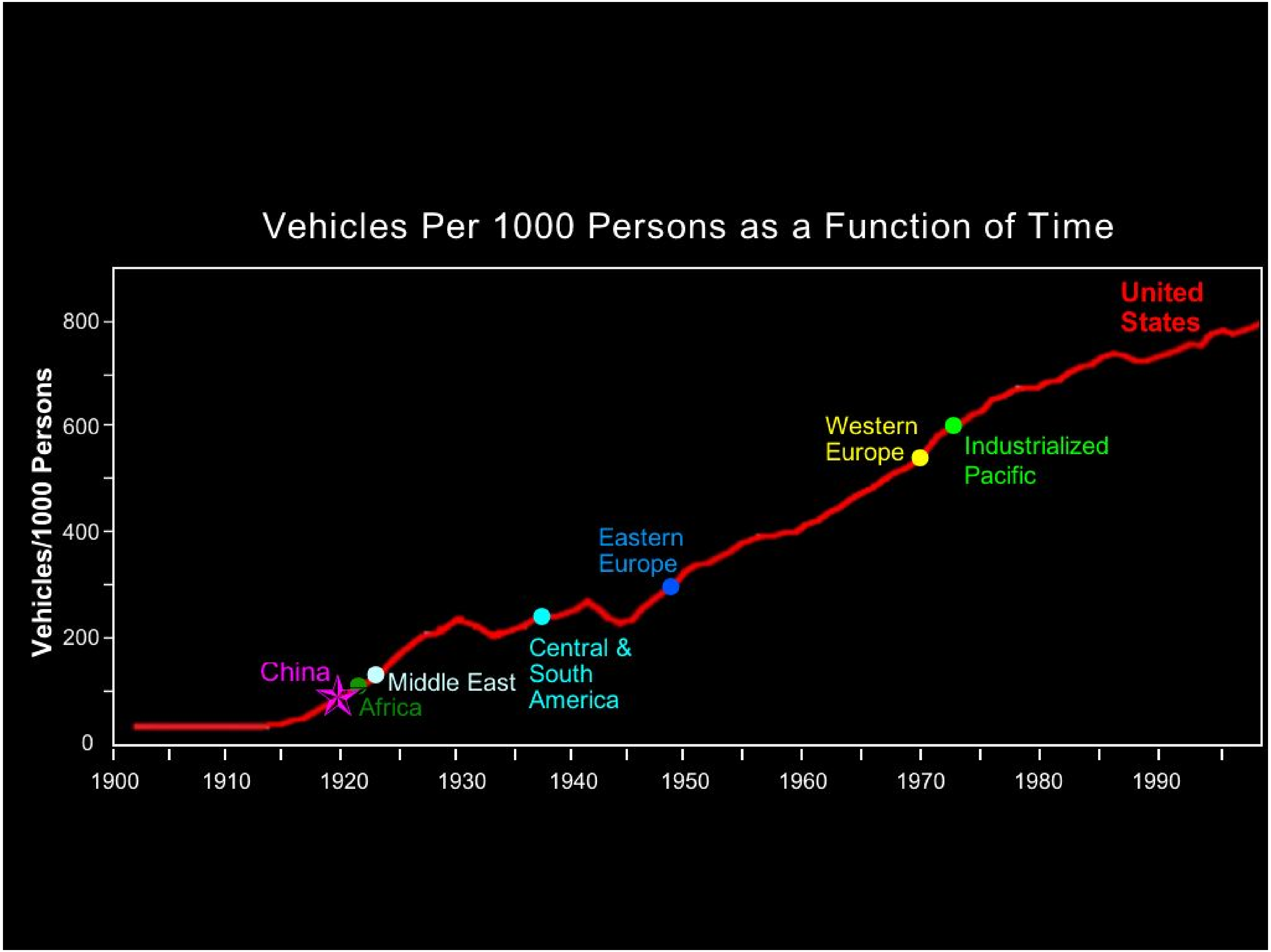

World *"Light"* Generation

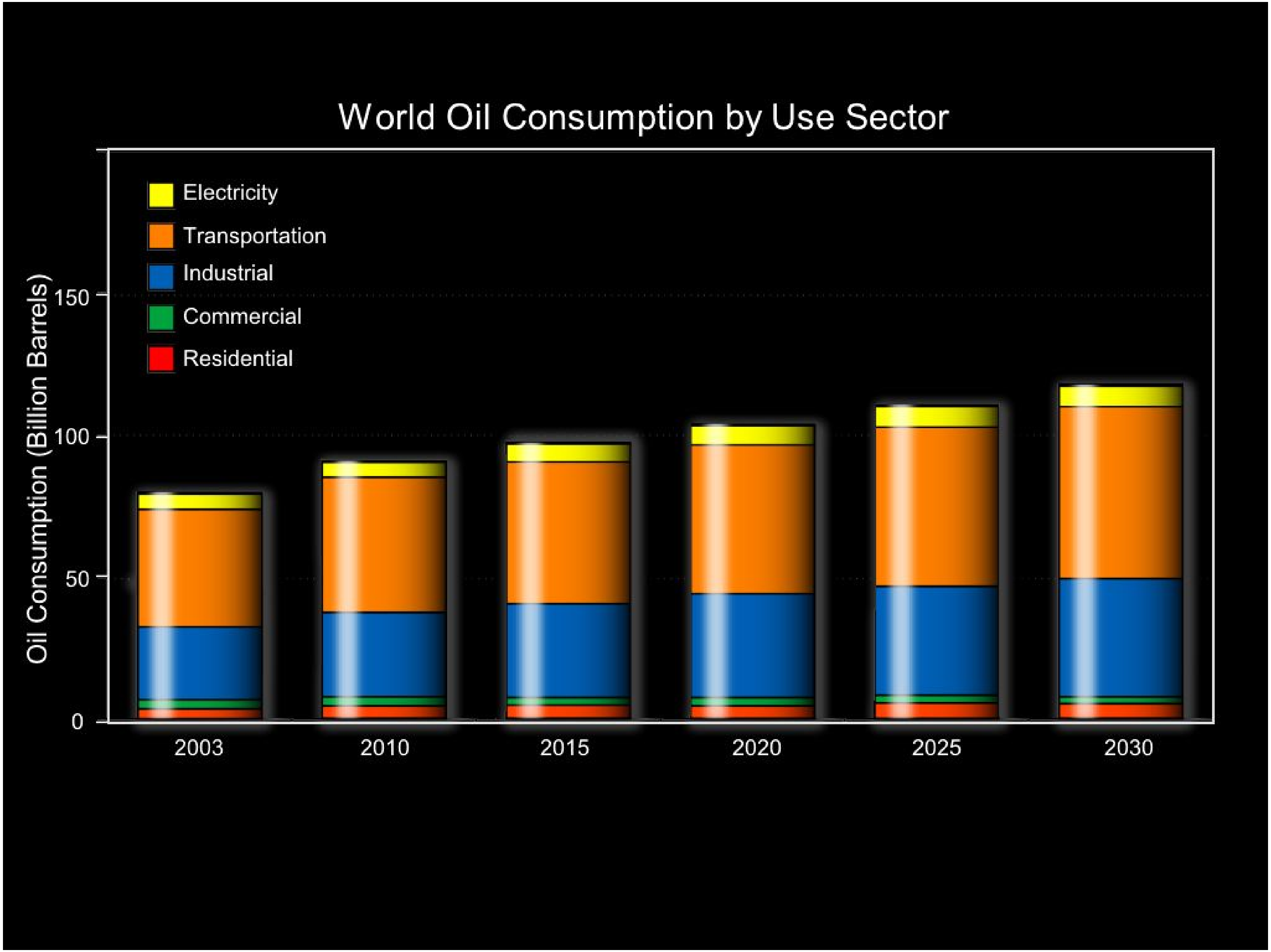


Source: 1850-1949, *Energy Perspectives: A Presentation of Major Energy and Energy-Related Data*, U.S. Department of the Interior, 1975; 1950-2005, *Annual Energy Review 2000*, Table 1.3.


World Population: Historical Perspectives
Human Population (Billions)
8
6
4
2
0
Old Stone Age
New Stone Age
Bronze Age
Iron Ages
Middle Ages
Agricultural Revolution
Hunter-gatherers
Cave Art
Metal Working
Irrigation Ploughing
Christian Era
Industrial Era
50,000
10,000
8000
6000
4000
2000
0
Years Before Present
BC | AD

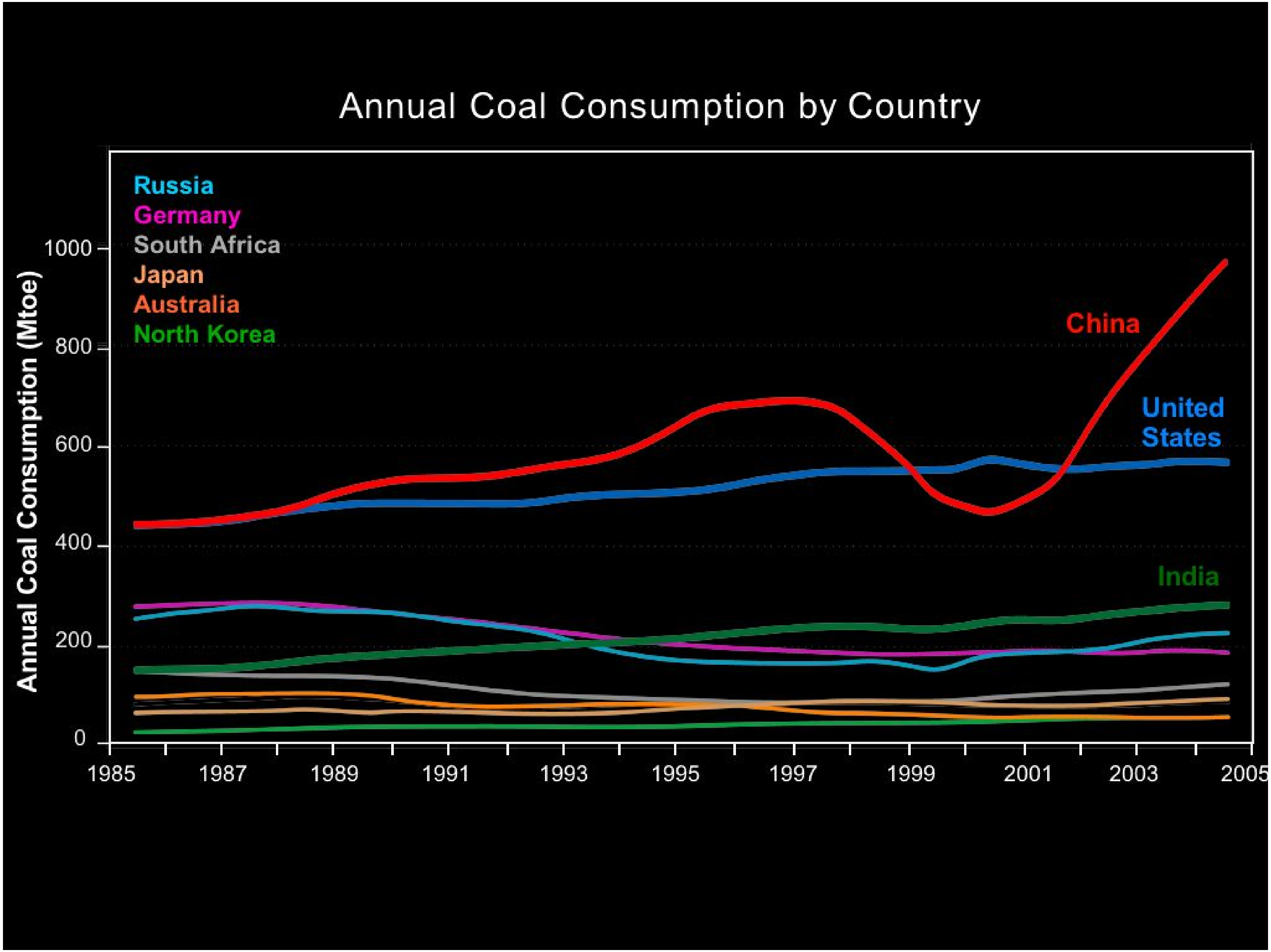

World Oil Comparison
Oil Reserves
Saudi Arabia 22.4%
Iran 11.3%
Iraq 9.7%
Kuwait 8.4%
UAE 8.3%
Venezuela 6.5%
Russia 6.1%
Kazakhstan 3.4%
Libya 3.0%
Nigeria 3.0%
United States 2.4%
Oil Use
United States 24.8%
China 8.0%
Japan 6.9%
Russia 3.5%
Germany 3.3%
India 2.9%
Canada 2.7%
South Korea 2.7%
Mexico 2.5%
France 2.4%
Saudi Arabia 2.0%


Vehicles Per 1000 Persons as a Function of Time
Vehicles/1000 Persons
0
200
400
600
800
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
United States
Western Europe
Industrialized Pacific
Eastern Europe
Central & South America
China
Middle East
Africa



World Oil Consumption by Use Sector
Electricity
Transportation
Industrial
Commercial
Residential
Oil Consumption (Billion Barrels)
150
100
50
0
2003
2010
2015
2020
2025
2030


World Coal Comparison
Coal Reserves
China 32.2%
Australia 22.2%
Romania 17.6%
Hungary 10.1%
Turkey 5.8%
Kazakhstan 5.0%
Brazil 2.2%
United States 1.2%
Venezuela 0.4%
Canada 0.3%
India 0.3%
Coal Use
China 28.7%
United States 23.3%
India 7.4%
Russia 3.5%
Germany 3.3%
India 2.9%
Canada 2.7%
South Korea 2.7%
Mexico 2.5%
France 2.4%
Saudi Arabia 2.0%

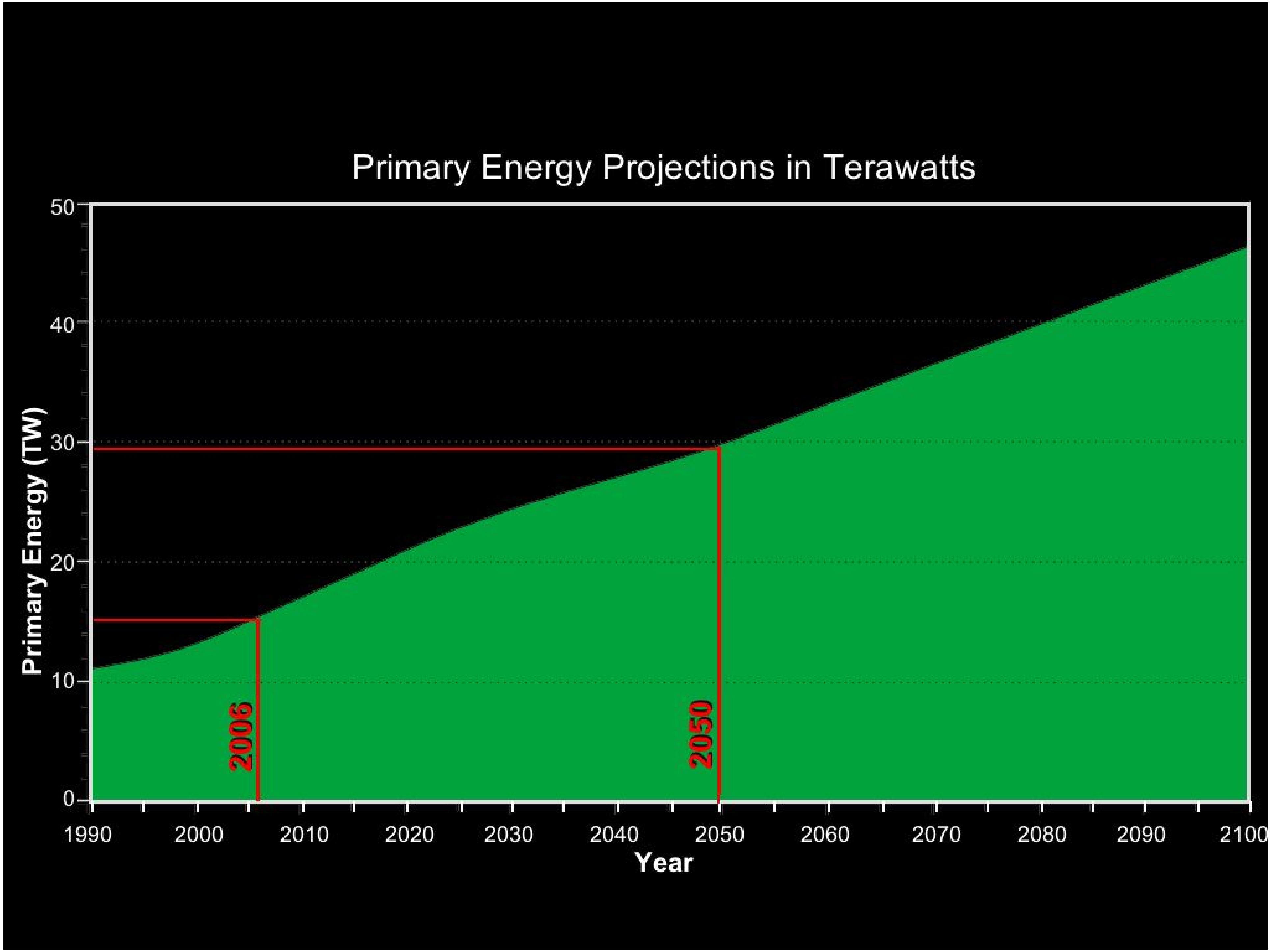


Annual Coal Consumption by Country
Russia
Germany
South Africa
Japan
Australia
North Korea
China
United States
India
Annual Coal Consumption (Mtoe)
1000
800
600
400
200
0
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005

The Challenges *(The Terawatt Dilemma . . .)*

Worldwide Energy Consumption (now to the future):

2005: About 14 TW total primary energy
By 2050, *we will need an additional 10-15 TW!*



Primary Energy Projections in Terawatts
Primary Energy (TW)
Year
0
10
20
30
40
50
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2006
2050

The Challenges *(The Terawatt Dilemma . . .)*

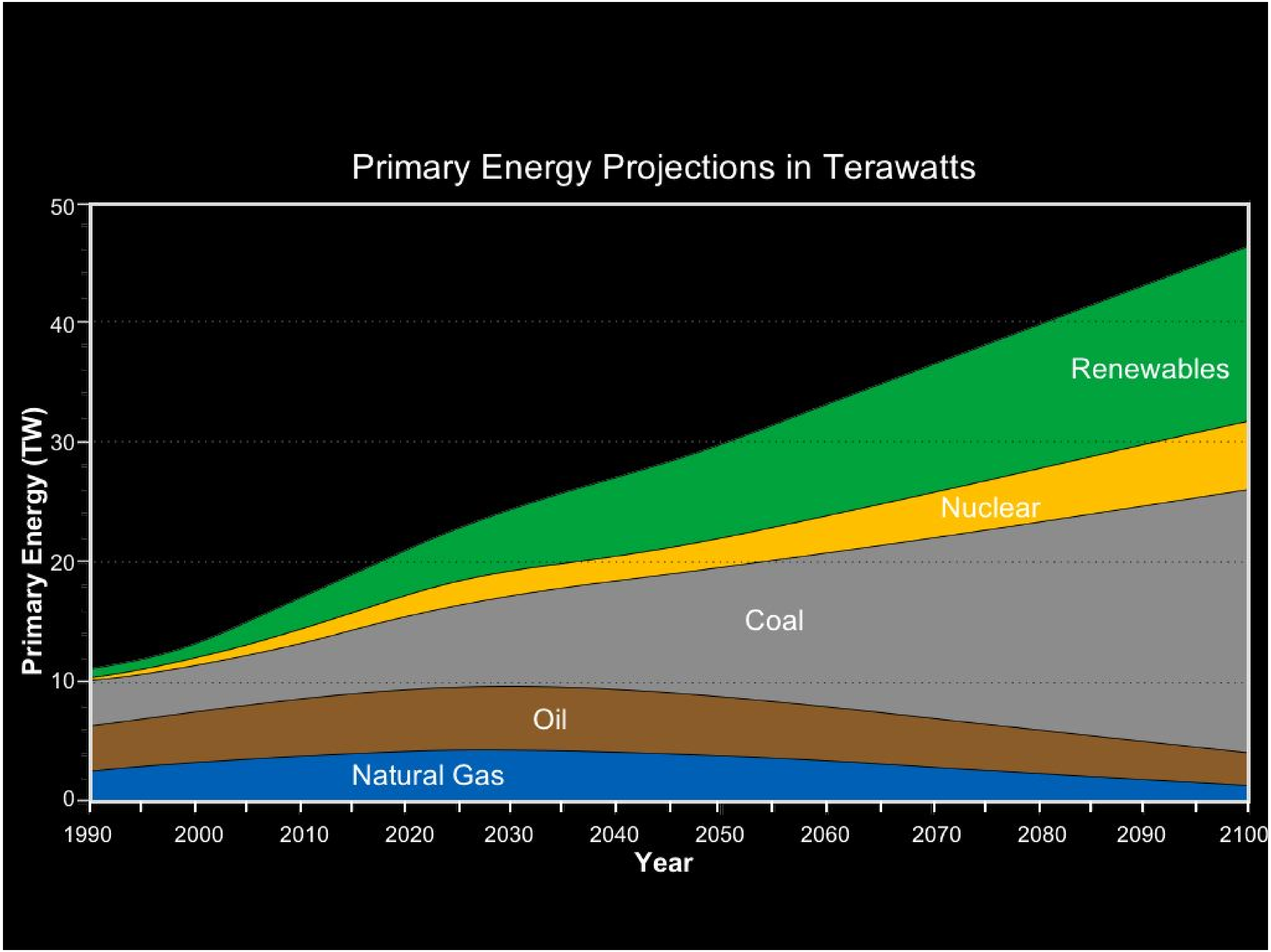
Worldwide Energy Consumption (now to the future):

2005: About 14 TW total primary energy
By 2050, *we will need an additional 10-15 TW!*

Energy to meet this future?

Electricity: ***Fossil Fuels . . . Nuclear, Renewables . . . Other?***

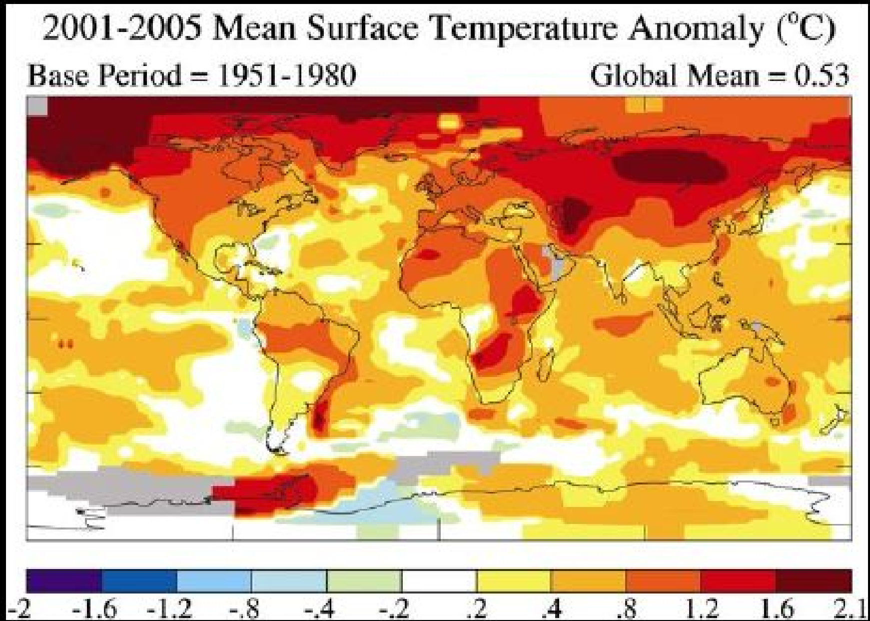
Fuels: ***Fossil sources . . . Hydrogen, methanol, ethanol, others?***

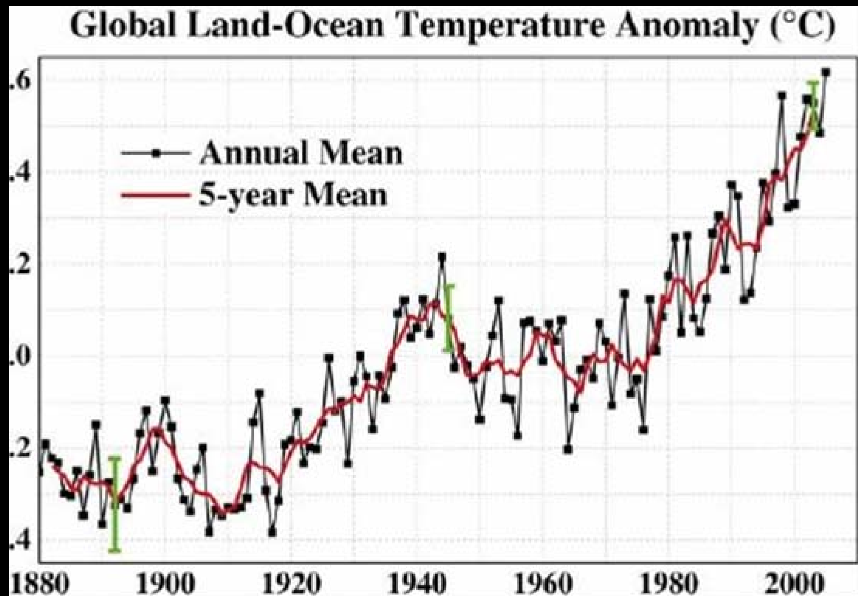


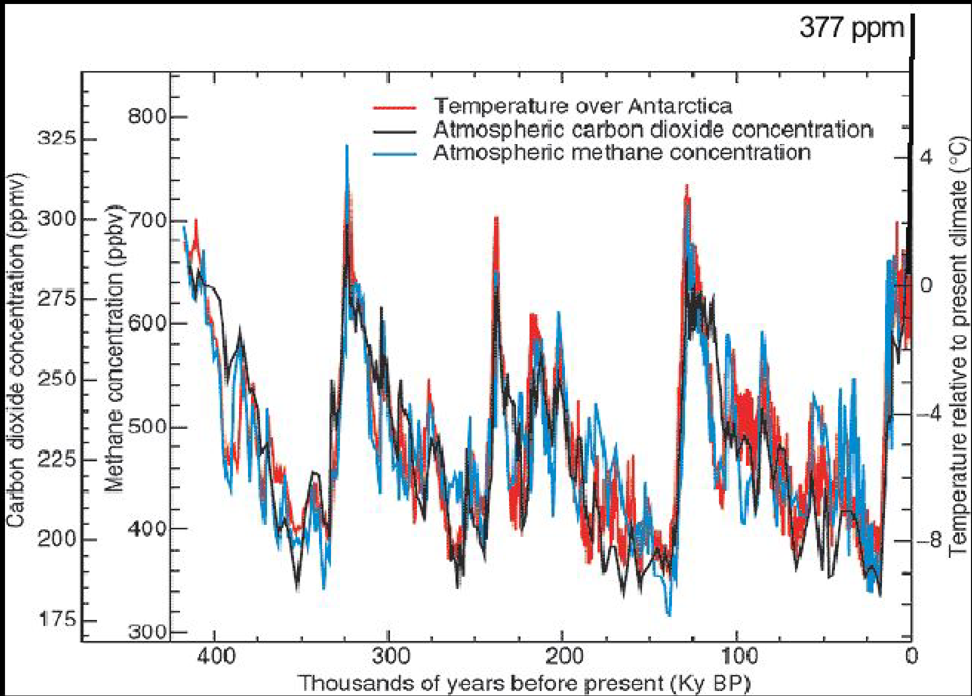
Primary Energy Projections in Terawatts
Primary Energy (TW)
0
10
20
30
40
50
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Renewables
Nuclear
Coal
Oil
Natural Gas

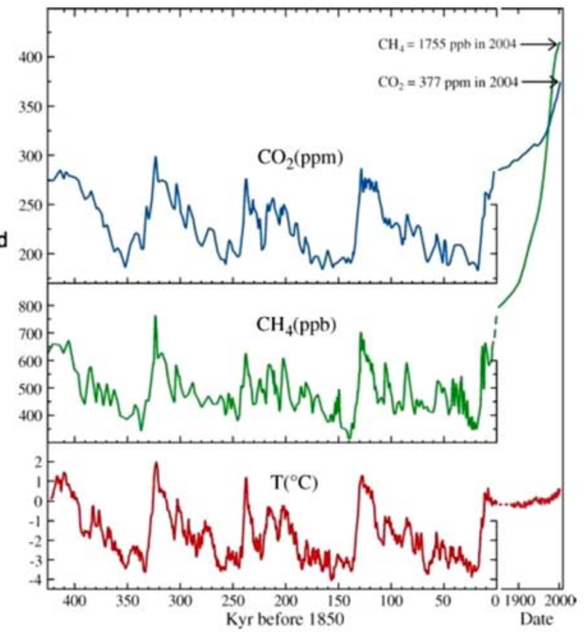
1. The Background: Global Climate Change

"A threat to our planet", Dr. James Hansen, NASA


2001-2005 Mean Surface Temperature Anomaly (°C)
Base Period = 1951-1980
Global Mean = 0.53
-2 -1.6 -1.2 -.8 -.4 -.2 .2 .4 .8 1.2 1.6 2.1

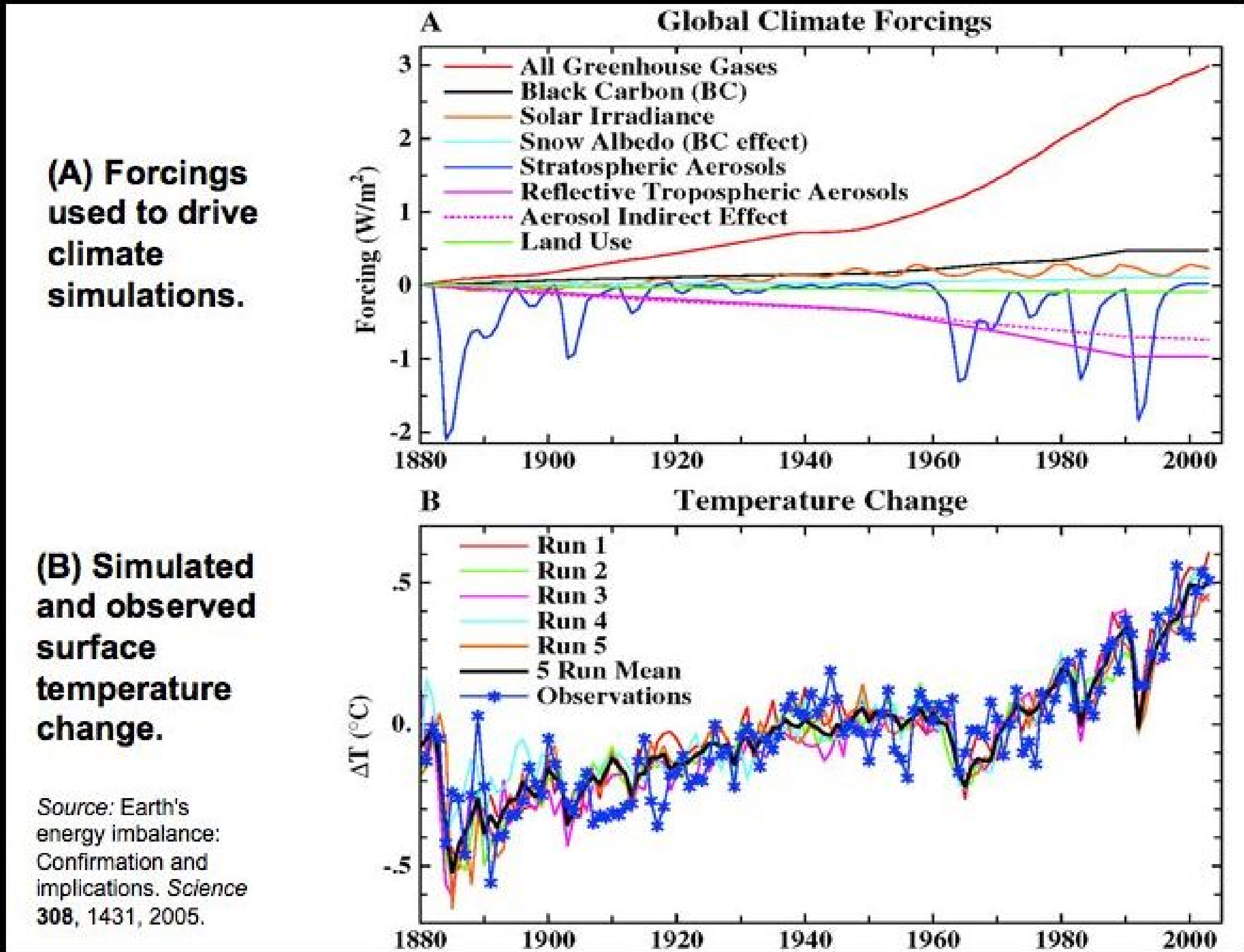

Global Land-Ocean Temperature Anomaly (°C)
Annual Mean
5-year Mean
.6
.4
.2
.0
.2
.4
1880 1900 1920 1940 1960 1980 2000





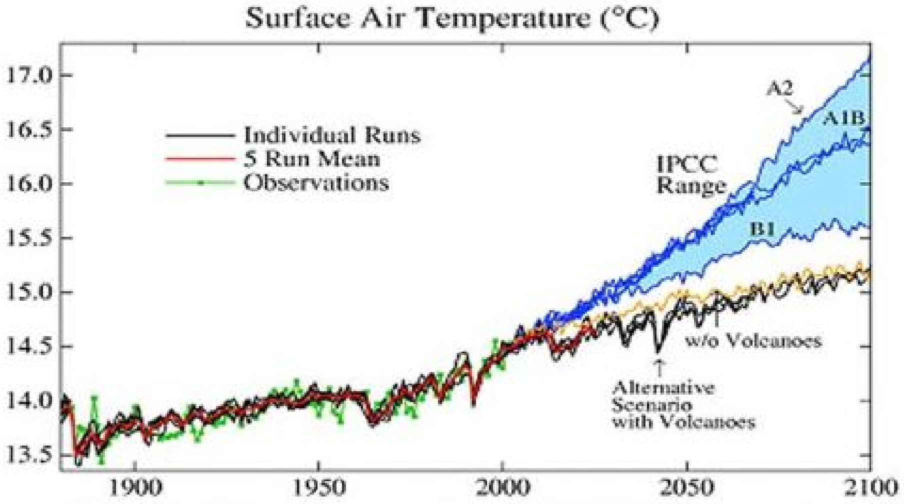
CO_2, CH_4 and estimated global temperature (Antarctic $\Delta T/2$ in ice core era) 0 = 1880-1899 mean.

Source: Hansen, *Clim. Change*, **68**, 269, 2005.



Hansen Models: Temperature change and ice area changes due to greenhouse gases (humans control global climate . . .)

21st Century Global Warming



Climate Simulations for IPCC 2007 Report

- **Climate Model Sensitivity ~ 2.7°C for $2xCO_2$**
  (consistent with paleoclimate data & other models)
- **Simulations Consistent with 1880-2003 Observations**
  (key test = ocean heat storage)
- **Simulated Global Warming < 1°C in Alternative Scenario**

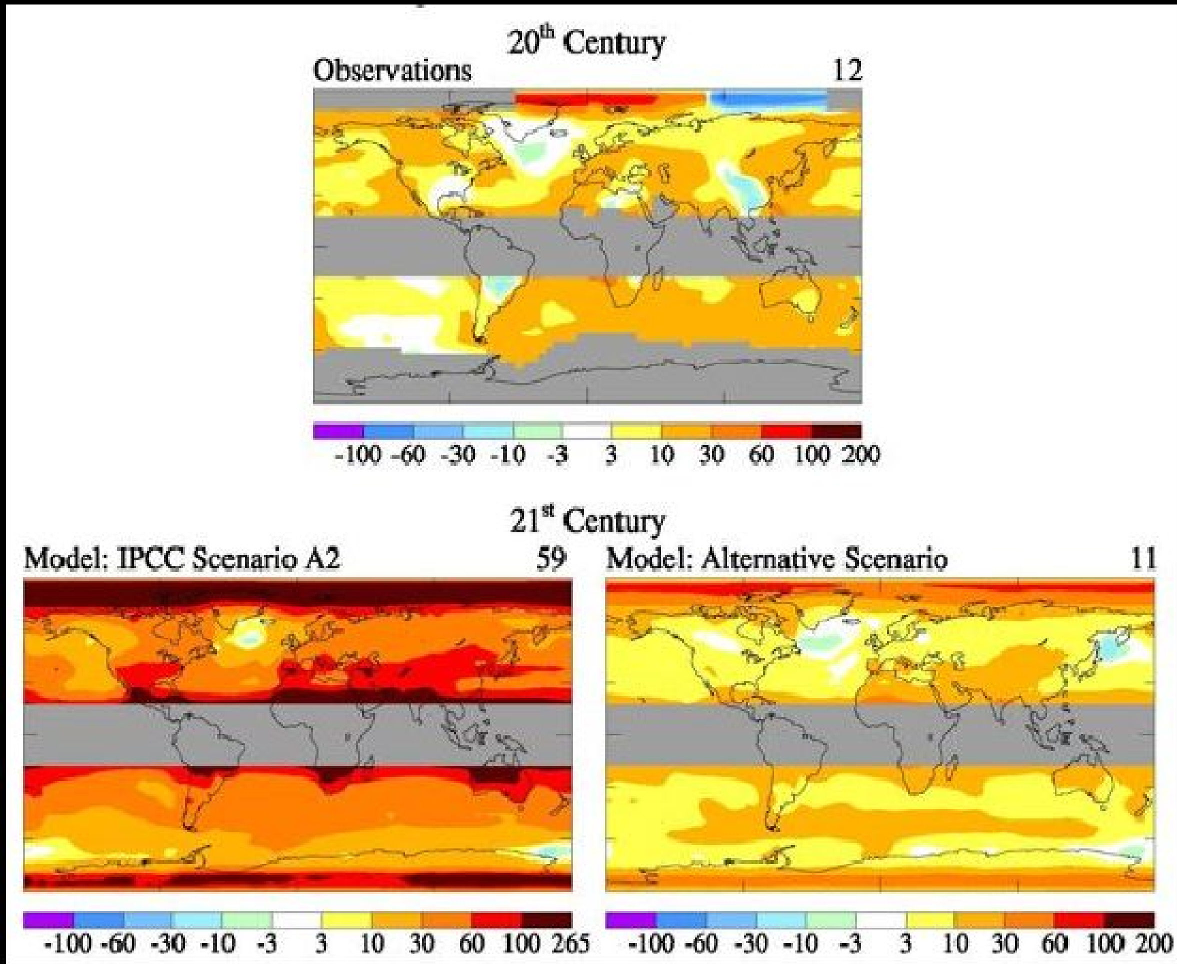
Conclusion: Warming < 1°C if additional forcing ~ 1.5 W/m^2

Source: Hansen et al., *to be submitted to J. Geophys. Res.*

Aim is to stabilize greenhouse gas emissions . . .

in balance with the climate system

Observation and Prediction:
Poleward Migration Rate of Isotherms *(km/decade)*



Evidence for Global Warming

- The 12 hottest years (over the last 145 years) have occurred in the last 15 years.

Rank	Year
1	2005
1	1998
3	2002
4	2003
5	2004
6	2001
7	1997
8	1990
9	1995
10	1999
11	2000
12	1991

Evidence for Global Warming

- The 12 hottest years (over the last 145 years) have occurred in the last 15 years.
- Glaciers in most parts of the world are receding.

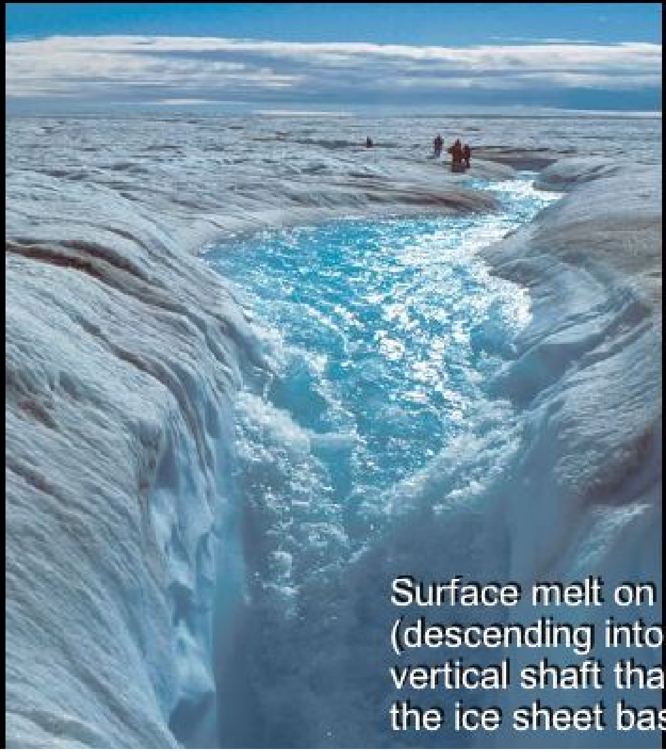
Riggs Glacier in Alaska, comparing 1941 & 2004 (Most of the 610 meter thick glaser has disappeared).

Upsala Glacier in Argentina, comparing 1928 and 2004, showing the glacier has mostly disappeared.

Evidence for Global Warming

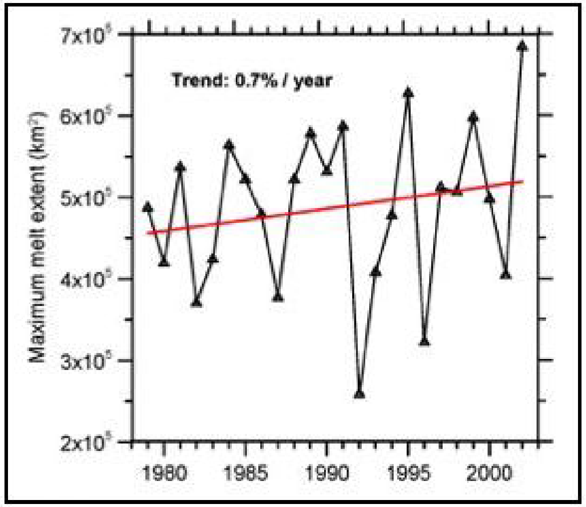
- The 12 hottest years (over the last 145 years) have occurred in the last 15 years.
- Glaciers in most parts of the world are receding.
- Over the last 100 years, the global sea level has risen about 10 cm-25 cm (20%-30% of this is due to thermal expansion).
- Significant changes have been observed in many local habitats affecting plants, coral, tundra, birds, polar bears, etc.

Increasing ice discharges from major ice stream (Jacobshavn) in Greenland

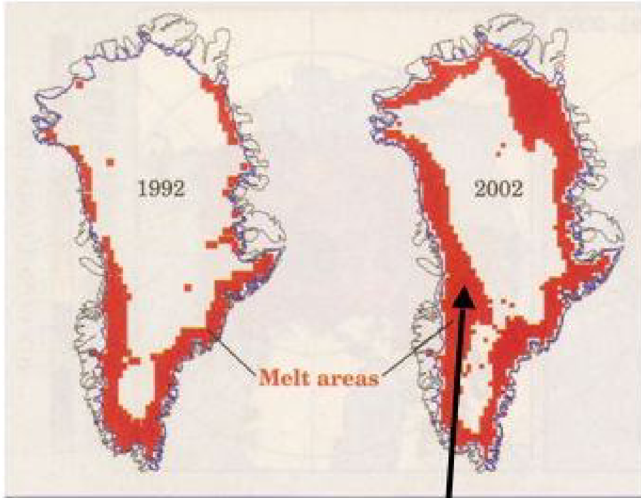


Surface melt on Greenland (descending into a "moulin", vertical shaft that carries melt to the ice sheet base).

Increasing Melt Area on Greenland



- 2002 all-time record melt area
- Melting up to elevation of 2000 m
- 16% increase from 1979 to 2002



70 meters thinning in 5 years

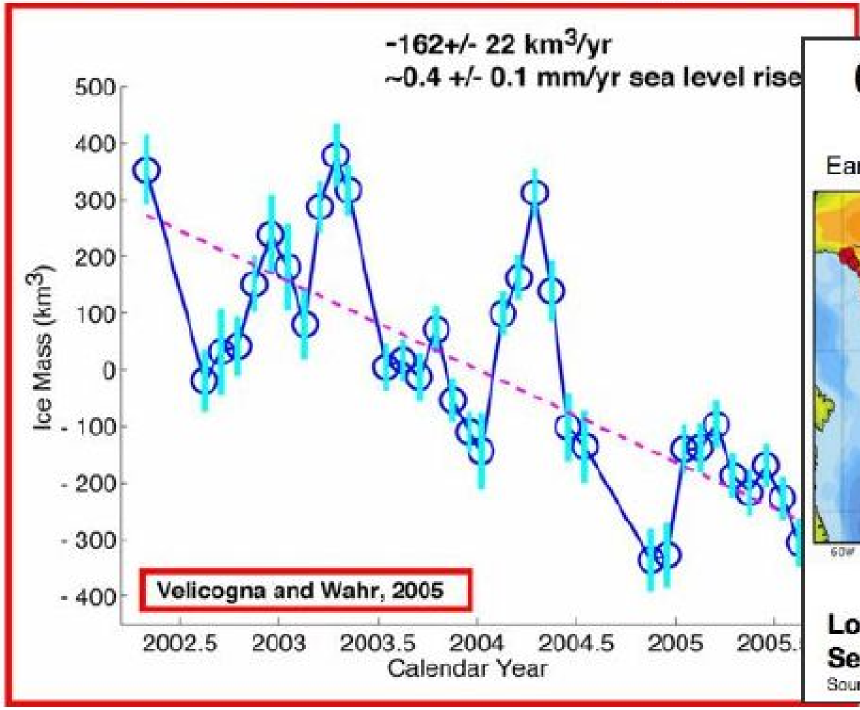
Satellite-era record melt of 2002 was exceeded in 2005.

Source: Waleed Abdalati, Goddard Space Flight Center

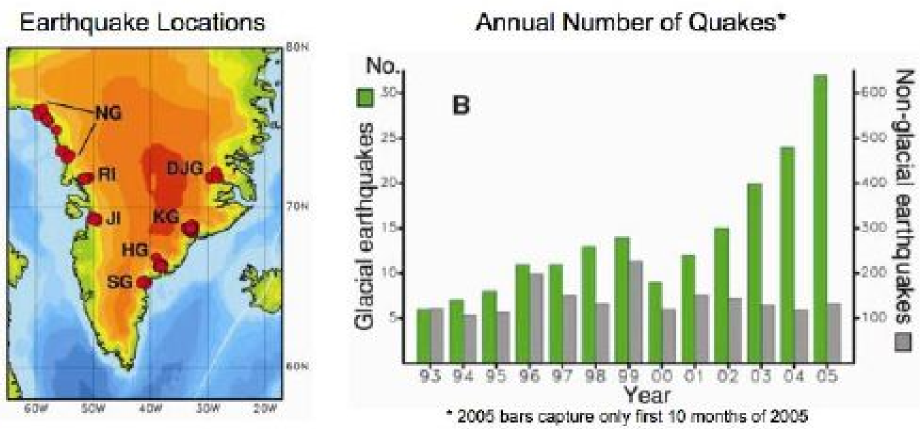
Evidence for Global Warming

- The 12 hottest years (over the last 145 years) have occurred in the last 15 years.
- Glaciers in most parts of the world are receding.
- Over the last 100 years, the global sea level has risen about 10 cm-25 cm (20%-30% of this is due to thermal expansion).
- Significant changes have been observed in many local habitats affecting plants, coral, tundra, birds, polar bears, etc.

Greenland Mass Loss – From Gravity Satellite



Glacial Earthquakes on Greenland



Location and frequency of glacial earthquakes on Greenland. Seismic magnitudes are in range 4.6 to 5.1.

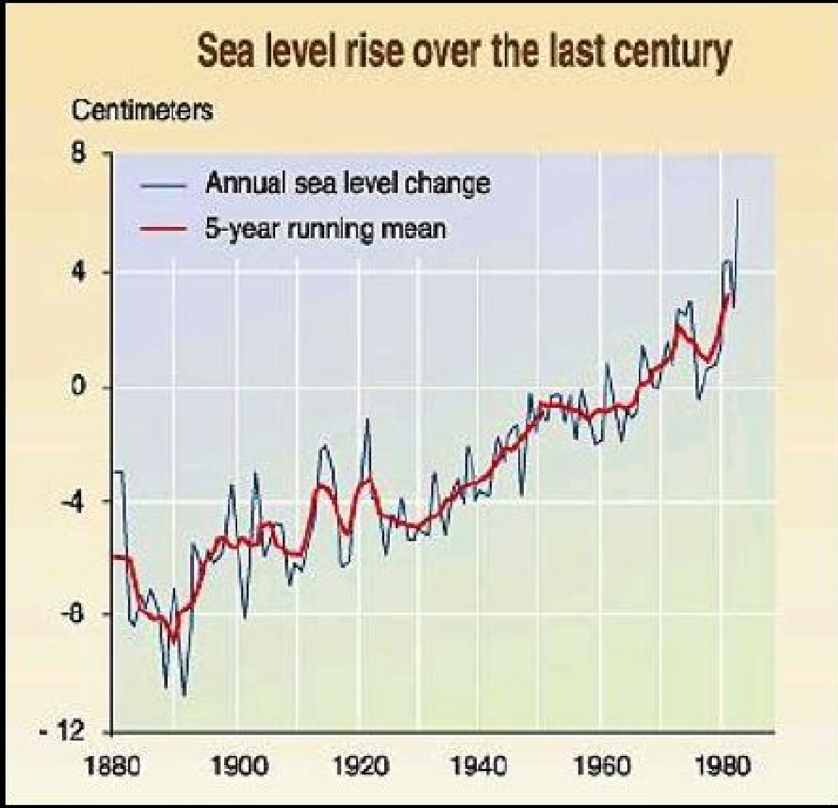
Source: Ekstrom, Nettles and Tsai, *Science*, **311**, 1756, 2006.

Evidence for Global Warming

- The 12 hottest years (over the last 145 years) have occurred in the last 15 years.
- Glaciers in most parts of the world are receding.
- Over the last 100 years, the global sea level has risen about 10 cm-25 cm (20%-30% of this is due to thermal expansion).
- Significant changes have been observed in many local habitats affecting plants, coral, tundra, birds, polar bears, etc.
- Worldwide precipitation patterns have changed significantly over the last 100 years.
- Both the duration and the highest wind speeds of cyclones and hurricanes have increased by about 50% over the last 50 years (some argue that part of this is cyclical).

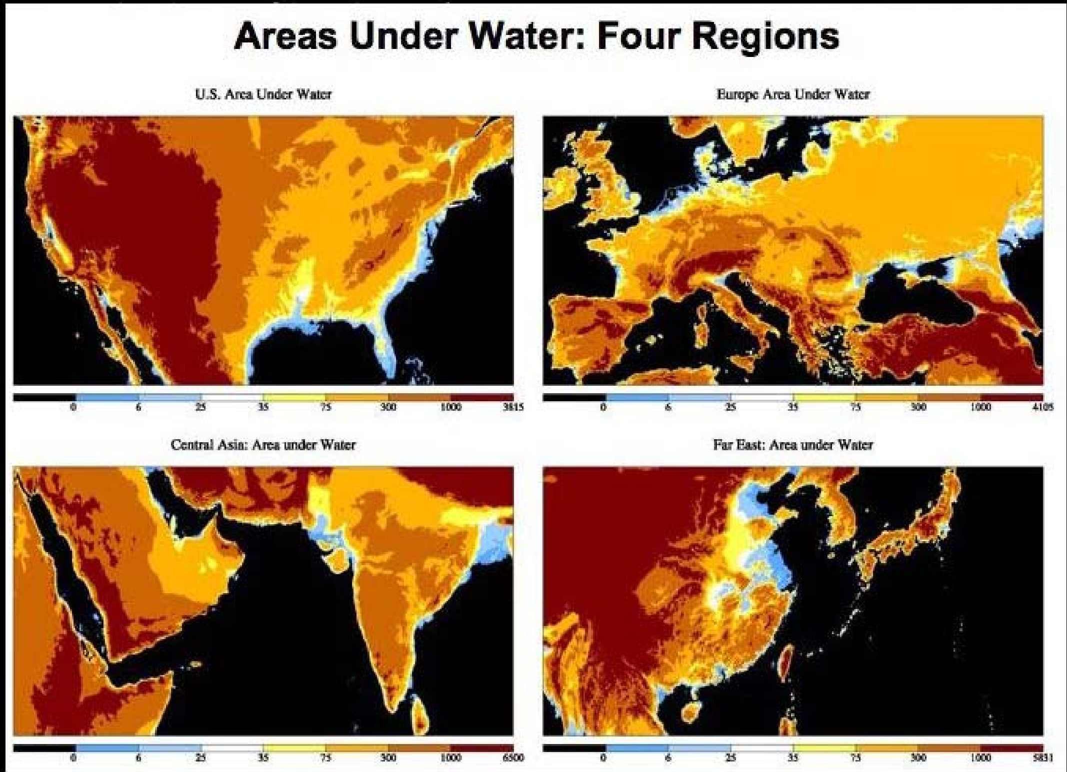
Consequences of Global Warming

- Accelerating rise in sea levels *(Destruction of cities; relocation of people; loss of land area)*



Consequences of Global Warming

- Accelerating rise in sea levels *(Destruction of cities; relocation of*



Population (millions) in 2000

Region (total population)	Population Under Water (for given sea level rise)			
	6m	*25 m*	*35m*	*75m*
United States (283)				
East Coast	9	41	51	70
West Coast	2	6	9	19
China + Taiwan (1275+23)	93	224	298	484
India + Sri Lanka (1009+19)	46	146	183	340
Bangladesh (137)	24	109	117	130
Indonesia + Malaysia (212+22)	23	72	85	117
Japan (127)	12	39	50	73
Western Europe (454)	26	66	88	161

Consequences of Global Warming

- Accelerating rise in sea levels *(Destruction of cities; relocation of people; loss of land area)*
- More extreme weather (floods, hurricanes, droughts, . . .)
- Ocean thermohaline circulation slowdown or abrupt cessation *(the Gulf Stream stops!)*
- Alteration of natural habitats (extinction of species; potential for increasing desertification; relocation of farms, ranches--threat to food production)

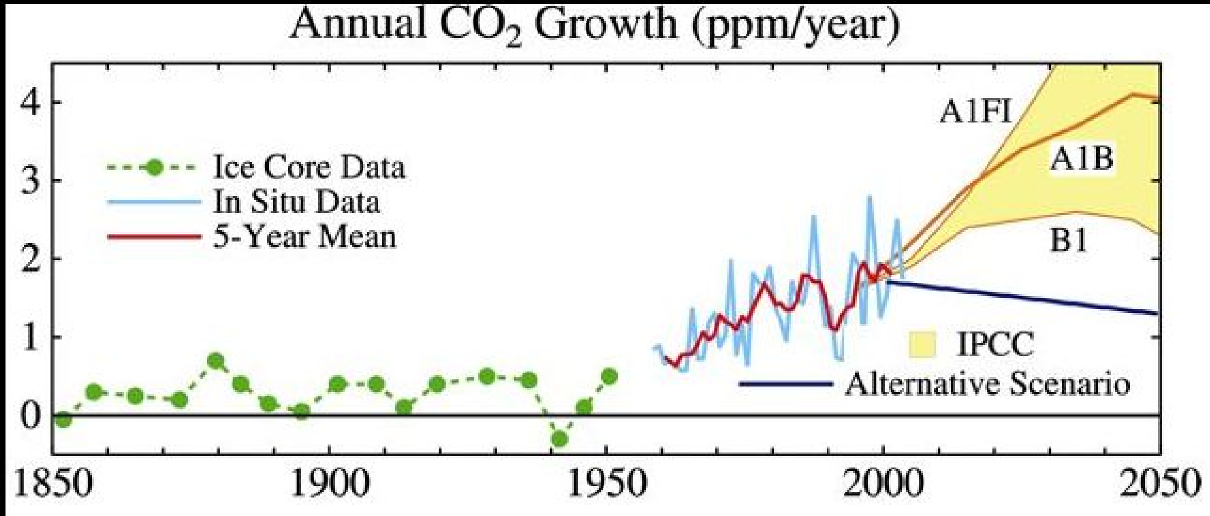
Survival of Species

1. **"Business-as-Usual" Scenario**
   - **Global Warming ~ 3ºC**
   - **Likely Extinctions ~ 50 percent**
2. **"Alternative" Scenario**
   - **Global Warming ~ 1ºC**
   - **Likely Extinctions ~ 10 percent**

Climate Feedbacks → Scenario Dichotomy

Consequences of Global Warming

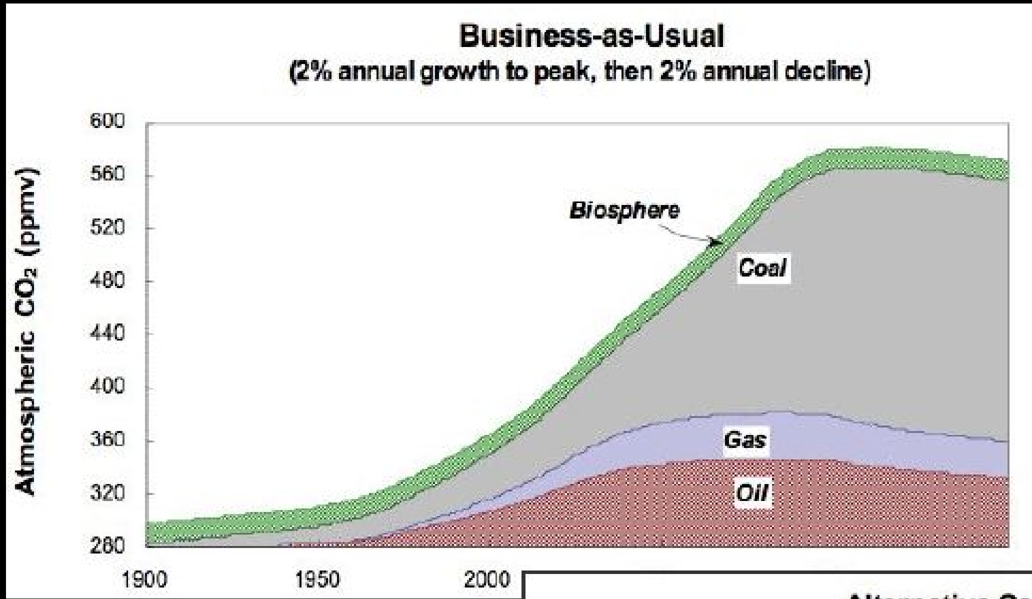
- Accelerating rise in sea levels *(Destruction of cities; relocation of people; loss of land area)*
- More extreme weather (floods, hurricanes, droughts, . . .)
- Ocean thermohaline circulation slowdown or abrupt cessation *(the Gulf Stream stops!)*
- Alteration of natural habitats (extinction of species; potential for increasing desertification; relocation of farms, ranches--threat to food production)
- More heat-related diseases; health deterioration
- Economic strain/failures; increased world tensions (war)

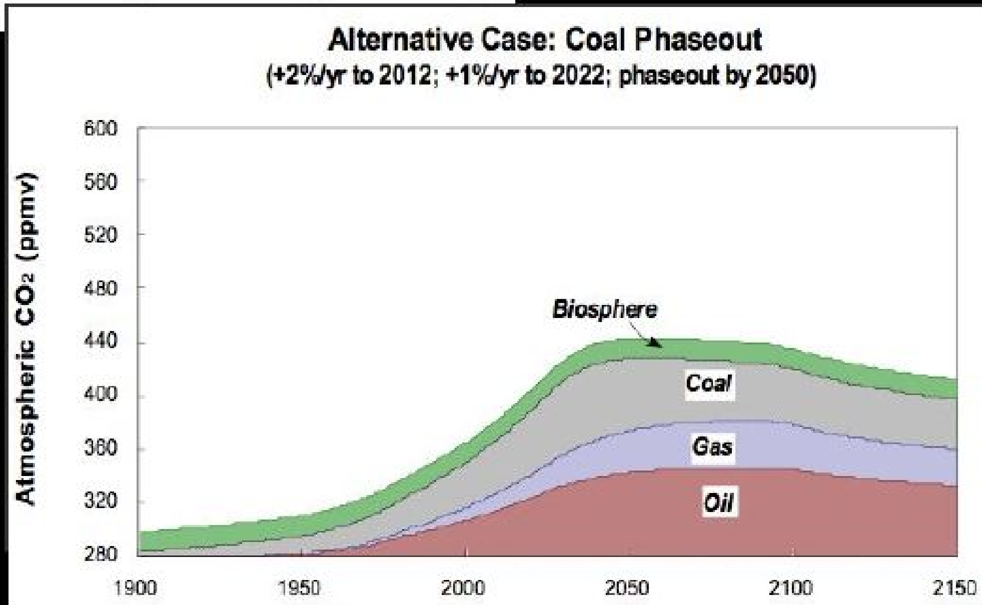


Growth rate of atmospheric CO_2 (ppm/year).

*Source: Hansen and Sato, PNAS, **101**, 16109, 2004.*

We don't change . . .





Toward "450 ppm/yr CO_2" . . .

The telling of the story . . . ozone vs. climate change

	Ozone Case	Global Climate
Scientists	Clear warning	Fail to make clear distinction between climate change and BAU means a different planet
Media	Reported messages well	False "balance"; leap to hopelessness
Special Interests	Initial skepticism, but did not engage in disinformation. Instead, pursued advanced technologies	Disinformation campaigns, emphasis on short-term profits
Public	Quick response (spray cans replaced). No additional CFC infrastructure built	Understandably confused, disinterested
Government	U.S. and Europe leadership. Allowed delay & technical assistance to developing world.	Affected by special interests; fails to leadl assistance to developing world.

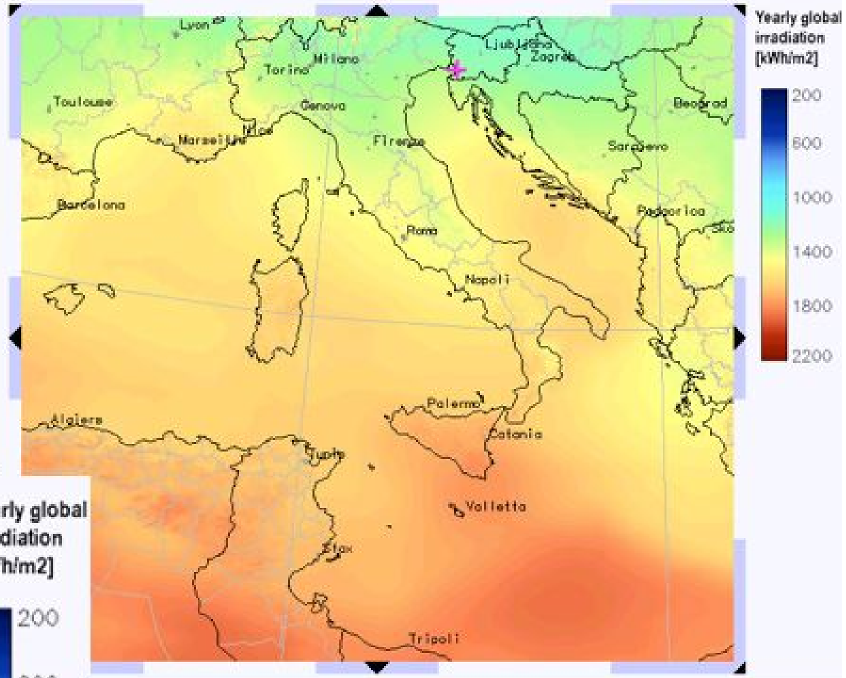

Need to solve the inequities . . .

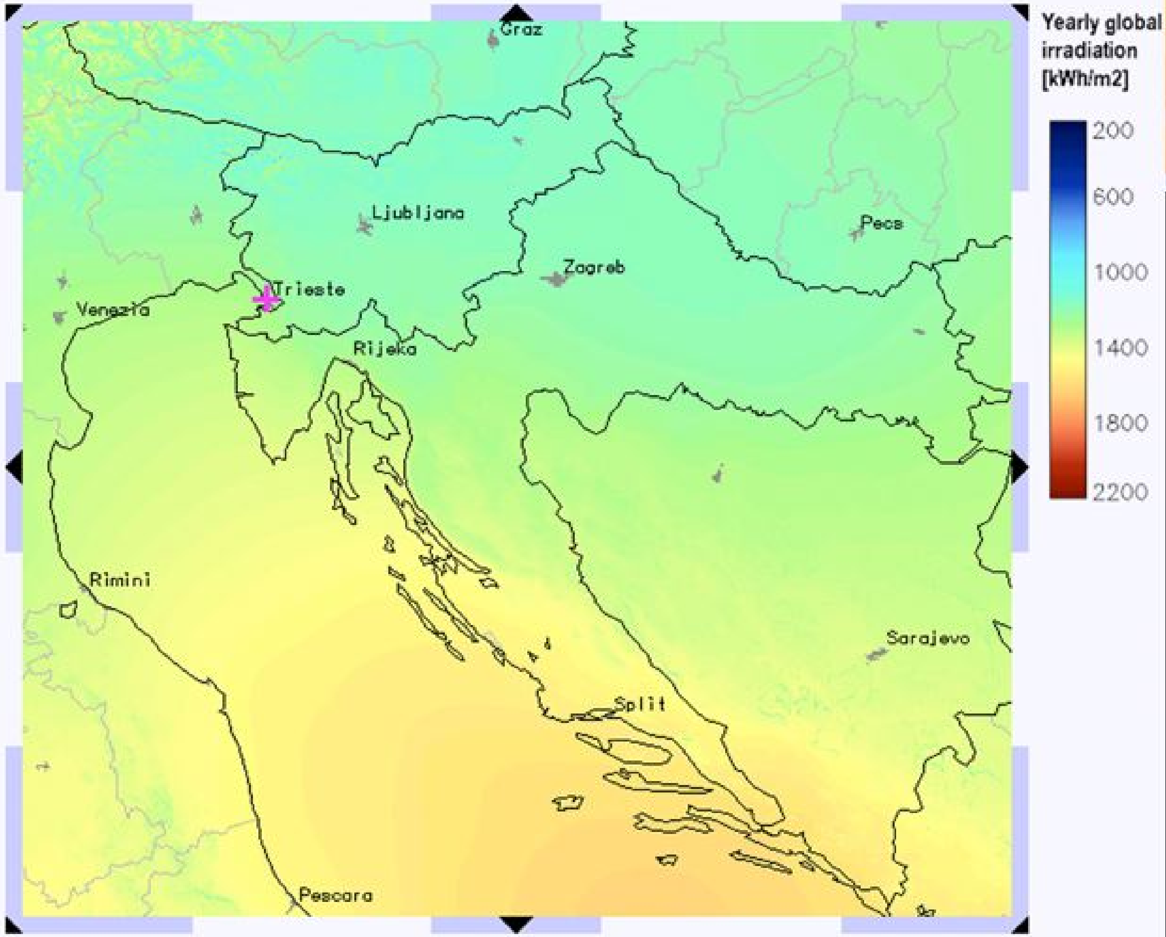
Is *solar* part of the solution?

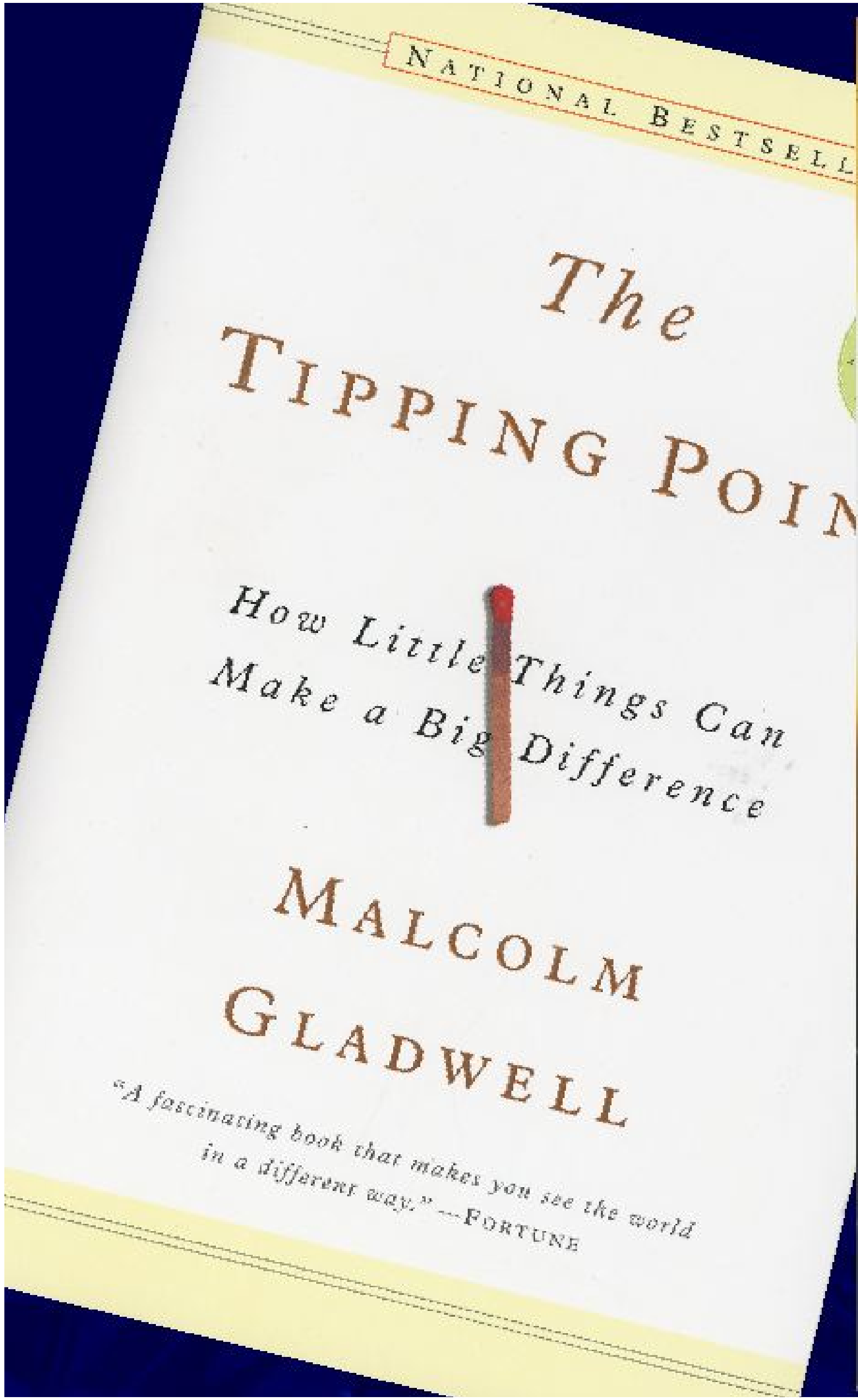
Solar is real . . .
now and for our future

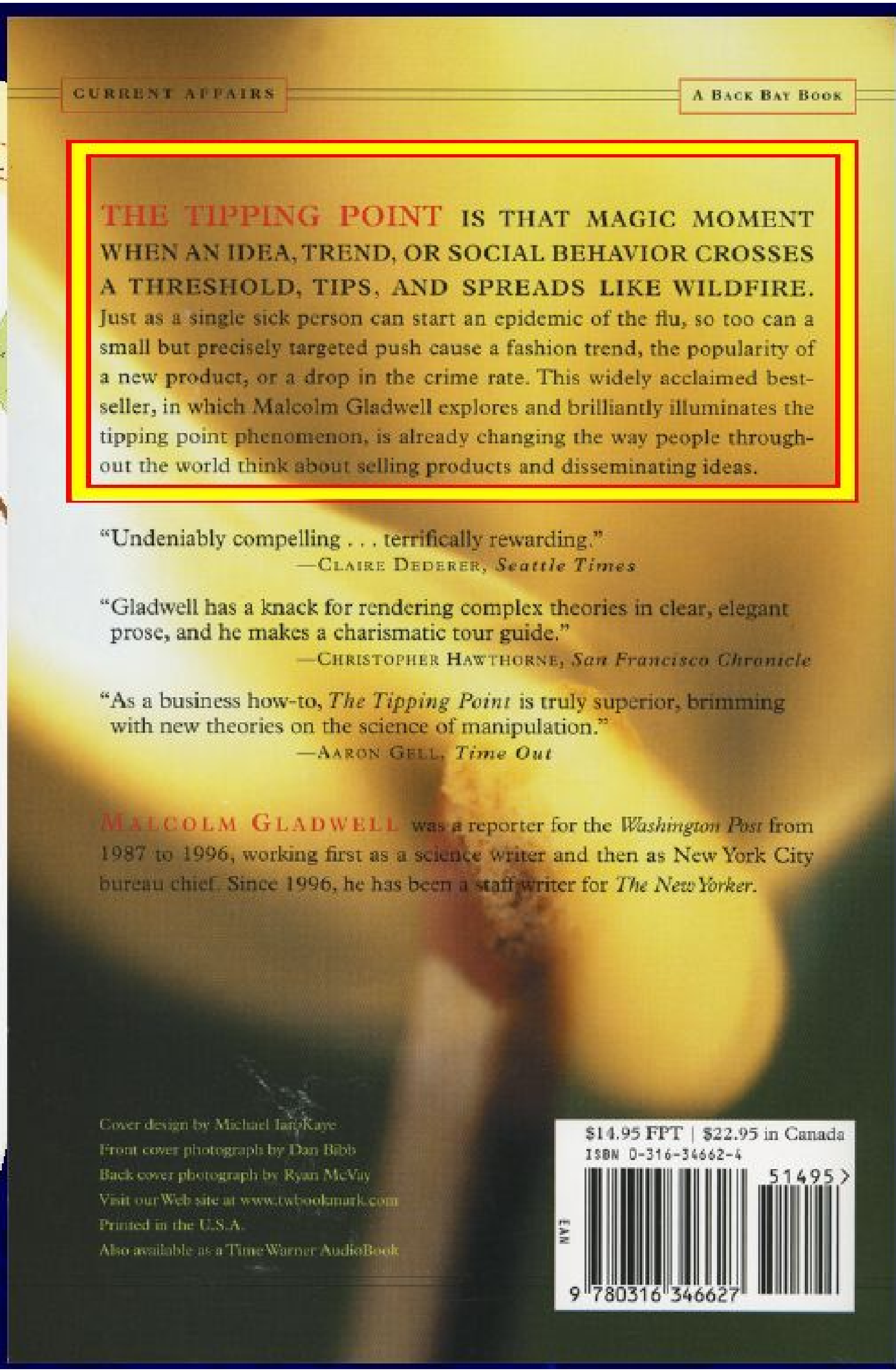
Important issues for solar:

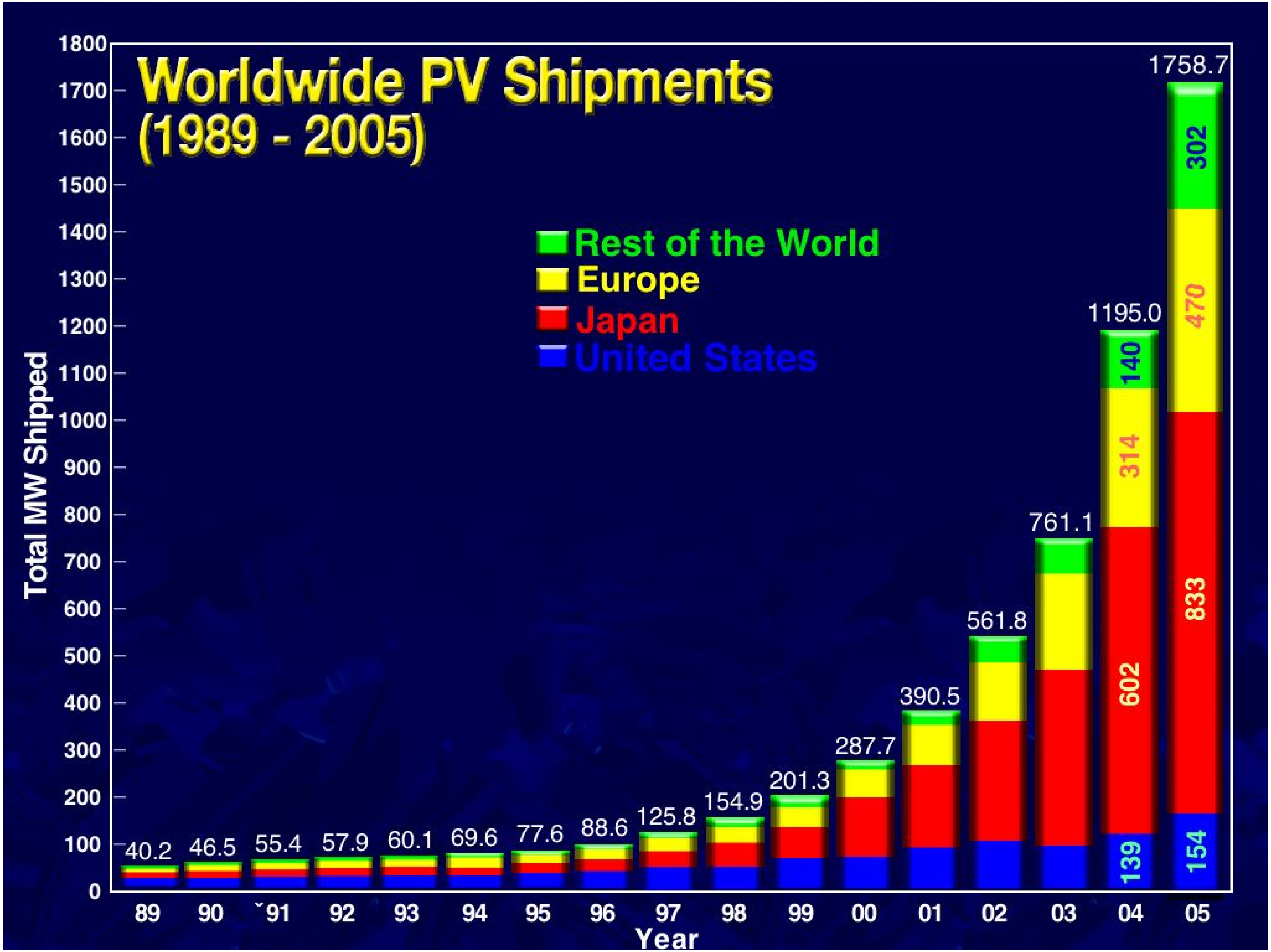
1. Solar Resource *(Need to know)*
2. Efficiency (buildings, appliances, . . .) *(Need to have)*


Yearly global irradiation [kWh/m2]
200
600
1000
1400
1800
2200
Lyon
Ljubljana
Zagreb
Milano
Torino
Toulouse
Genova
Beograd
Marseille
Nice
Firenze
Sarajevo
Barcelona
Podgorica
Roma
Napoli
Palermo
Algiers
Catania
Tunis
Valletta
Sfax
Tripoli

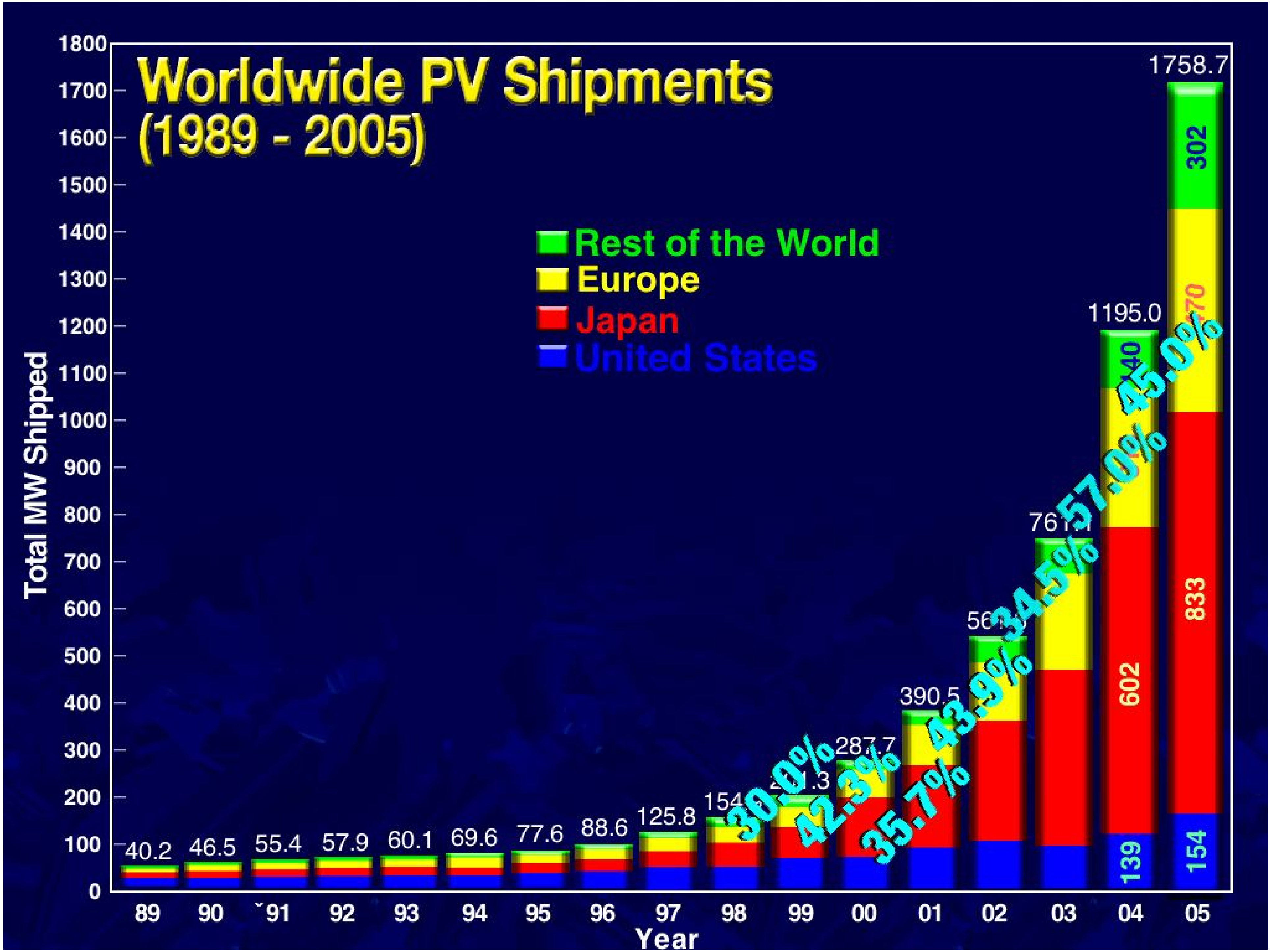

Yearly global irradiation [kWh/m2]
200
600
1000
1400
1800
2200
Graz
Ljubljana
Pecs
Zagreb
Trieste
Venezia
Rijeka
Rimini
Sarajevo
Split
Pescara


NATIONAL
The
TIPPING
How Little Things Can Make a Big Difference
MALCOLM GLADWELL
"A fascinating book that makes you see the world in a different way." —FORTUNE


CURRENT AFFAIRS
A BACK BAY BOOK
THE TIPPING POINT IS THAT MAGIC MOMENT WHEN AN IDEA, TREND, OR SOCIAL BEHAVIOR CROSSES A THRESHOLD, TIPS, AND SPREADS LIKE WILDFIRE. Just as a single sick person can start an epidemic of the flu, so too can a small but precisely targeted push cause a fashion trend, the popularity of a new product, or a drop in the crime rate. This widely acclaimed best-seller, in which Malcolm Gladwell explores and brilliantly illuminates the tipping point phenomenon, is already changing the way people throughout the world think about selling products and disseminating ideas.
"Undeniably compelling . . . terrifically rewarding."
—CLAIRE DEDERER, Seattle Times
"Gladwell has a knack for rendering complex theories in clear, elegant prose, and he makes a charismatic tour guide."
—CHRISTOPHER HAWTHORNE, San Francisco Chronicle
"As a business how-to, The Tipping Point is truly superior, brimming with new theories on the science of manipulation."
—AARON GELL, Time Out
MALCOLM GLADWELL was a reporter for the Washington Post from 1987 to 1996, working first as a science writer and then as New York City bureau chief. Since 1996, he has been a staff writer for The New Yorker.
Cover design by Michael Ian Kaye
Front cover photograph by Dan Bibb
Back cover photograph by Ryan McVay
Visit our Web site at www.twbookmark.com
Printed in the U.S.A.
Also available as a Time Warner AudioBook
$14.95 FPT | $22.95 in Canada
ISBN 0-316-34662-4
51495 >
EAN
9 780316 346627



Worldwide PV Shipments
(1989 - 2005)
Rest of the World
Europe
Japan
United States
Total MW Shipped
Year
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
89
90
ˇ91
92
93
94
95
96
97
98
99
00
01
02
03
04
05
40.2
46.5
55.4
57.9
60.1
69.6
77.6
88.6
125.8
154.9
201.3
287.7
390.5
561.8
761.1
1195.0
1758.7
139
602
314
140
154
833
470
302



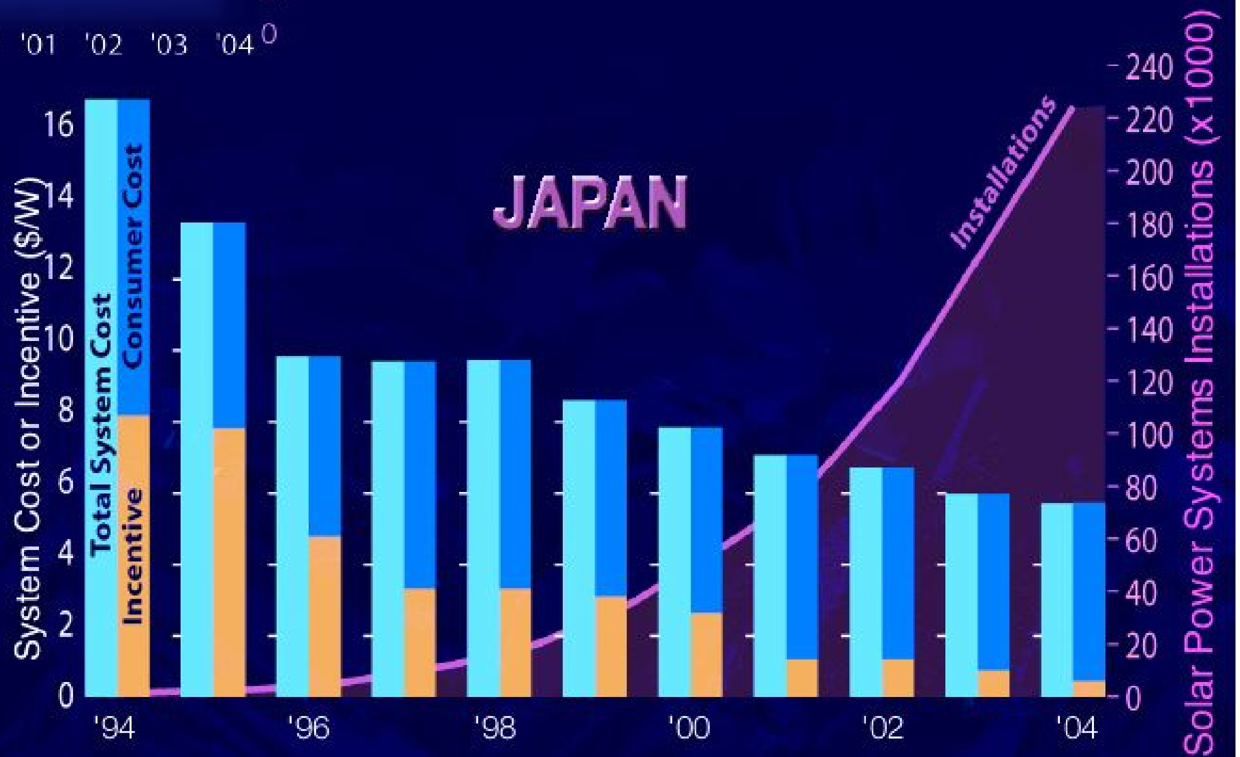
Worldwide PV Shipments
(1989 - 2005)
Rest of the World
Europe
Japan
United States
Total MW Shipped
Year
1758.7
1195.0
761.1
390.5
287.7
125.8
88.6
77.6
69.6
60.1
57.9
55.4
46.5
40.2
30.0%
42.3%
35.7%
43.9%
34.5%
57.0%
45.0%
302
833
154
602
139

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? ~1EU/month!)*

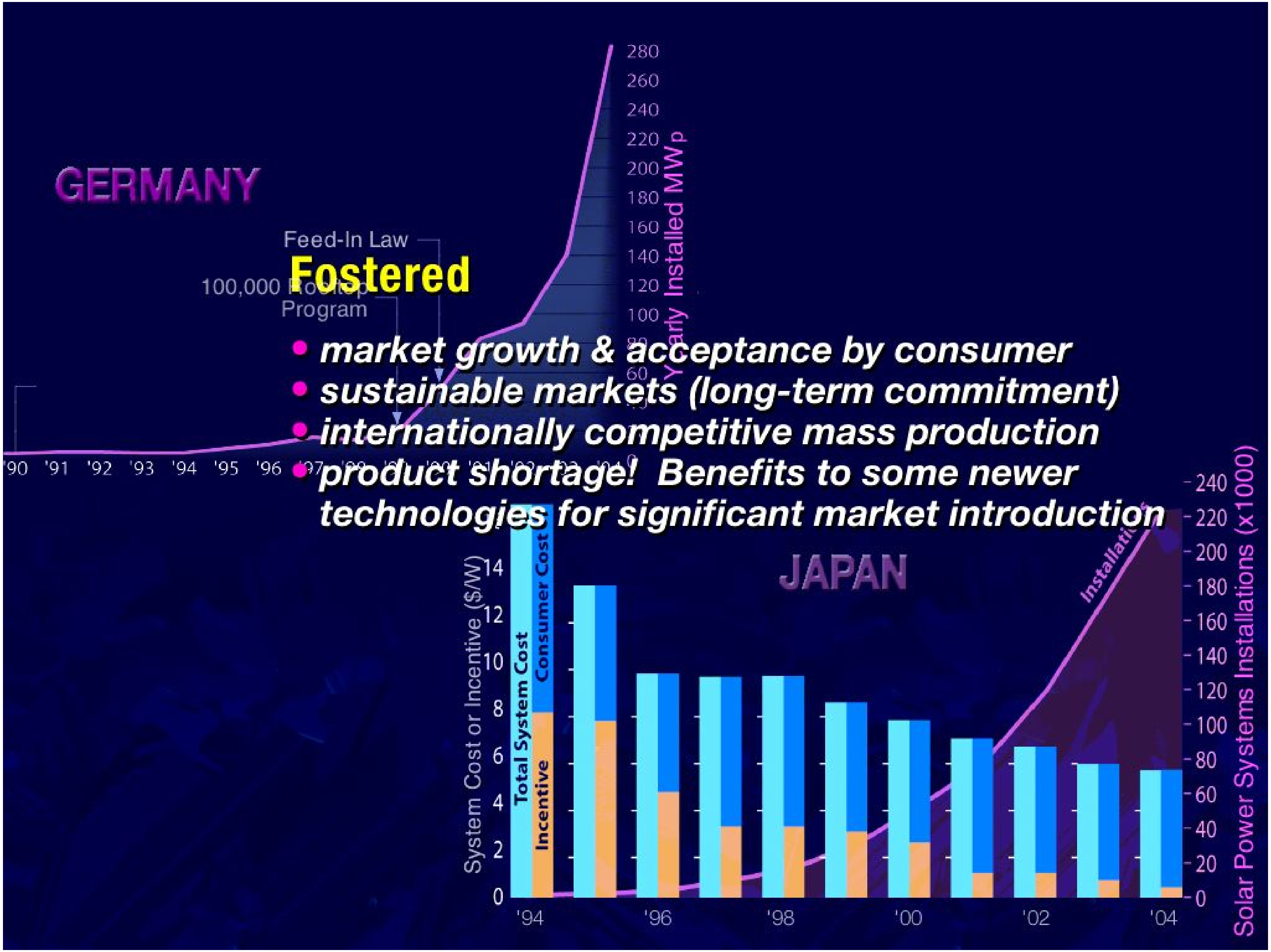
Japan Subsidy Program

- "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



Fostered

- *market growth & acceptance by consumer*
- *sustainable markets (long-term commitment)*
- *internationally competitive mass production*
- *product shortage! Benefits to some newer technologies for significant market introduction*



"What we are proposing . . . really does work. And . . . will deliver the proven benefits of more jobs, a cleaner environment, and more secure domestic energy."

By 2025: 1/2 of new U.S. electricity generation (100 GW)

By 2030: 500-fold growth in U.S. installed capacity over 2004
150-fold growth in U.S. annual shipments
40% reduction in consumer system price
80% reduction in consumer electricity rates
Direct employment more than supported now by General Electric

By 2050: Electricity equivalent to 40%-50% consumed in U.S. buildings

OUR Solar Power FUTURE

The U.S. Photovoltaics Industry Roadmap Through 2030 and Beyond

How?

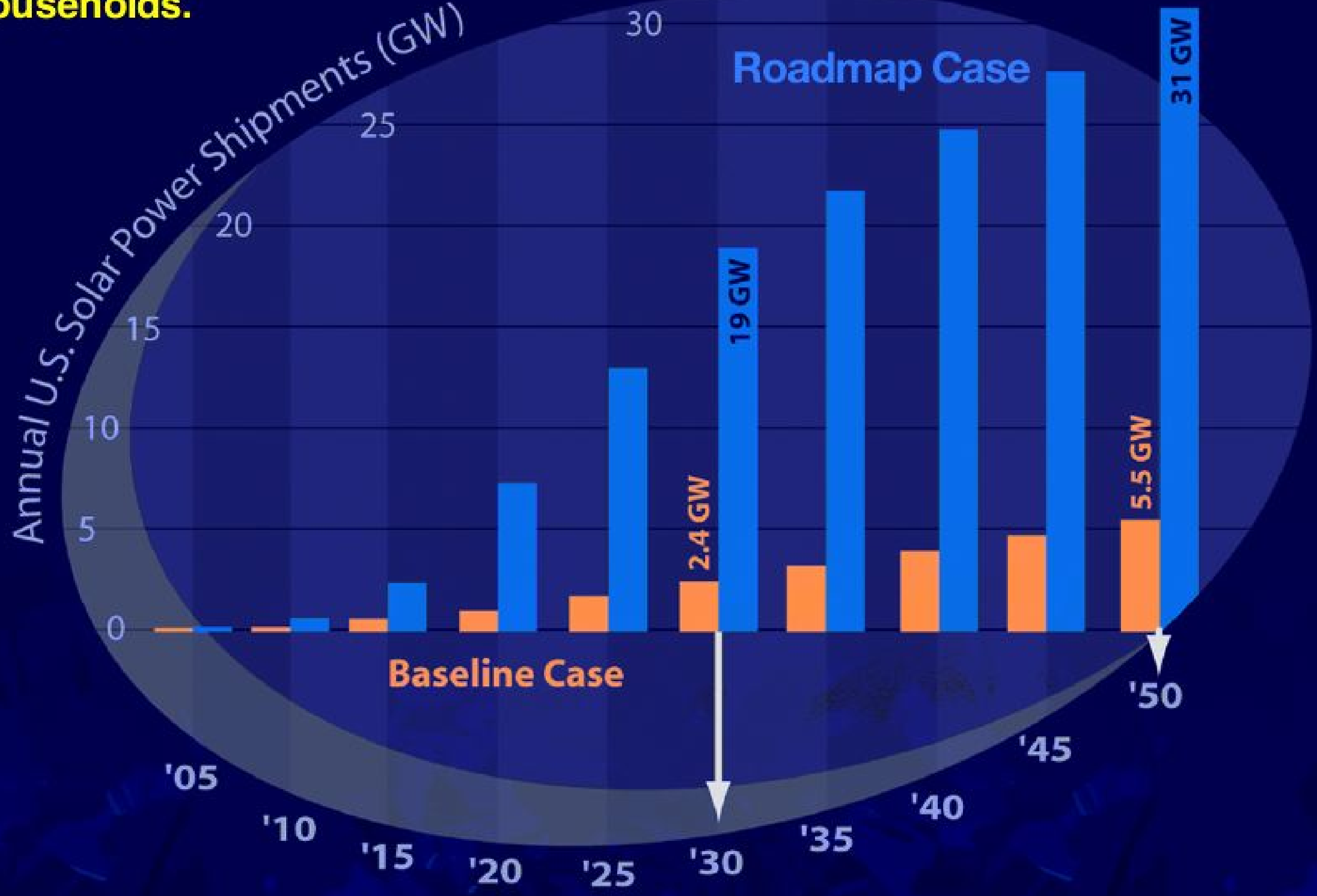
Reclaiming Market Leadership (Policies)

- Enact residential and commercial tax credits
- Establish uniform net metering and interconnection standards
- Boost federal government procurements (especially in applications to enhance security)
- Support state public benefit charge programs and other state & local initiatives; build strategic alliances with public & private oganizations

Maintaining Technology Ownership (R&D)

- Increase R&D investment to $250M/year by 2010
- Strengthen investments in crystalline silicon, thin film, and balance-of-systems components/new systems concepts
- Support higher-risk, longer-term R&D that can leapfrog beyond today's technologies (performance/cost)
- Enhance funding for facilities and equipment to shorten the time between lab discovery and industry use in manufacturing and products
- Grow partnerships among industry, universities and national laboratories

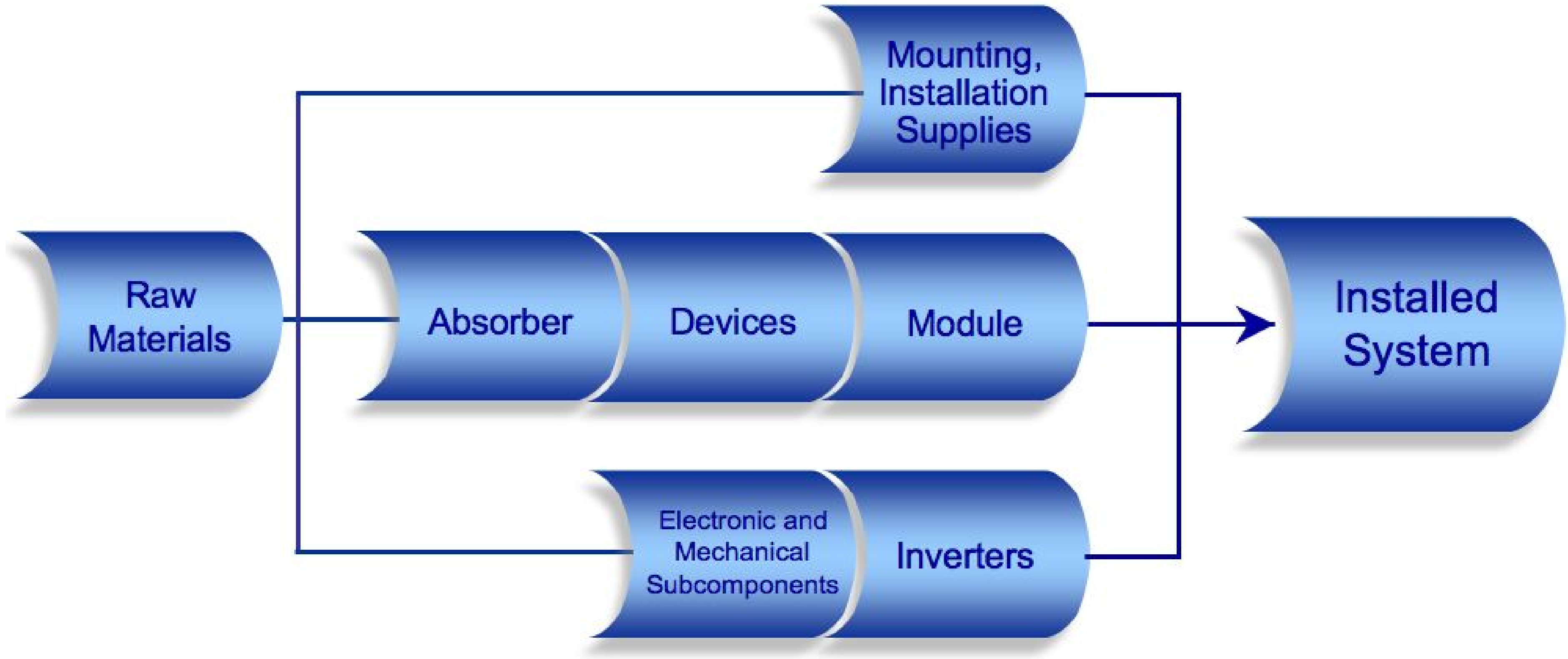
The Roadmap case would enhance annual solar electricty generation in 2030 by 360-billion kWh over the Baseline case—the amount of electricity consumed by 34 million households.



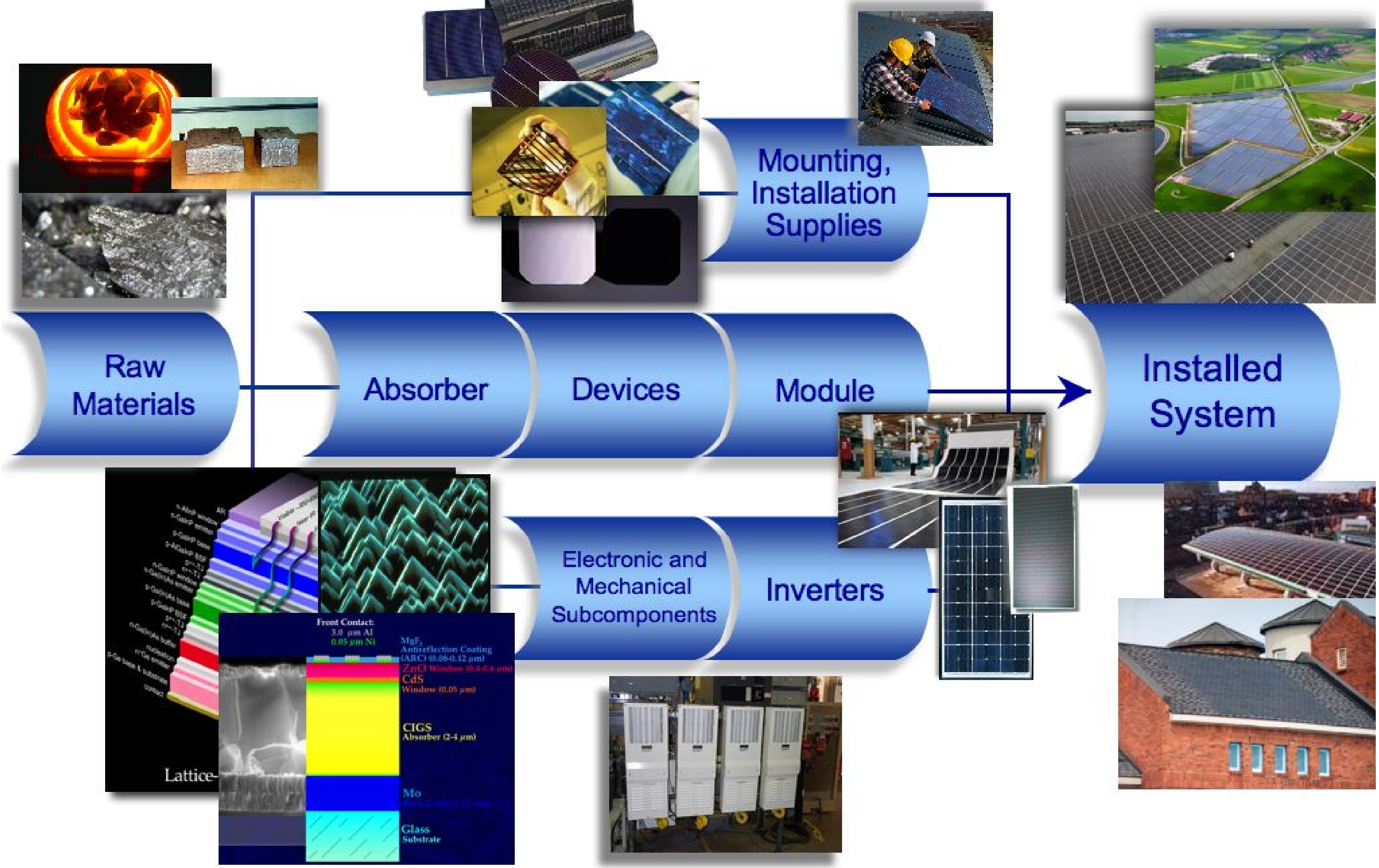
Comparison of annual U.S. solar power shipments under the Baseline and Roadmap cases.

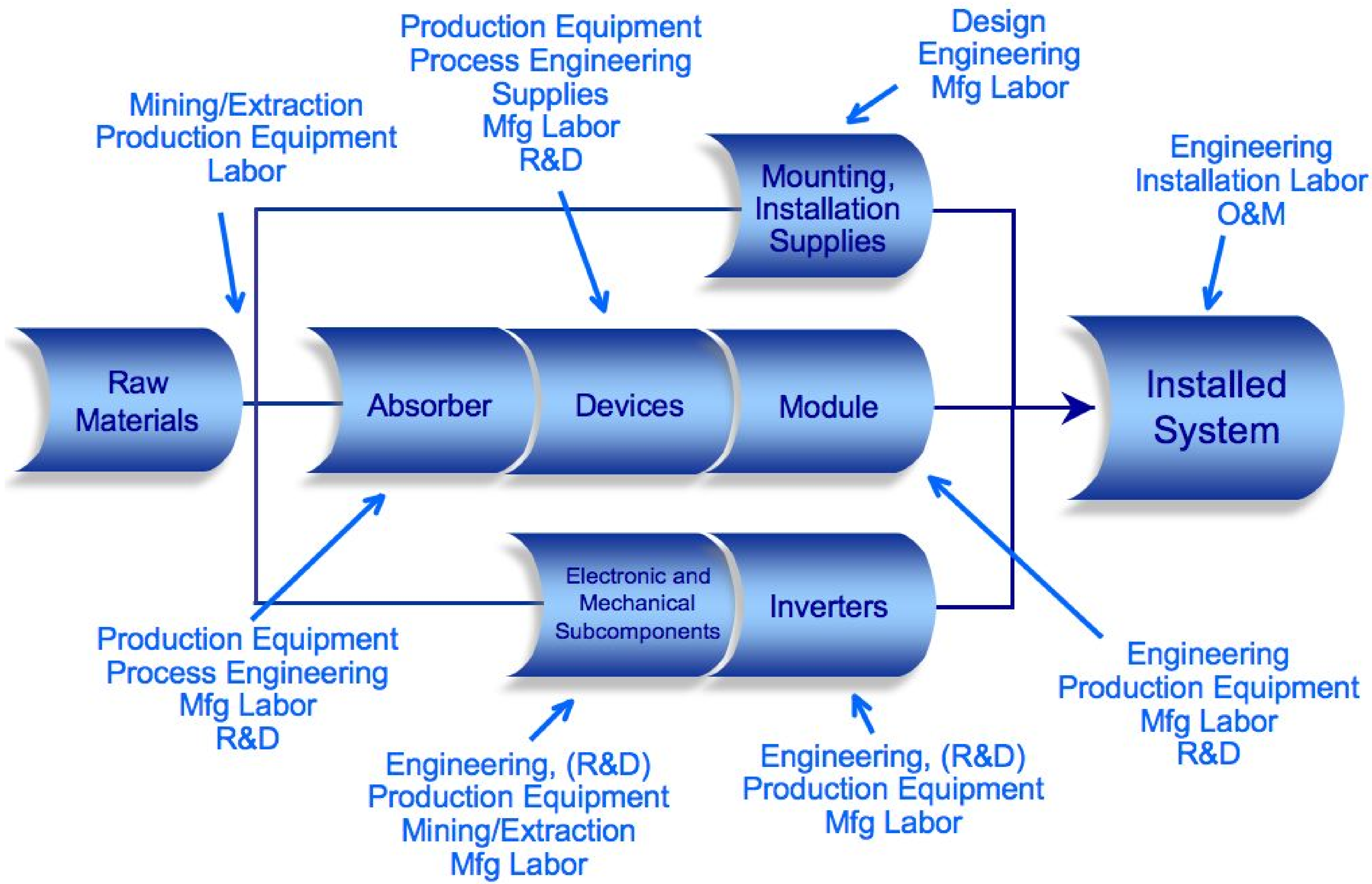
2030 and 2050 differences are highlighted by the arrows.

PV System Value Chain

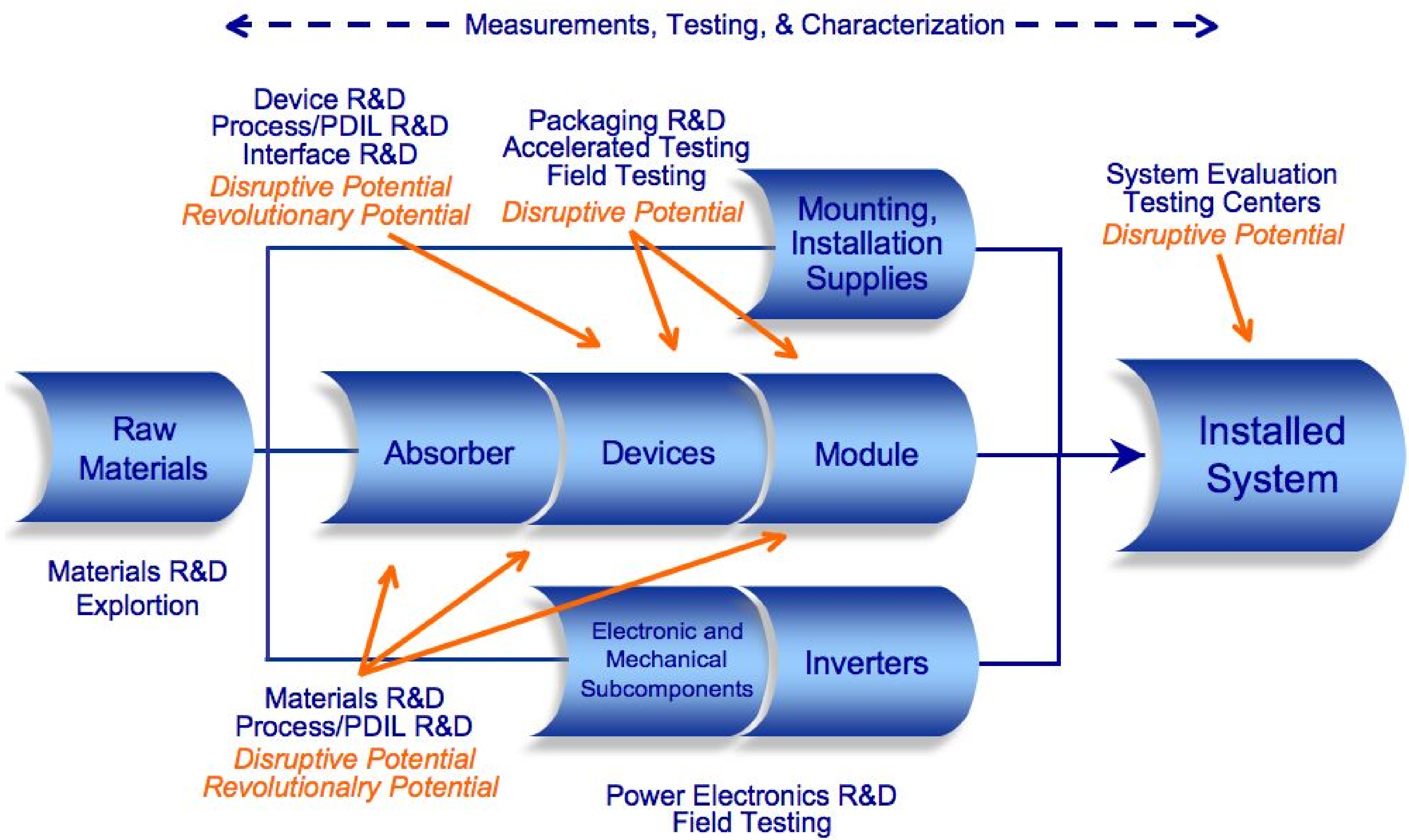


PV System Value Chain

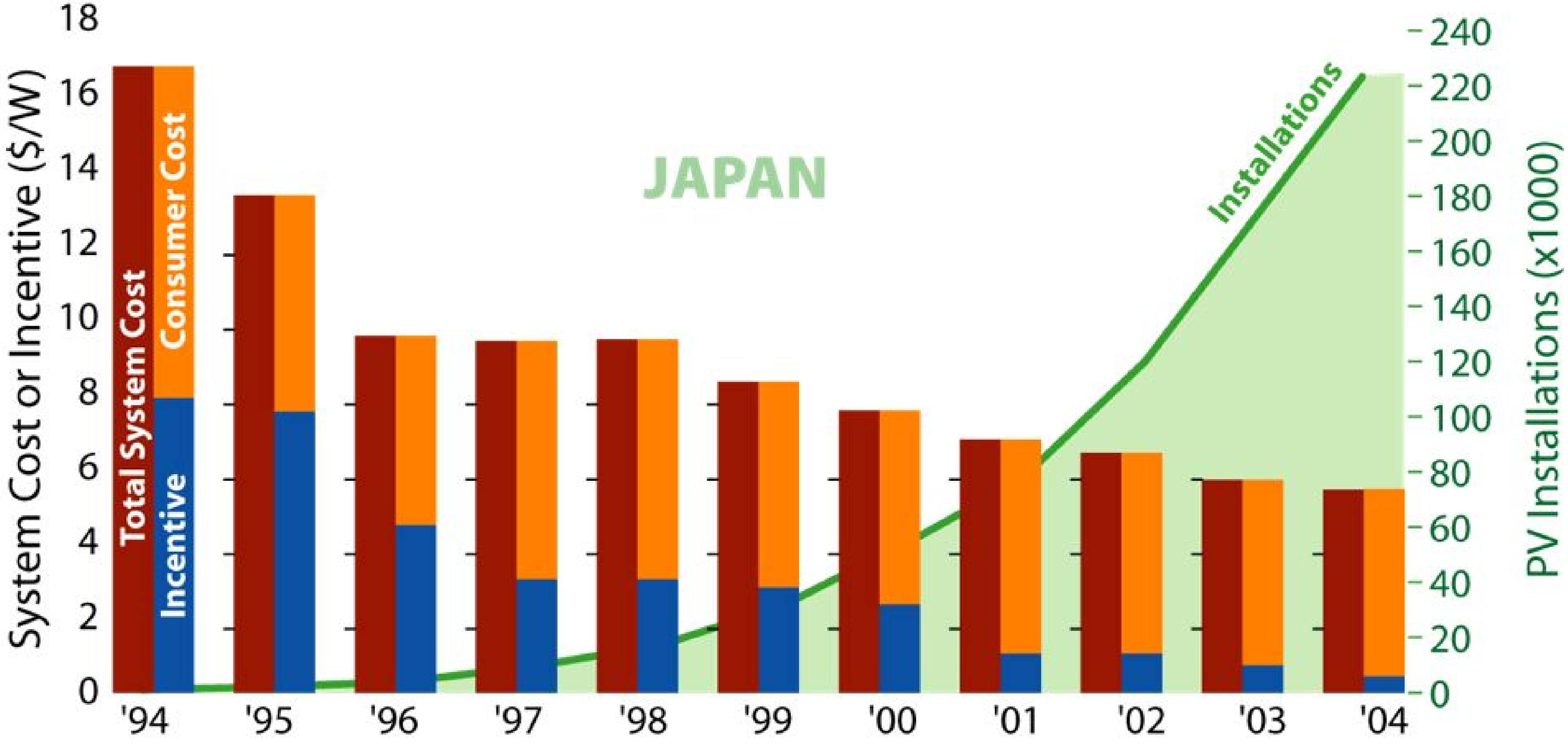


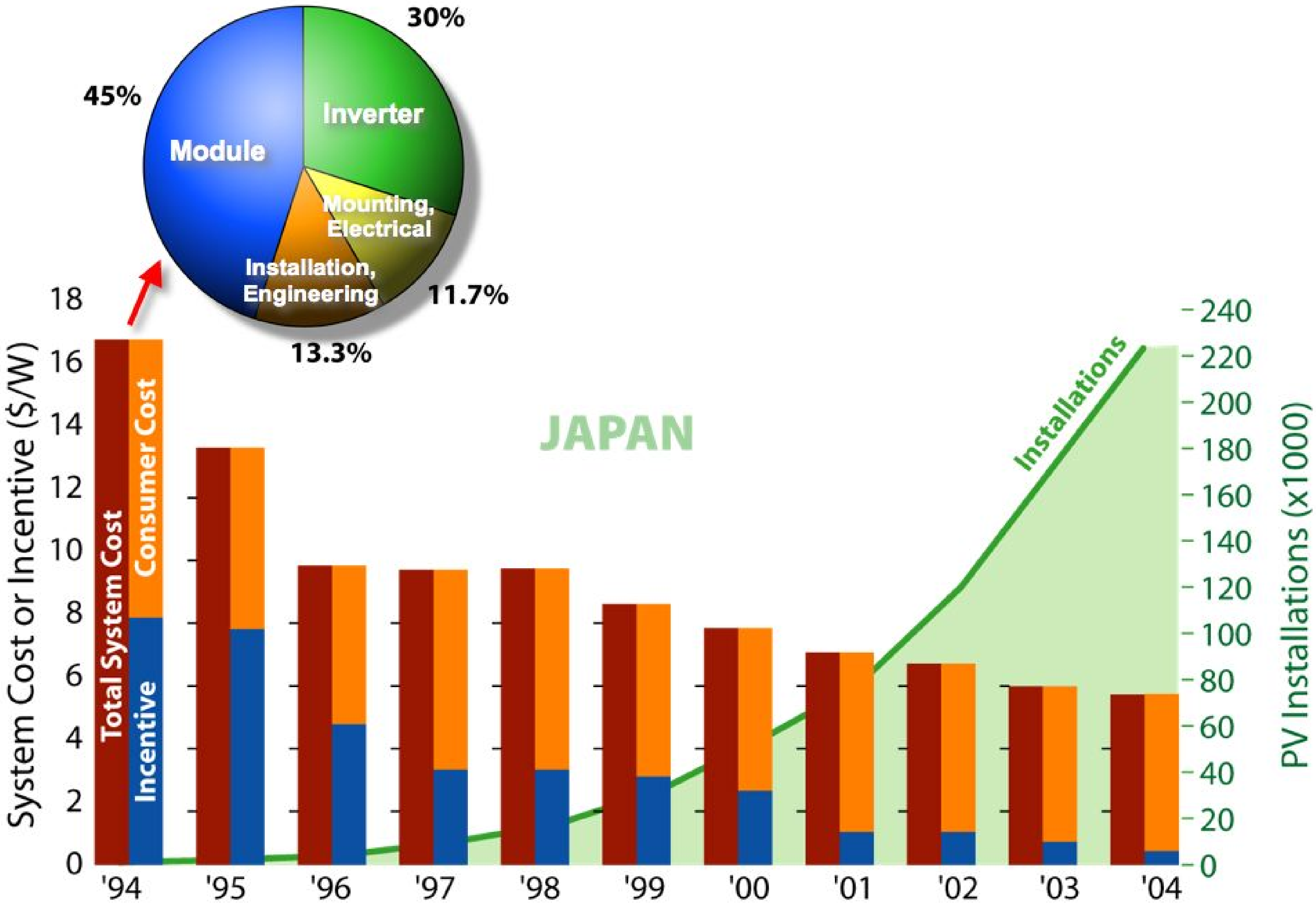

Production Equipment
Process Engineering
Supplies
Mfg Labor
R&D
Design
Engineering
Mfg Labor
Mining/Extraction
Production Equipment
Labor
Mounting,
Installation
Supplies
Engineering
Installation Labor
O&M
Raw
Materials
Absorber
Devices
Module
Installed
System
Electronic and
Mechanical
Subcomponents
Inverters
Production Equipment
Process Engineering
Mfg Labor
R&D
Engineering
Production Equipment
Mfg Labor
R&D
Engineering, (R&D)
Production Equipment
Mining/Extraction
Mfg Labor
Engineering, (R&D)
Production Equipment
Mfg Labor

Value Chain and Key Competencies

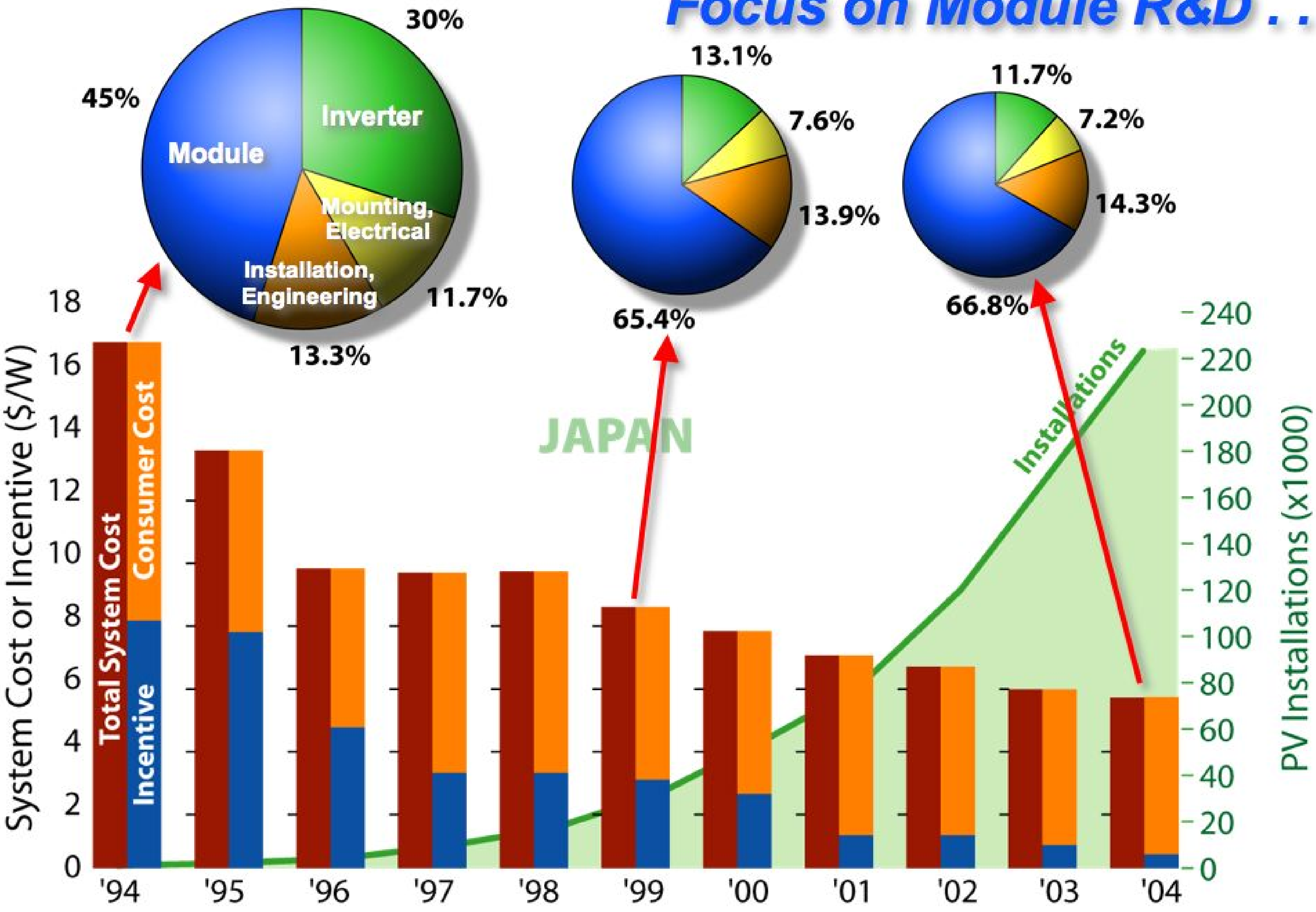


But, where to make the investment?

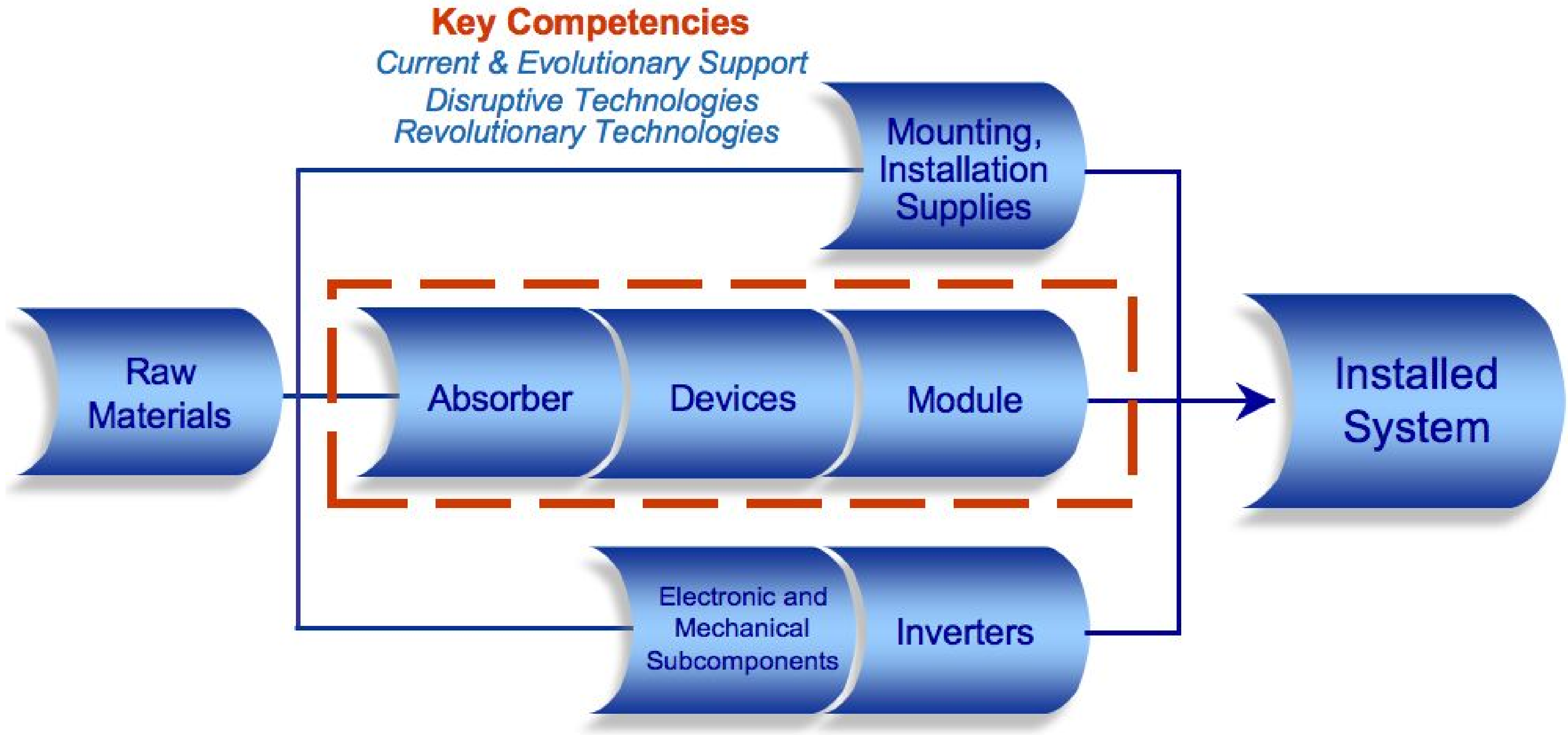


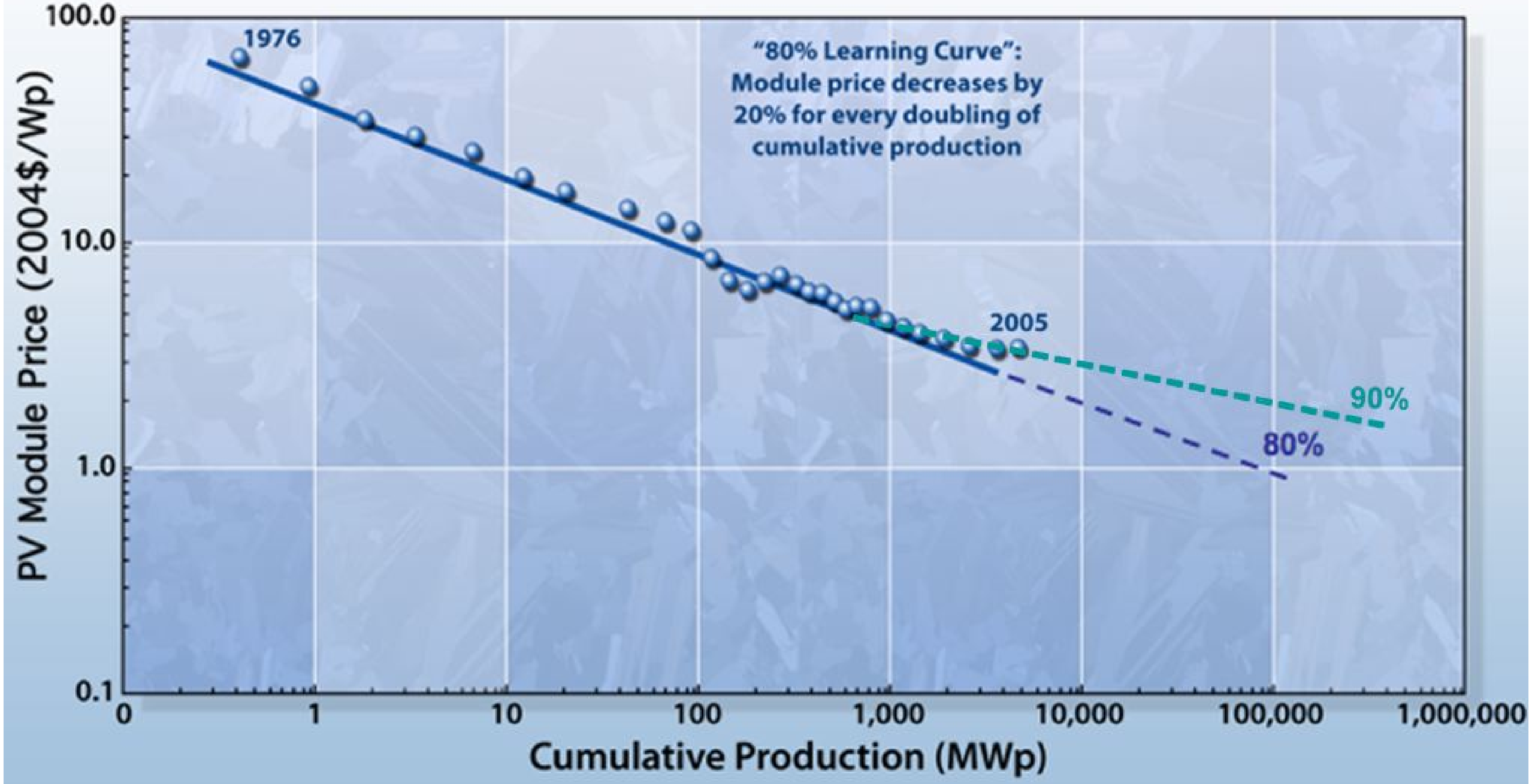

30%
45%
Inverter
Module
Mounting, Electrical
Installation, Engineering
11.7%
13.3%
18
16
14
12
10
8
6
4
2
0
System Cost or Incentive ($/W)
Total System Cost
Consumer Cost
Incentive
JAPAN
Installations
240
220
200
180
160
140
120
100
80
60
40
20
0
PV Installations (x1000)
'94
'95
'96
'97
'98
'99
'00
'01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

Focus on Module R&D . . .



PV System Value Chain





1976
"80% Learning Curve":
Module price decreases by
20% for every doubling of
cumulative production
2005
90%
80%
100.0
10.0
1.0
0.1
PV Module Price (2004$/Wp)
0
1
10
100
1,000
10,000
100,000
1,000,000
Cumulative Production (MWp)

Technololgy Investment Pathways

1st Generation PV
- Silicon

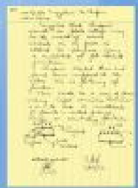
Evolutionary
(5-15 years)

The Beginning at Bell

April 25, 1954 – At a New York press conference, Daryl Chapin, Calvin Fuller, and Gerald Pearson present to the public the first material to directly convert enough sunlight into electricity to generate useful amounts of power. The New York Times recognizes their work as marking "the beginning of a new era, leading eventually to the realization of one of mankind's most cherished dreams—the harnessing of the almost limitless energy of the sun for the uses of civilization."

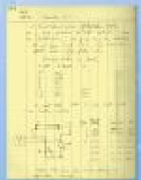
January 1954 – Starting with arsenic-doped silicon, Fuller diffuses boron to form a thin p-layer on top of the arsenic silicon. Chapin tests the new material and reports increased efficiencies, with the best cell converting 6% of incoming sunlight into electricity.

November/December 1953 – No matter what he tries, Chapin cannot exceed 4% efficiency with phosphorus-diffused silicon.



September/October 1953 – Chapin reports that a phosphorus-diffused silicon cell outperforms Pearson's original cell by a factor of 2, reaching 4% efficiency, and he proceeds to build a 0.1-watt solar generator.

May/June 1953 – Chapin chooses to concentrate on silicon in his photoelectric studies. Failing to get more power from other lithium-diffused silicon devices, he experiments with several phosphorus-diffused silicon cells produced in Fuller's diffusion furnace. Phosphorus-diffused silicon is more stable, and the p-n junction can be brought closer to the surface.



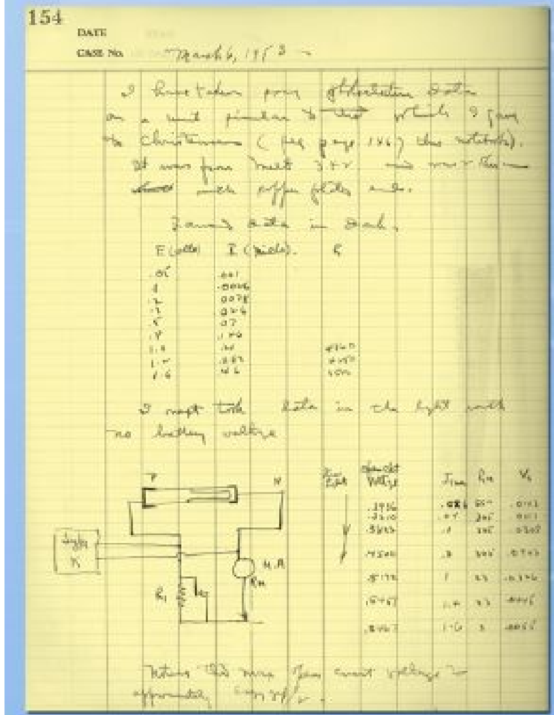
March 1953 – Pearson provides a device to Chapin, who reports obtaining 5 times more power from this sample than from previously tested commercial selenium cells. Chapin estimates that a lithium-diffused silicon device could theoretically produce 60 times more power than commercial selenium.

March 1953 – Gerald Pearson detects a strong photovoltaic effect in a rectifier built according to Fuller's diffusion method.

January-February 1953 – Daryl Chapin begins testing selenium solar cells in his studies of stand-alone power systems.

1952 – Calvin Fuller produces p-n junctions in silicon by lithium diffusion.

1947 – The transistor is invented.



March 1953 – Pearson provides a device to Chapin, who reports obtaining 5 times more power from this sample than from previously tested commercial selenium cells. Chapin estimates that a lithium-diffused silicon device could theoretically produce 60 times more power than commercial selenium.

March 1953 – Gerald Pearson detects a strong photovoltaic effect in a rectifier built according to Fuller's diffusion method.

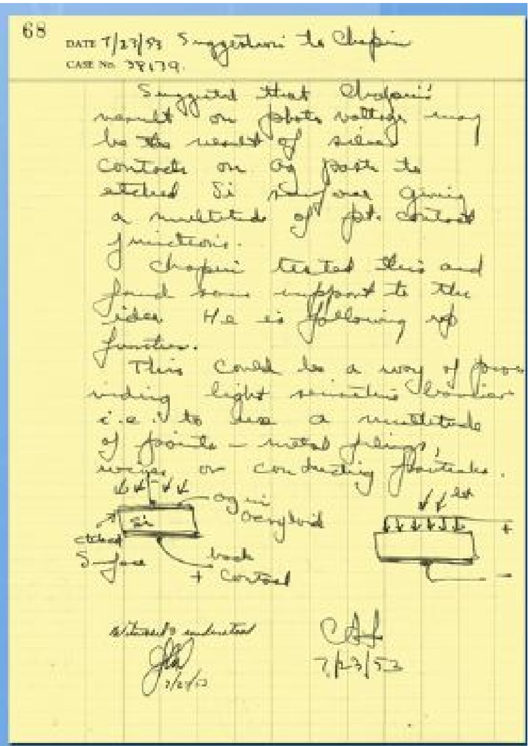
January-February 1953 – Daryl Chapin begins testing selenium solar cells in his studies of stand-alone power systems.

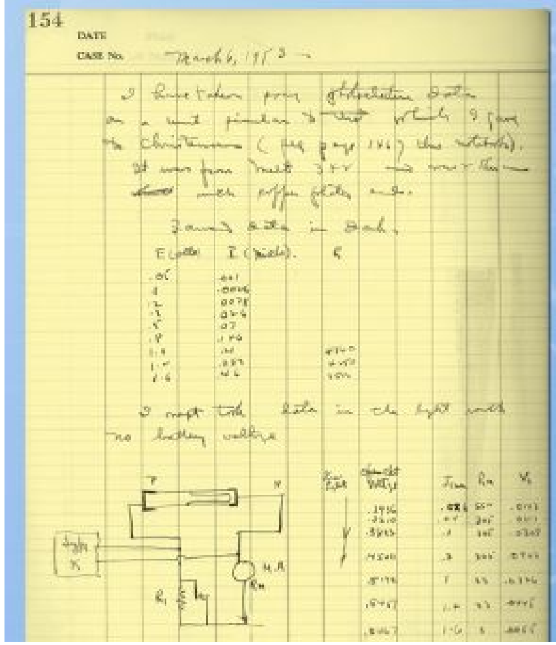
1952 – Calvin Fuller produces p-n junctions in silicon by lithium diffusion.

1947 – The transistor is invented.

September/October 1953 – Chapin reports that a phosphorus-diffused silicon cell outperforms Pearson's original cell by a factor of 2, reaching 4% efficiency, and he proceeds to build a 0.1-watt solar generator.

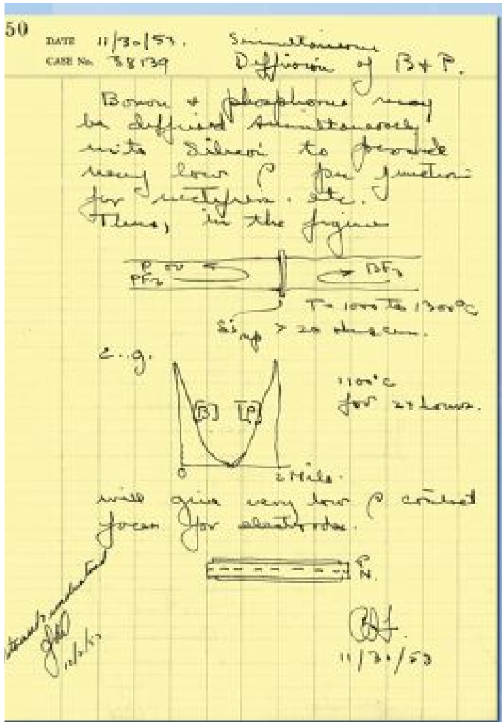
May/June 1953 – Chapin chooses to concentrate on silicon in his photoelectric studies. Failing to get more power from other lithium-diffused silicon devices, he experiments with several phosphorus-diffused silicon cells produced in Fuller's diffusion furnace. Phosphorus-diffused silicon is more stable, and the p-n junction can be brought closer to the surface.





March 1953 – Pearson provides a device to Chapin, who reports obtaining 5 times more power from this sample than from previously tested commercial selenium cells. Chapin estimates that a lithium-diffused silicon device could theoretically produce 60 times more power than commercial selenium.

March 1953 – Gerald Pearson detects a strong photovoltaic effect in a rectifier built according to Fuller's diffusion method.

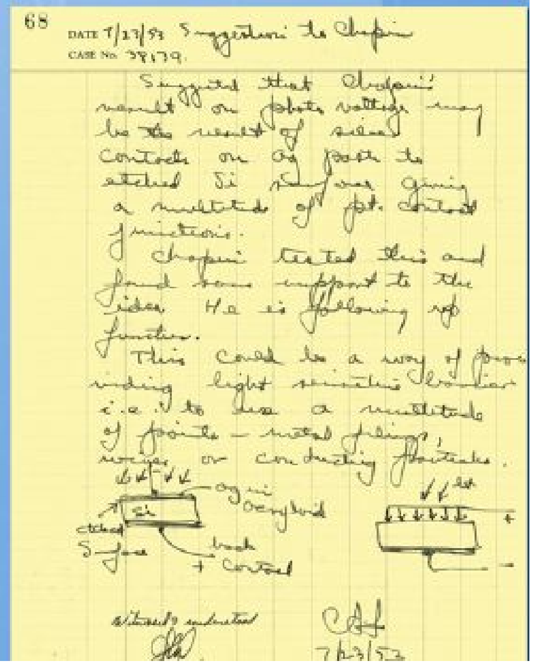


January 1954 – Starting with arsenic-doped silicon, Fuller diffuses boron to form a thin p-layer on top of the arsenic silicon. Chapin tests the new material and reports increased efficiencies, with the best cell converting 6% of incoming sunlight into electricity.

November/December 1953 – No matter what he tries, Chapin cannot exceed 4% efficiency with phosphorus-diffused silicon.

September/October 1953 – Chapin reports that a phosphorus-diffused silicon cell outperforms Pearson's original cell by a factor of 2, reaching 4% efficiency, and he proceeds to build a 0.1-watt solar generator.

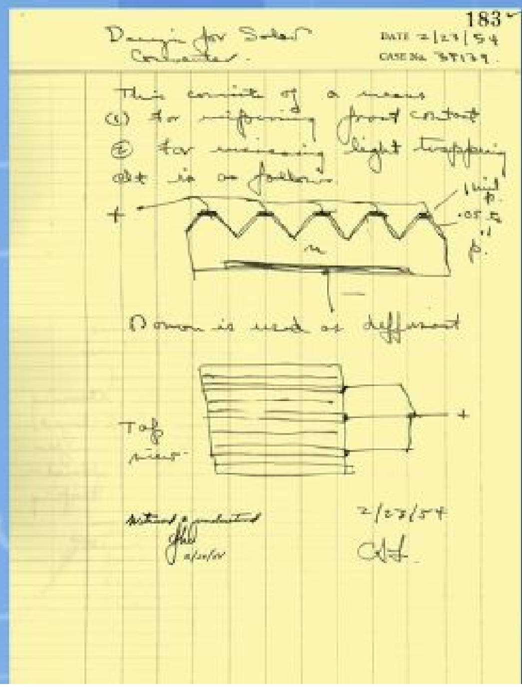
May/June 1953 – Chapin chooses to concentrate on silicon in his photoelectric studies. Failing to get more power from other lithium-diffused silicon devices, he experiments with several phosphorus-diffused silicon cells produced in Fuller's diffusion furnace. Phosphorus-diffused silicon is more stable, and the p-n

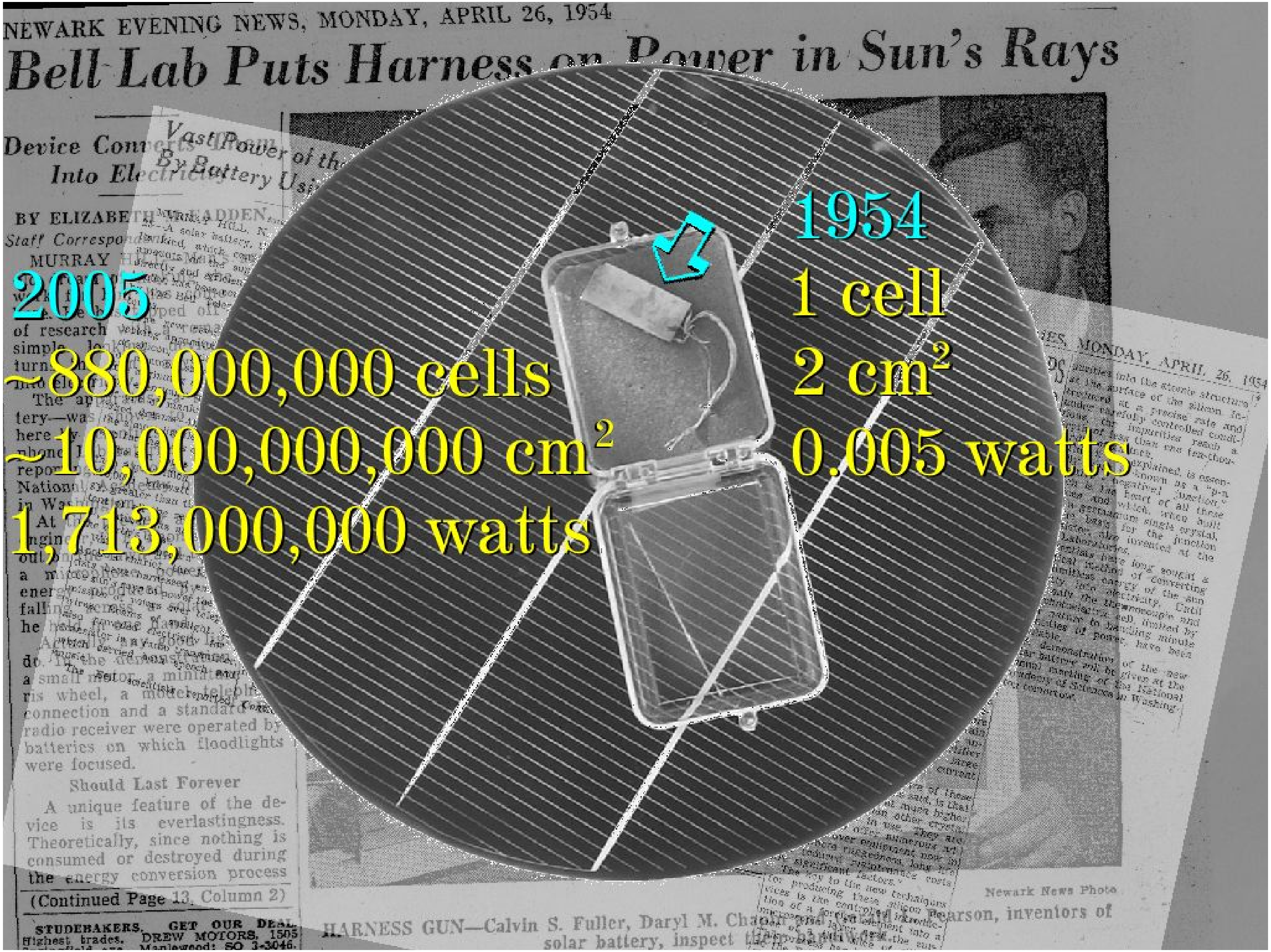


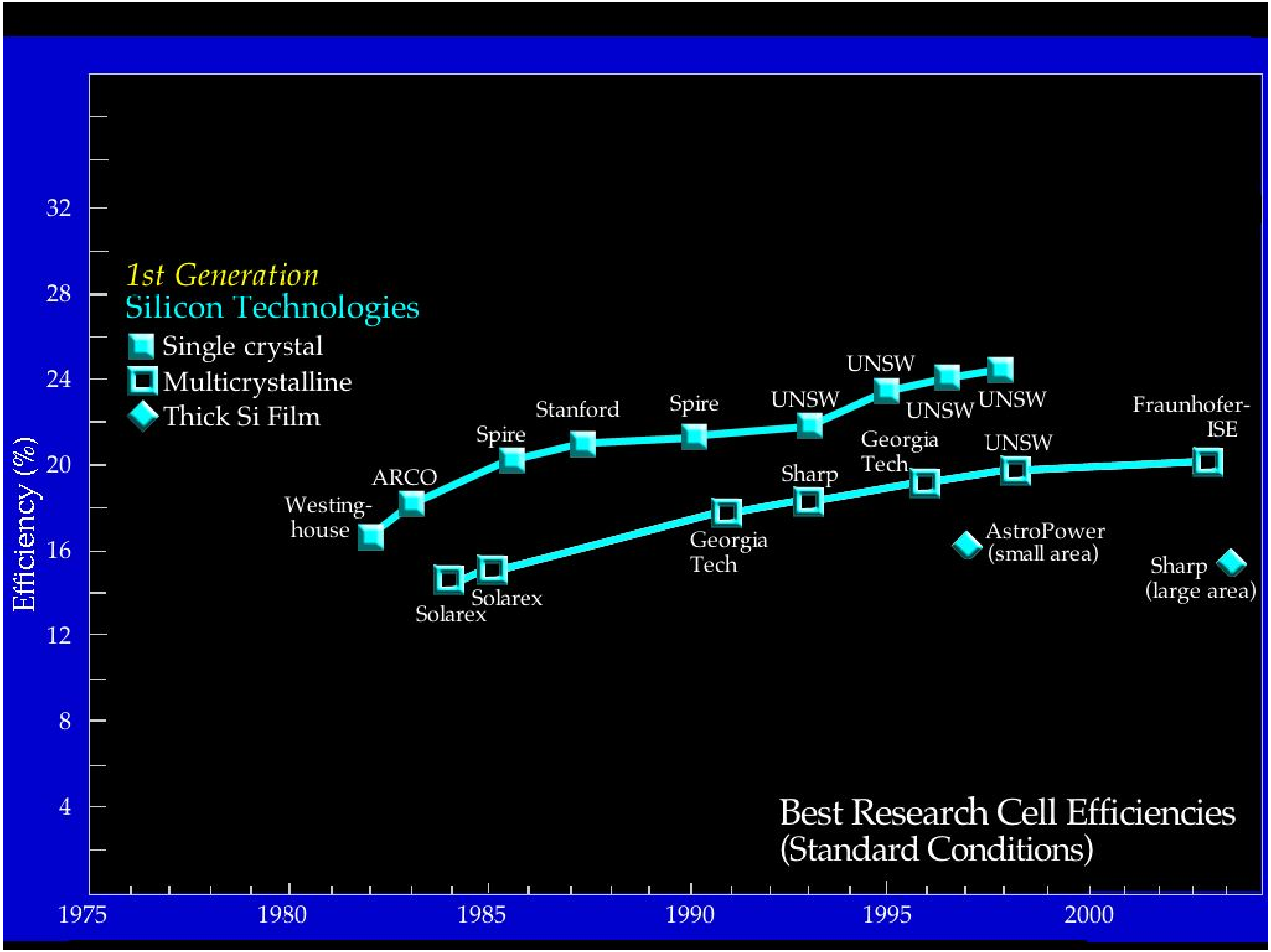
The Beginning at Bell

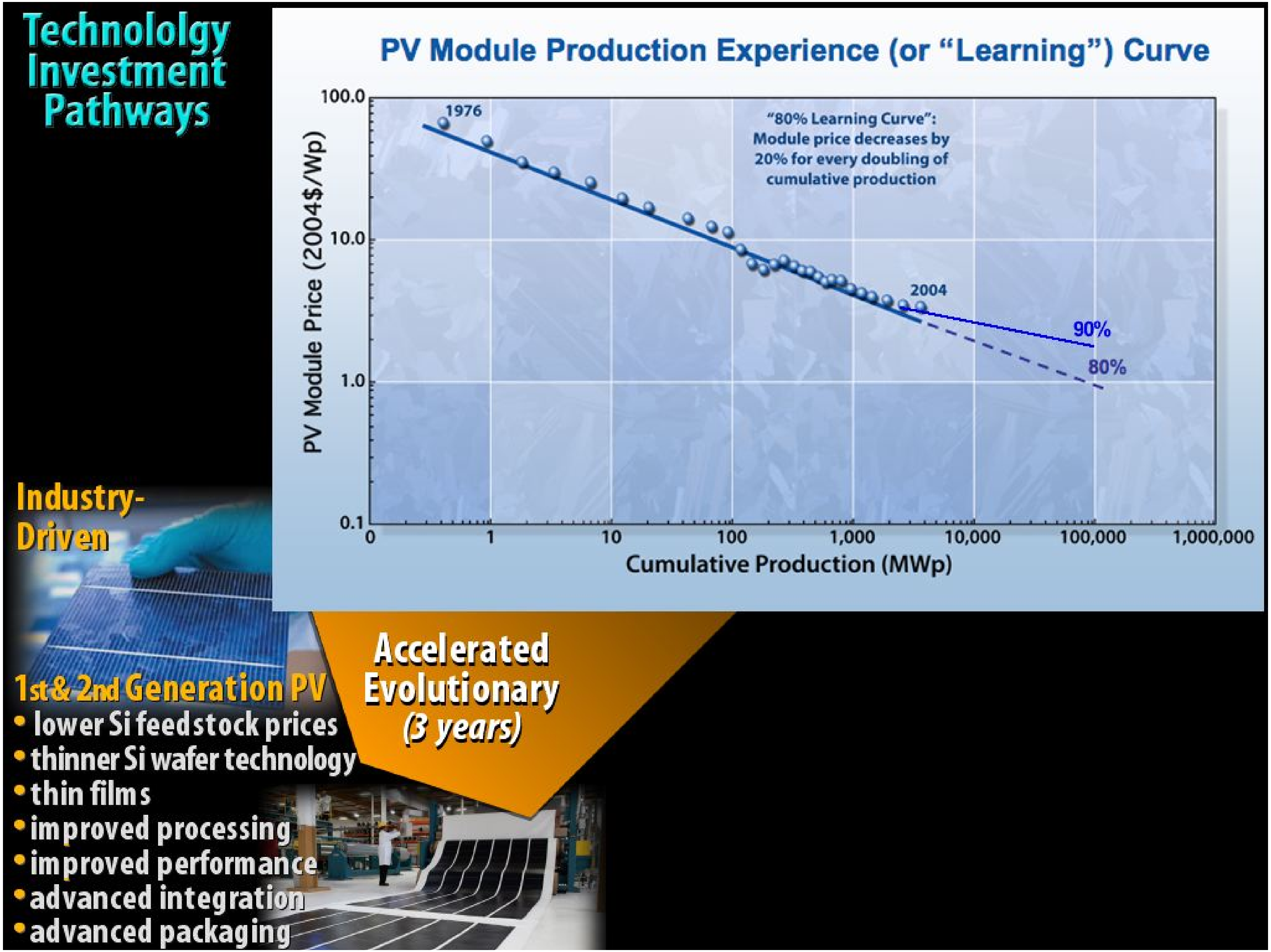
Need to move renewable technologies faster from the laboratory bench *(research stage)* to the consumer *(commercial stage)*--like Bell Laboratories did 50 years ago

April 25, 1954 – At a New York press conference, Daryl Chapin, Calvin Fuller, and Gerald Pearson present to the public the first material to directly convert enough sunlight into electricity to generate useful amounts of power. The New York Times recognizes their work as marking "the beginning of a new era, leading eventually to the realization of one of mankind's most cherished dreams—the harnessing of the almost limitless energy of the sun for the uses of civilization."

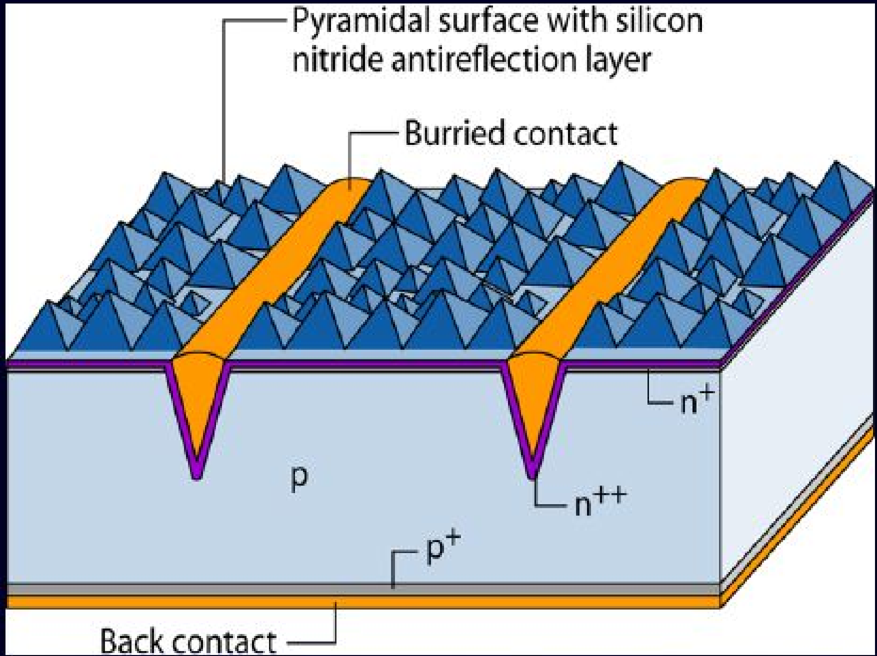



NEWARK EVENING NEWS, MONDAY, APRIL 26, 1954
Bell Lab Puts Harness
ower in Sun's Rays
2005
~880,000,000 cells
~10,000,000,000 cm²
1,713,000,000 watts
1954
1 cell
2 cm²
0.005 watts
Should Last Forever
(Continued Page 13, Column 2)
Newark News Photo

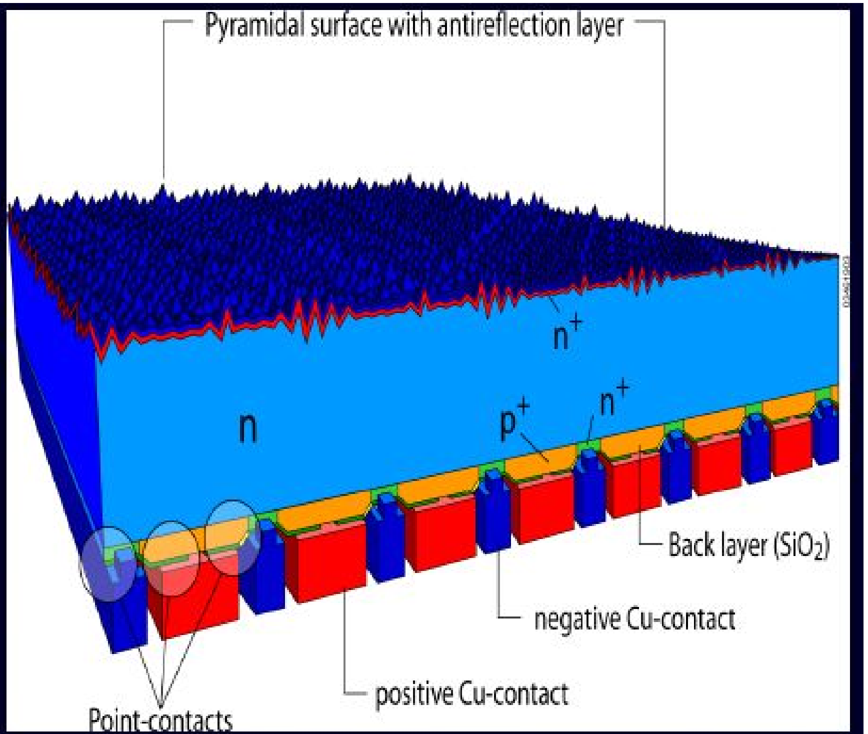

1st Generation
Silicon Technologies
Single crystal
Multicrystalline
Thick Si Film
Efficiency (%)
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
Westing-house
ARCO
Spire
Stanford
Spire
UNSW
UNSW
UNSW
UNSW
Solarex
Solarex
Georgia Tech
Sharp
Georgia Tech
UNSW
Fraunhofer-ISE
AstroPower (small area)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


Technololgy Investment Pathways
PV Module Production Experience (or "Learning") Curve
PV Module Price (2004$/Wp)
100.0
10.0
1.0
0.1
1976
2004
"80% Learning Curve": Module price decreases by 20% for every doubling of cumulative production
90%
80%
0
1
10
100
1,000
10,000
100,000
1,000,000
Cumulative Production (MWp)
Industry-Driven
1st & 2nd Generation PV
• lower Si feedstock prices
• thinner Si wafer technology
• thin films
• improved processing
• improved performance
• advanced integration
• advanced packaging
Accelerated Evolutionary
(3 years)

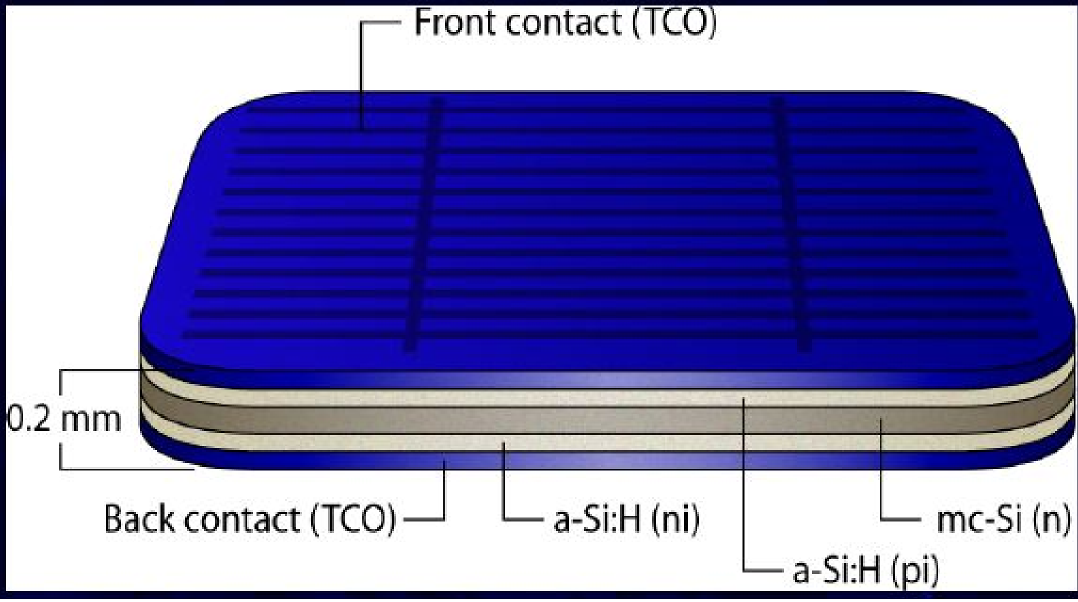
PV Si 20% Club



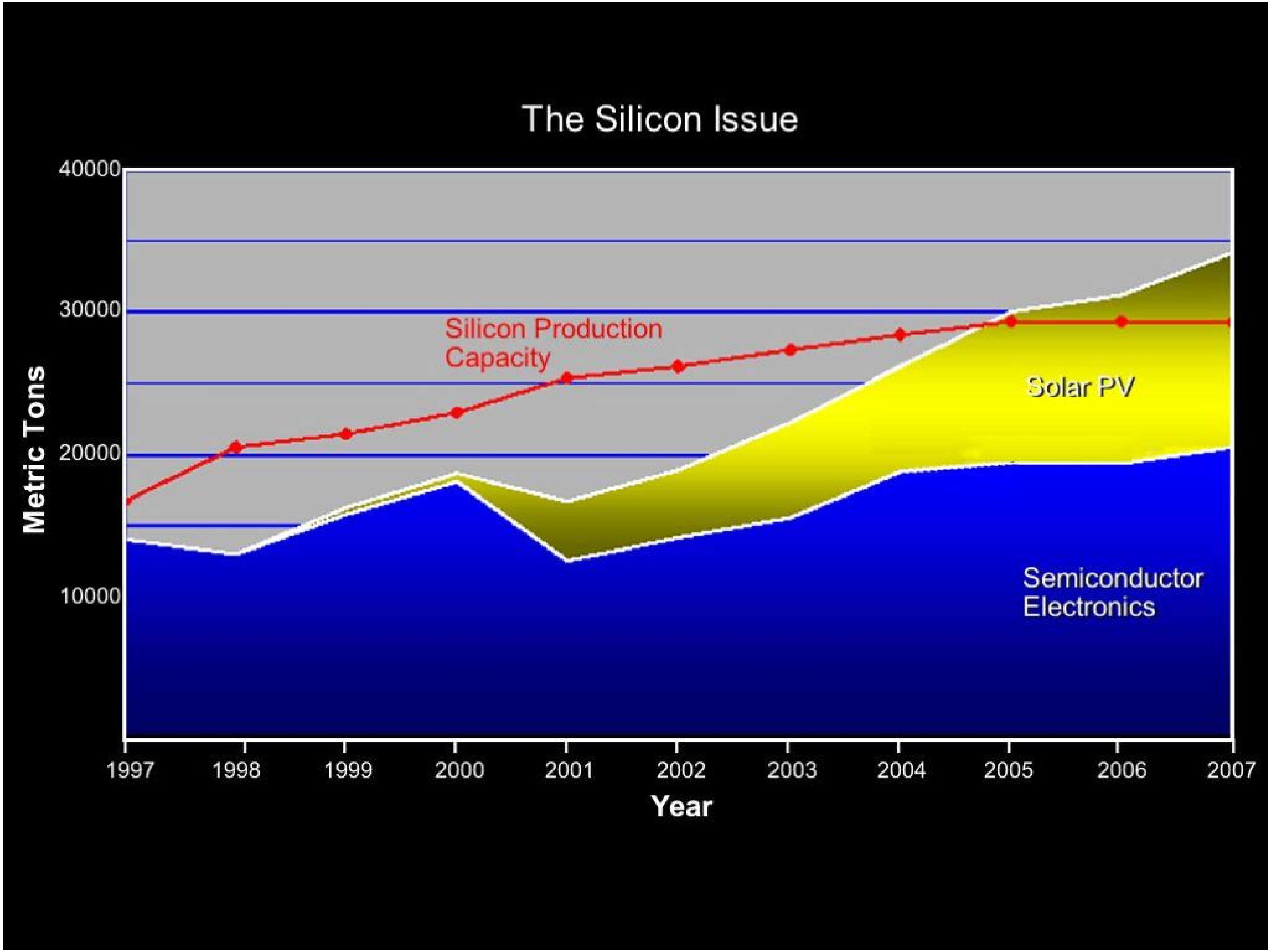
BP Saturn



SunPower Cell



Sanyo HIT Cell



The Silicon Issue
Metric Tons
40000
30000
20000
10000
Silicon Production
Capacity
Solar PV
Semiconductor
Electronics
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year

Benefits . . .

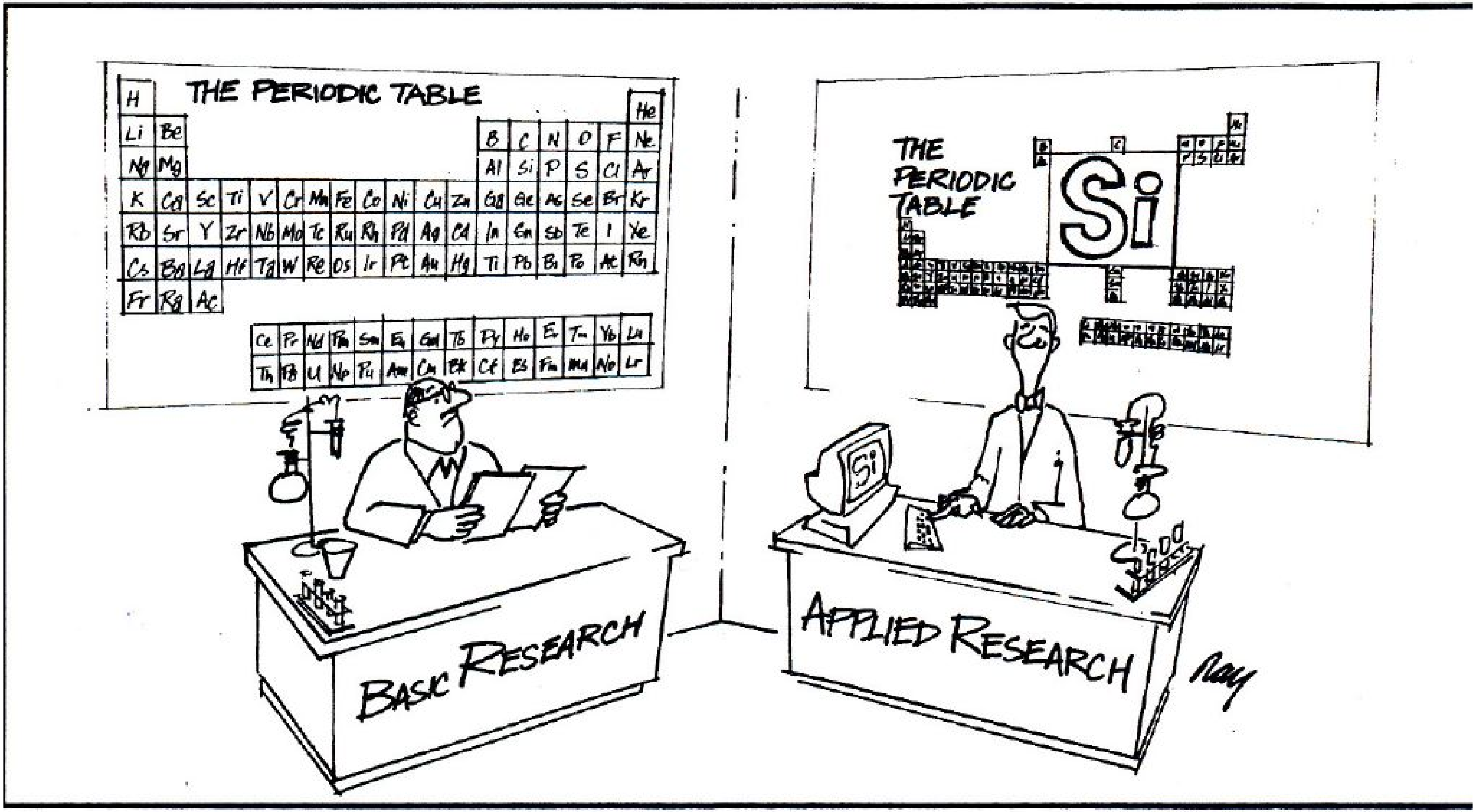
Made the Si industry examine itself.

- Better Si material utilization
- Process improvements
- Performance improvements

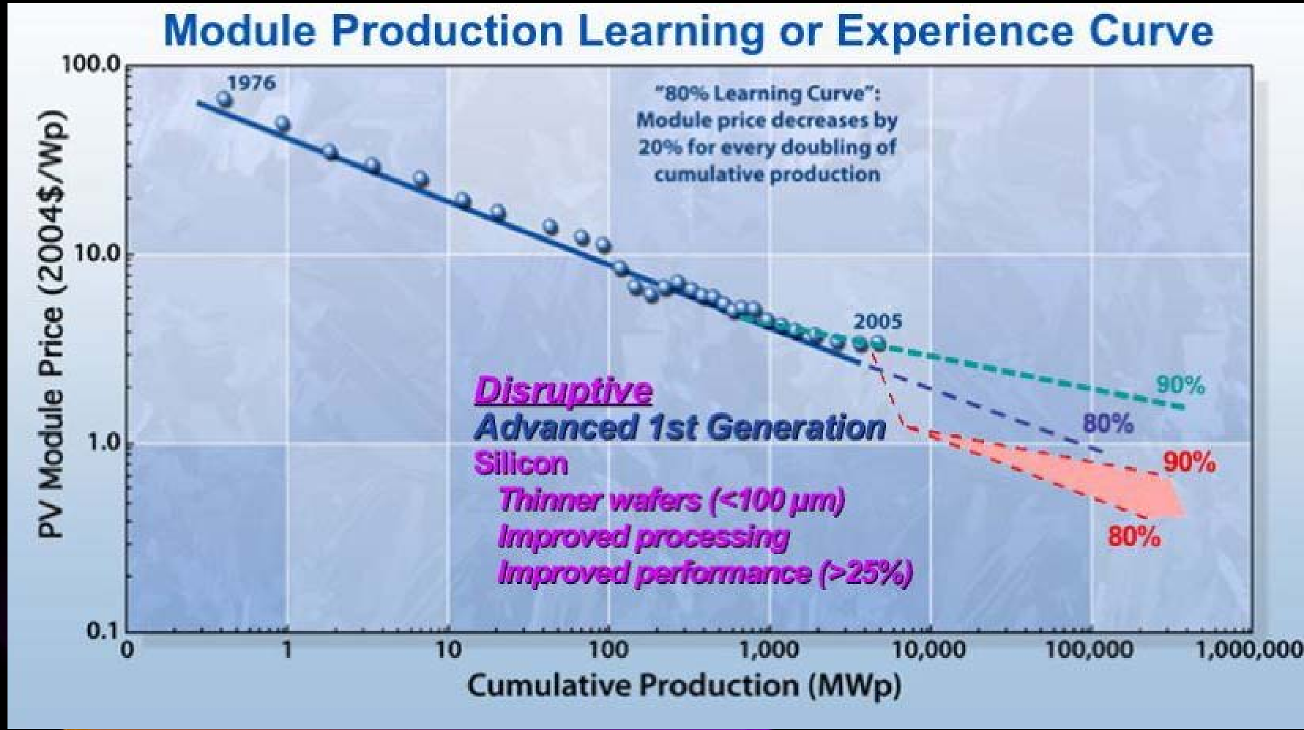
Accelerated other technologies.

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

Problem: Si Shortage


THE PERIODIC TABLE
THE PERIODIC TABLE
Si
Si
BASIC RESEARCH
APPLIED RESEARCH
Ray

Technololgy Investment Pathways



Industry-Driven

1st & 2nd Generation PV

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

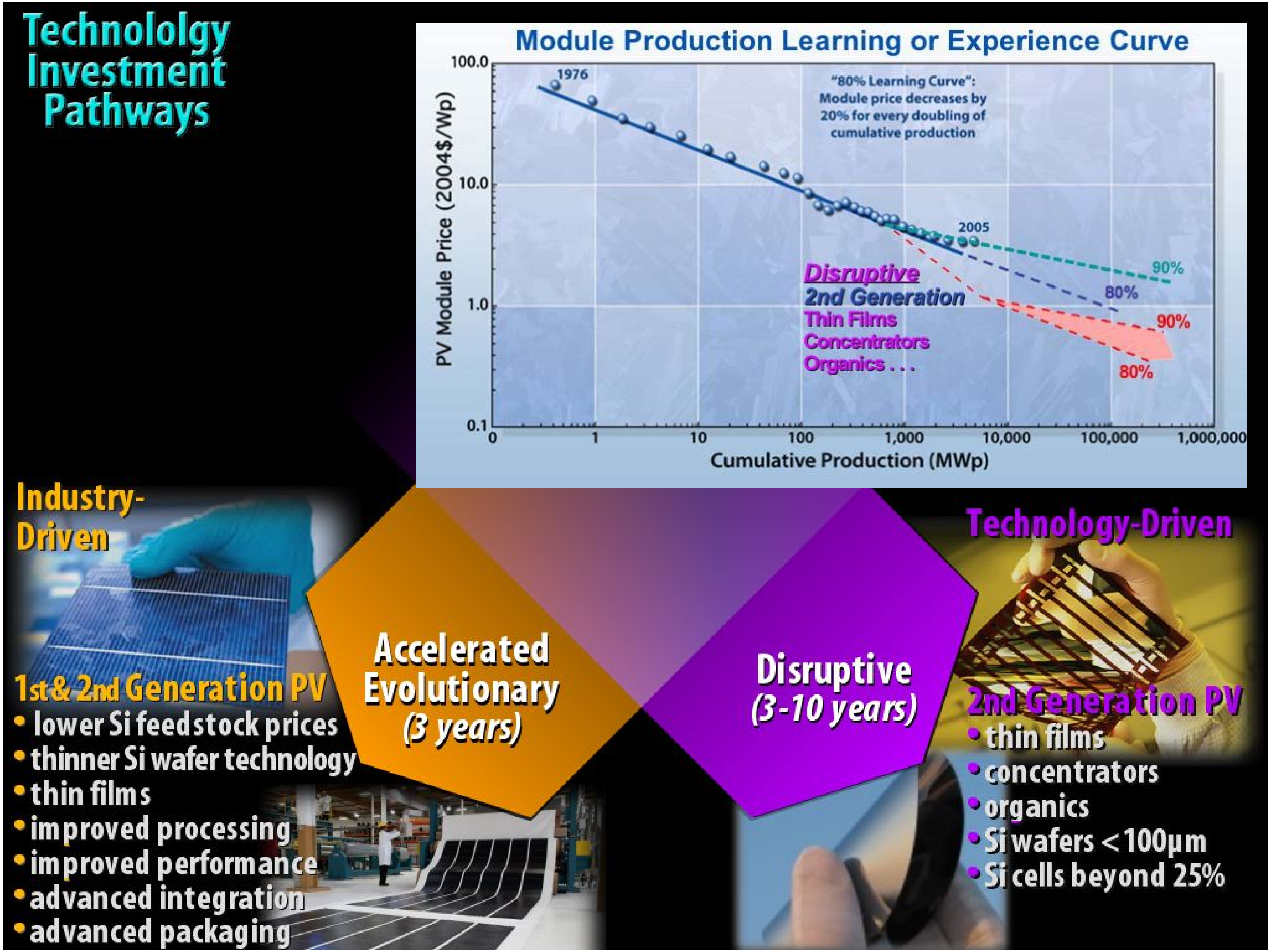
Accelerated Evolutionary
(3 years)

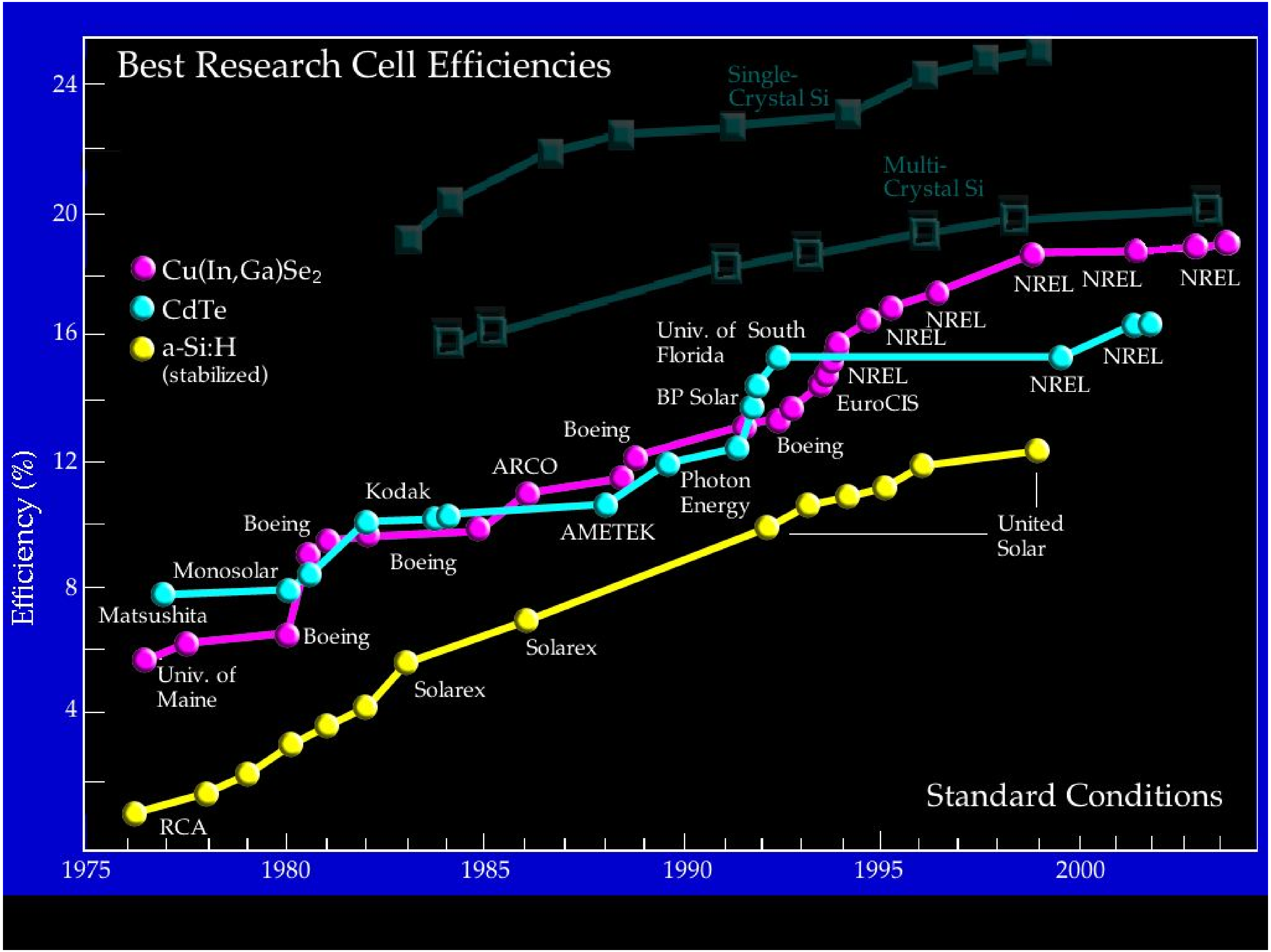
Disruptive
(3-10 years)

Technology-Driven

2nd Generation PV

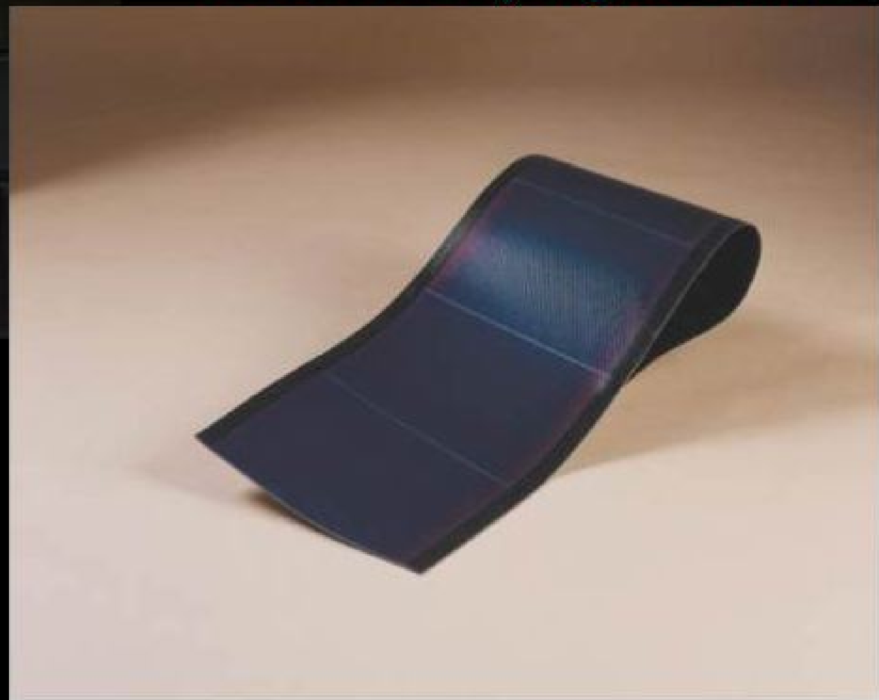
- thin films
- concentrators
- organics
- Si wafers < 100μm
- Si cells beyond 25%


Technololgy Investment Pathways
Module Production Learning or Experience Curve
PV Module Price (2004$/Wp)
100.0
10.0
1.0
0.1
1976
2005
"80% Learning Curve": Module price decreases by 20% for every doubling of cumulative production
Disruptive
2nd Generation
Thin Films
Concentrators
Organics . . .
90%
80%
90%
80%
0
1
10
100
1,000
10,000
100,000
1,000,000
Cumulative Production (MWp)
Industry-Driven
1st & 2nd Generation PV
• lower Si feedstock prices
• thinner Si wafer technology
• thin films
• improved processing
• improved performance
• advanced integration
• advanced packaging
Accelerated Evolutionary
(3 years)
Disruptive
(3-10 years)
Technology-Driven
2nd Generation PV
• thin films
• concentrators
• organics
• Si wafers <100μm
• Si cells beyond 25%

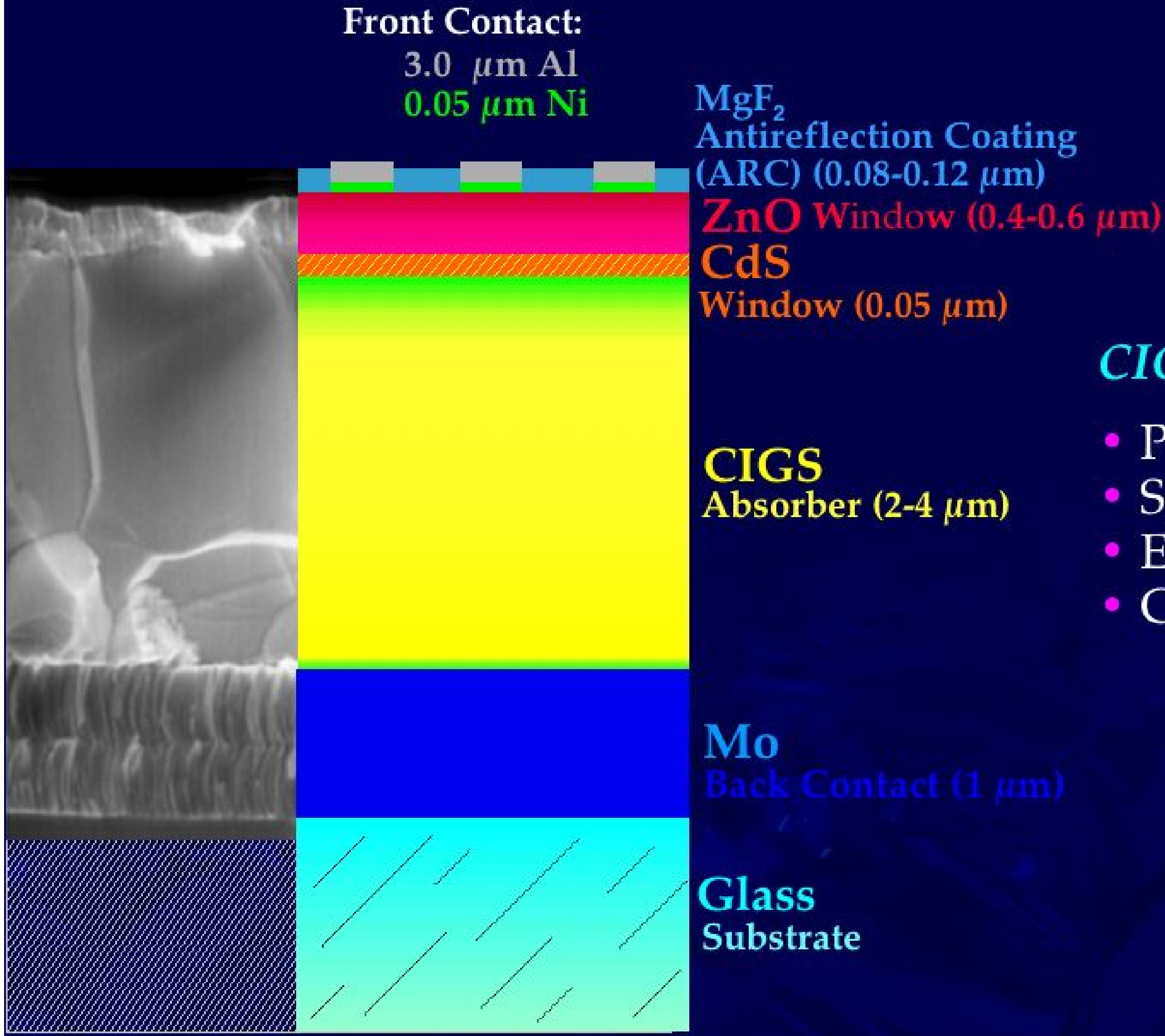

Best Research Cell Efficiencies
Single-Crystal Si
Multi-Crystal Si
Cu(In,Ga)Se2
CdTe
a-Si:H (stabilized)
Efficiency (%)
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
Matsushita
Monosolar
Univ. of Maine
Boeing
Kodak
ARCO
AMETEK
Photon Energy
Univ. of Florida
South
BP Solar
EuroCIS
NREL
RCA
Solarex
United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

Flexible shingle laminate

Flexible roofing laminate

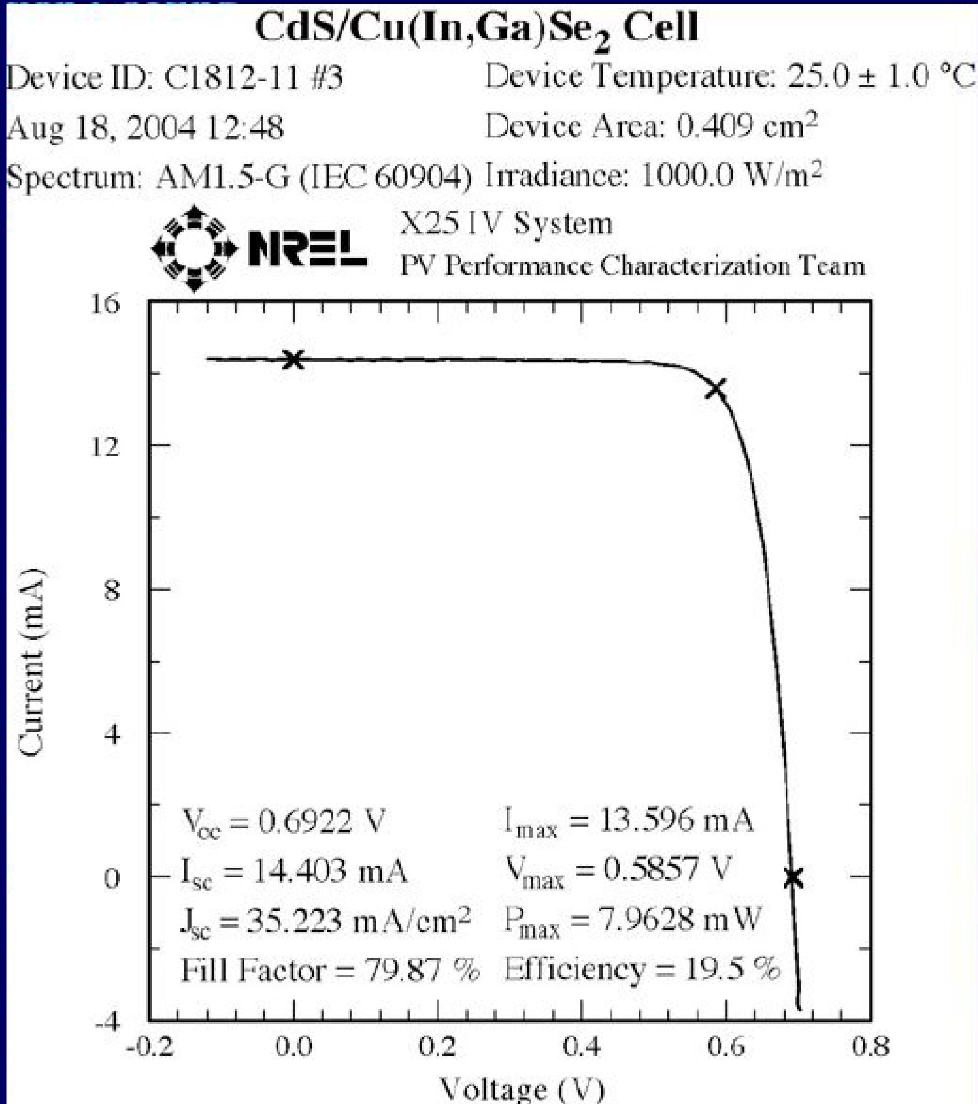


Thin-Film $Cu(In,Ga)(S,Se)_2$ - CIGSSe



CIGS Deposition

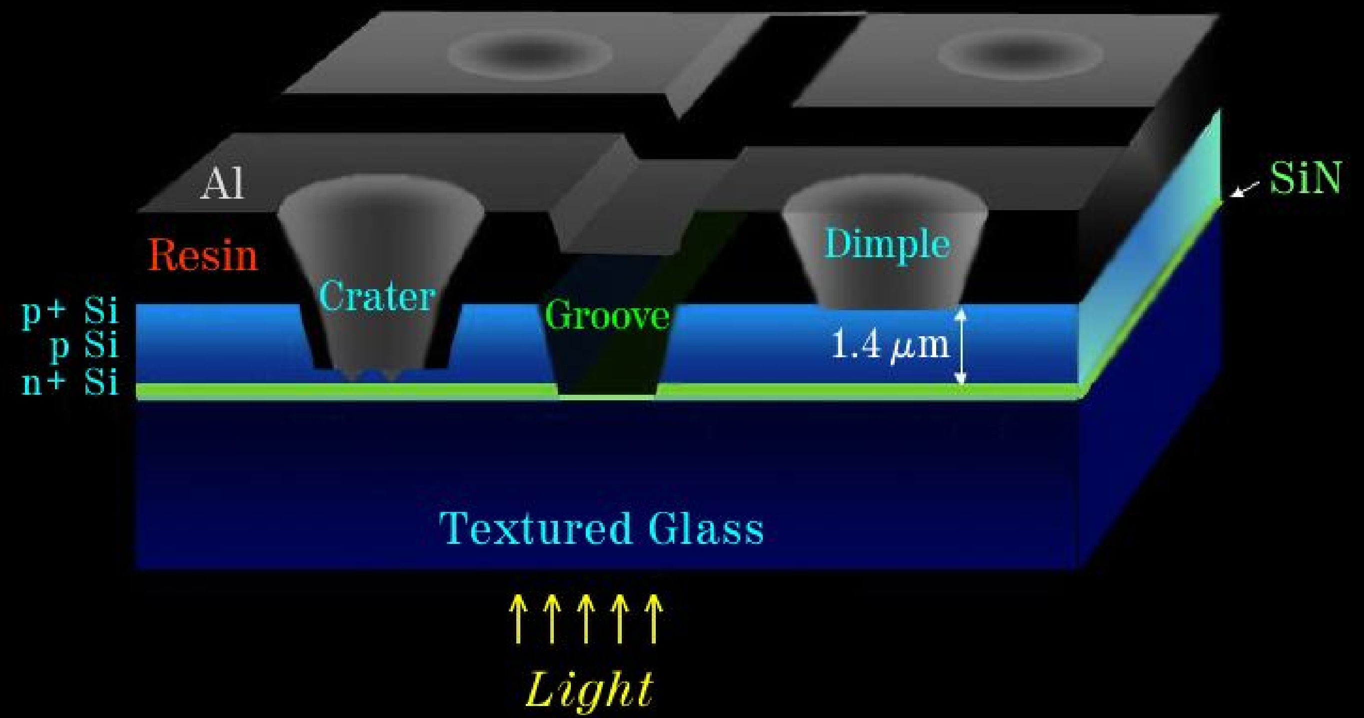
- PVD (elemental deposition)
- Sputtering / gas reaction
- Electrodeposition
- Chemical deposition

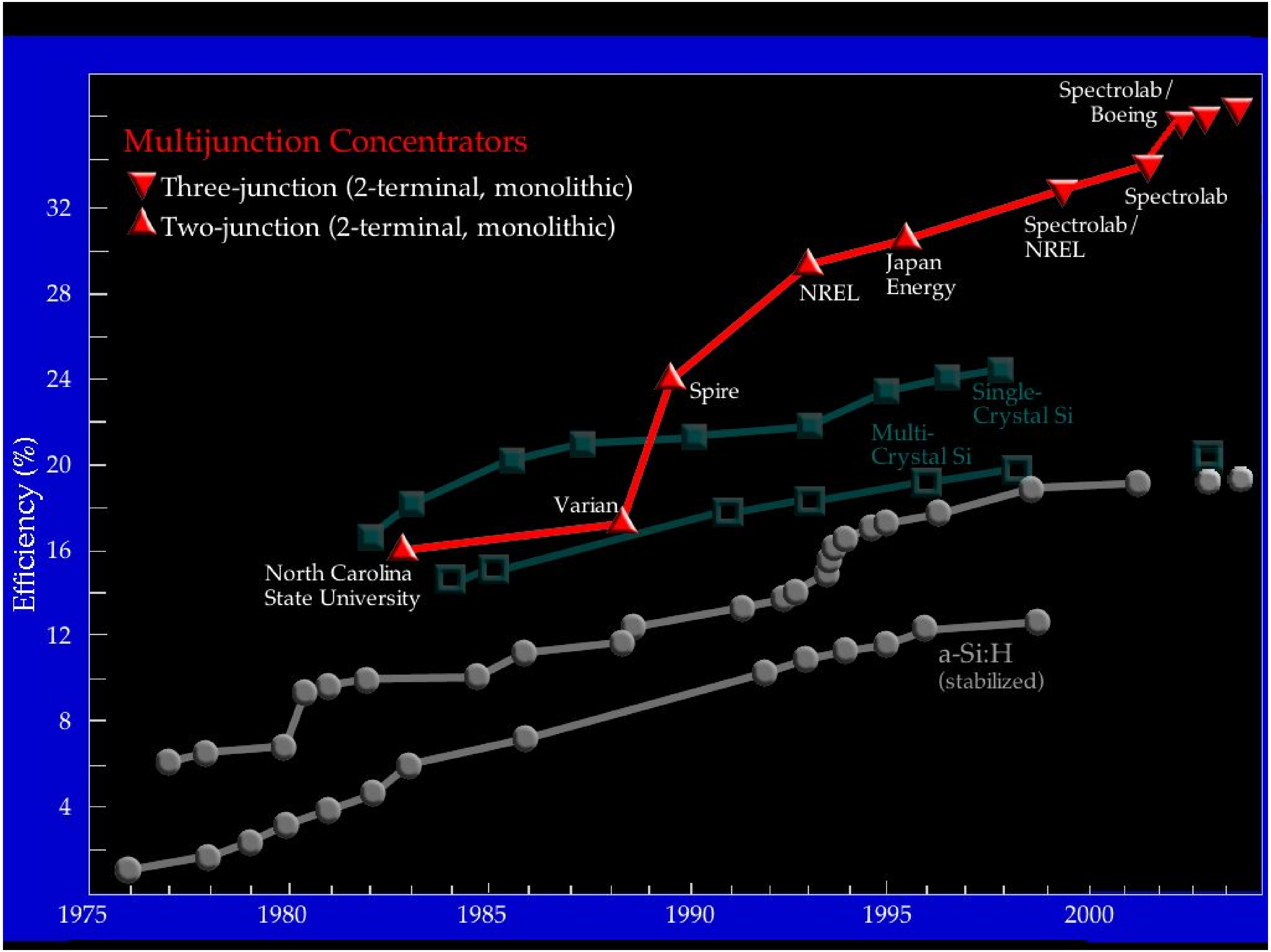


CdS/Cu(In,Ga)Se2 Cell
Device ID: C1812-11 #3
Aug 18, 2004 12:48
Spectrum: AM1.5-G (IEC 60904)
Device Temperature: 25.0 ± 1.0 °C
Device Area: 0.409 cm2
Irradiance: 1000.0 W/m2
NREL
X25 IV System
PV Performance Characterization Team
Current (mA)
Voltage (V)
Voc = 0.6922 V
Isc = 14.403 mA
Jsc = 35.223 mA/cm2
Fill Factor = 79.87 %
Imax = 13.596 mA
Vmax = 0.5857 V
Pmax = 7.9628 mW
Efficiency = 19.5 %

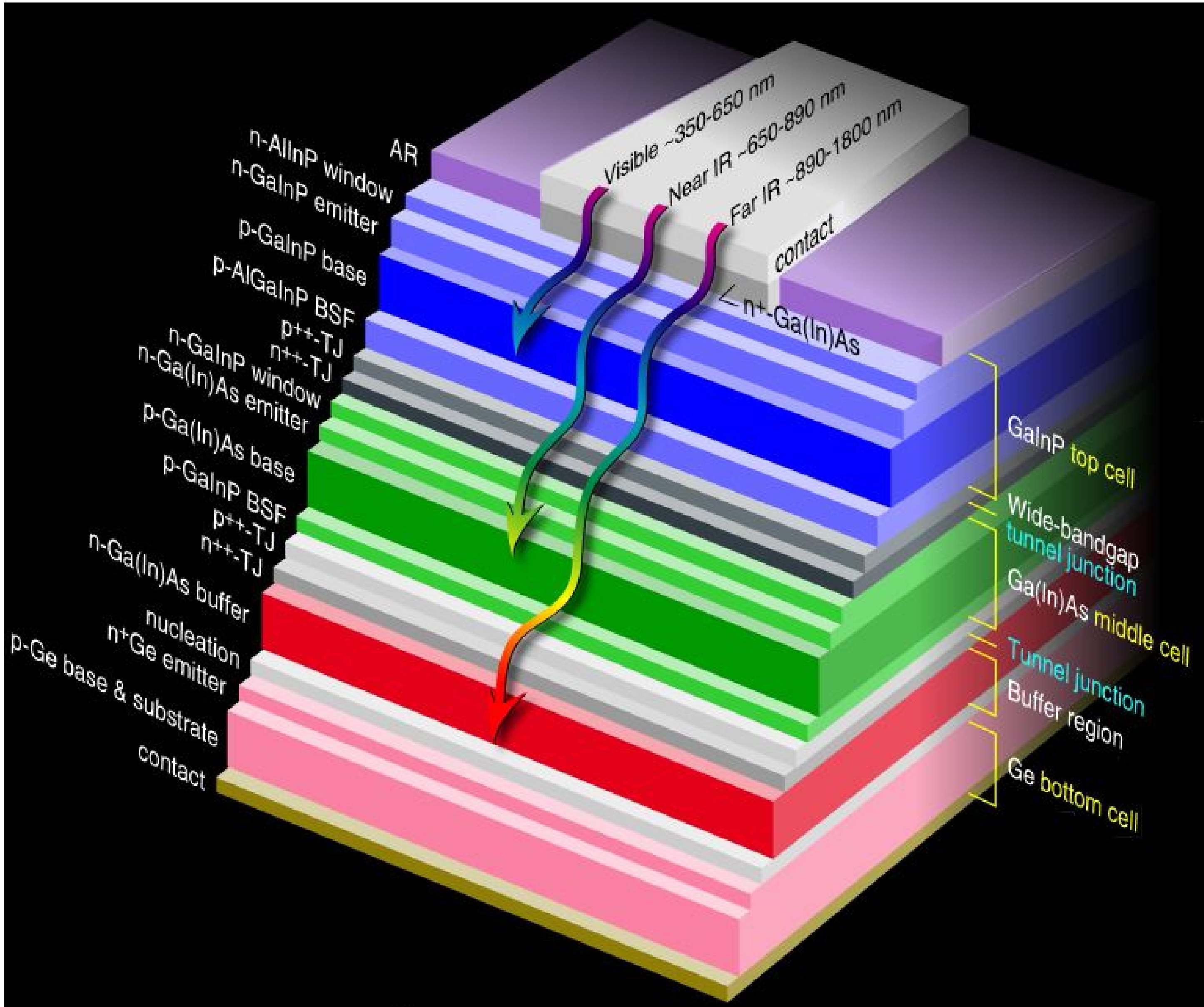
Thin-Film Silicon

CSG: "*Crystalline Silicon on Glass*"

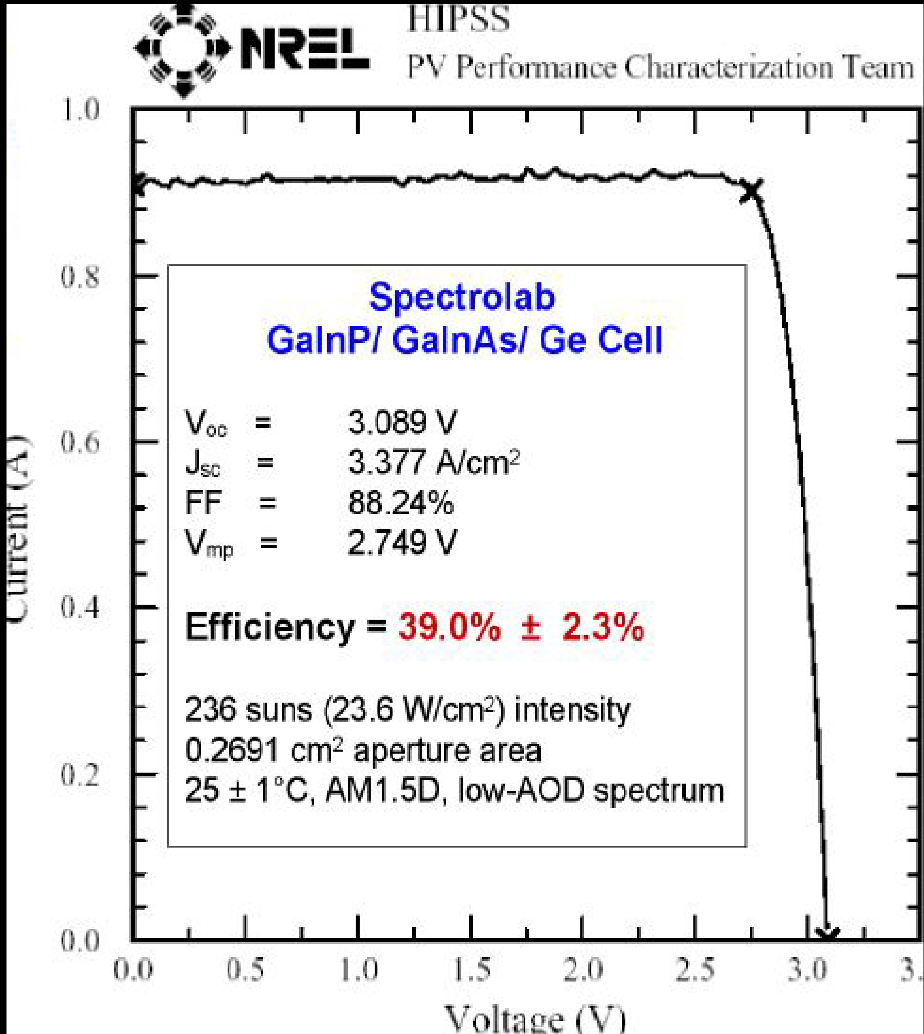




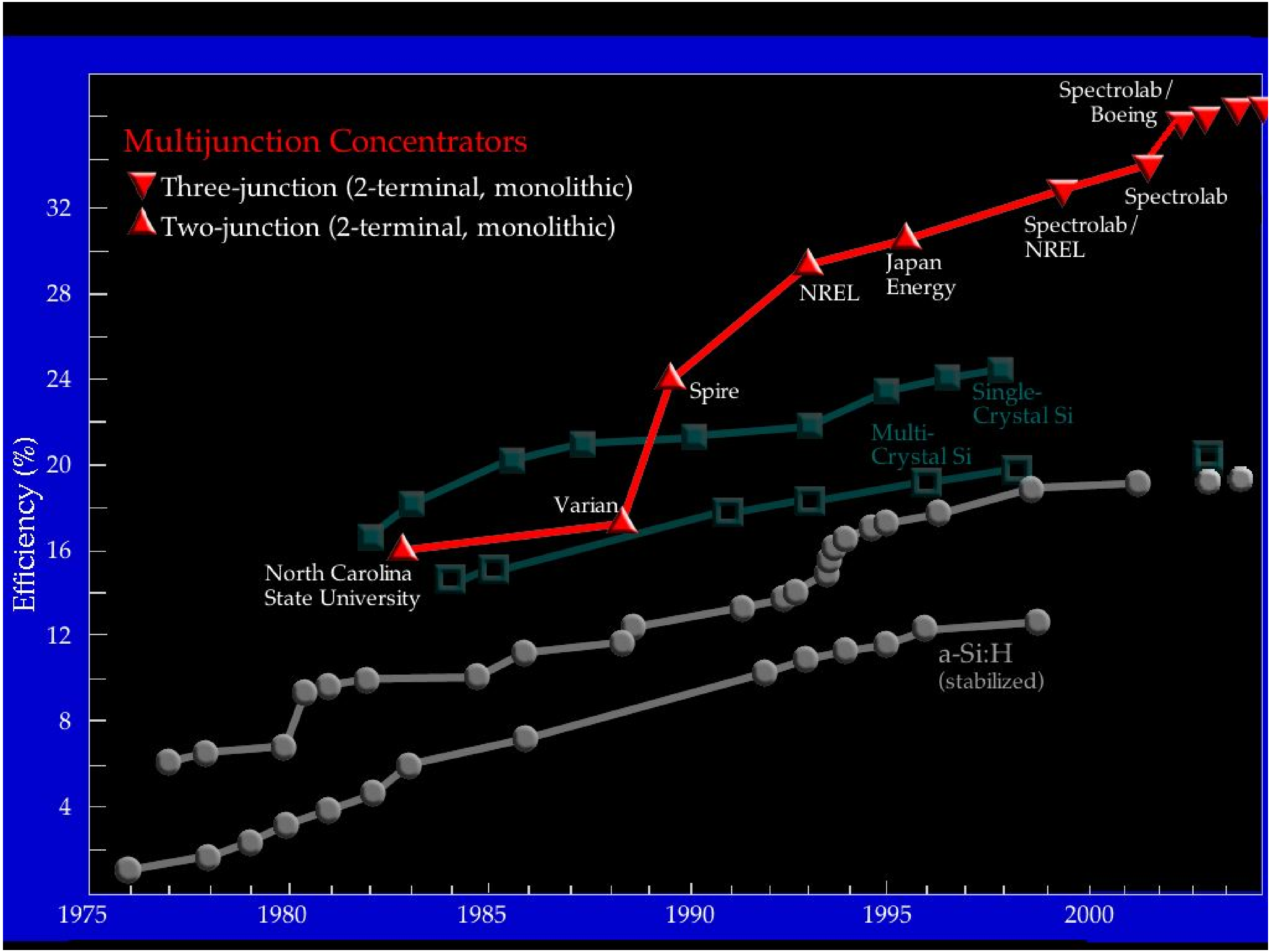
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Spectrolab / Boeing
Spectrolab
Spectrolab / NREL
Japan Energy
NREL
Spire
Varian
North Carolina State University
Single-Crystal Si
Multi-Crystal Si
a-Si:H (stabilized)
Efficiency (%)
4
8
12
16
20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



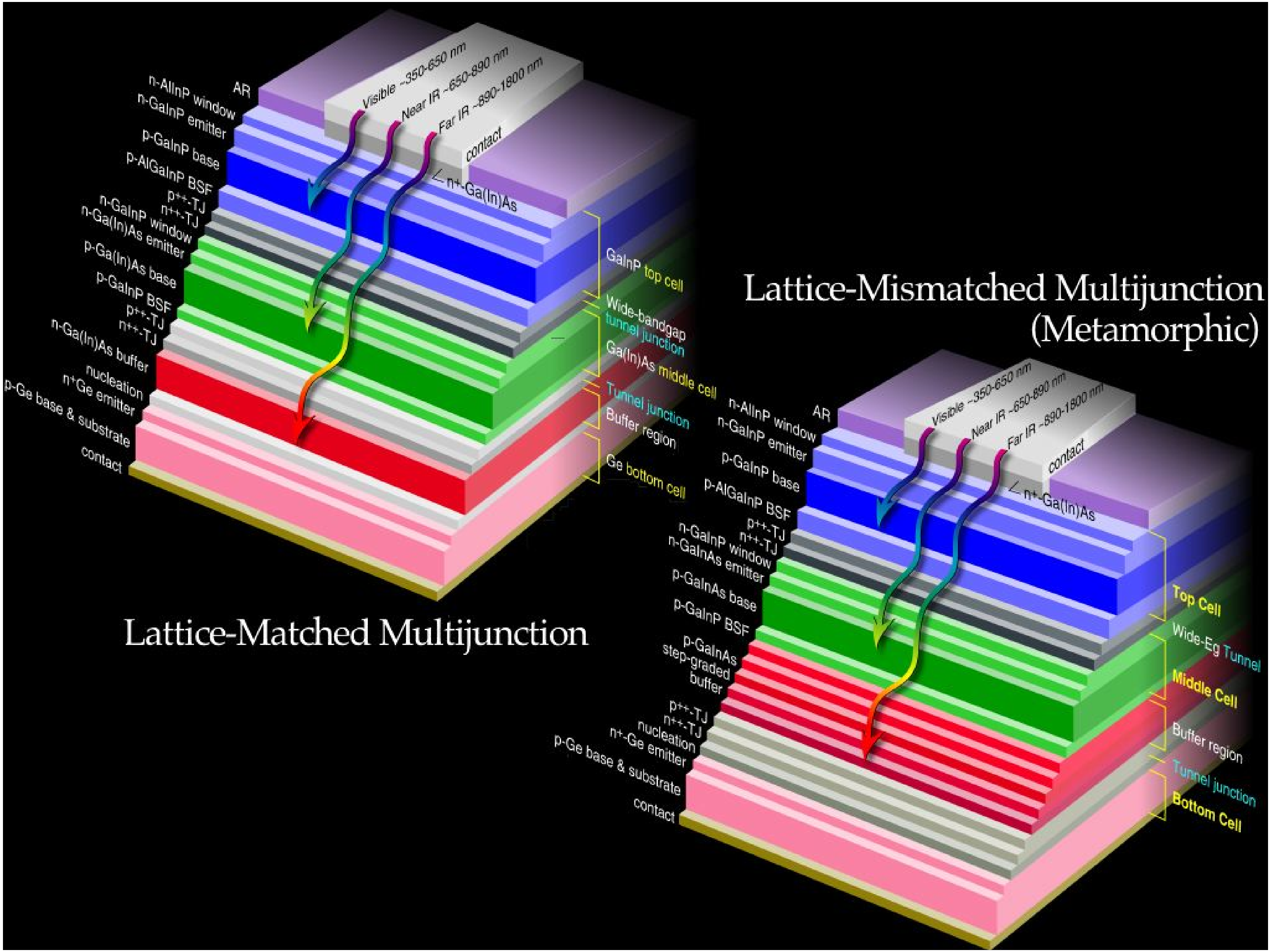
Lattice-Matched Multijunction



HIPSS
PV Performance Characterization Team
Spectrolab
GaInP/ GaInAs/ Ge Cell
Voc = 3.089 V
Jsc = 3.377 A/cm2
FF = 88.24%
Vmp = 2.749 V
Efficiency = 39.0% ± 2.3%
236 suns (23.6 W/cm2) intensity
0.2691 cm2 aperture area
25 ± 1°C, AM1.5D, low-AOD spectrum
Current (A)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Voltage (V)



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



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-Matched Multijunction
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**

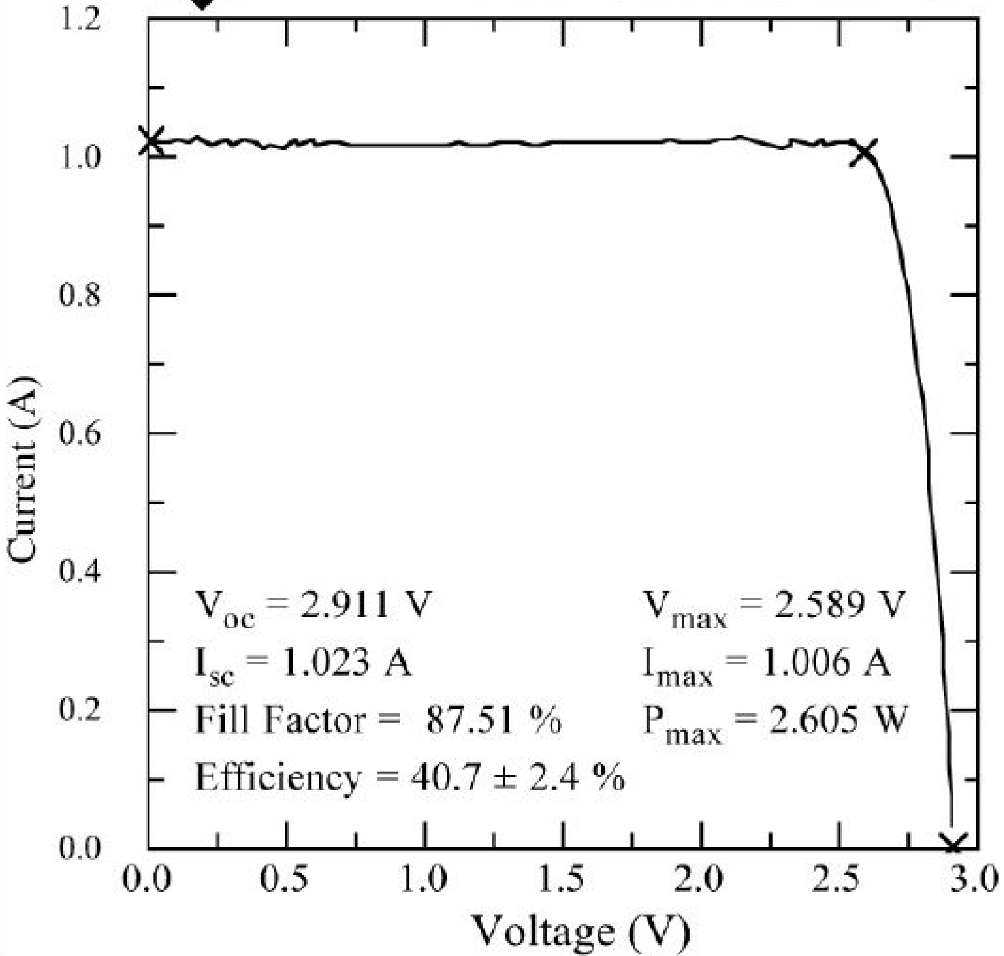
Sample: 6997-C407 Device Temperature = 25.0°C

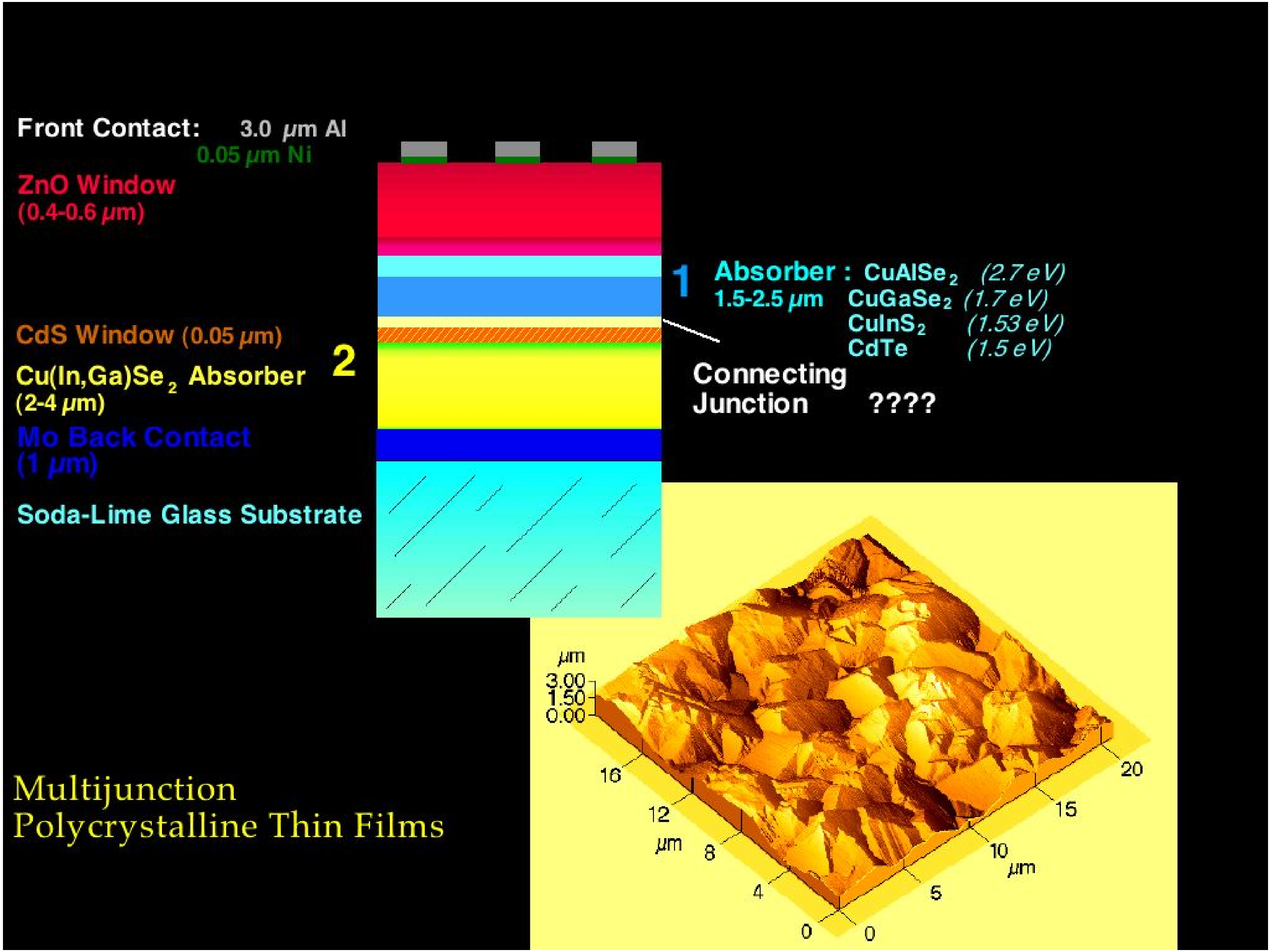
Wed, Sep 6, 2006 7:46 PM area used = 0.26685 cm^2

HiPer Direct Reference Irradiance: 240037.1W/m^2

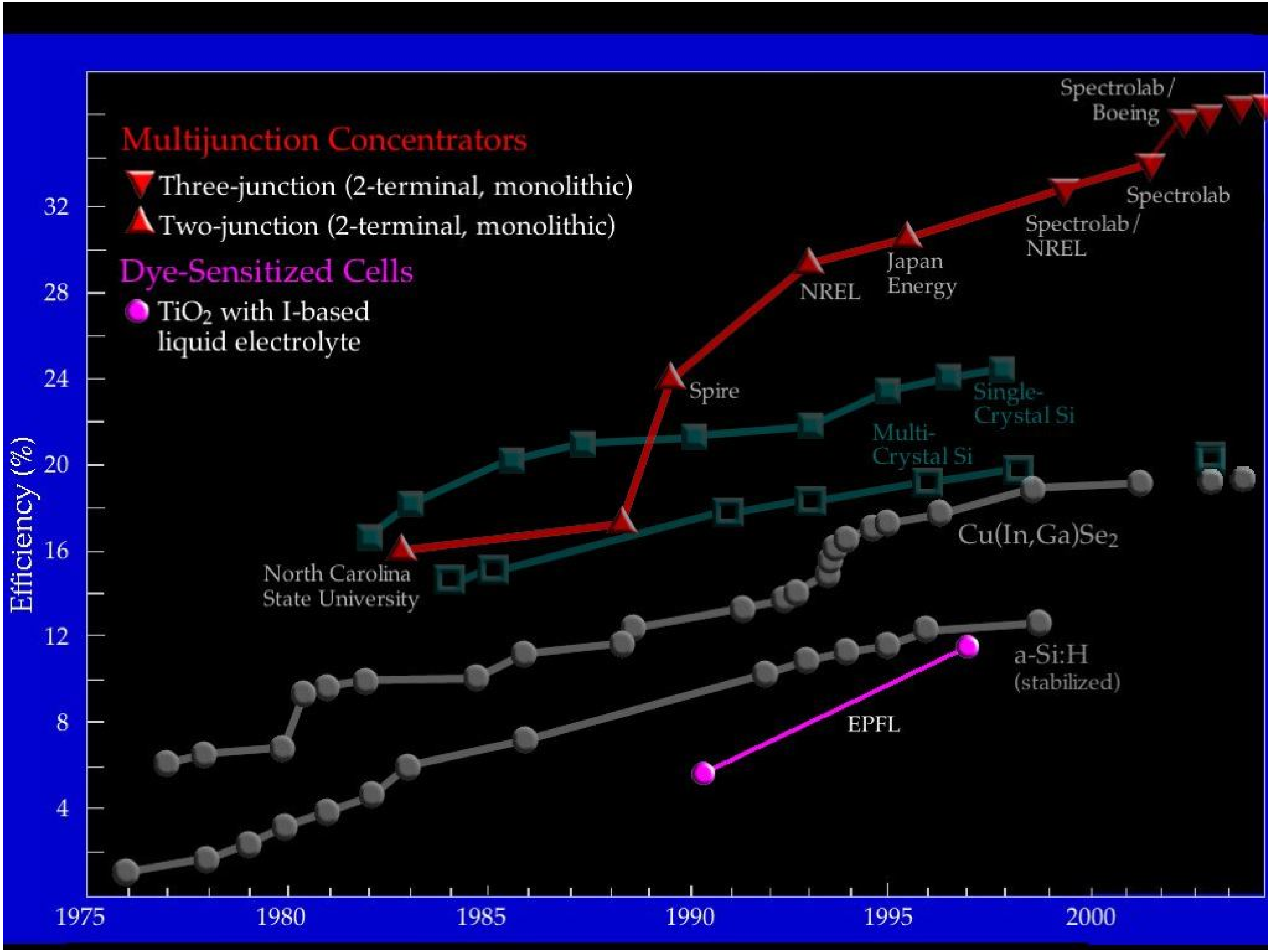
NREL HIPSS

PV Performance Characterization Team

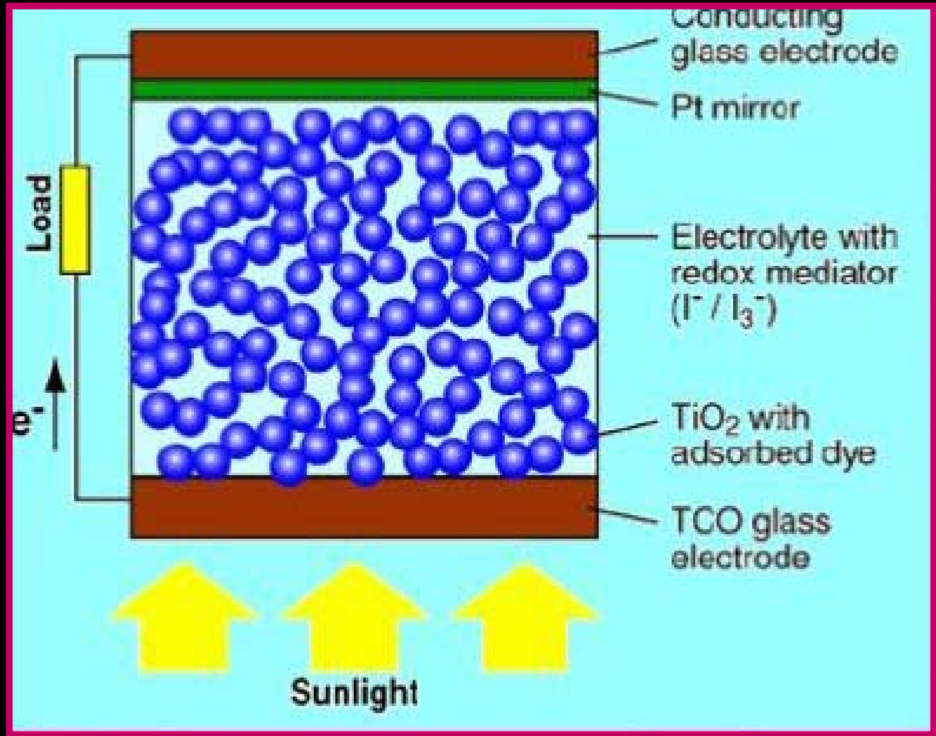




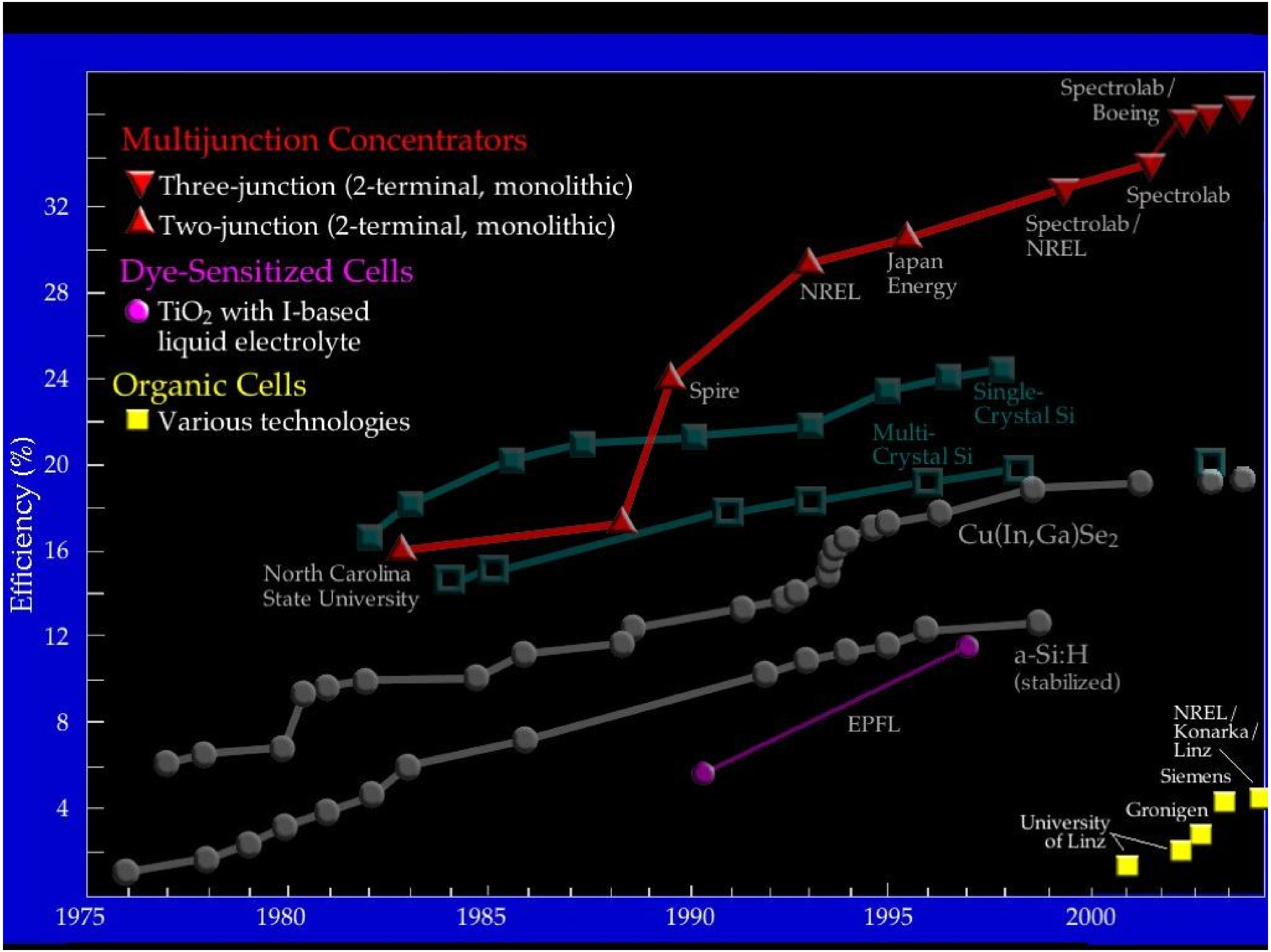
Front Contact: 3.0 μm Al
0.05 μm Ni
ZnO Window
(0.4-0.6 μm)
CdS Window (0.05 μm)
Cu(In,Ga)Se2 Absorber
(2-4 μm)
Mo Back Contact
(1 μm)
Soda-Lime Glass Substrate
1
2
Absorber : CuAlSe2 (2.7 eV)
1.5-2.5 μm CuGaSe2 (1.7 eV)
CuInS2 (1.53 eV)
CdTe (1.5 eV)
Connecting
Junction ????
μm
3.00
1.50
0.00
16
12
μm
8
4
0
0
5
10
μm
15
20
Multijunction
Polycrystalline Thin Films



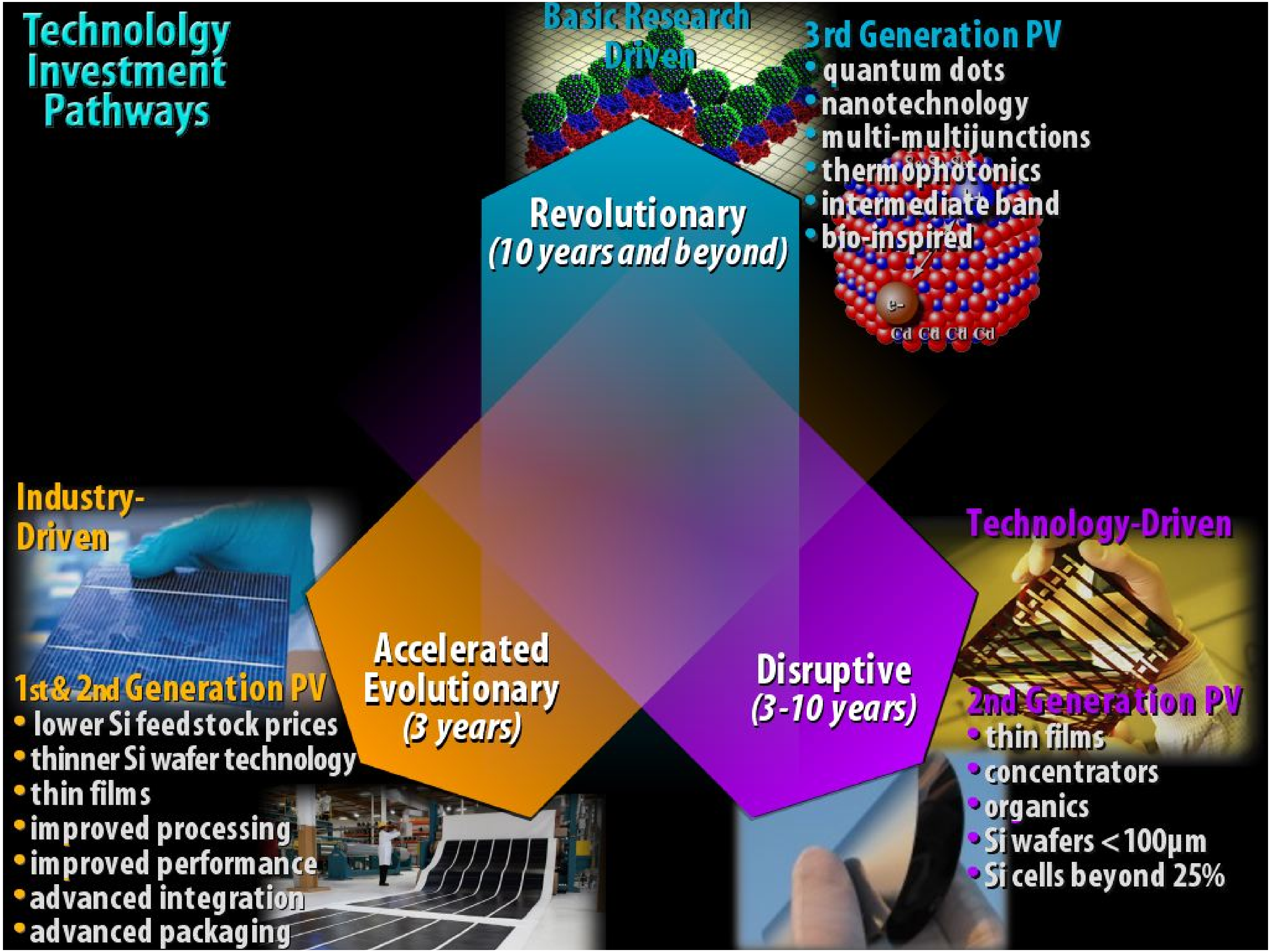
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Dye-Sensitized Cells
TiO_2 with I-based liquid electrolyte
Spectrolab / Boeing
Spectrolab
Spectrolab / NREL
Japan Energy
NREL
Spire
Single-Crystal Si
Multi-Crystal Si
North Carolina State University
$Cu(In,Ga)Se_2$
a-Si:H (stabilized)
EPFL
Efficiency (%)
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000

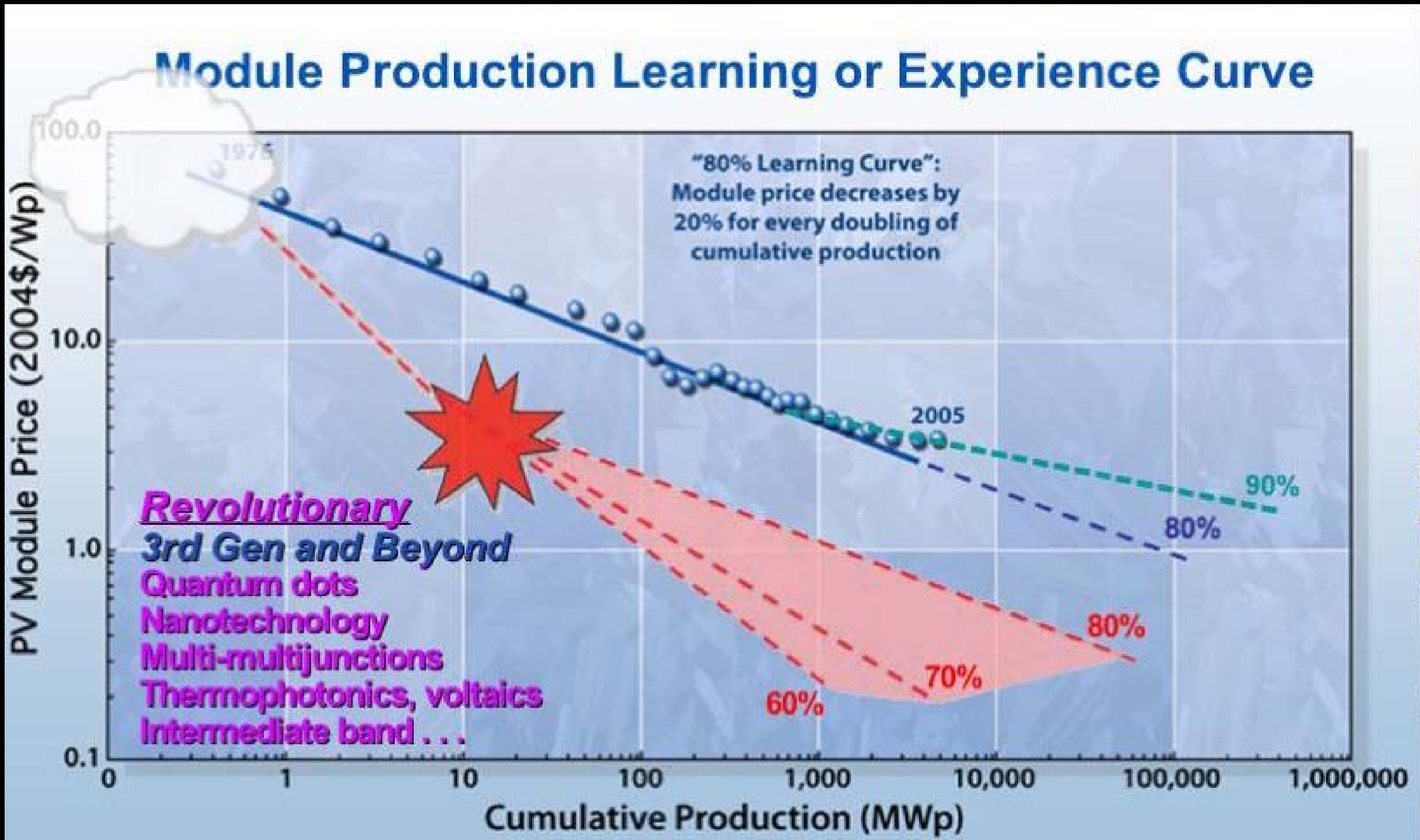


Conducting glass electrode
Pt mirror
Electrolyte with redox mediator (I^- / I_3^-)
TiO_2 with adsorbed dye
TCO glass electrode
Load
e^-
Sunlight



Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Dye-Sensitized Cells
TiO2 with I-based liquid electrolyte
Organic Cells
Various technologies
Spectrolab / Boeing
Spectrolab
Spectrolab / NREL
Japan Energy
NREL
Spire
Single-Crystal Si
Multi-Crystal Si
Cu(In,Ga)Se2
North Carolina State University
a-Si:H (stabilized)
EPFL
NREL / Konarka / Linz
Siemens
Gronigen
University of Linz
Efficiency (%)
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000


Technololgy Investment Pathways
Basic Research Driven
3rd Generation PV
• quantum dots
• nanotechnology
• multi-multijunctions
• thermophotonics
• intermediate band
• bio-inspired
Revolutionary
(10 years and beyond)
Industry-Driven
Technology-Driven
Accelerated Evolutionary
(3 years)
Disruptive
(3-10 years)
1st & 2nd Generation PV
• lower Si feedstock prices
• thinner Si wafer technology
• thin films
• improved processing
• improved performance
• advanced integration
• advanced packaging
2nd Generation PV
• thin films
• concentrators
• organics
• Si wafers <100μm
• Si cells beyond 25%



Module Production Learning or Experience Curve
100.0
1976
"80% Learning Curve": Module price decreases by 20% for every doubling of cumulative production
PV Module Price (2004$/Wp)
10.0
1.0
0.1
2005
90%
80%
80%
70%
60%
Revolutionary
3rd Gen and Beyond
Quantum dots
Nanotechnology
Multi-multijunctions
Thermophotonics, voltaics
Intermediate band . . .
0
1
10
100
1,000
10,000
100,000
1,000,000
Cumulative Production (MWp)

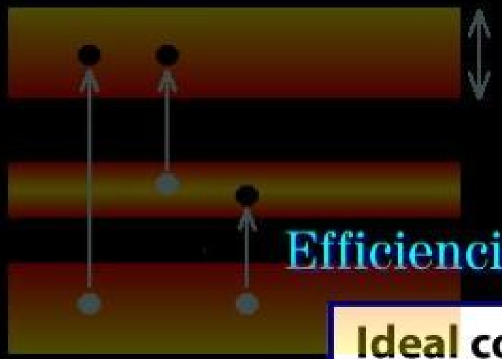
3rd, 4th, . . . Future Generations

Revolutionary Technologies for Our Next Generations of Consumers

. . . quantum dot, pod, rod and other novel structures; nanotechnologies; multiple-junctions…
with efficiencies 2-3 *times* those for conventional PV

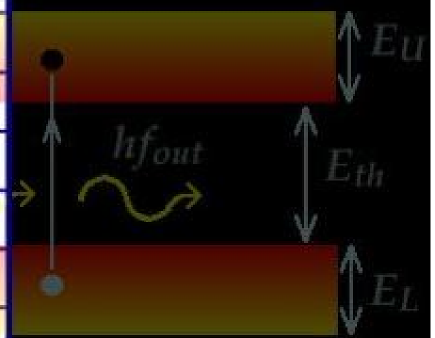
. . . high-risk research

. . . the fringes of technology exploration

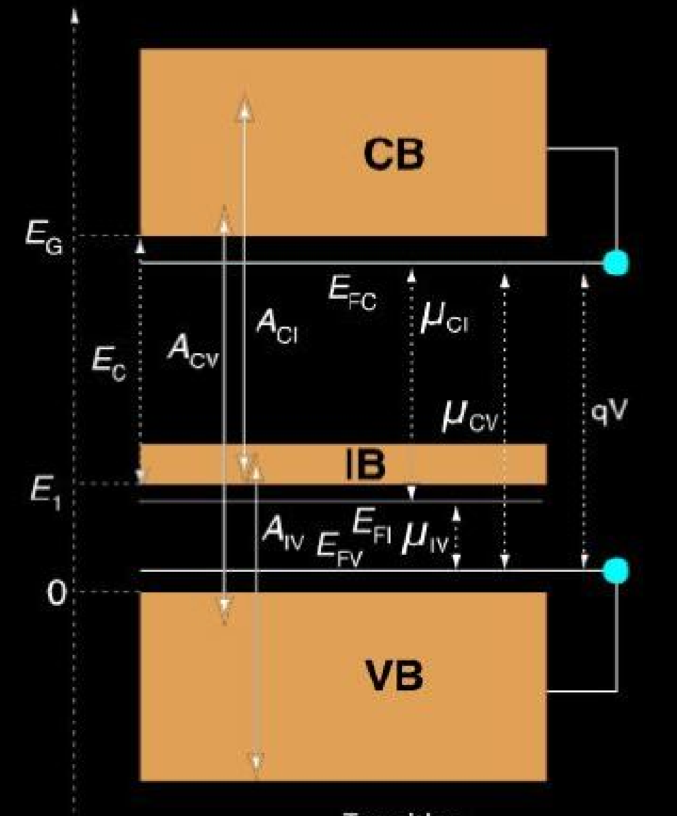


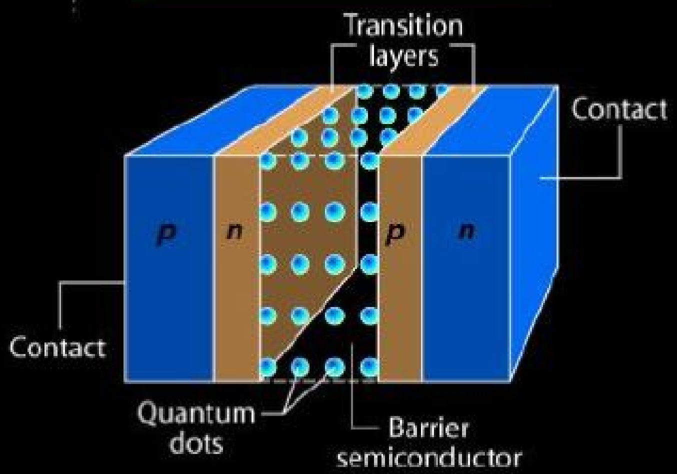
Efficiencies for Ideal Future Generation Solar Cells

Ideal converter; $T_S = 6000K$, $T_a = 300K$ isotropic illumination	**Efficiency**
Carnot	0.950
Landsberg	0.933
Multijunction	0.868
Impact ionisation, best Q	0.868
Solar thermal	0.854
Hot electrons	0.854
Thermophotovoltaic	0.854
Thermophotonic	0.854
Intermediate band, (MQD or alloy)	0.632
2nd photon pumped MQW	0.632
Shockley & Queisser limit	0.403



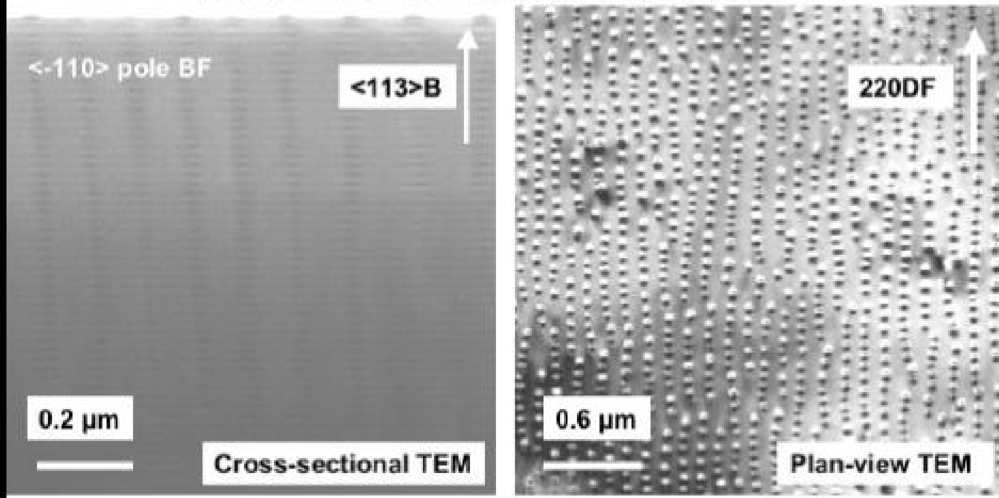
Intermediate Band Solar Cells





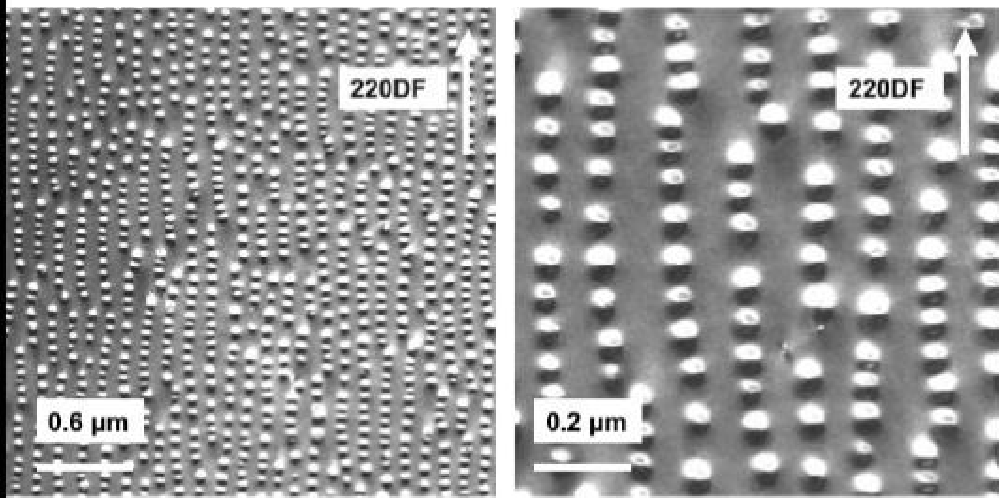
A. Norman, M Romero, and M. Al-Jassim, (NREL), A. Luque, A. Marti, Spain

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

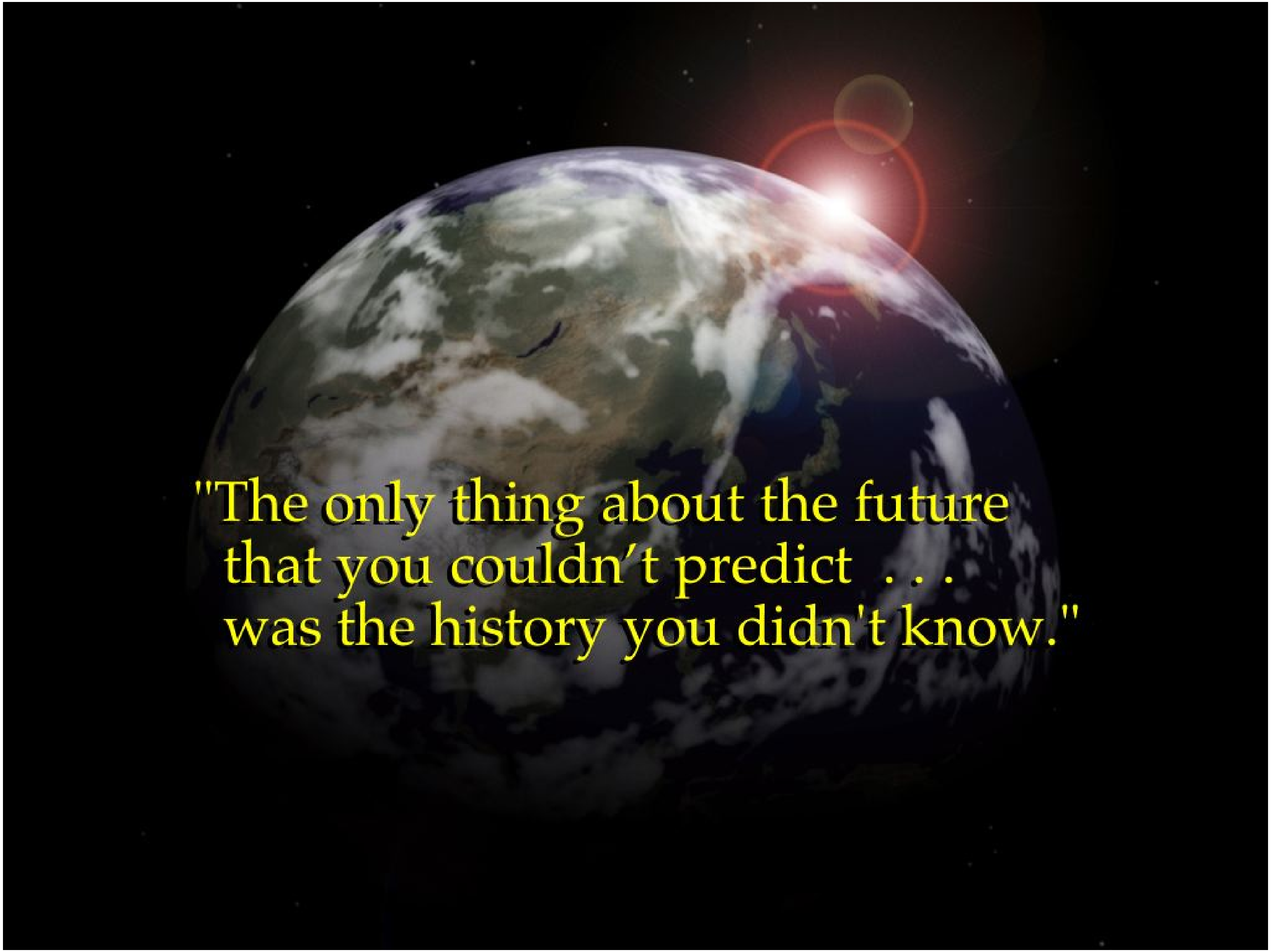


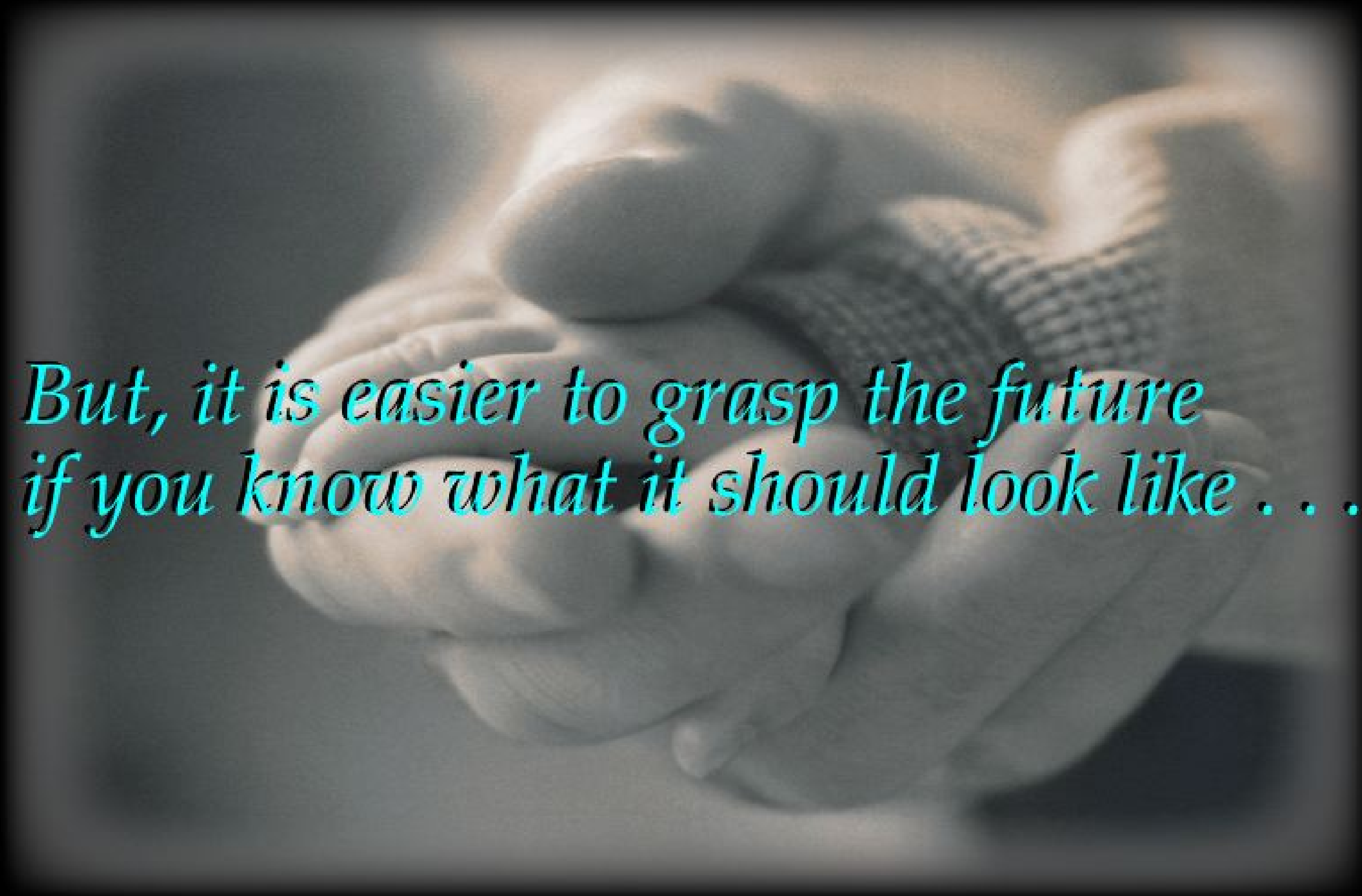
- QD arrays are being grown to test concept of intermediate band solar cell proposed by A. Marti and A. Luque

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



- Chains of quantum dots along <110>


"The only thing about the future
that you couldn't predict . . .
was the history you didn't know."


But, it is easier to grasp the future
if you know what it should look like . . .