太阳能光伏发电：一场新的电力革命

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Outlines

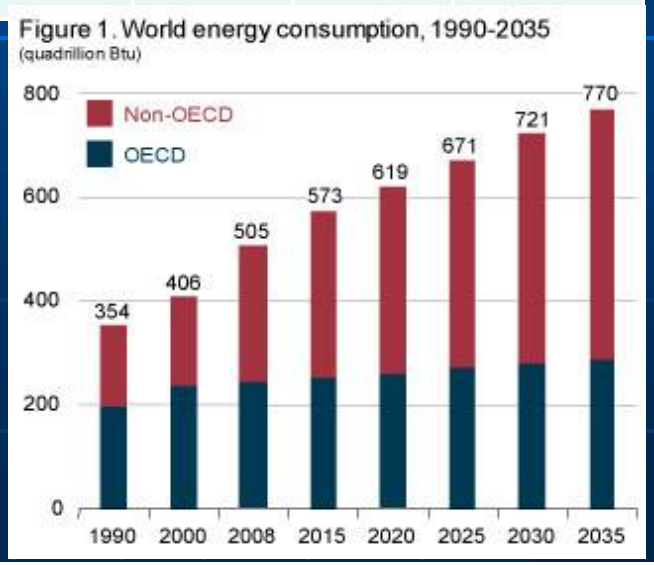
1. 为什么要新能源?
2. 光伏发电到底需要多大规模？
3. 光伏发电现实吗?
4. 光伏发电的主要挑战是什么？
5. 光伏技术的现在与将来
6. 结束语

1．为什么要新能源?

应对来自能源危机与环境污染的挑战

World Consumption of Primary Energy Sources

Unit: Quadrillion Btu	2006	2007	2008	2015	2020	2025	2030	2035	Average annual change
Coal	127.2	133.3	139.0	157.3	164.6	179.7	194.7	209.1	1.5%
Oil	171.7	172.7	173.0	187.2	196.8	207.1	216.6	225.2	1.0%
Natural gas	107.5	110.9	114.3	127.3	138.0	149.4	162.3	174.7	1.6%
Nuclear	27.8	27.1	27.2	33.2	38.9	43.7	47.4	51.2	2.4%
Other	47.1	48.5	51.3	68.5	82.2	91.7	100.6	109.5	2.9%
Total	481.3	492.6	504.7	573.5	619.5	671.5	721.5	769.8	1.6%

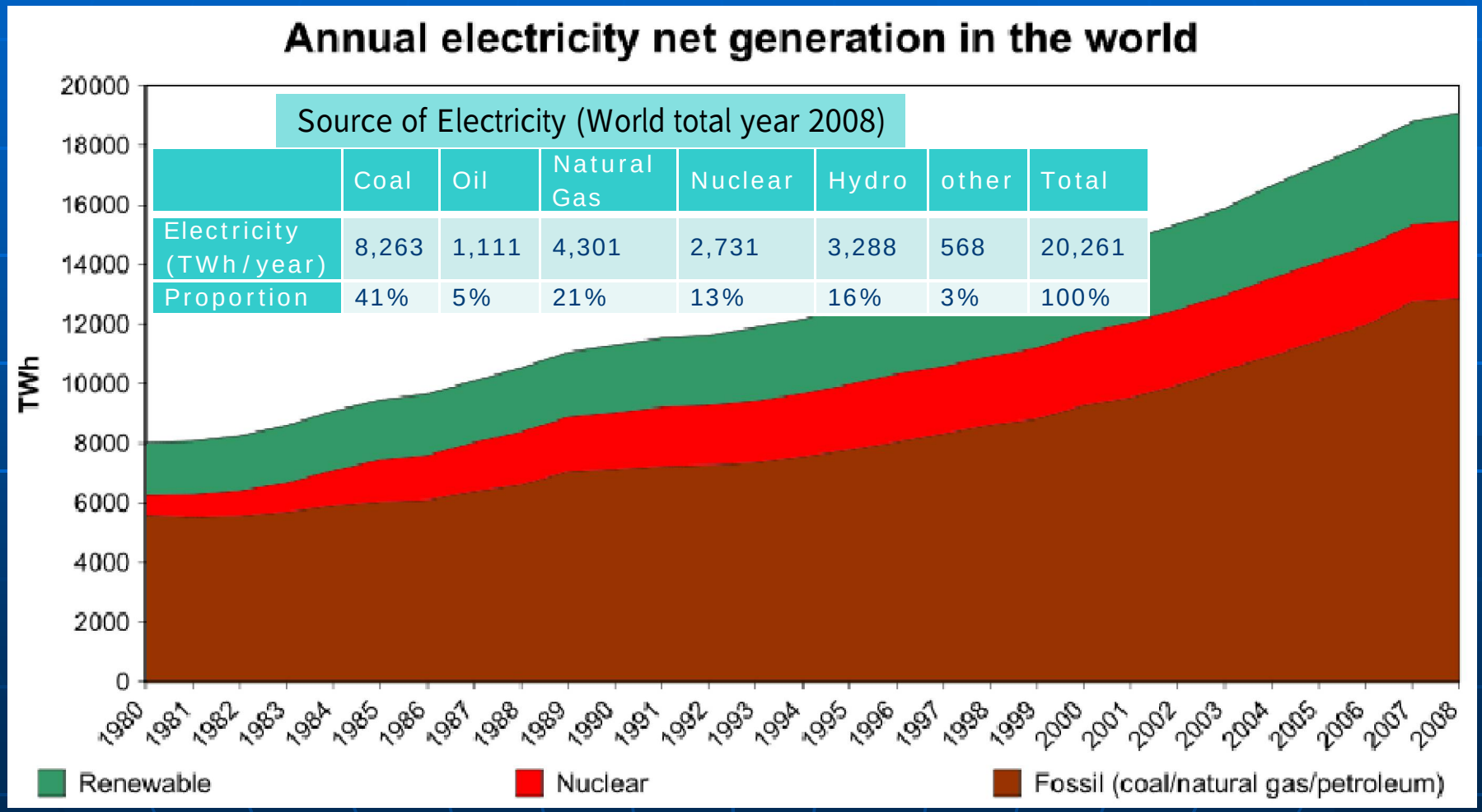


1 quad. Btu=2.93×10^{11} kWh=1.055×10^{18} J

- 1Q=2.93×10^{14} kWh=1.055×10^{21} J (=1000 qrad. Btu)
- World Annual Primary Energy Consumption=0.481Q, in 2006

http://www.eia.gov/forecasts/ieo/index.cfm

世界近年发电量及来源



http://en.wikipedia.org/wiki/Electricity_generation

World Resources (2007)

Energy Source	Recoverable Reserve (Q)	Years
Coal	25.2	204
Oil	7.72	50
Natural Gas	6.62	64
Fission	8.5-674	20-1549
Fusion	Enough for several millions years	
Geothermal	56	133
Hydropower	0.07/year	
Biological	0.013/year	
Wind	51/year (1700TW) 0.54-5.1/year extractable	
Solar	5160/year 1100 usable for land-based conversion	

Would Energy Council: 2004 Survey of Energy Resources□
英国石油公司（BP）数据

中国能源现状与挑战

中国能源短缺，环境污染严重

能源类型 Er		e (World)
煤炭		nes
石油		nes
天然气 (		
核燃料		s
水电 (H		r

消耗大（2011年）

石油：4.9 亿吨（进口2.86亿吨), 美国9.41亿吨

天然气：1290亿立方米

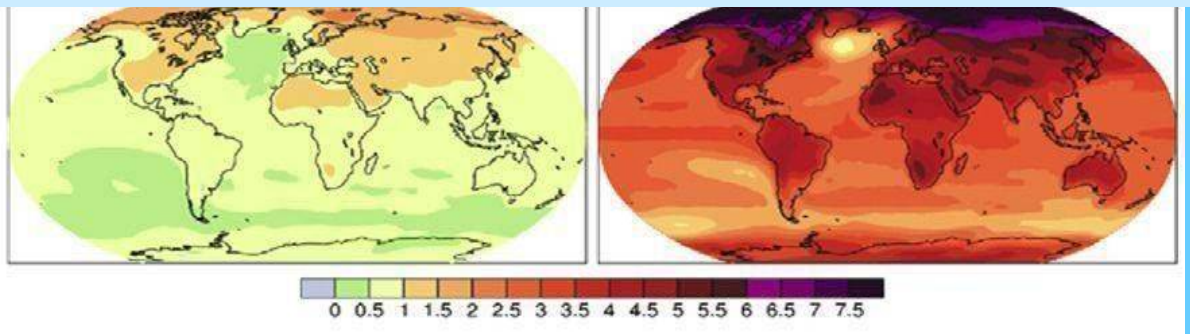
煤：35.7 亿吨，占世界48.2%

污染严重（自2007年）

CO_2排放量世界第一

SO_2排放量世界第一

环境污染 ： 温室效应



• Proved recoverable res

中国近年发电量及占世界比例

	总量		水电		火电		核电		全球	中国占全球比例
年份	发电量/亿度	同比增长	发电量/亿度	占总量	发电量/亿度	占总量	发电量/亿度	占总量	发电量/亿度	
2004	21943	15.18	3310	15.1	18103	82.5	504.7	2.3		
2005	24975	13.82	3964	15.9	20437	81.8	530.9	2.13	181840	13.7
2006	28344	13.5	4167	14.7	23573	83.2	543	1.92	190280	14.9
2007	32559	14.44	4867	15	26980	82.9	626	1.92	198948	16.4
2008	34334	5.18	5633	16.4	27793	81.0	684	1.99	201870	17.0
2009	36506	7							200793	18.2
2010	41413	13.3							213251	19.4
2011	47217	11.7								

中国电监会和中国电力企业联合会，World Bank report

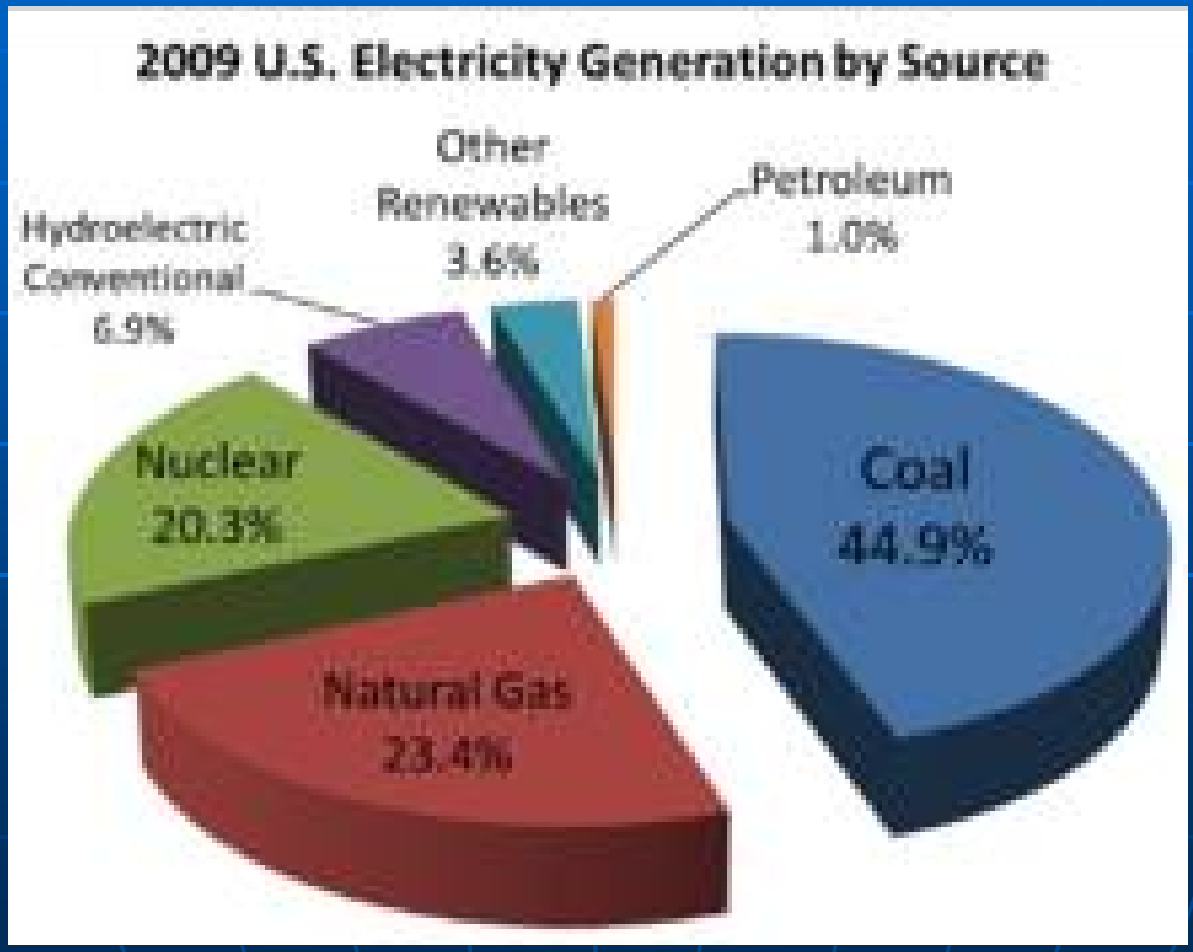
发电的主要形式

Thermo Power Generation

Hydropower

Nuclear Power

Sources generating electricity in US



http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html

Smog

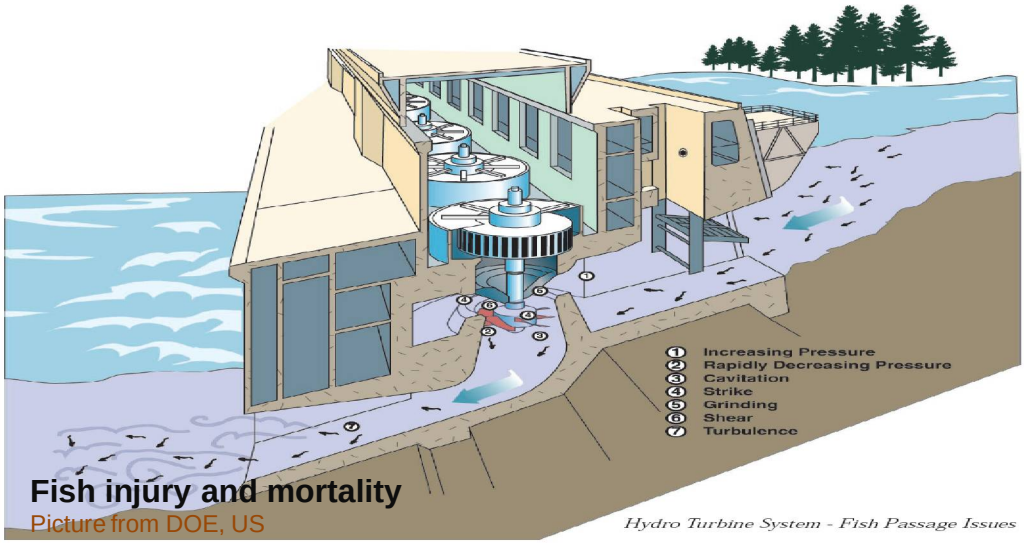
Acid Rain

Global Warming


Gulf of Mexico Oil Disaster
Daniel Beltra
GREENPEACE


Takes several months to clean up


Gulf of Mexico Oil Disaster
Most birds affected by an oil spill die!!

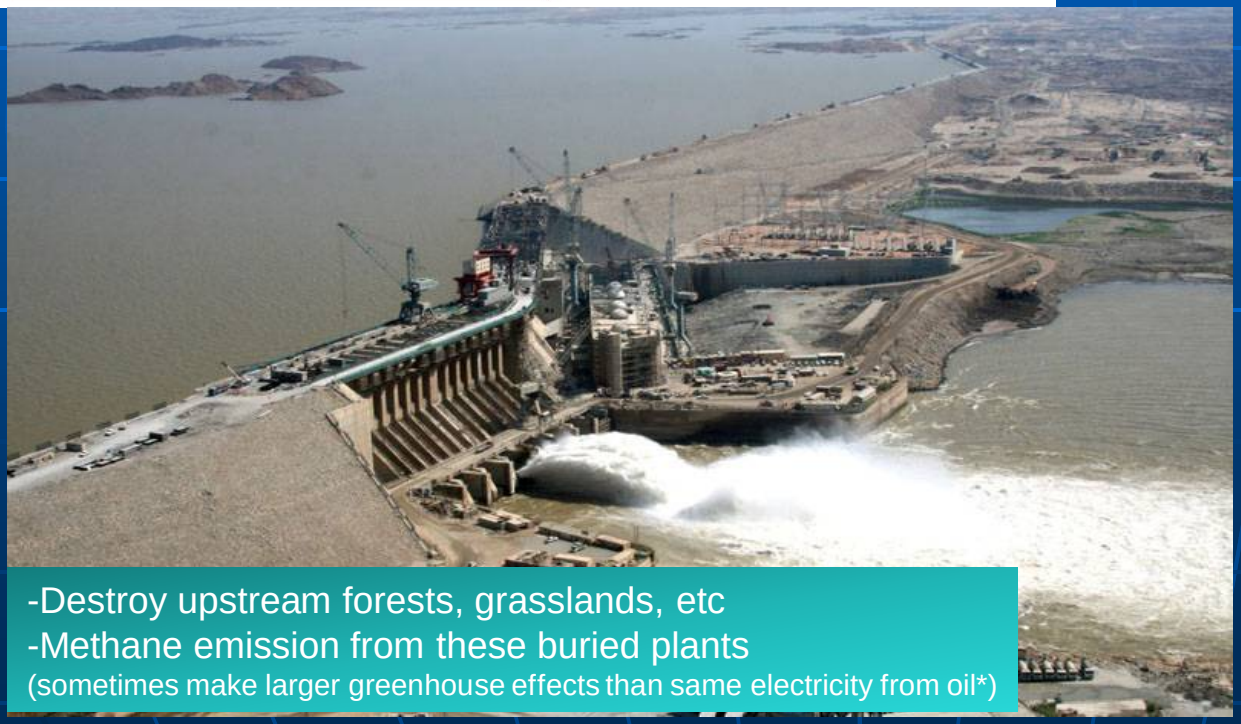


Fish injury and mortality

Picture from DOE, US

Loss of land

Merowe Dam



-Destroy upstream forests, grasslands, etc

-Methane emission from these buried plants

(sometimes make larger greenhouse effects than same electricity from oil*)

RELOCATION

40-80 MILLION PEOPLE RELOCATED IN 2008

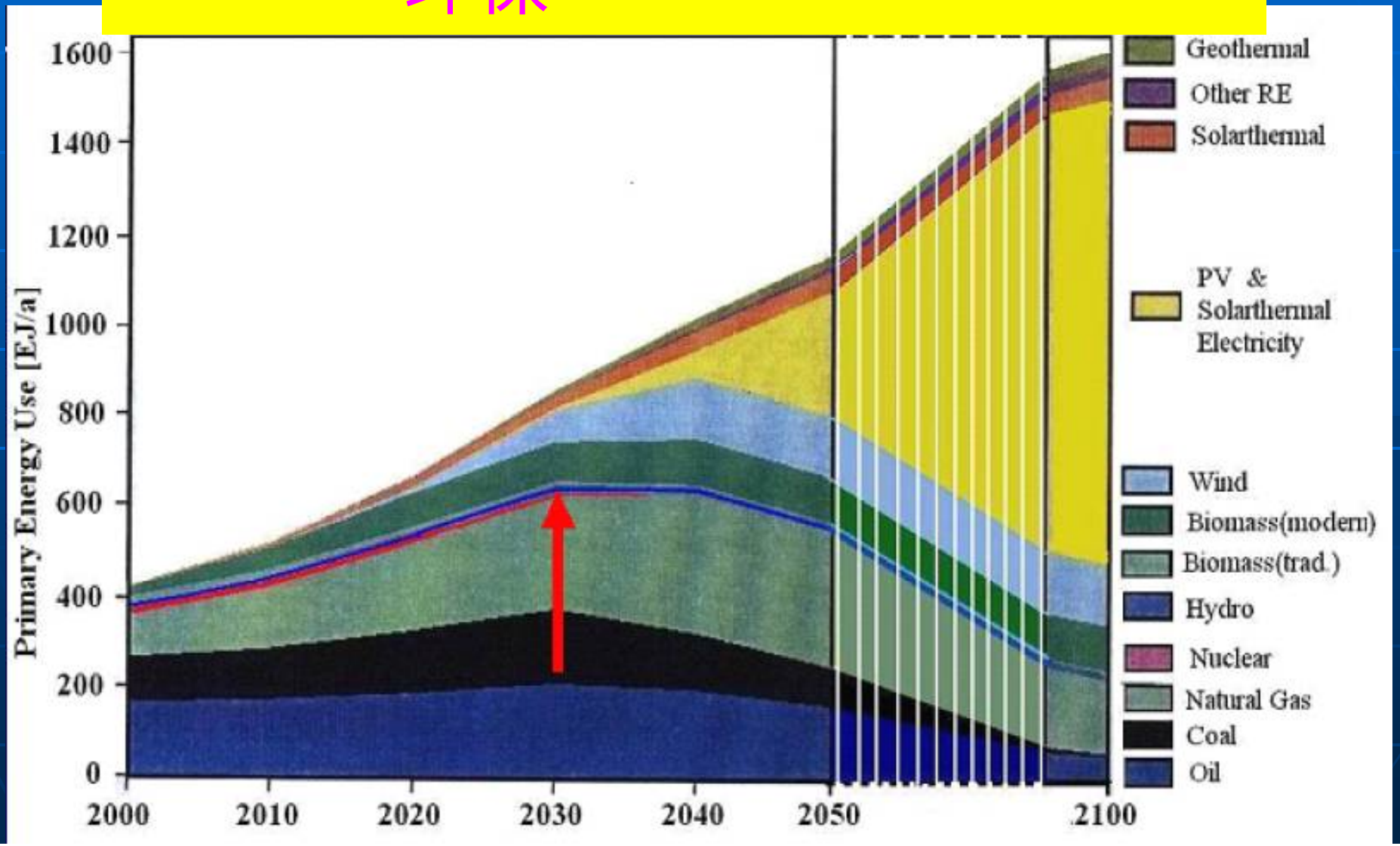
* New Scientist http://www.newscientist.com/article/dn7046-hydroelectric-powers-dirty-secret-revealed.html


The worst nuclear accident since the Chernobyl explosion in 1986 is unfolding in northern Japan at the **Fukushima Daiichi power plant**. Reactors 1, 2 and 3 are in critical stages.
Reactor 4
Reactor 3
Reactor 2
Reactor 1


Kawamata
Iitate
Minami Sōma
30km
20km
Katsurao
Namie
Tamura
Futaba
Okuma
Fukushima Daiichi
Kawauchi
Tomioka
Naraha
Hirono
Iwaki
10km

出路： 再生能源 —光伏太阳能发电

- 太阳能用之不竭
- 环保



2. 光伏发电到底需要多大规模？

- Total power consumption:
  15 TW
- Electricity generation capacity:
  5 TW
- Average up-time 12 hours/day, generating 2.13×10^{13} kW.h/year

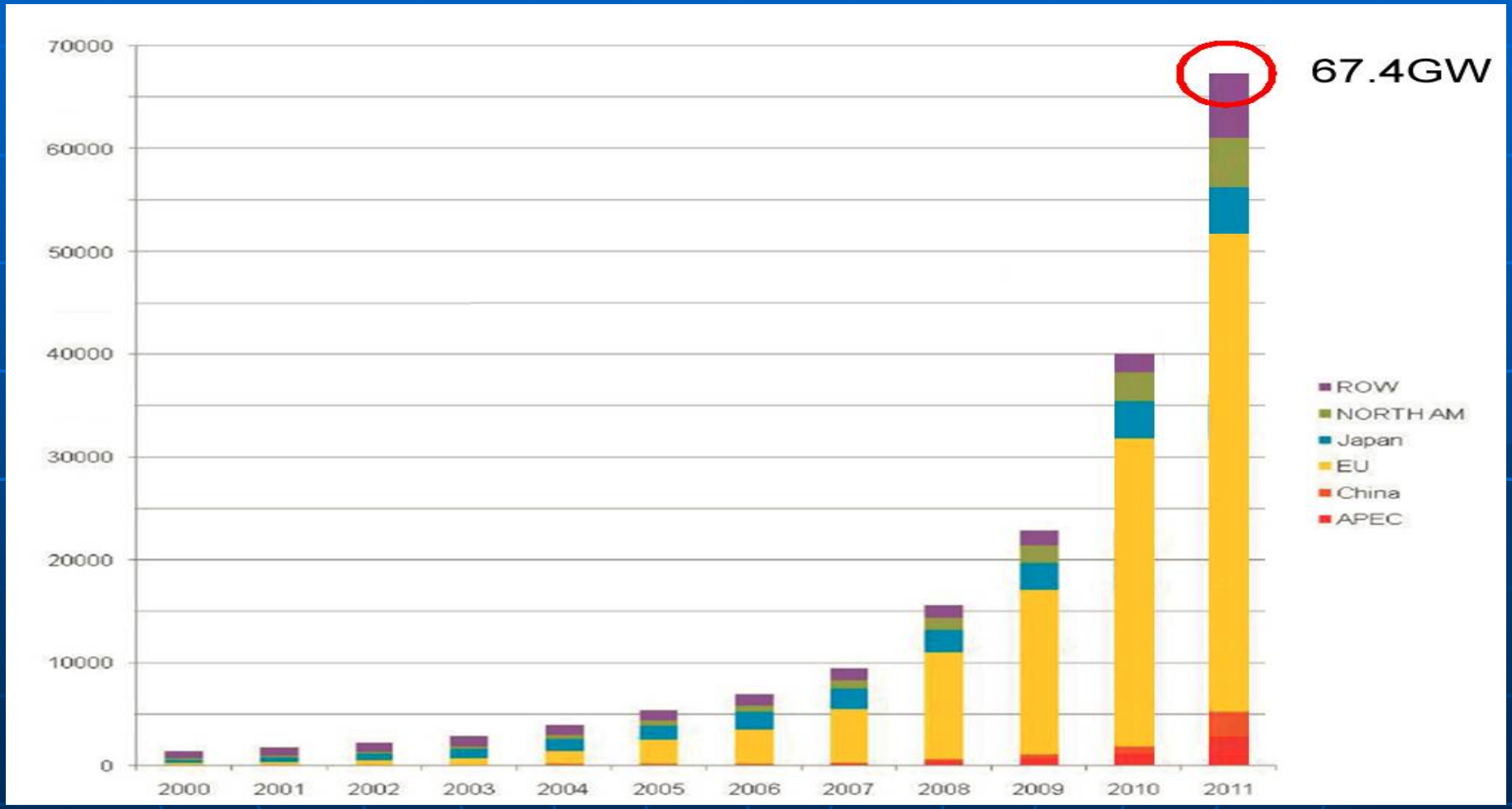
Scale of Electrical Power

- PV facility Average up-time 4-6 hours/day
- PV facility capacity: 30 TW in mid-21st Century
- Able to generate upto 4.5×10^{13} kW.h/year

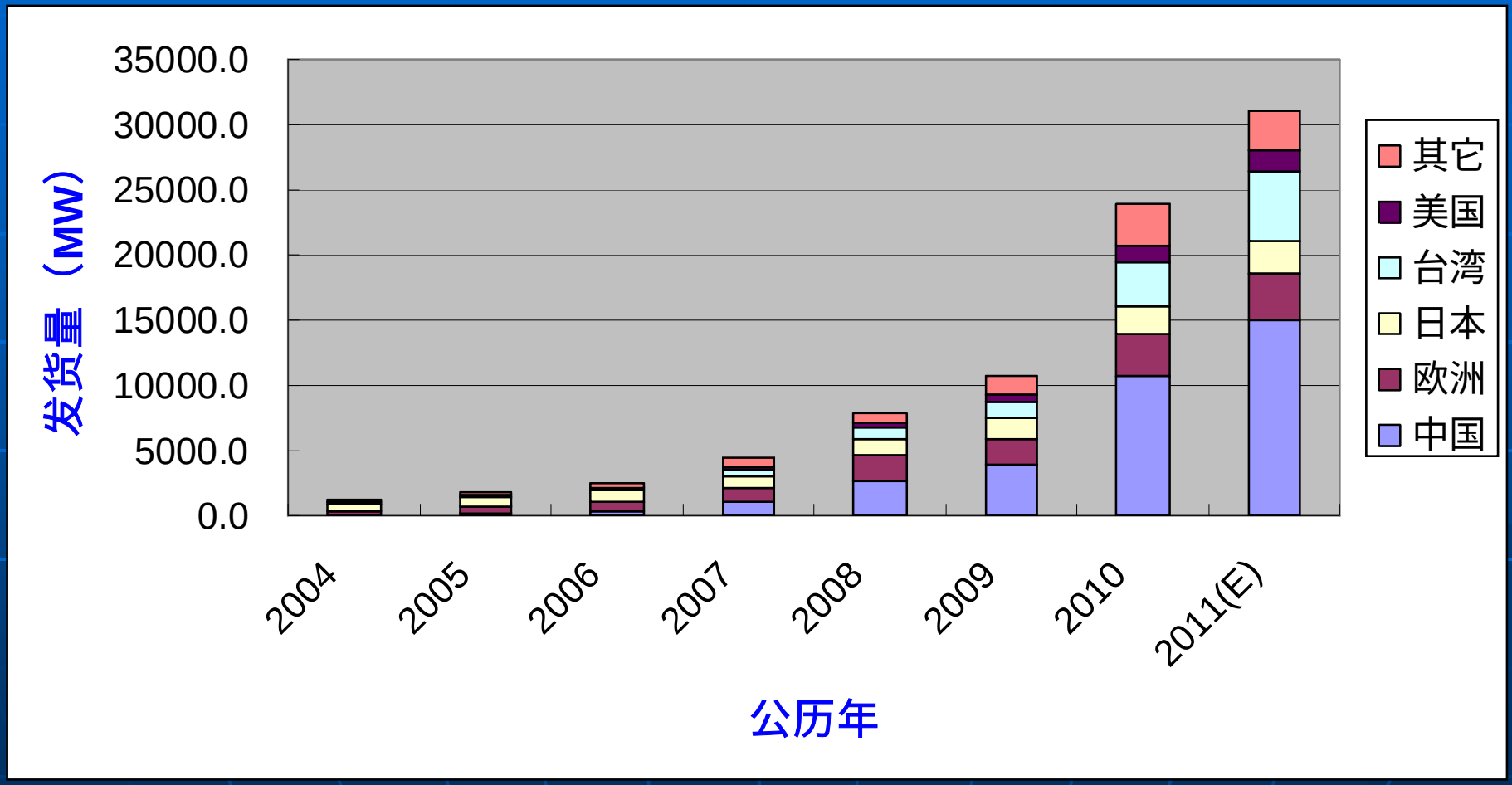
- Assuming 30 years life time, it requires 1 TW/year installation for 30 years
- Afterwards, it reaches steady state

2011 年全世界新增光伏发电容量27.5GW

世界累计装机容量


70000
60000
50000
40000
30000
20000
10000
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
67.4GW
ROW
NORTH AM
Japan
EU
China
APEC

全球光伏组件生产规模



距离1TW还有30多倍
PV production is far from saturation

投资过热吗？
暂时的！！！

中国能源结构

电力生产

2011年总发电量:

4500 TWh=45000亿度(美国 41000亿度)

2011年总装机: 1040GW

火电: 762GW

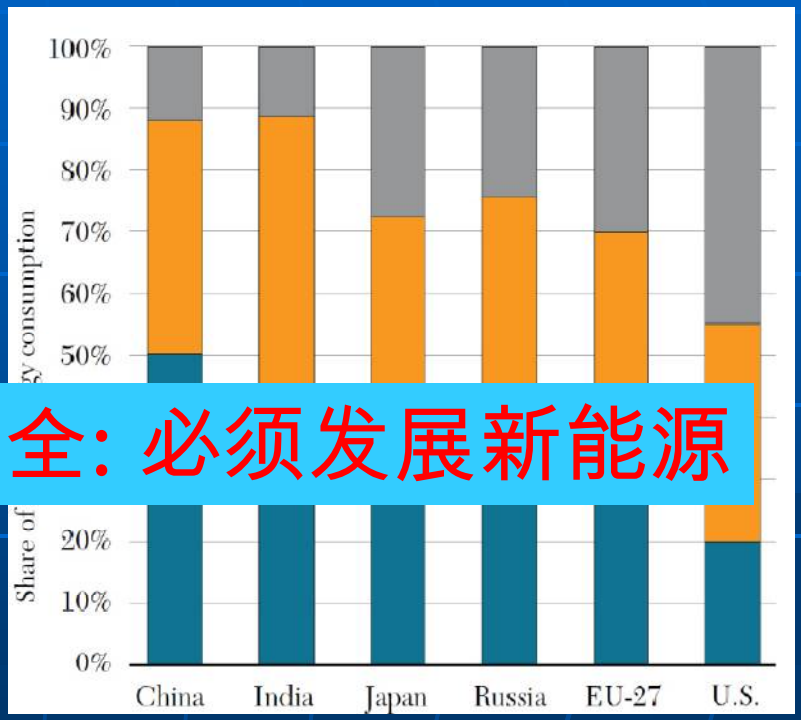
水电: 220

核电: 12

风电: 45

太阳能发电: 3.3

能源消费



2009 IEA World Energy

国家能源战略, 能源安全: 必须发展新能源

21世纪中页，如全部采用
PV发电, 共需6TW光伏组件，发90000亿度

3．光伏发电现实吗？

- 5160 Q/year to Earth
- 1100 Q usable for land-based conversion

- World annual primary energy consumption (2008), = 0.505 Q, 40% of which generating electricity.
- In 2010, a total of 2.13×10^{13} kW.h electricity were generated, which is 0.0727 Q
- ~0.5‰ globe land surface required for PV installation, using conversion efficiency 15% (0.485Q solar energy is required)

- ~0.28% electricity at 2010

Solar Land Area Requirements

6 Boxes at 3.3 TW Each

Solar Radiation has a low energy density

Solar Land Area in China

Electricity in 2010:

China: 4141.3 billion kWh (19.4%);

World: 21325.1 billion kWh

Source: EIA refer to the attachment, EIA= Energy Information Administration

Land area:

China: 9,640,821 km^2 (6.5%);

World: 148,939,063 km^2 (100%)

Source: wikipedia

http://en.wikipedia.org/wiki/List_of_countries_and_outlying_territories_by_area

Total Area required (225 kWh/m^2.yr @15% of insolation 1500kWh/m^2.yr):

$$A = 4141.3 \times 10^9 \div 225 = 18406 \ km^2$$

Shenzhen: 1,952.84 km^2

全国所有建筑屋顶装上太阳能电池

城市及县城建成区
面积4.9万平方公里

假设屋顶面积为建成区面积的1/5

城市及县屋顶
面积0.98万平方公里

村镇公共建筑
面积0.22万平方公里

假设屋顶面积为建筑面积的1/5

村镇公共建筑屋顶
面积0.044万平方公里

村镇住宅及生产建筑
面积3.014万平方公里

假设屋顶面积为建筑面积的1/2

村镇住宅生产屋顶
面积1.507万平方公里

每年日照
2200小时
1500度/平米.年

装上转化
效率为
15%的太
阳能电池

56948亿度
≈1.38倍
2010年全国发电量

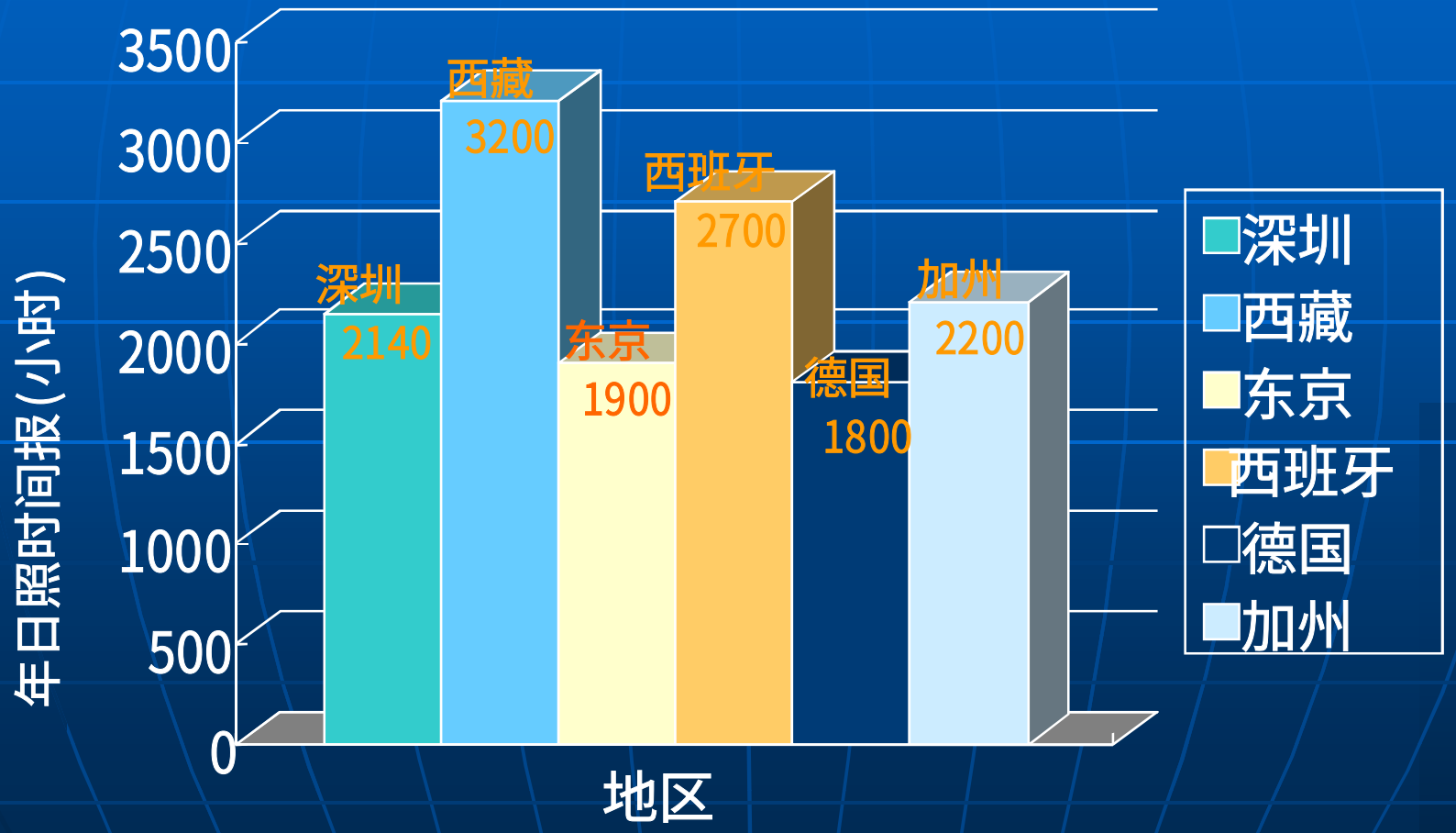
建筑面积来自中华人民共和国住房和城乡建设部

全国太阳辐射量分布情况

- 太阳辐射量主要与地理纬度、海拔高度、云层厚度和空气污染度等有关

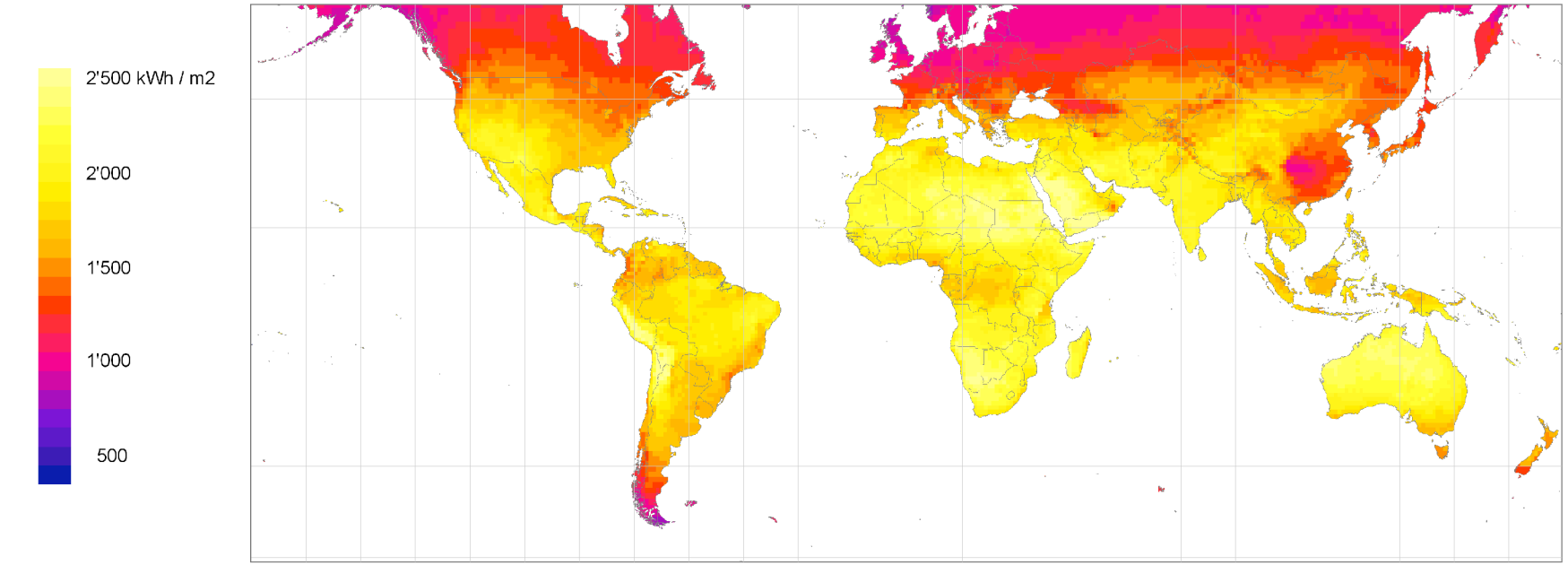
	太阳辐射指标	
地区	全年日照时数（小时）	太阳辐照总量（kW.h/平方米*年）
西藏，新疆东南部，青海西部，宁夏和甘肃北部	2800-3300	1850-2300
内蒙，宁夏南部，甘肃中部，青海东部，西藏东南部，新疆南部，河北西北部，山西北部	3000-3300	1600-1850
山东，河南，云南，吉林，新疆北部，陕北，山西南部，甘肃东南部，广东南部，闽南，河北东南部	2200-3000	1400-1600
湖北，湖南，广西，浙江，闽北，皖南，苏南，粤北，陕南，黑龙江	1400-2200	1160-1400
贵州，四川	1000-1400	930-1160

全球主要太阳能使用国家的年平均日照时间



全球照度图

Yearly sum of global irradiance



Source: Meteonorm 6.0 (www.meteonorm.com); uncertainty 10%
Period: 1981 - 2000; grid cell size: 1°

June 2008

METEOTEST

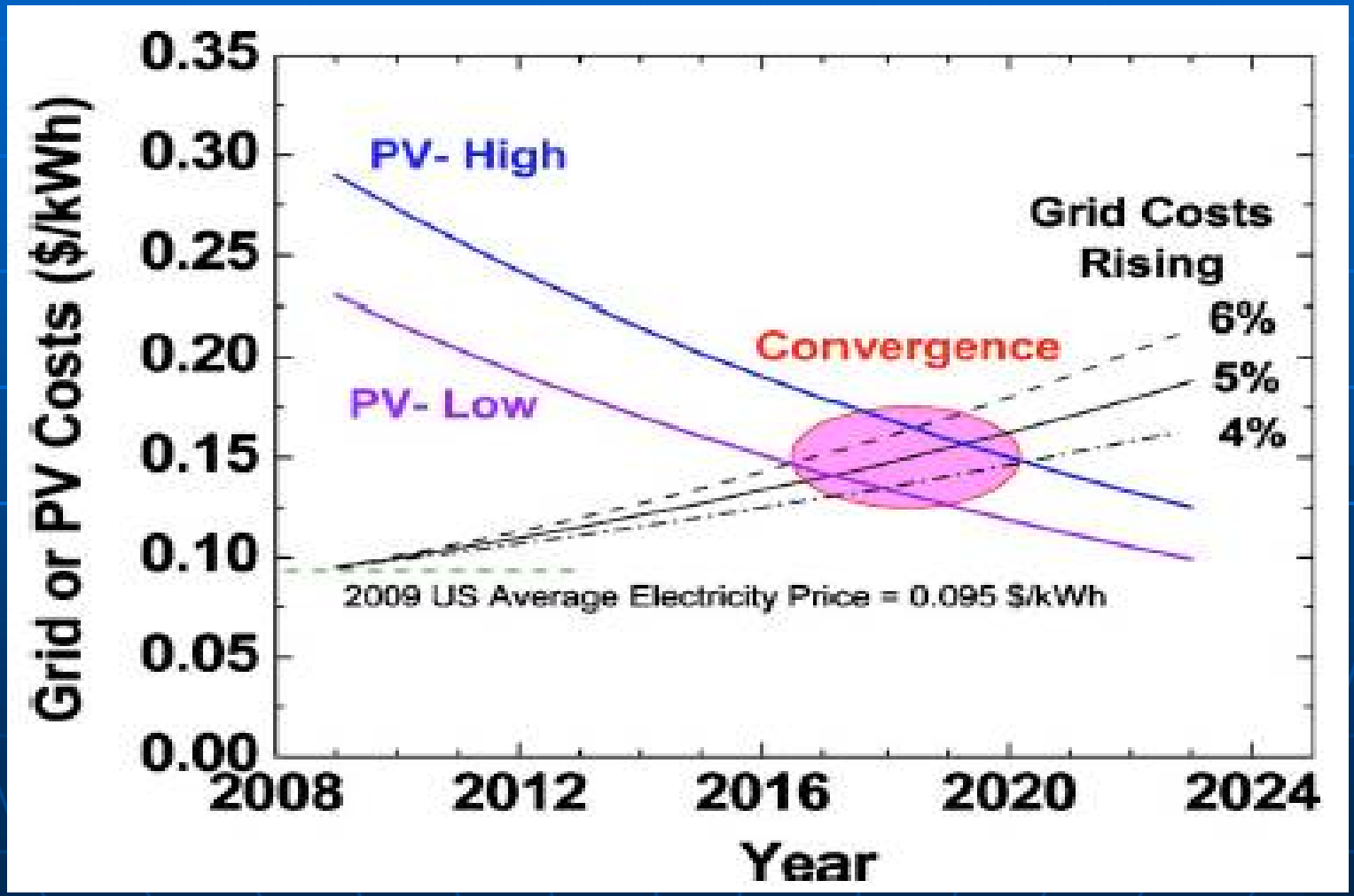
Comparison

Biomass Energy Potential

Global: Top Down

- Requires Large Areas Because Inefficient (0.3%)
- 3 TW requires ≈ 600 million hectares = 6×10^{12} m^2
- 20 TW requires ≈ 4×10^{13} m^2
- Total land area of earth: 1.3×10^{14} m^2
- Hence requires 4/13 = 31% of total land area

4．光伏发电的主要挑战是什么？
与化石能源价格竞争



Types of Solar Cells

1st Generation:

- Single crystalline silicon (c-Si)
- Polycrystalline silicon (c-Si)

2nd Genration (Thin Films):

- Amorphous silicon (a-Si:H)
- Cadmium telluride (CdTe)
- Copper indium gallium selenide (CIGS)

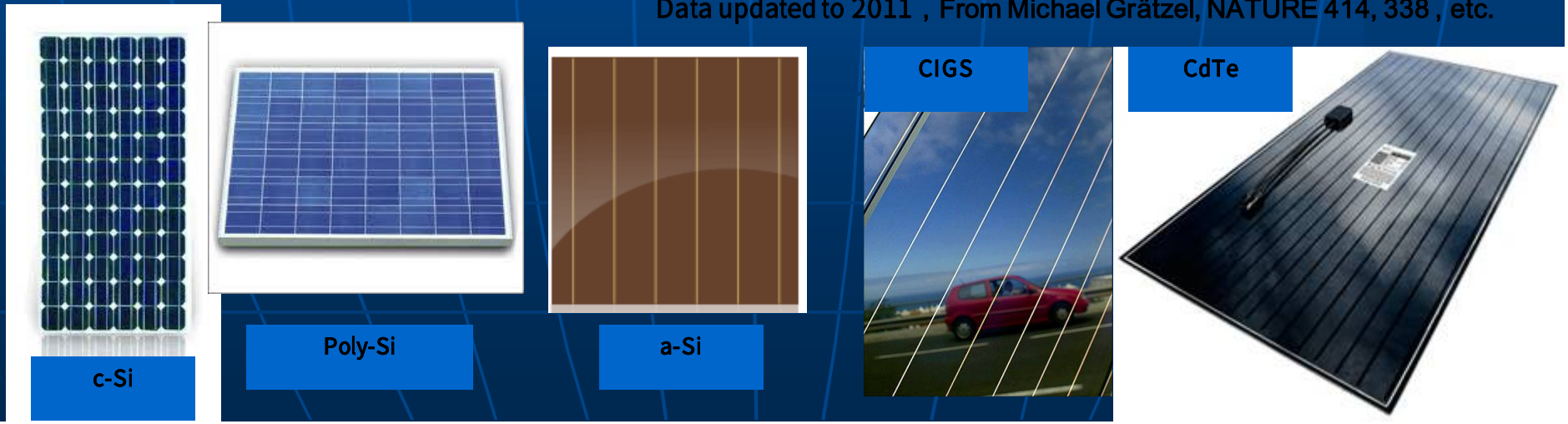
3rd Genration (Thin Films):

- Organic PV, Sensitized cells,
- Gallium arsenide tandem solar cells , etc

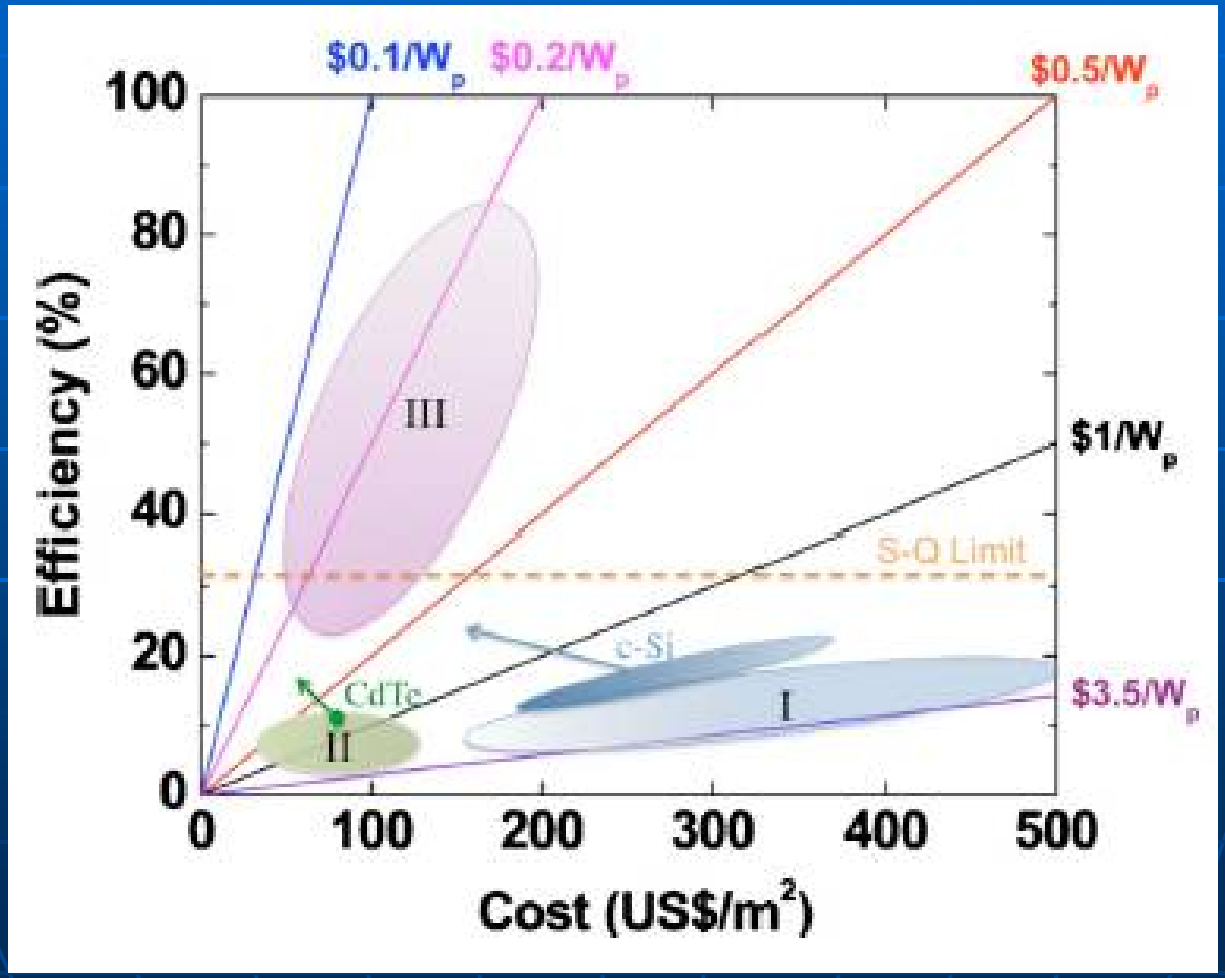
Various Commercial Solar Cells

Type of cell	Efficiency (%) Cell	Module	Pros	Cons	Application
c-Si	25	10—18.8	High efficiency, long lifetime, mature industry	High cost, high energy consumption, bottleneck in raw materials supply	Solar farm, rooftop
Poly-Si	20.3	9—17.2	Mature industry	High cost, complex fabrication	Solar farm, rooftop
a-Si	13	6—9	Low cost, commercialized	Low efficiency, decay	Solar farm, rooftop, BIPV
CIGS	20.3	9—15.7	High efficiency, low cost	Complex fabrication, scale-up production, stabilized yield, In reserve	Solar farm, rooftop, BIPV
CdTe	17.3	6—11.7	Low cost, simple fabrication	Toxicity, Te reserve	Solar farm, rooftop, BIPV

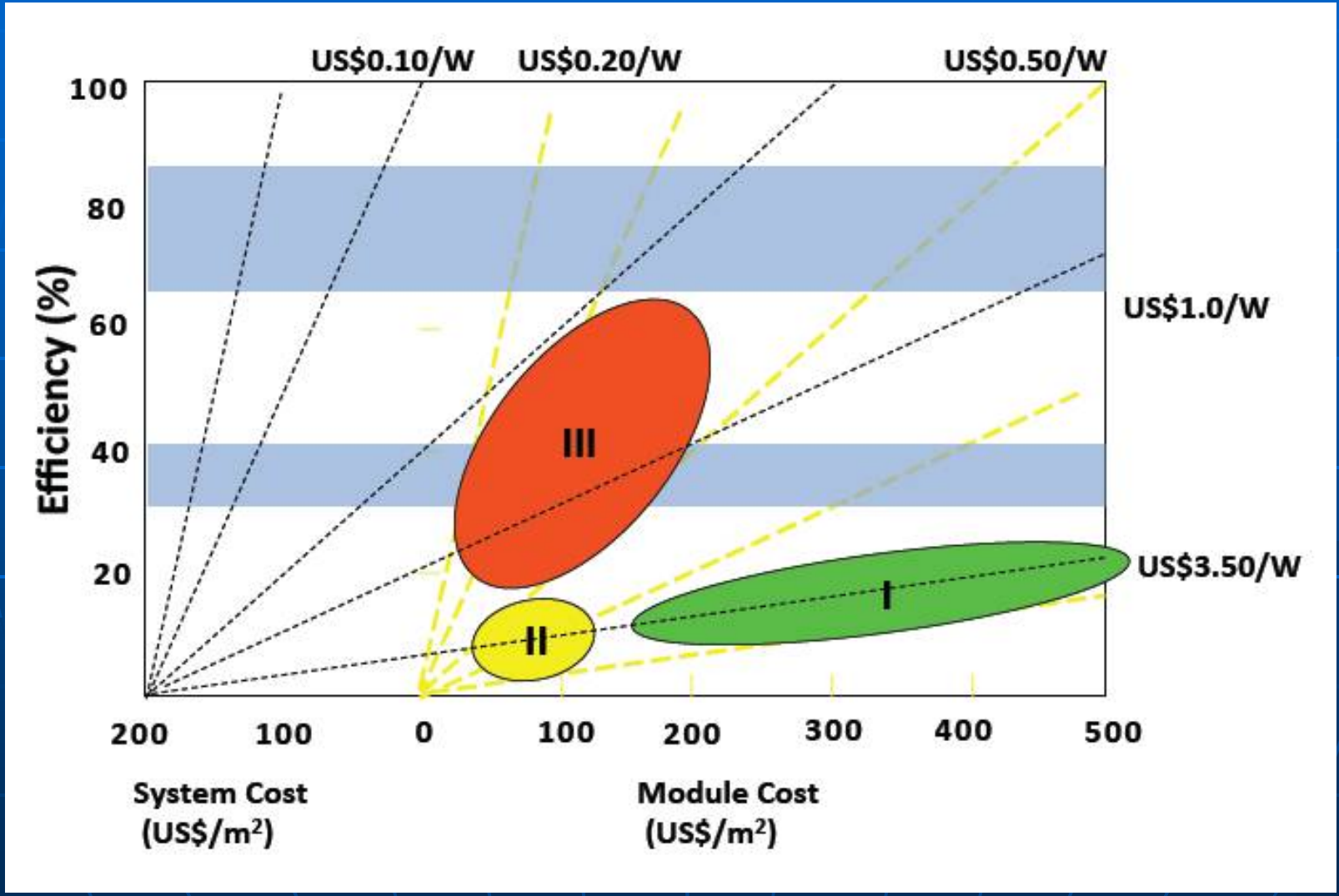
Data updated to 2011, From Michael Grätzel, NATURE 414, 338, etc.



Cost of PV Panels

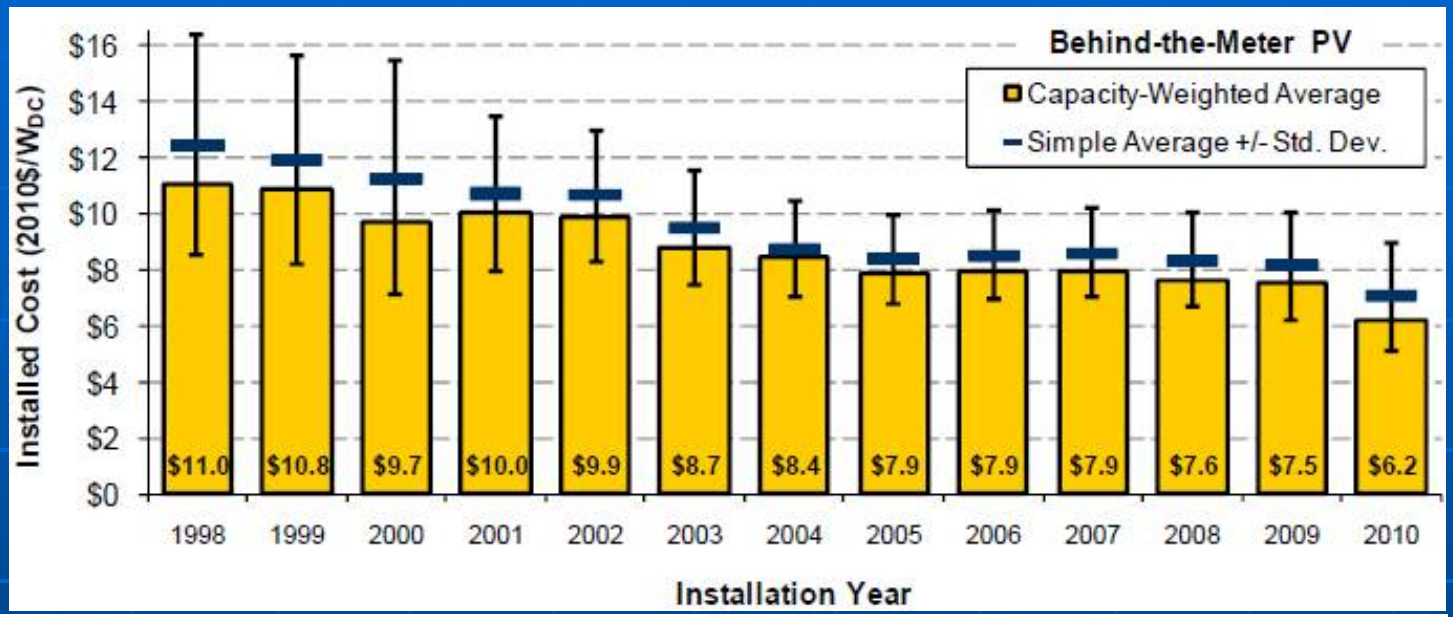


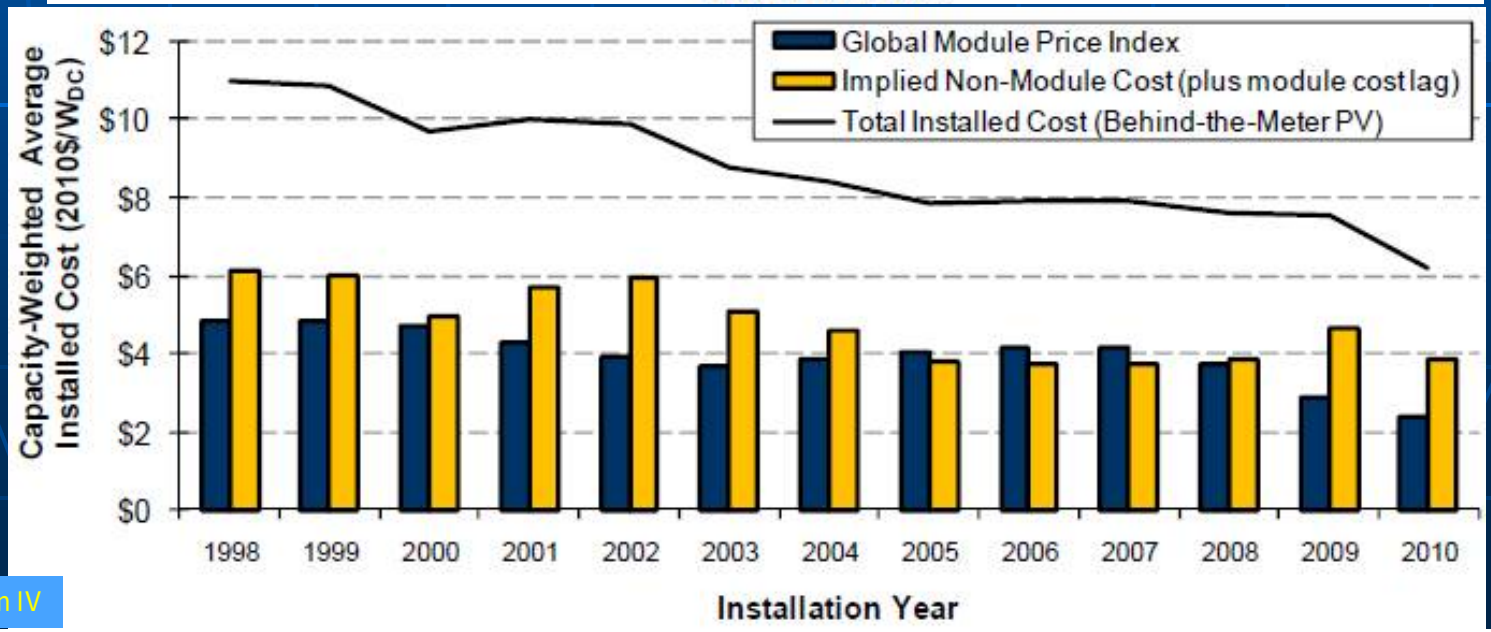
Cost of PV Systems



Courtesy: G. Conibeer, UNSW

Historical Cost of PV Systems (USA)





光伏组件、光伏系统和光伏发电的当前价格

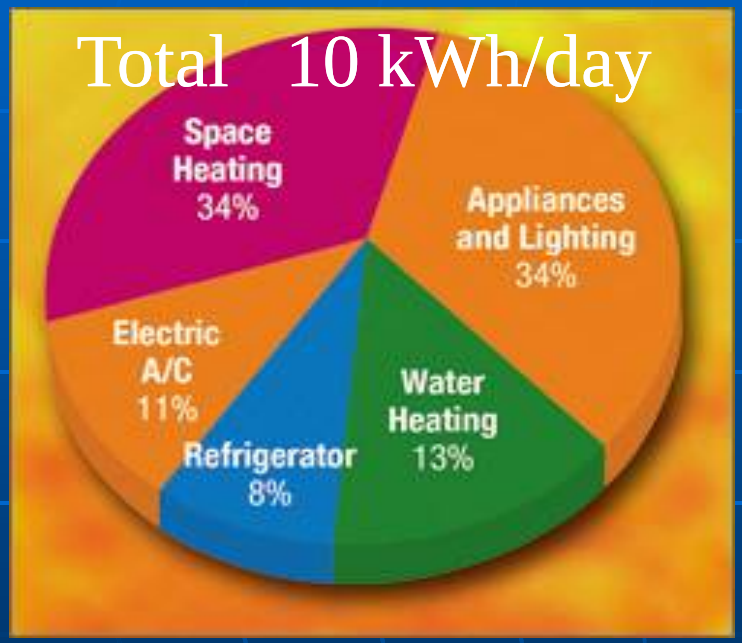
晶硅组件价格	5.5-6.0 Yuan/Wp
晶硅组件成本	~$0.8USD/Wp
a-Si 组件价格	5-6 Yuan/Wp
a-Si 组件成本	$0.6 USD/Wp
LS-PV系统价格	10-12 Yuan/Wp
光伏建筑系统价格	About 12 Yuan/Wp
光伏电价 (初投资每瓦12元，年满发1500小时)	1.0Yuan/kWh (IRR = 8%)

“平价上网”指日可待！

Courtesy: Wang Sicheng, Energy Research Institute, NDRC

Affordable： PV for a house ($100m^2$)

- Cheap?
- Enough Space for Installation?



PV system has 25 yrs lifetime
In 25 years (电费@5%rate increase)
电费: RMB 114,552 – 171,828
投资计划: 开始RMB36,000，
每年从中扣电费，
余额投资@5%回报
今年RMB1.00/kWh, 可交11年电费
今年RMB0.66/kWh, 可交16年电费

- 15% conversion,
- ~4.1 $kWh/m^2 \cdot day$ radiation from Sun ($1500 kWh/m^2 \cdot yr$)
- 0.615 kWh/m^2 day, → 16 m^2 or 2.4 kW_p

障碍: Si PV system on market:15元/Wp → 36,000元 → 10-15年电费

Global electricity price comparison

http://en.wikipedia.org/wiki/Electricity_pricing

Country / Territory	US cents / 1kWh	As of
Argentina	05.74	2006
Australia	19.67 to 28.88	2011
Belgium	29.06	20111101November 1, 2011
Brazil	34.18	20110101January 1, 2011
Canada	10.78	20110101January 1, 2011
Chile	23.11	20110101January 1, 2011
China	10-to 16.0	20110101January 1, 2011
Croatia	17.55	20080701July 1, 2008
Denmark	40.38	20111101November 1, 2011
Dubai	07.62	2011
Finland	20.65	20111101November 1, 2011
France	19.39	20111101November 1, 2011
Germany	36.48	20111101November 1, 2011
Hong Kong (HK Is.)	12.04	20120101January 1, 2012
Hungary	23.44	20111101November 1, 2011
Iceland	03.93	20120101January 1, 2012
Iran	02.00 to 19.00	20110701July 1, 2011
Ireland	28.36	20111101November 1, 2011
Israel	12.34	20120101January 1, 2012
Italy	28.39	20111101November 1, 2011
Jamaica	07.35 to 16.80	20110601June 1, 2011
Latvia	15.40	20111101November 1, 2011
Malaysia	07.42	20071201December 1, 2007
Moldova	11.11	20110401April 1, 2011

Country / Territory	US cents / 1kWh	As of
Netherlands	28.89	20111101November 1, 2011
Pakistan	02.06 to 14.62	20110506May 6, 2011
Perú	10.44	2007
Philippines	30.46	20100301March 1, 2010
Portugal	25.25	20111101November 1, 2011
Russia	09.58	20120101January 1, 2012
Singapore	22.11	20120101January 1, 2012
South Africa	05.37	20080701July 1, 2008
Spain	27.06	20120101January 1, 2012
Sweden	27.10	20111101November 1, 2011
Taiwan	07 to 17	20081001October 1, 2008
Thailand	04.46 to 09.79	20110305March 5, 2011
Tonga	57.95	20110601June 1, 2011
Turkey	13.1	20110701July 1, 2011
UK	21.99	20111101November 1, 2011
Ukraine	03.05 to 03.95	2011
Uruguay	14.47 to 22.89	20110218February 18, 2011
USA	11.20	2011
Uzbekistan	04.95	2011
Vietnam	06.20 to 10.01	2011

光伏发电的固有缺点

不连续-不稳定-不可调度

将光伏和谐、友好地融入电网

使光伏发电做到可预测、可调整、可控制和可调度

机遇？

- *过去多年光伏制造企业是光伏事业的发展主要推动力，光伏系统公司到了该发力的时候了。*
- *蓄电、储能系统也要跟上去。*

光伏发电的各种应用

Toys


FERRIS WHEEL
Solar Power

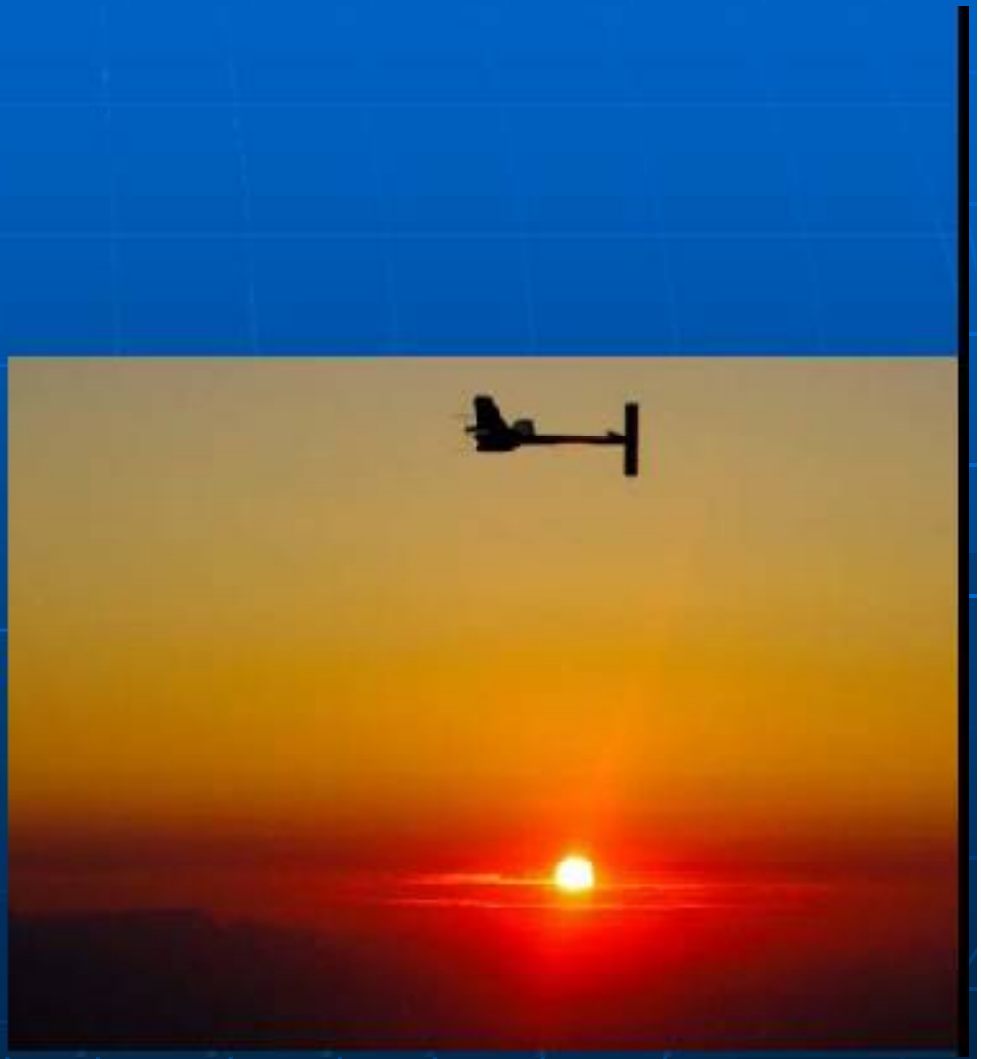

e.Sal
http://www.jingpinwanju.com


SOLAR VEHICLE

Vehicles

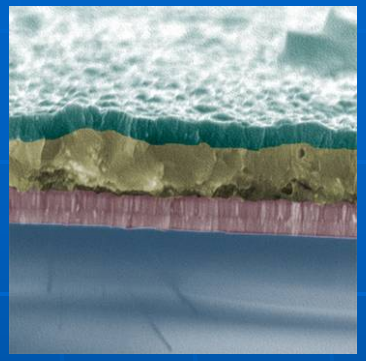
Airplane

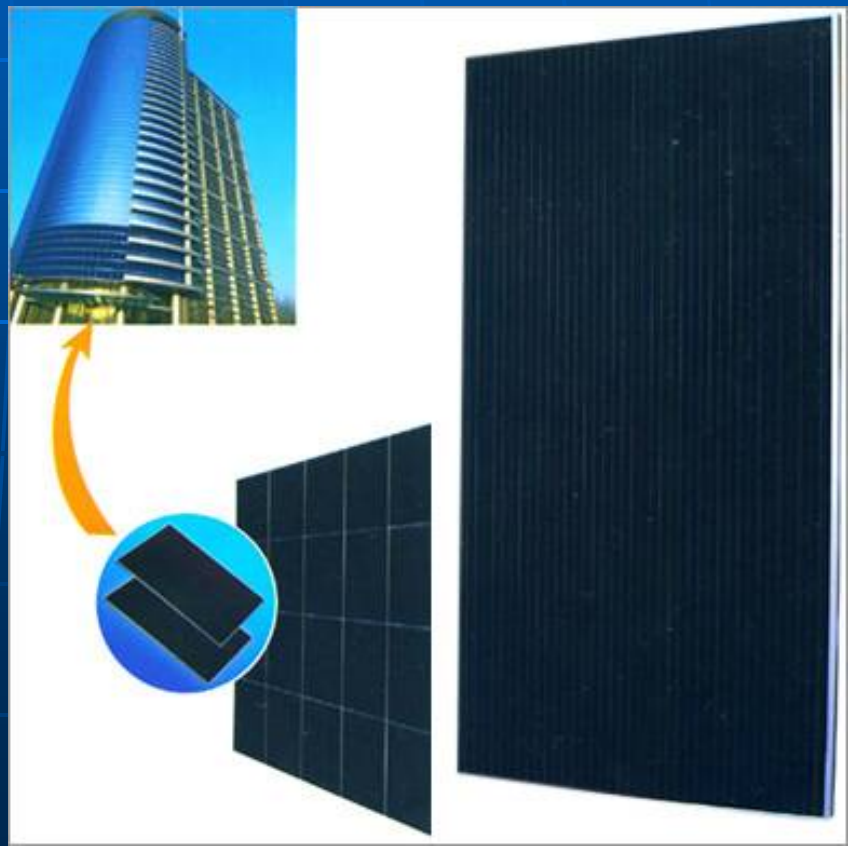
2010年7月8H清晨，“太阳驱动”在首次成功完成夜间飞行后，停在帕耶那机场上。它创造了26小时零9分钟的不间断飞行记录，这也是太阳能飞机持续时间最长、飞行高度最高的世界记录



Houses

Thin Film BIPV





Solar Power Plants

Solar power plant, Toledo province, Castile-La Mancha, Spain
B27-423831 age fotostock Rights Managed Photograph

Satellites

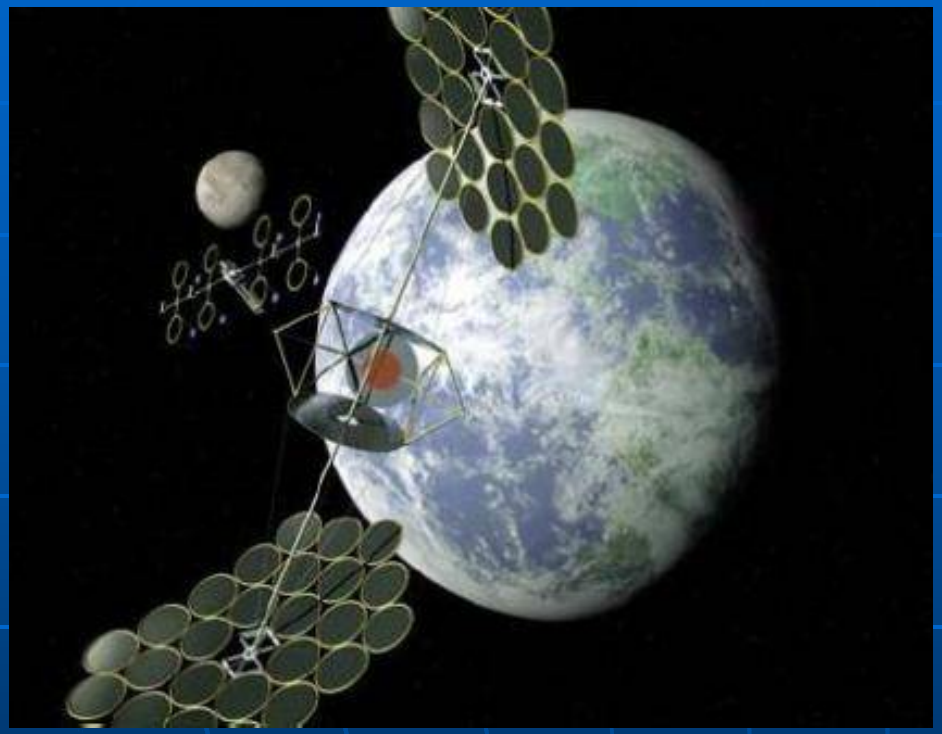
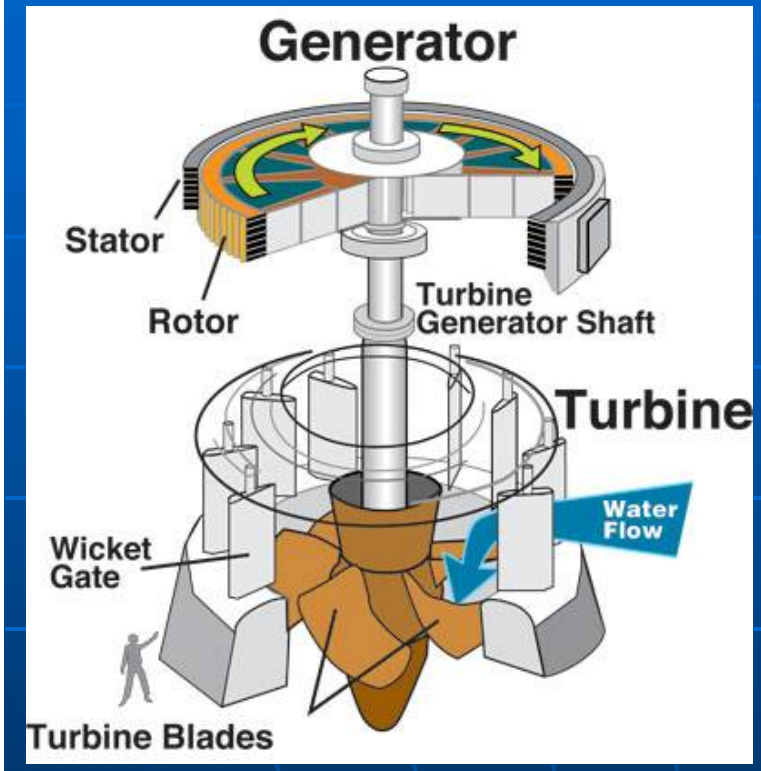
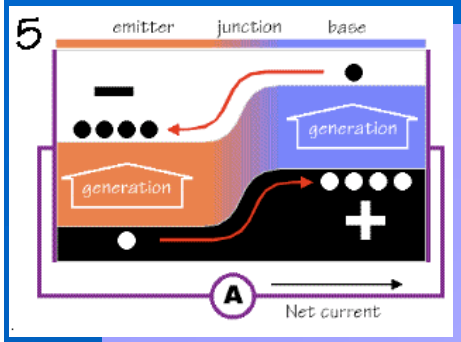


Fig. 1 International Space Station(ISS)

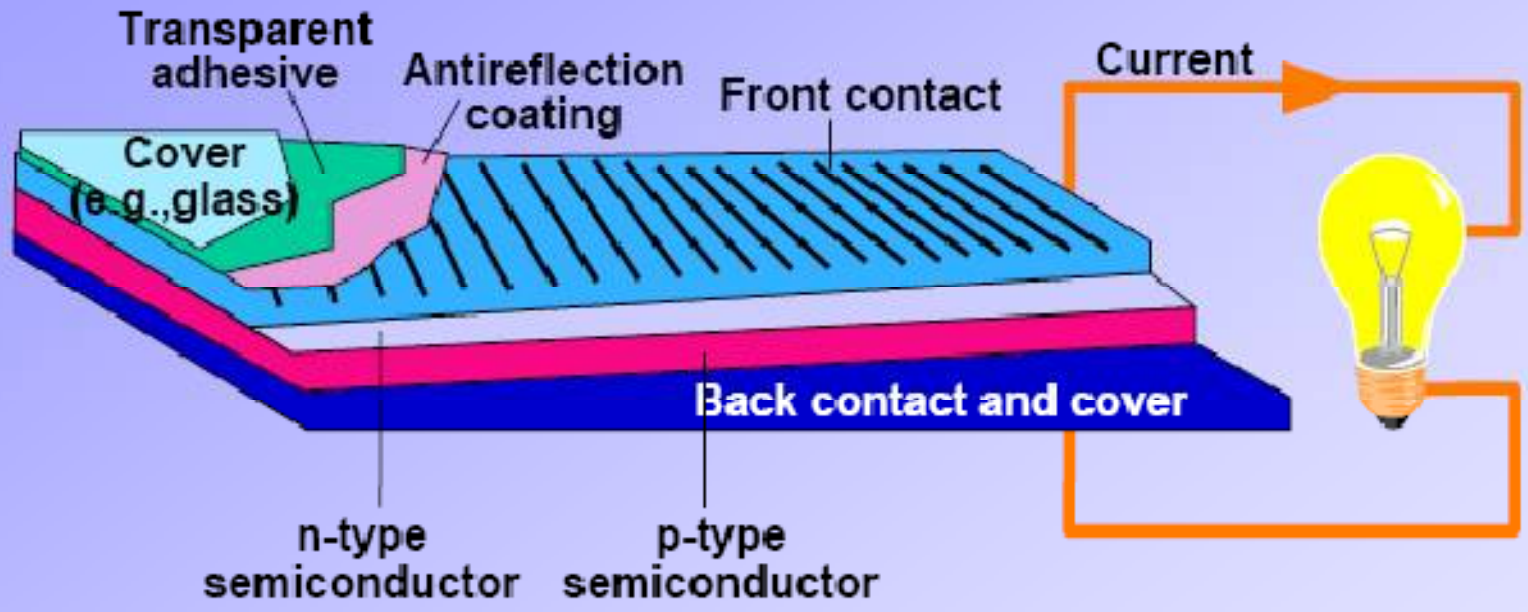
5. 光伏技术的现在与将来

传统发电技术


Generator
Stator
Rotor
Turbine
Generator Shaft
Turbine
Water
Flow
Wicket
Gate
Turbine Blades



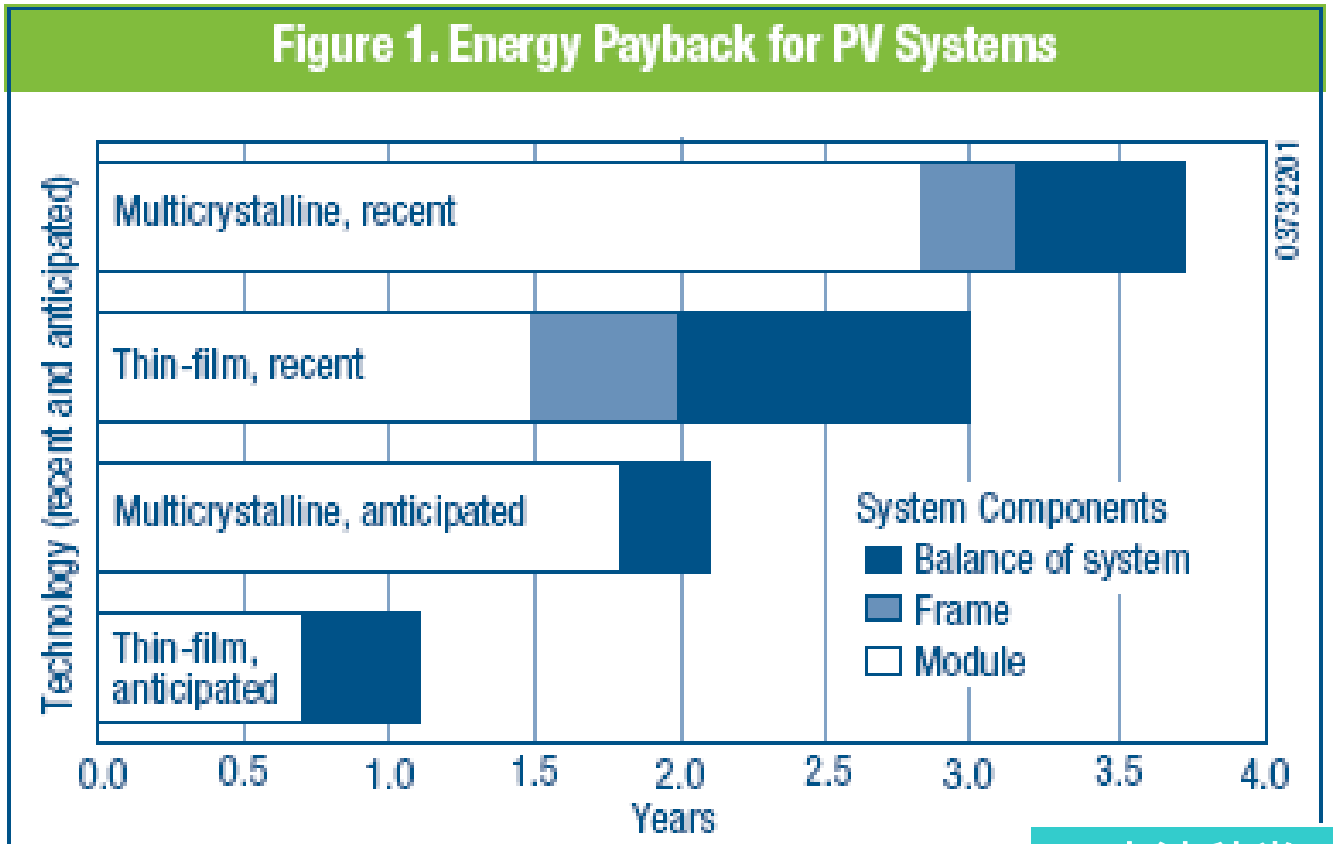
Solar Cell Structure



$$\text{Solar cell efficiency (\%)} = \frac{\text{Power out (W)} \times 100\%}{\text{Area (m}^2\text{)} \times 1000\ \text{W/m}^2}$$

10% efficiency = 100 W/m^2 or 10 W/ft^2

Energy Payback Time

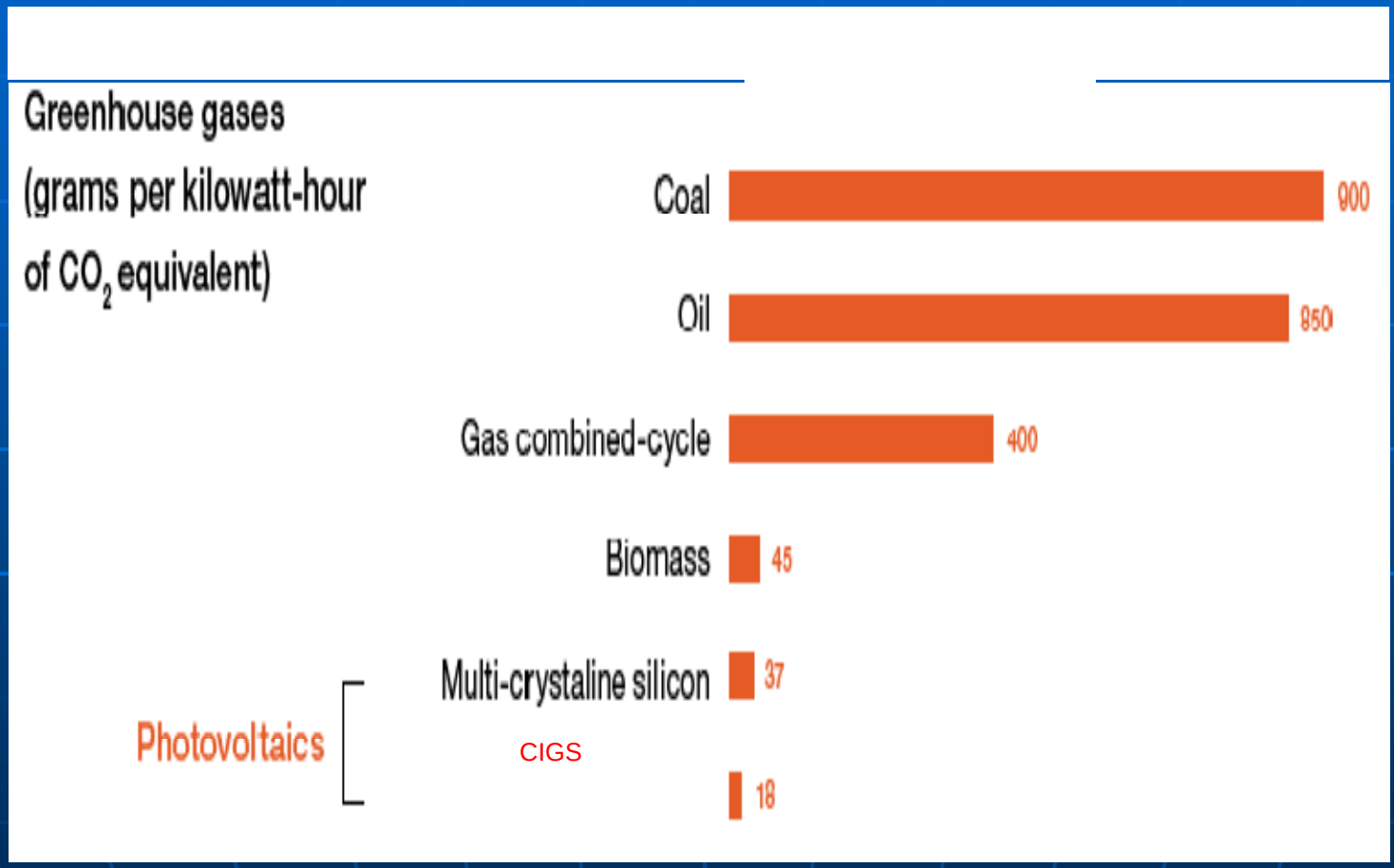


Reaping the environmental benefits of solar energy requires spen
make the PV system. But as this graphic shows, the investment is
30-year system life, PV systems will provide a net gain of 26 to 2
tion-free and greenhouse-gas-free electrical generation.

电池种类	能量回报期
晶硅电池	2.7年
碲化镉电池	1年
非晶硅电池	1.3年
铜铟镓硒电池	<1年

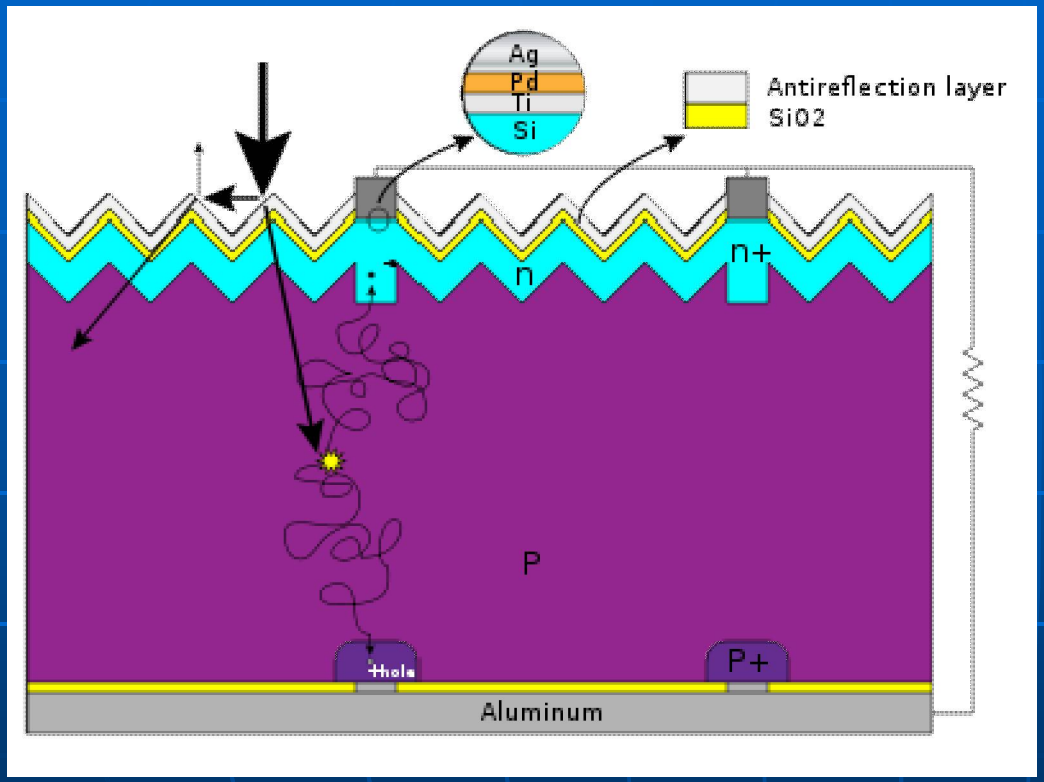
http://www.renewable-energy-sources.com/2008/04/16/photovoltaic-energy-payback-time/

低碳技术，环保

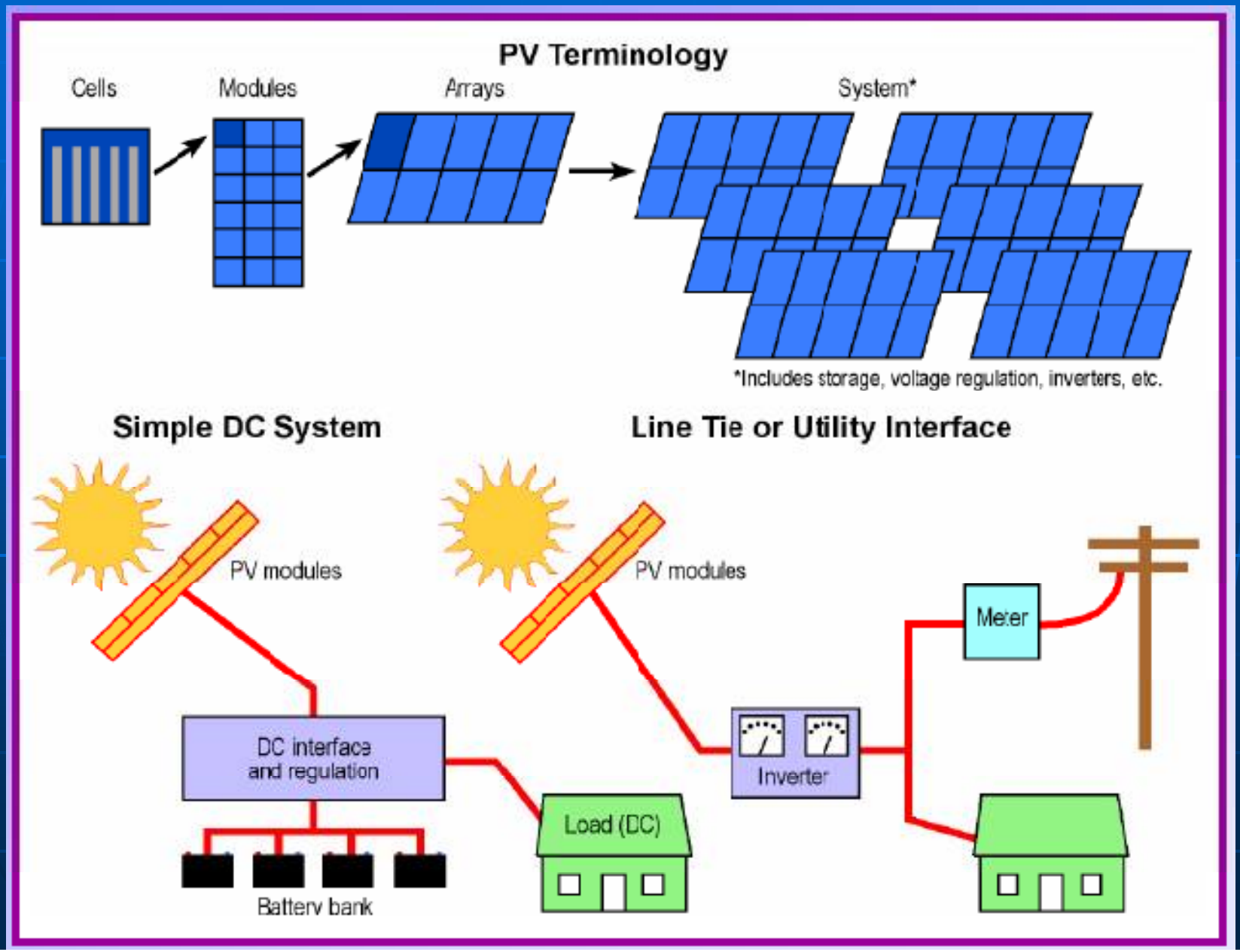


European Photovoltaic Industry Association

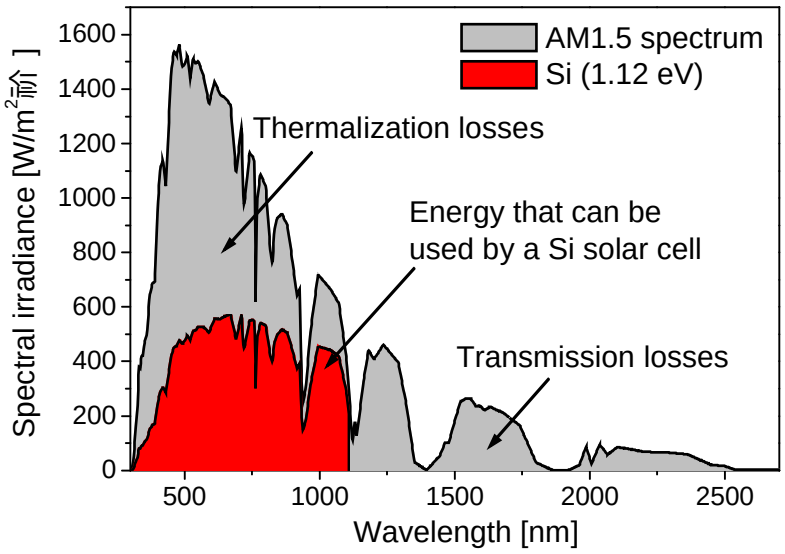
Si p-n Junction and Electrodes

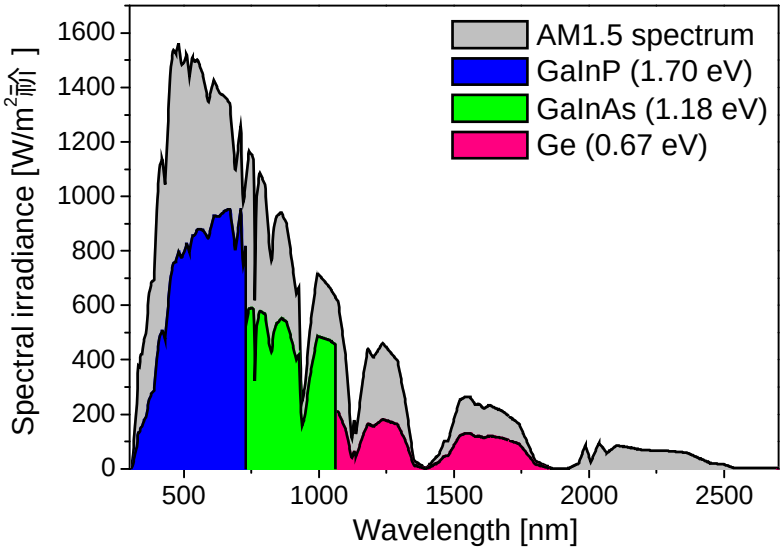


PV Electricity: Modes of Use



Theoretical Efficiency





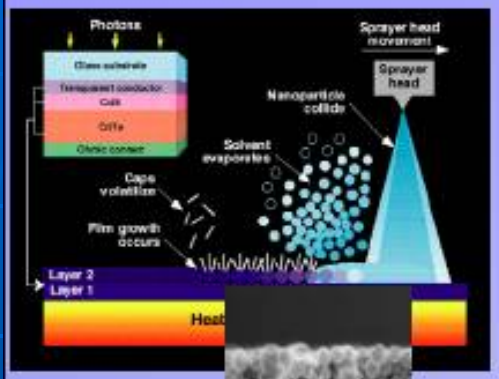
Detailed-balance efficiency limit (terrestrial):

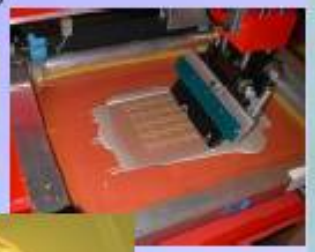
- **Single junction: 31 % at E_g = 1. 3 eV (Shockley and Queisser)**
  best ~ 25% (GaAs and Si)
- **Multi-junction: 49% (best three junction ~ 34%)**
- **Multi-exciton generation (QE > 1): 41% (device?)**

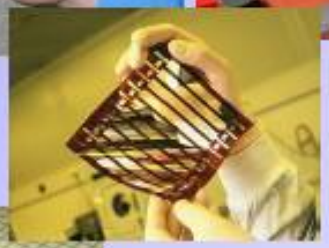
Future Technology

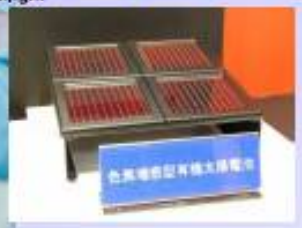
Future Generation PV Technologies

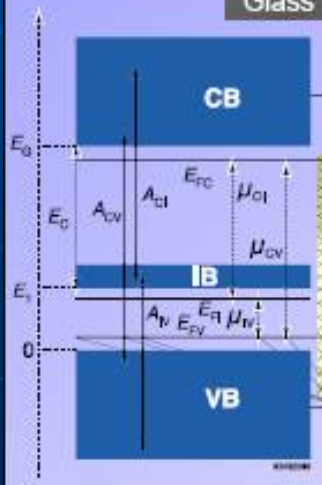
- Opportunities for innovation – ultra low cost, ultra high efficiencies, new materials, new device physics
  - Nanoparticle precursors
  - Exciton cells (dye, polymer, organic, small molecules, etc.)
  - Quantum dots, hot-carrier, impurity band cells

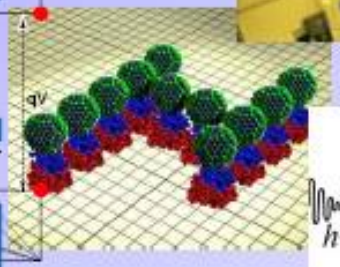


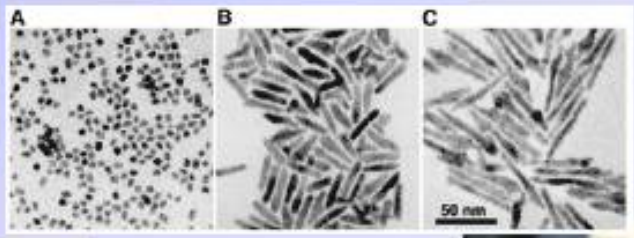


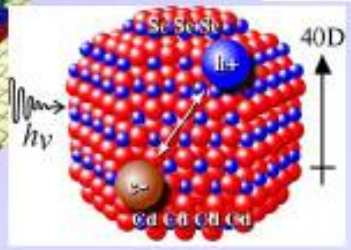


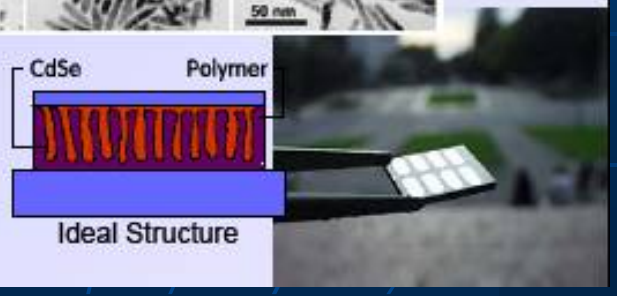




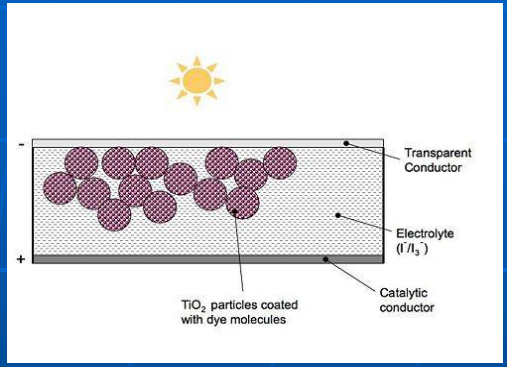


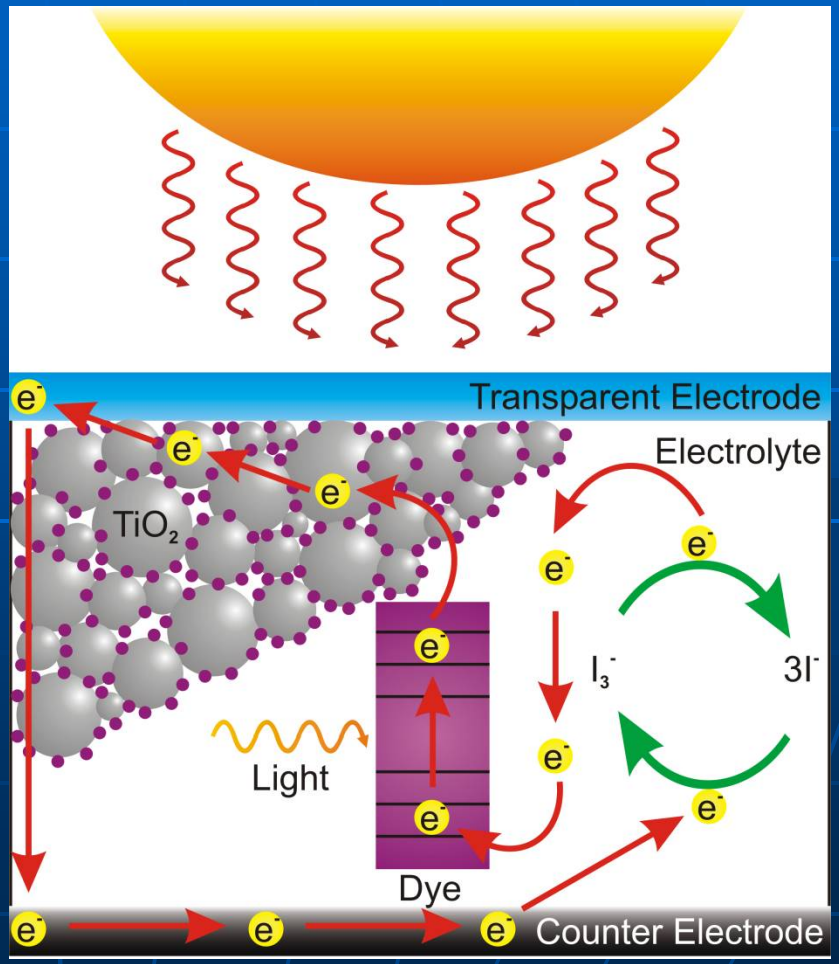






Dye Sensitized Solar Cells

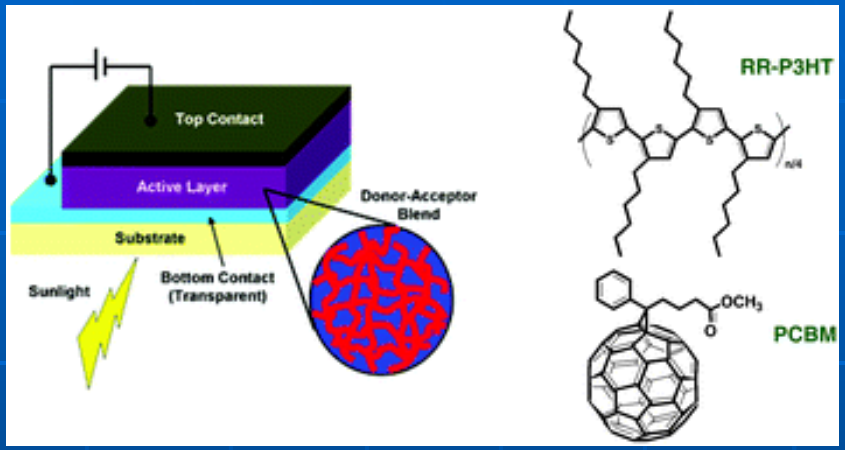


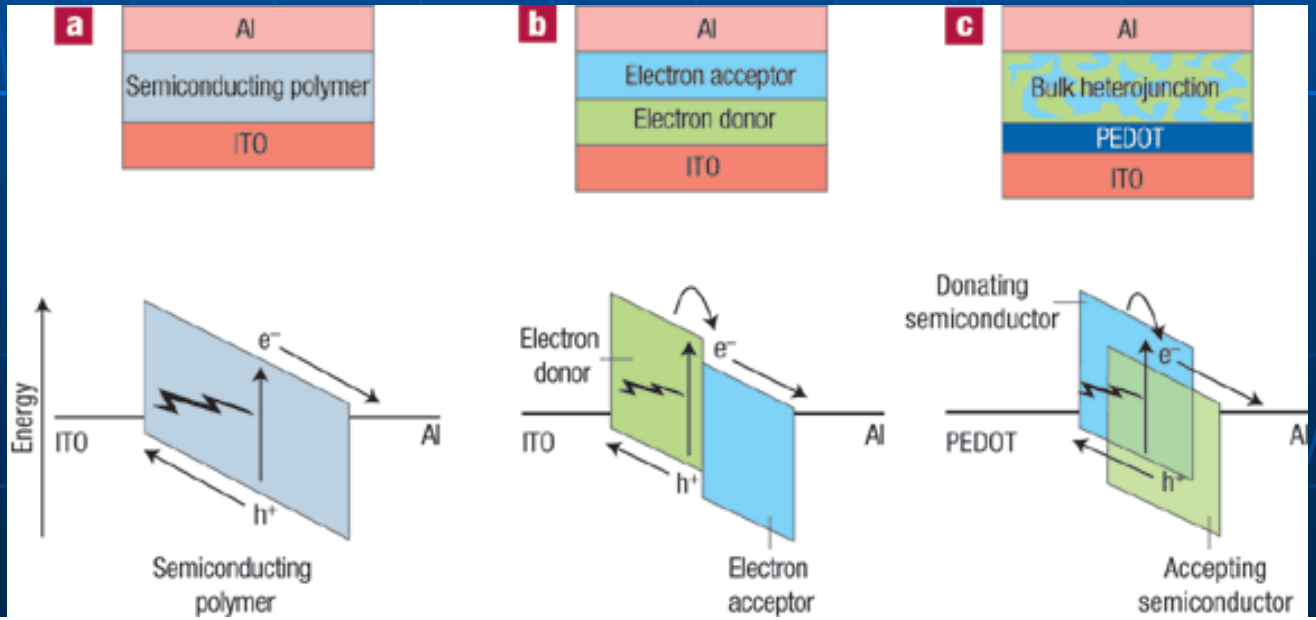


- Charge transfer without p-n junction
- Dye as absorber
- Nanoparticles as electrode
- I^-/I_3^- electrolyte used as counter electrode
- Record efficiency 12.3%

Polymer Solar Cells

PET - Polyethylene terephthalate
ITO - Indium Tin Oxide
PEDOT:PSS - Poly(3,4-ethylenedioxythiophene)
Active Layer (usually a polymer:fullerene blend)
Al - Aluminium

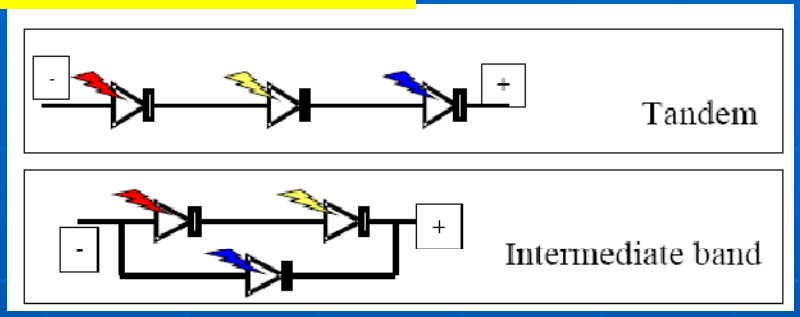




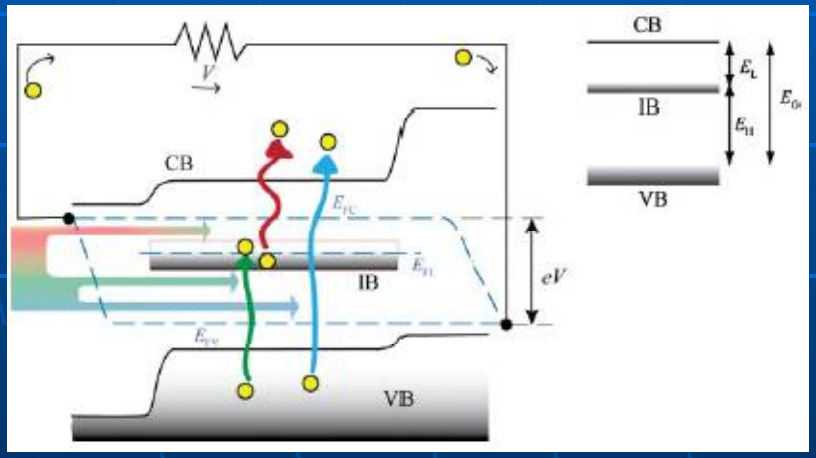
Record efficiency: 6.77% (Dec. 2009)

Intermediate Band Solar Cells

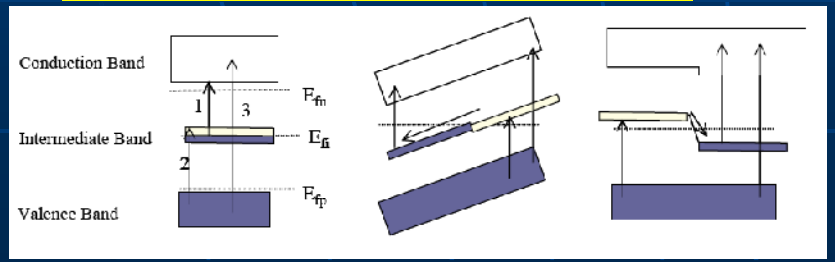
To make use of more photons in the solar spectrum



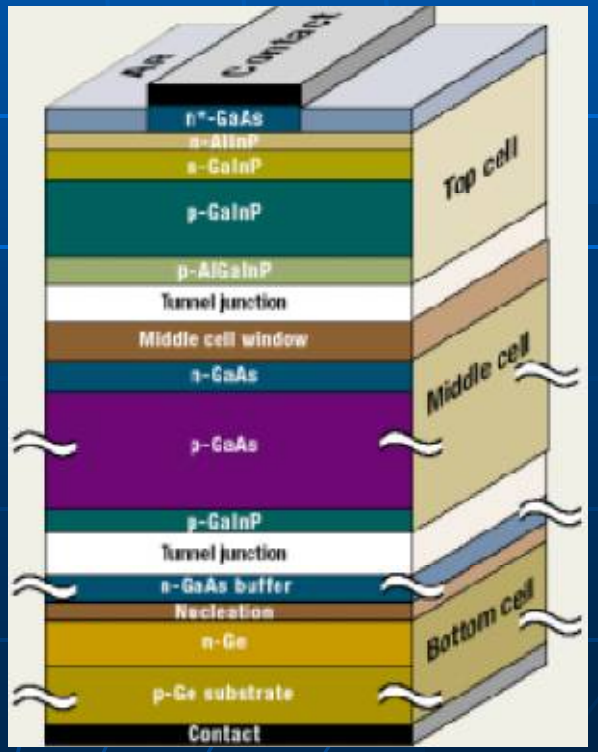
IB Solar Cell (limiting efficiencies 63,7%)



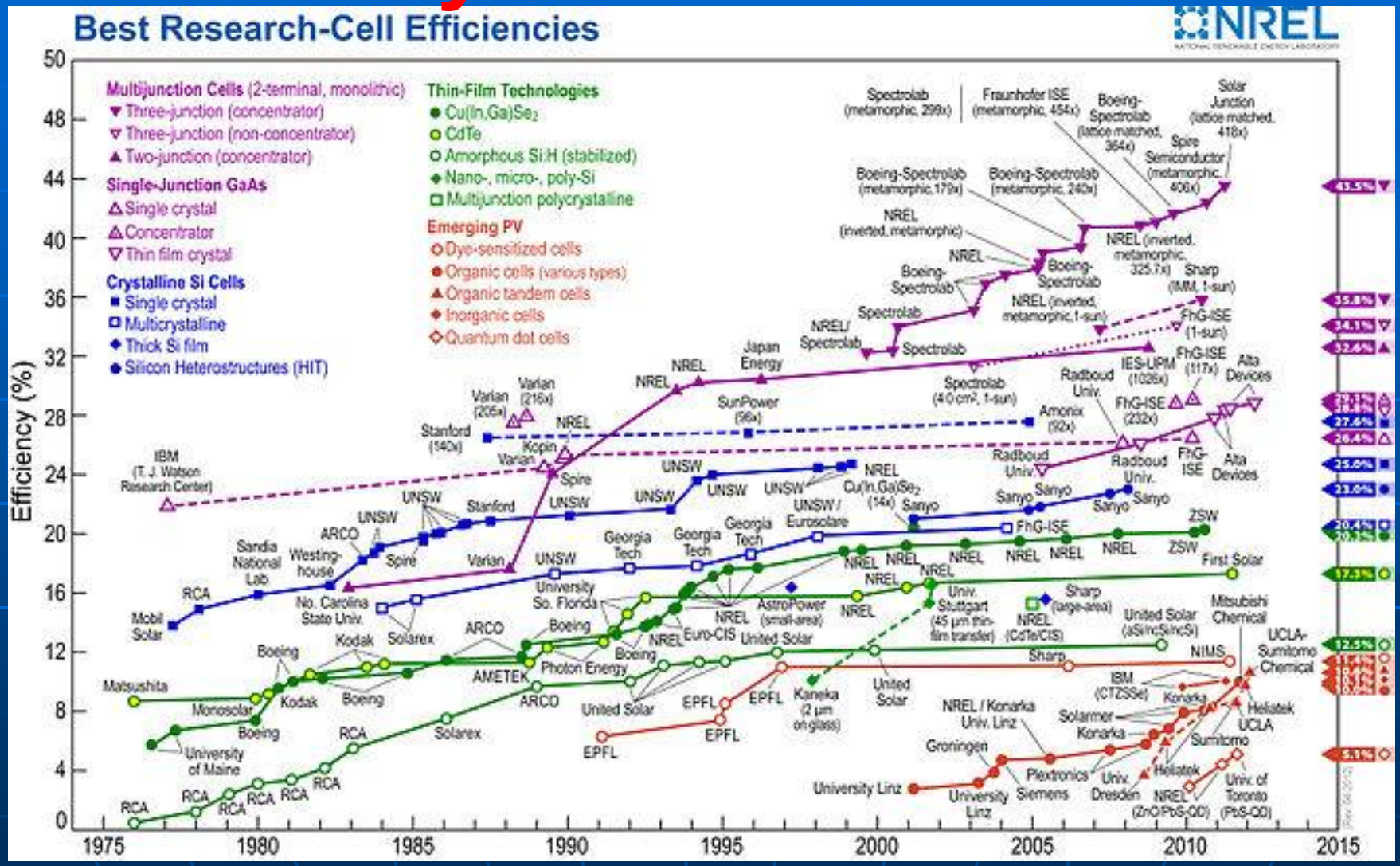
Various schemes of band structure



Tandem Solar Cell (63.7%)

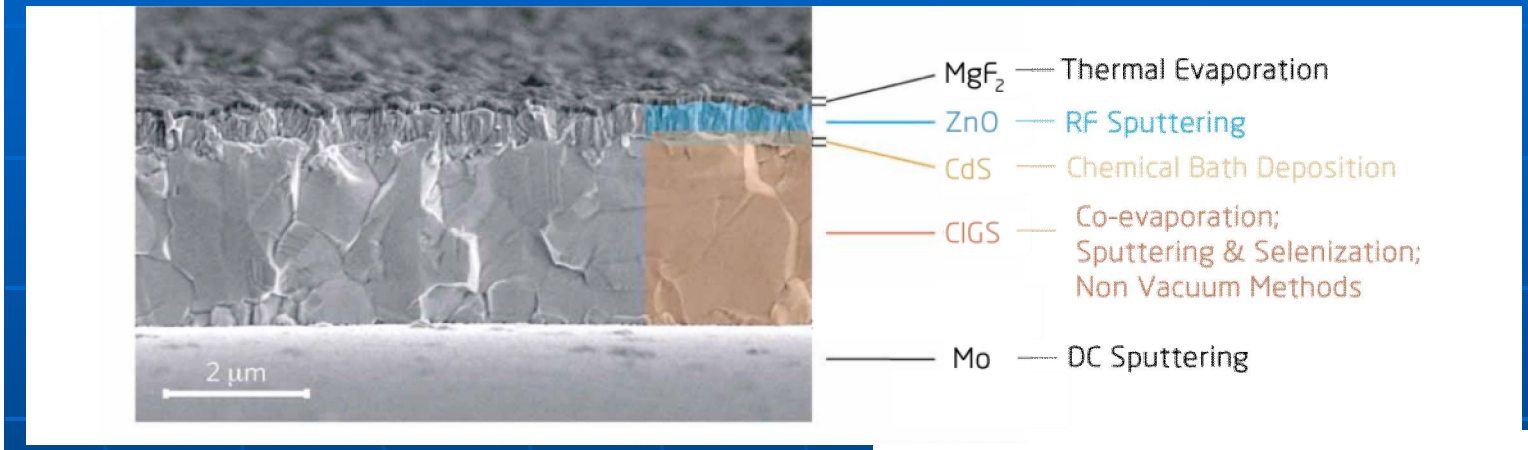


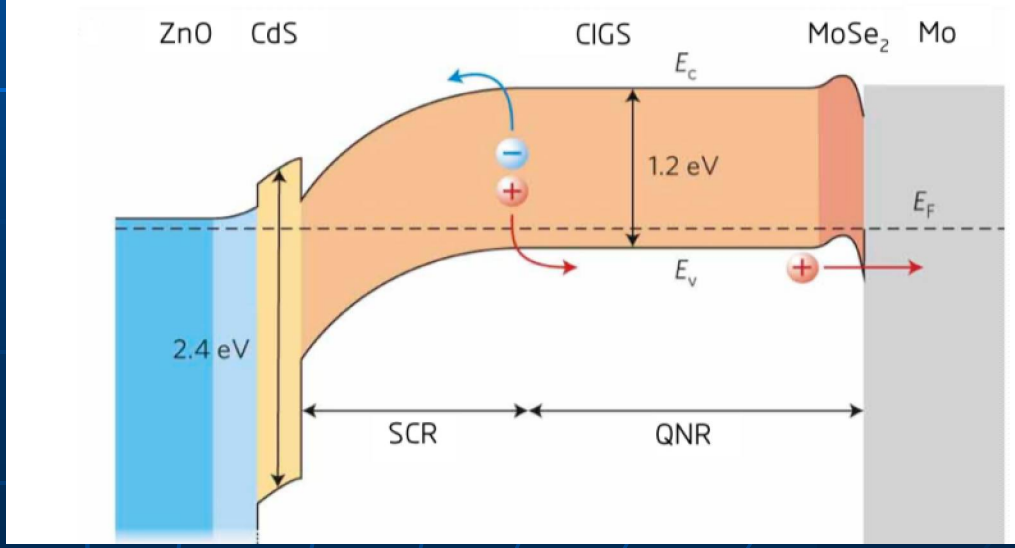
Efficiency of Best Solar Cells



NREL/PR-520-44106
Presented at the Association of Industrial Metallizers, Coaters and Laminators (AIMCAL) Fall Technical Conference 2008 and 22nd International Vacuum Web Coating Conference held October 19-22, 2008 in Myrtle Beach, South Carolina.

Our Research:
$Cu(InGa)Se_2$ Solar Cells





Our approach:

- Advanced Technology
  - Co-evaporation, Record setting technology
  - Sputtering/selenization, Technology for industrialization

- Equipment manufacturing in China

  Imported equipment cost: 30-50% of total cost
  - Appropriate manufacture technology in China
  - 1/2 -1/3 of equipment cost if made in China
  - First step: 10 cm x10 cm, Conversion efficiency: >15%
  - Second step: 60 cm x40 cm, Conversion efficiency: 12%
  - Full production line: 120 cm x60 cm, Conversion efficiency: 12%

Brief History Photovoltaic Solar Cells

Silicon

Discovery of photoelectric effect 1839
Edmund Becquerel

1st c-silicon solar cell 1954
η = 6%

1st commercial silicon module 1963

c-silicon solar cell 1985
η = 20%

c-silicon solar cell 1999
η = 25%

poly c-silicon solar cell 2004
η = 20.4%

CIGS

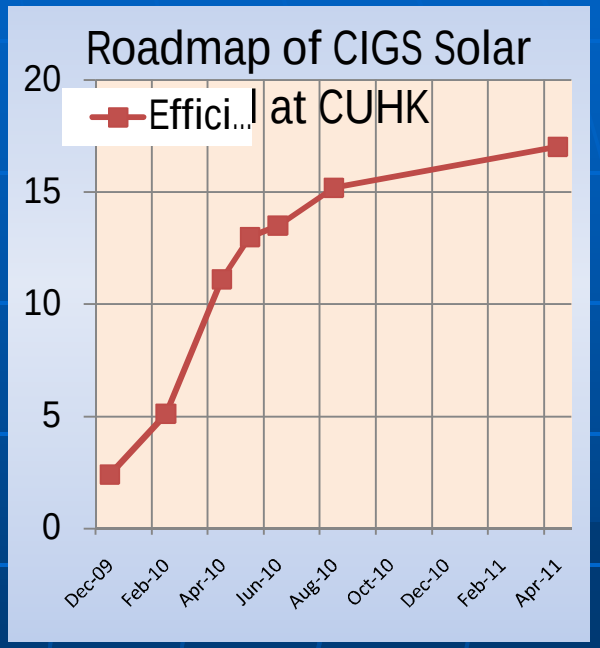
$CuInSe_2$ single crystal solar cell 1974
η = 12%

Thin film $CuInSe_2$ solar cell 1983
η > 10%

1st commercial $Cu(In,Ga)Se_2$ module 1998

Thin film $Cu(In,Ga)Se_2$ solar cell 2010
η = 20.3%

Our CIGS



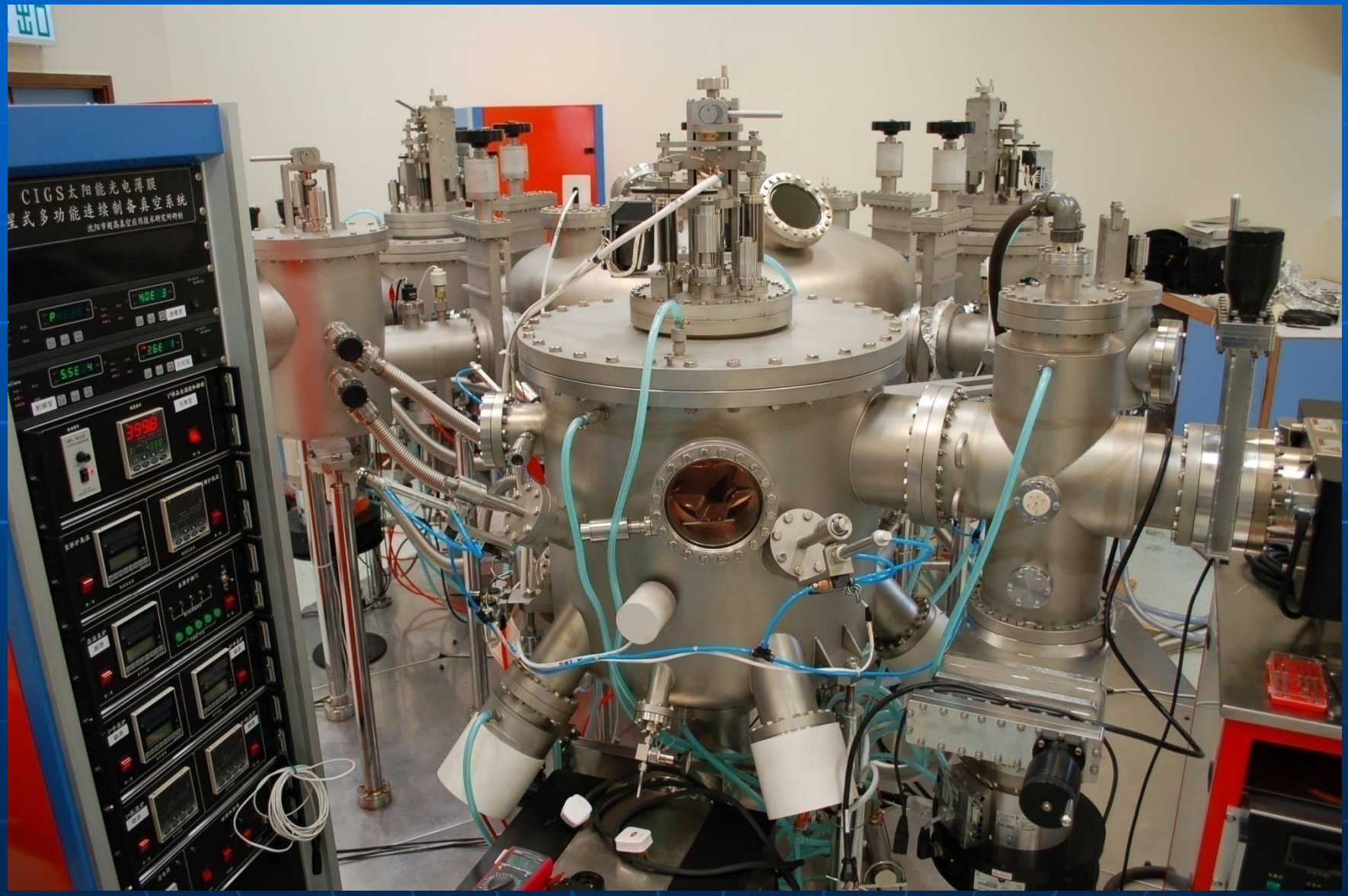
2008 Design of equipment

2009 CIGS PV Program started
η = 2.4% @ end of 2009

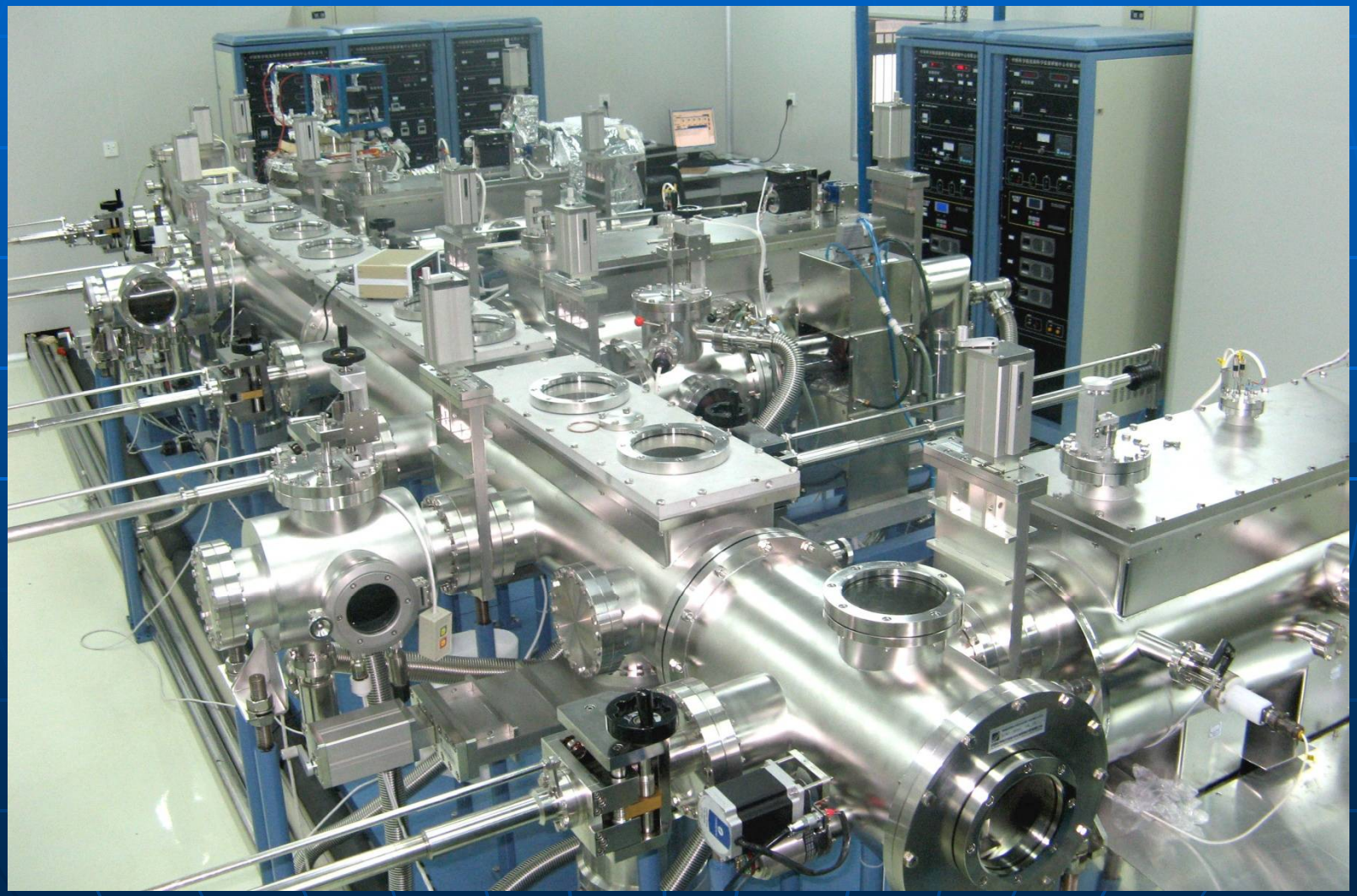
2010 Thin film CIGS solar cell
η = 15.2%

2011 Thin film CIGS solar cell
η = 17.03%

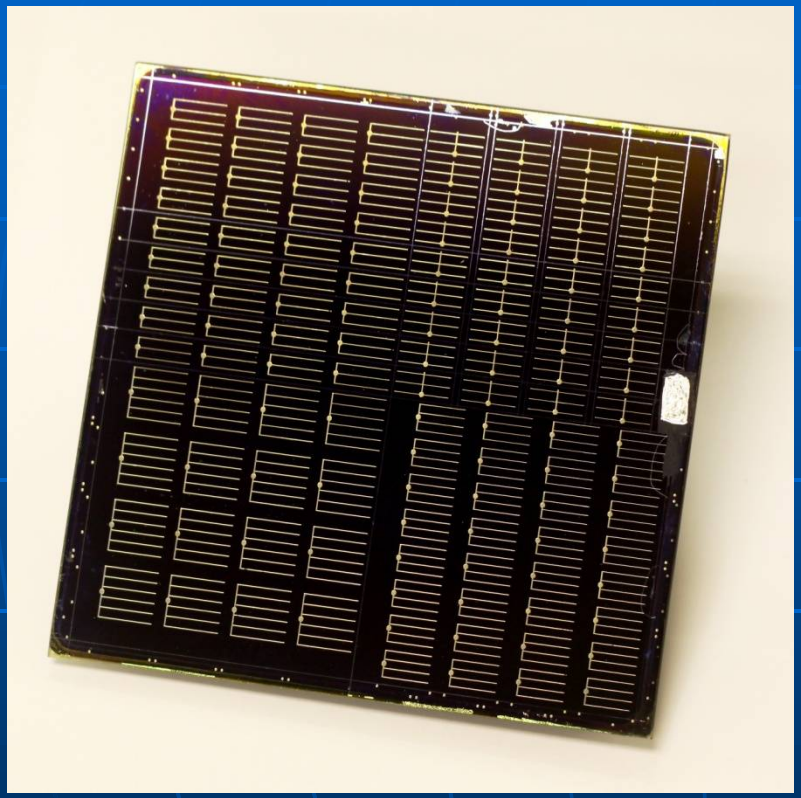
CIGS Solar Cell Growth Equipment in CUHK



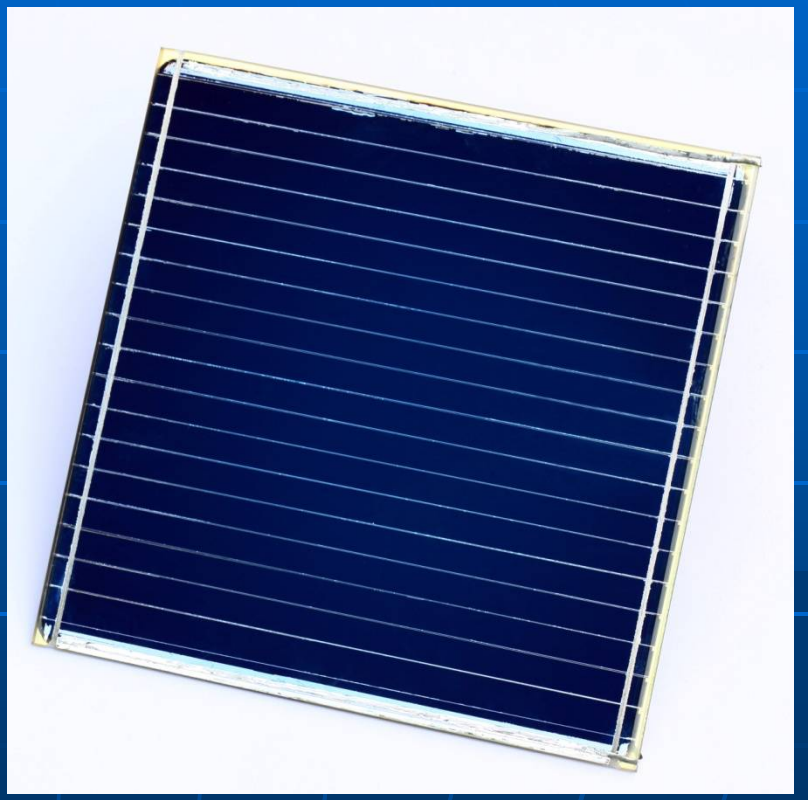
CIGS Fabrication System:
SZ Institute of Advanced Technology



CIGS solar cell and module

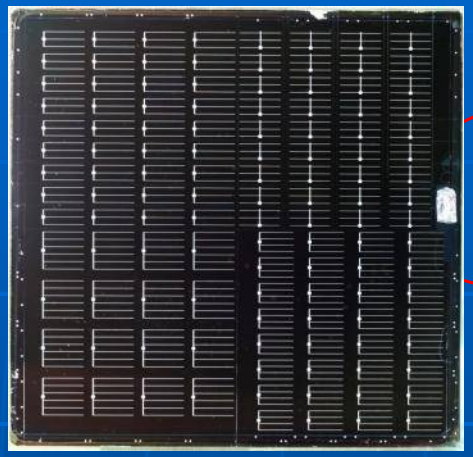


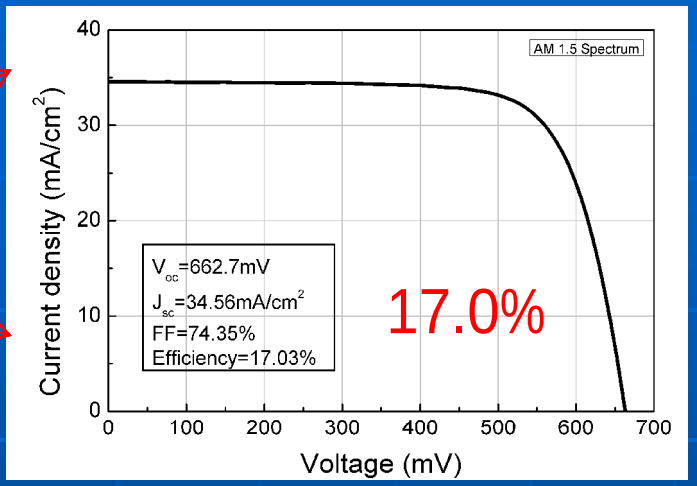
CIGS solar cell with Ni/Al grid on top



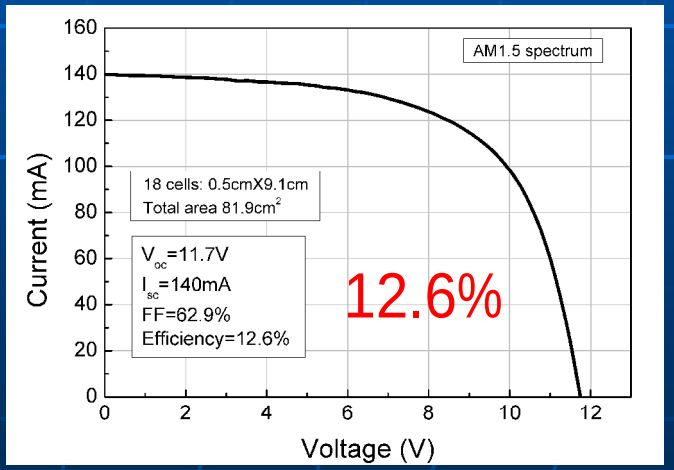
CIGS 10cm × 10cm solar module

Champion solar cell and module





Champion small solar cell: 0.5cm^2



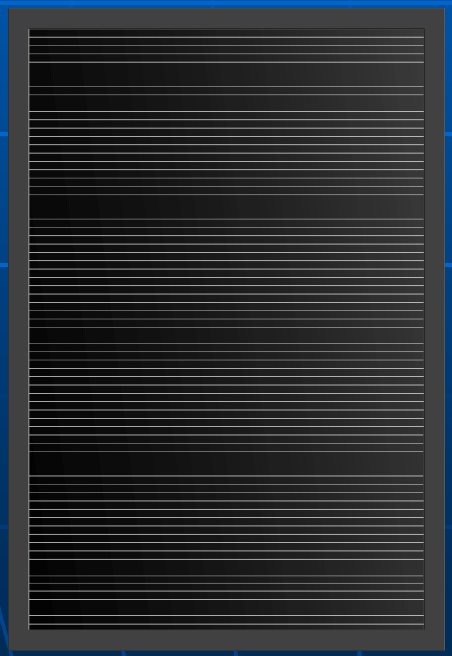
Champion solar mini-module: 10cmX10cm (non-gridded)

Best efficiency in Greater China Region

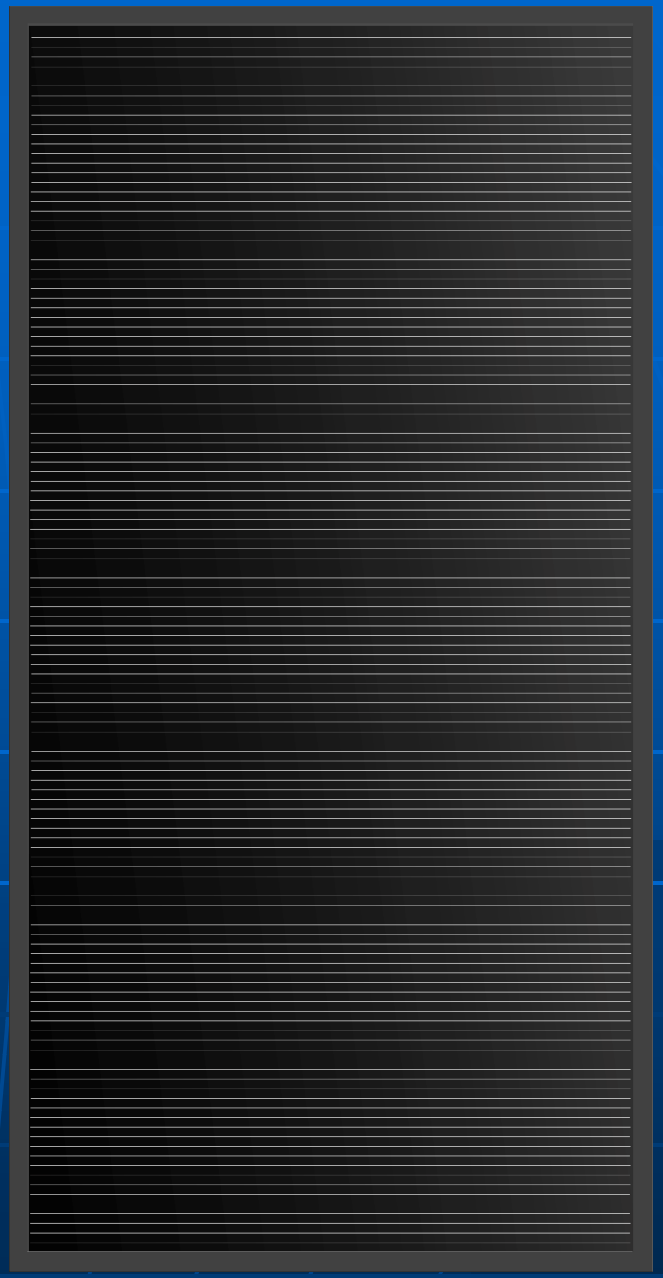
Increase parallel processing:

No batch processing available
Large size of modules
Big Machines
High entry investment

10cm×10cm



40cm×60cm

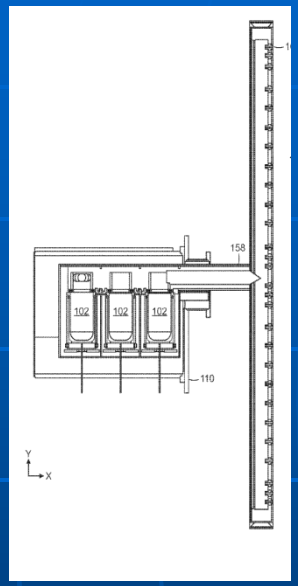


60cm×120cm

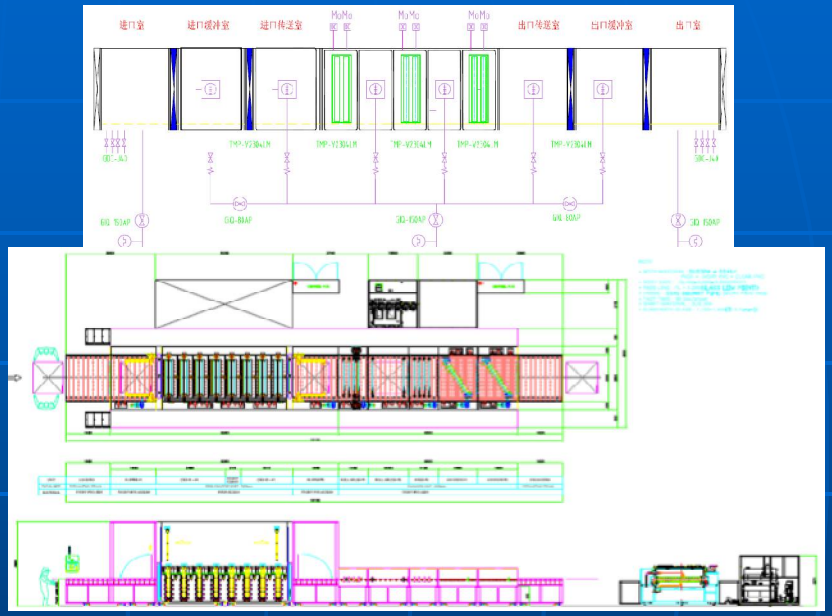
On-going Pilot Manufacture System

关键部件研发

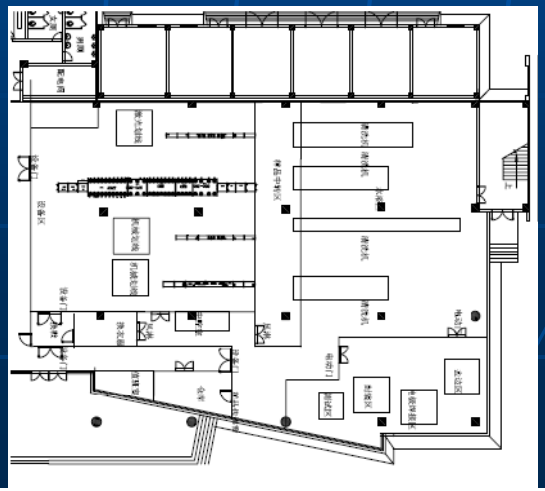
线性蒸发器



整线集成，工艺定型



中试场地建设



6. 结束语

- 温家宝：人民需要蓝天和绿地，子孙后代需要长远发展，现今的建设不能牺牲后人的发展，要为子孙后代著想。要节能减排、发展绿色经济，转变发展方式，转变经济结构，不再走工业化发展的老路。
- 可持续性发展：我们忍心为我们的子孙后代留下一个烂摊子，还是创造一种可持续发展的模式？

Thank you