How to get electricity from nuclear fusion

Rafael Kleiman

Engineering Physics

kleiman@mcmaster.ca

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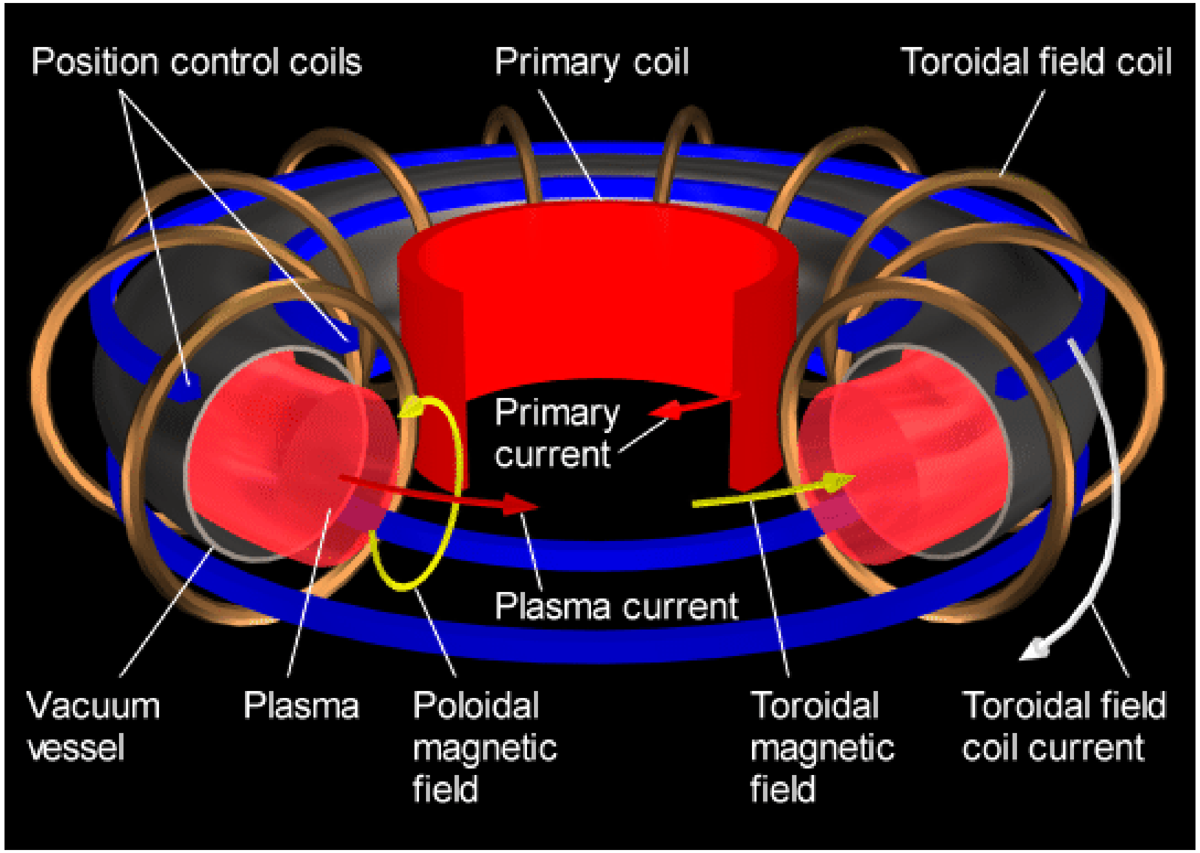
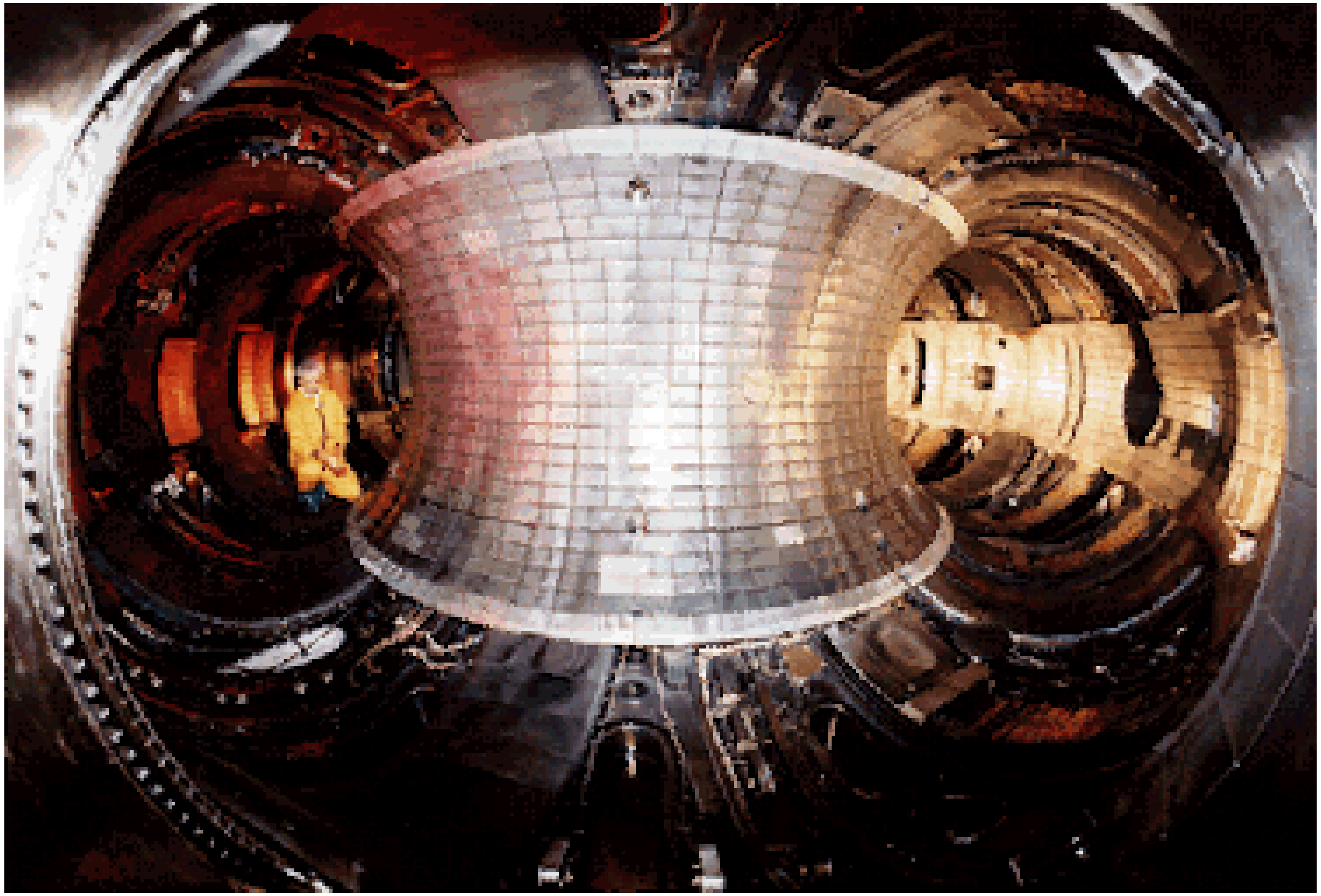
Tokamak fusion reactor



Tokamak fusion reactor



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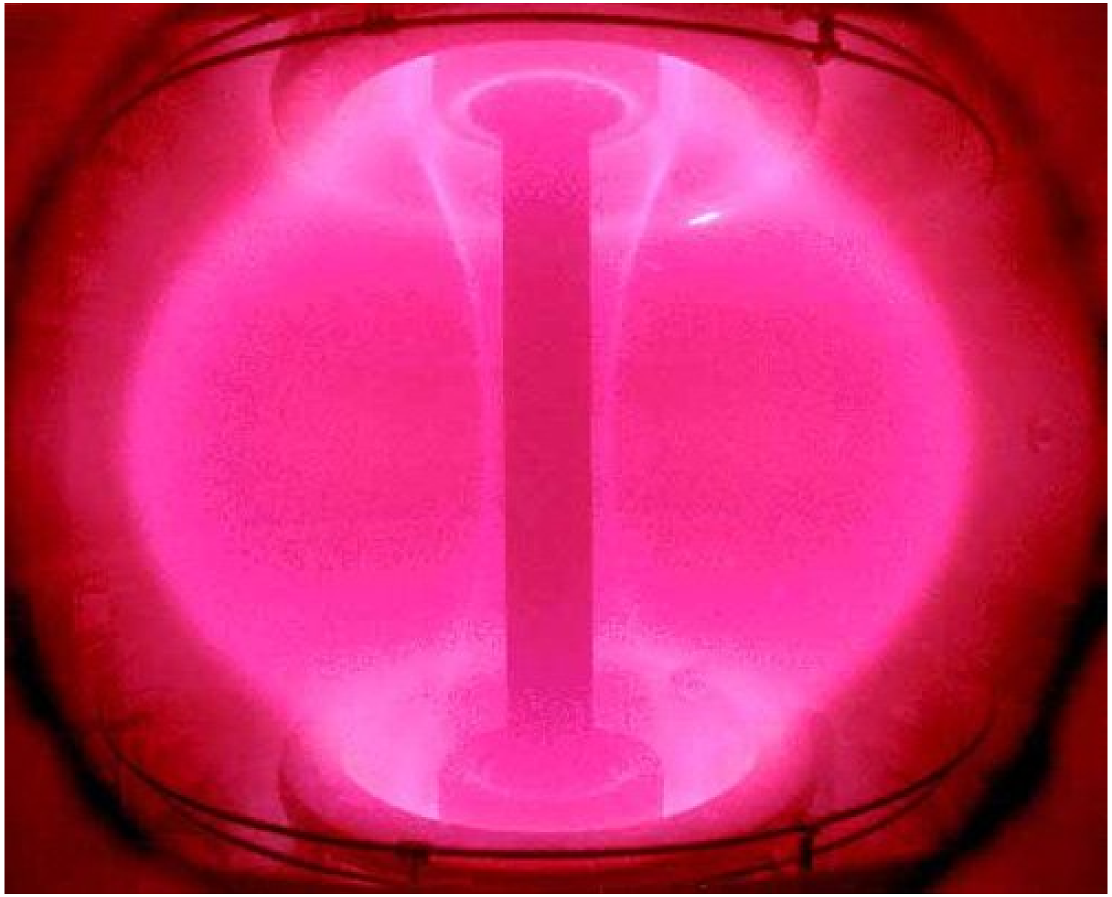
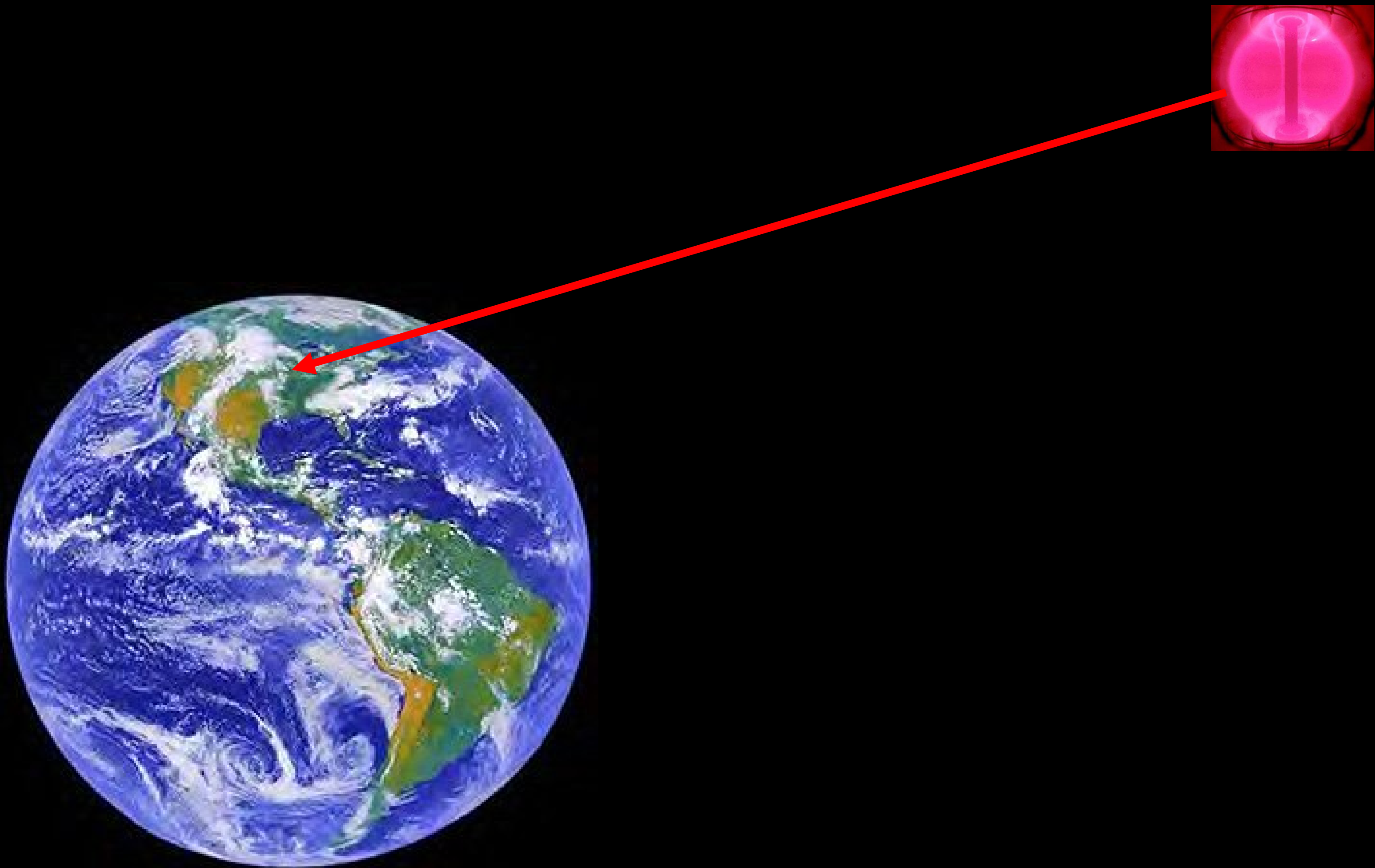


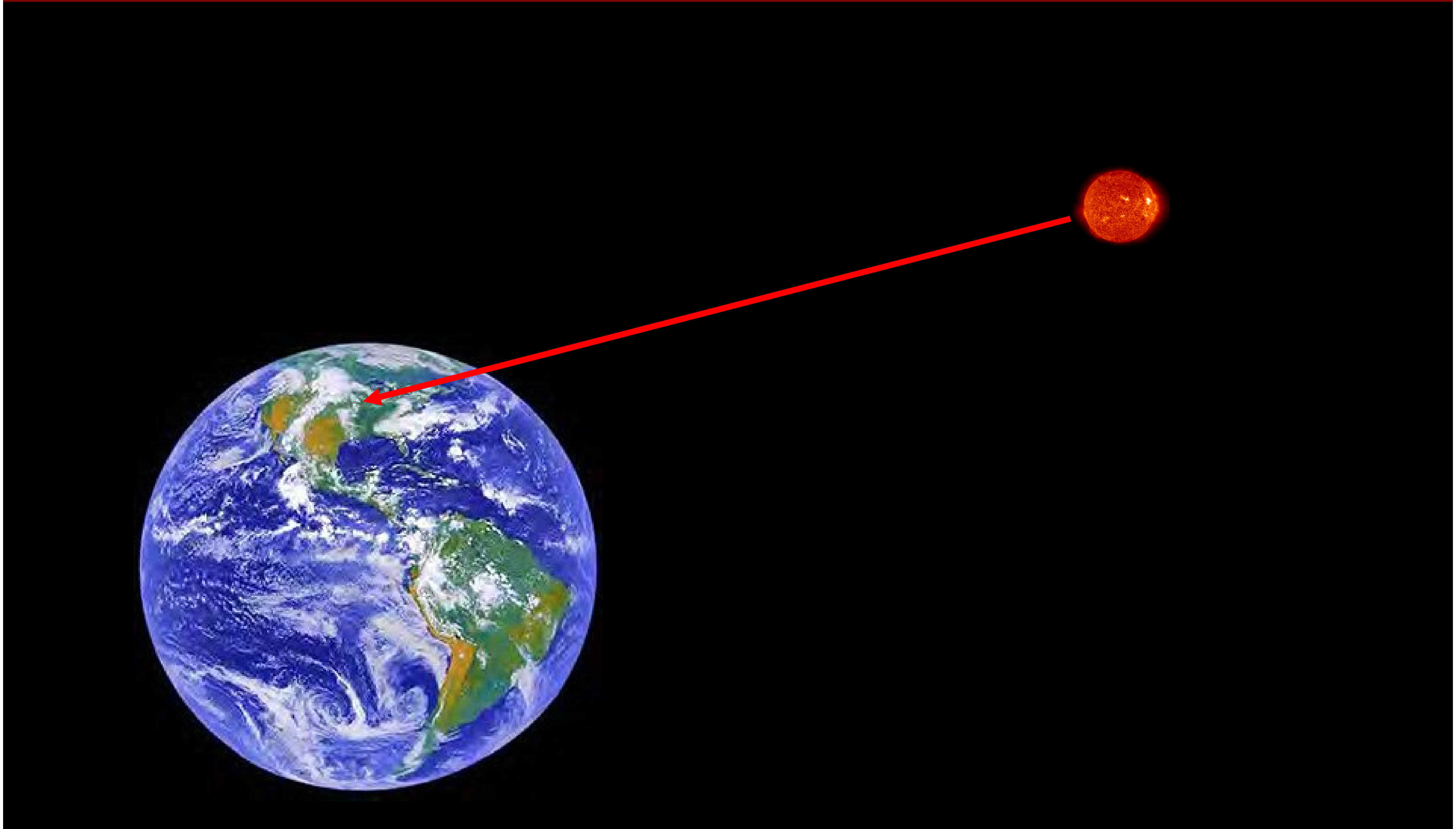
Concept

For safety reasons let’s put it out in space and beam the energy back to earth

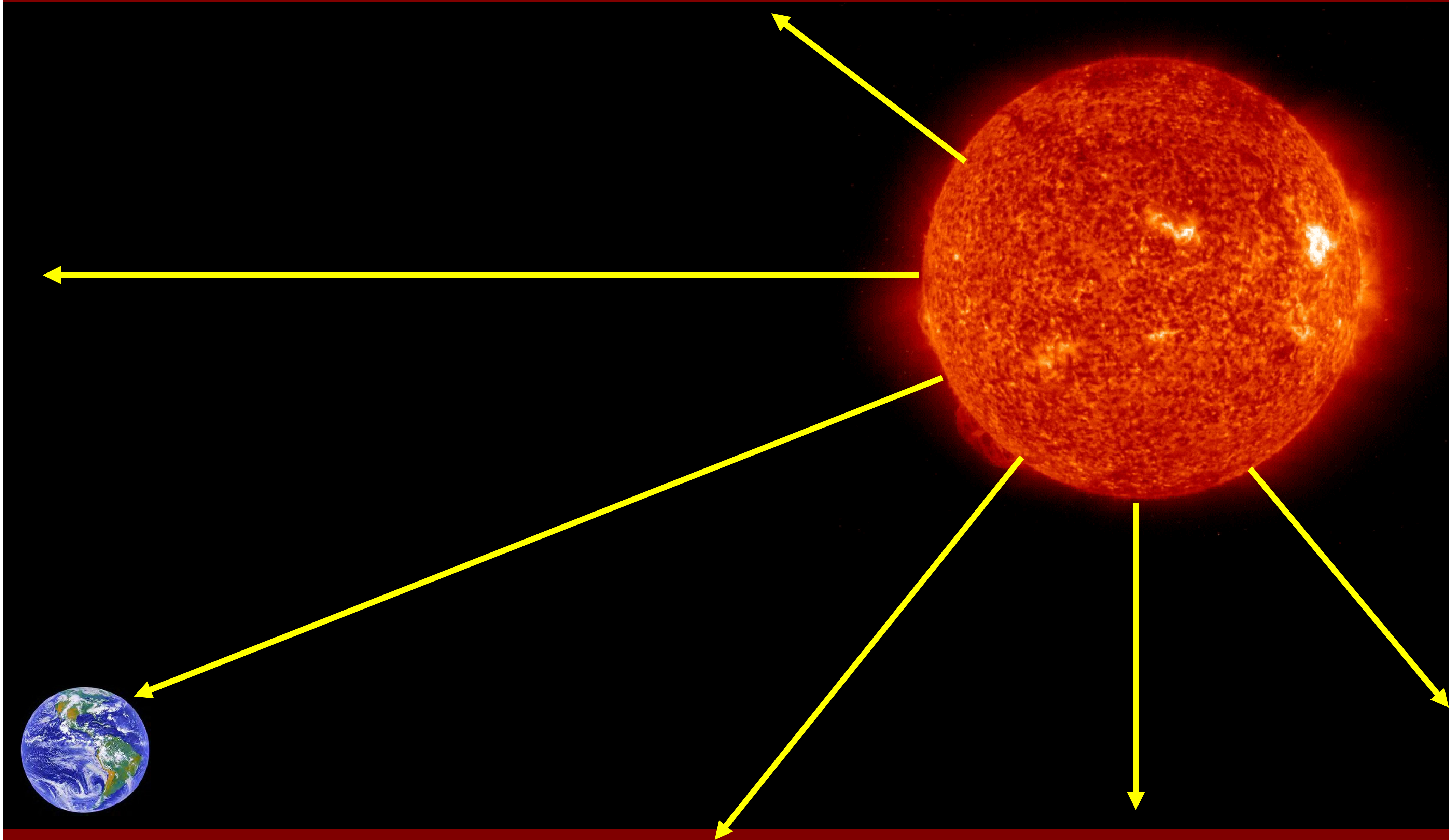
Satellite-based fusion reactor I



Satellite-based fusion reactor II



Large-scale fusion reactor = our Sun



Solar energy production

The sun acts like a black body at 5800K, providing ~1kW/m^2 of power to earth

$A = \pi r^2 = \pi\ (6371\ \text{km})^2 = 1.28 \times 10^{14}\ \text{m}^2$

$P = 1.28 \times 10^{17}\ \text{W}$

$E = P \times \text{time} = 1.28 \times 10^{14}\ \text{kW} \times 8766\ \text{hr/yr}$

$E = 1.12 \times 10^{18}\ \text{kW-hr/year}$

Annual worldwide electricity consumption

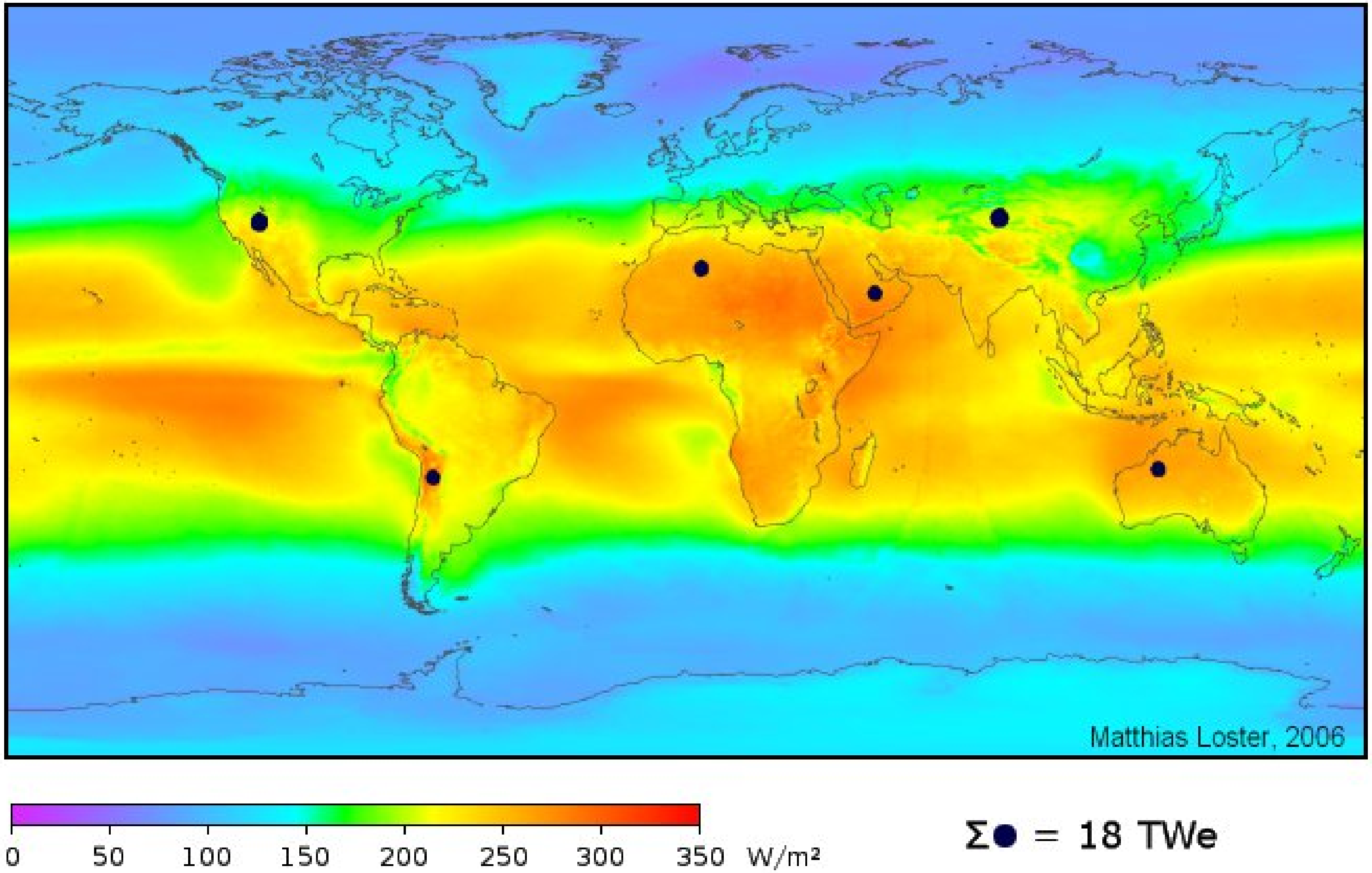
$E = 20{,}300\ \text{TW-hr/yr}$ (in 2008)

$E = 2.03 \times 10^{13}\ \text{kW-hr/yr}$ (in 2008)

Life on Earth

- Photosynthesis adapted to provide energy to plants
- Plant growth and degradation sequestered energy and CO_2 for hundreds of millions of years …“fossil fuels”

Worldwide Solar Insolation



$=1.8 \times 10^{13}$W

World Energy Sources

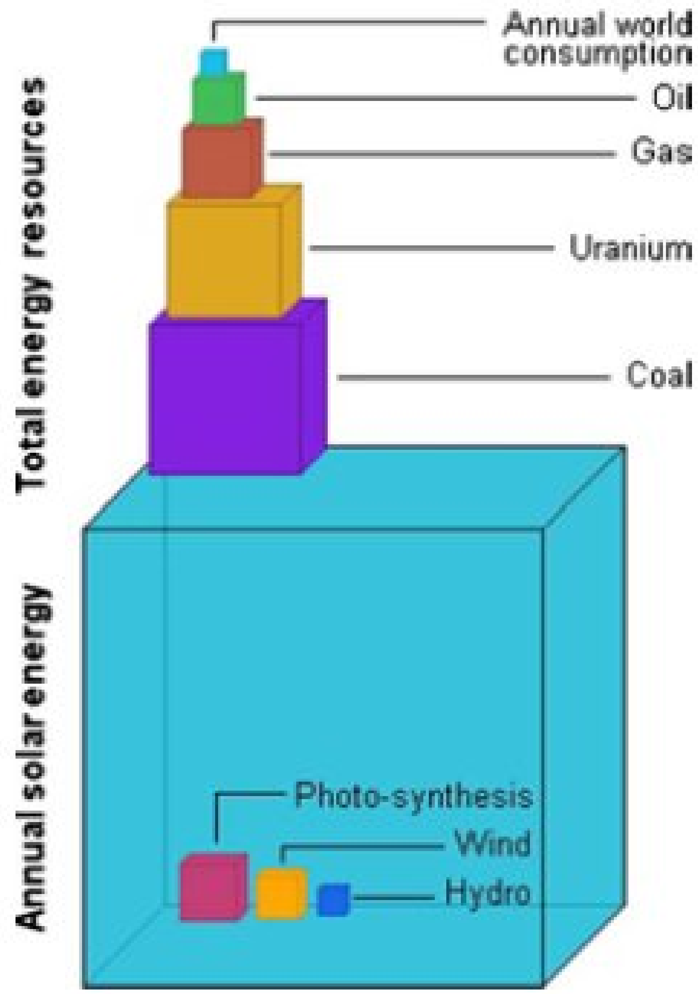


FIGURE 11.1 Order of magnitude of energy sources on earth (Source: Lomborg, 2001).

World Energy Generation

Worldwide Energy Generation

Energy Source	World total	Proportion
Coal	8,263	41%
Oil	1,111	5.5%
Gas	4,301	21%
Fossil Fuel	**13,675**	**67%**
Hydro	3,288	16%
Geothermal	65	0.30%
Solar PV	12	0.06%
Solar Thermal	0.9	0.004%
Wind	219	1.1%
Tide	0.5	0.00%
Renewable	**3,584**	**18%**
Nuclear	**2,731**	**13%**
Biomass	198	1.00%
Waste	69	0.30%
Other	4	0.02%
Biomass	**271**	**1.30%**
Total	**20,261**	**100%**

TW-hr/year

World Energy Situation

Worldwide Energy Generation

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TW-hr/year

We are using fossil fuels heavily

-Running out

-Dumping CO_2 into atmosphere → GHG issue → climate change

Solar energy is by far the largest resource

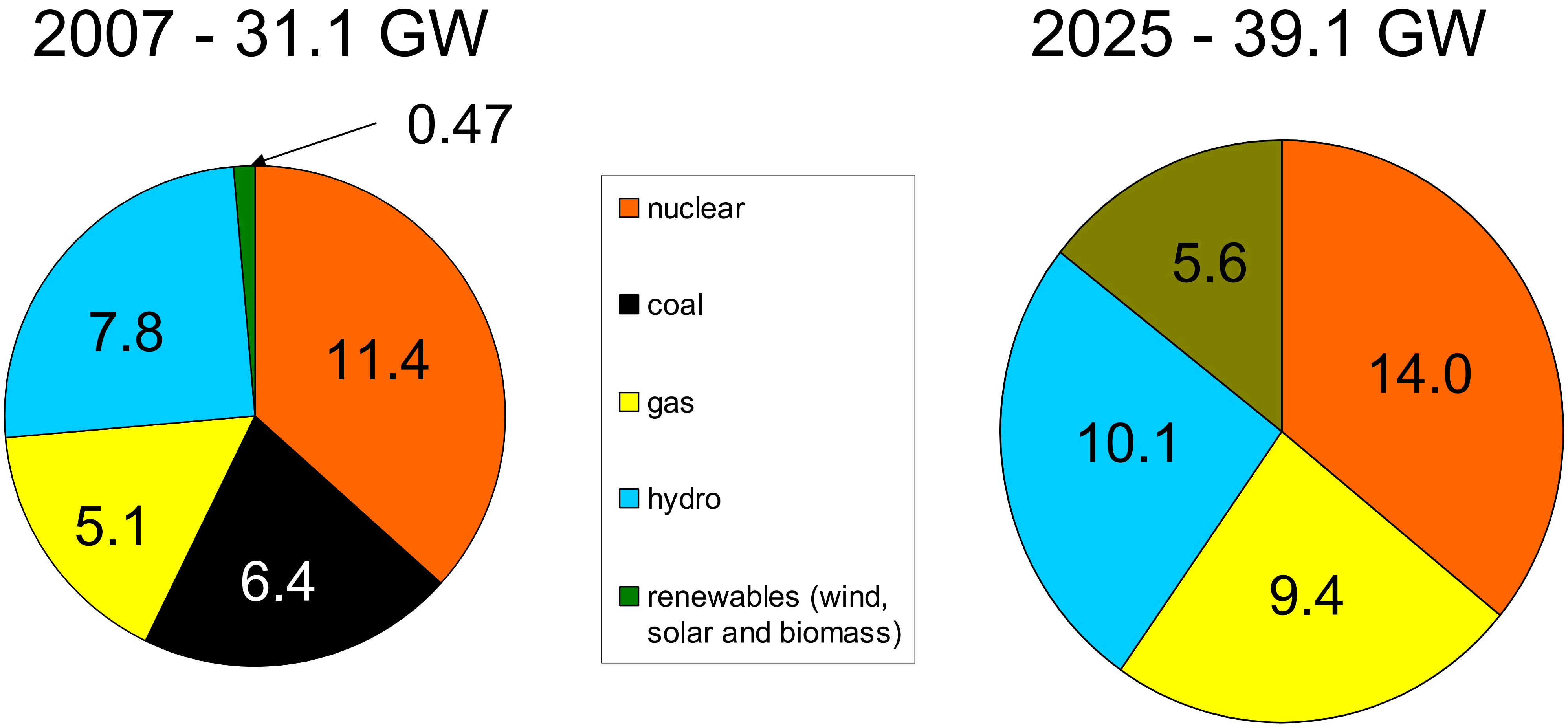
Note that:

Fossil fuels were formed by (past) solar

Hydro, wind and bio fuels are formed by (present) solar

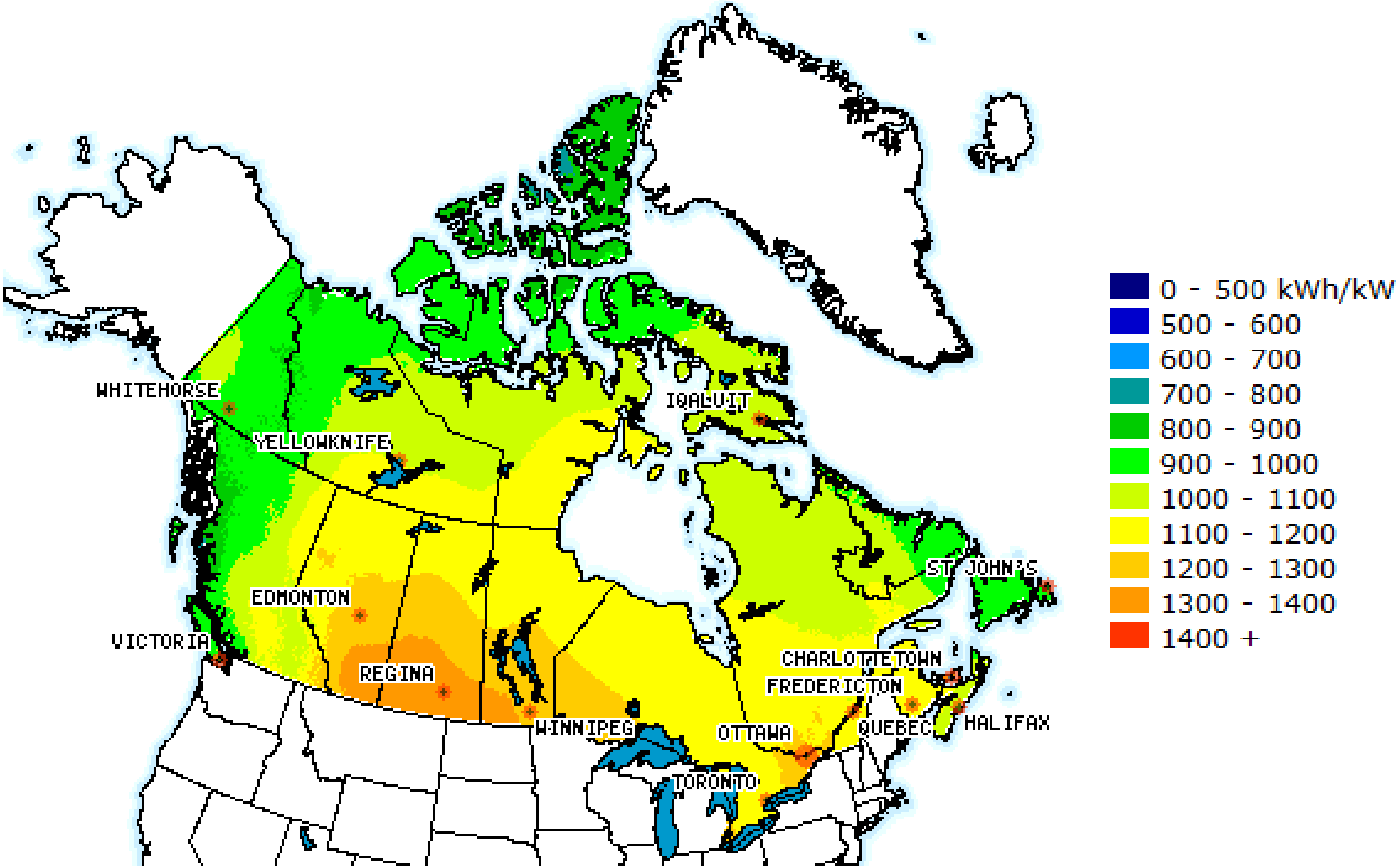
Nuclear (fission), geothermal and tide are not solar in origin

Ontario Energy Mix Directive



does not include 6.3 GW from demand conservation

Canadian Solar Insolation



Source: Natural Resources Canada

Solar cells: how to get electricity from the sun

Rafael Kleiman
Engineering Physics
kleiman@mcmaster.ca

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Why get energy from the sun?

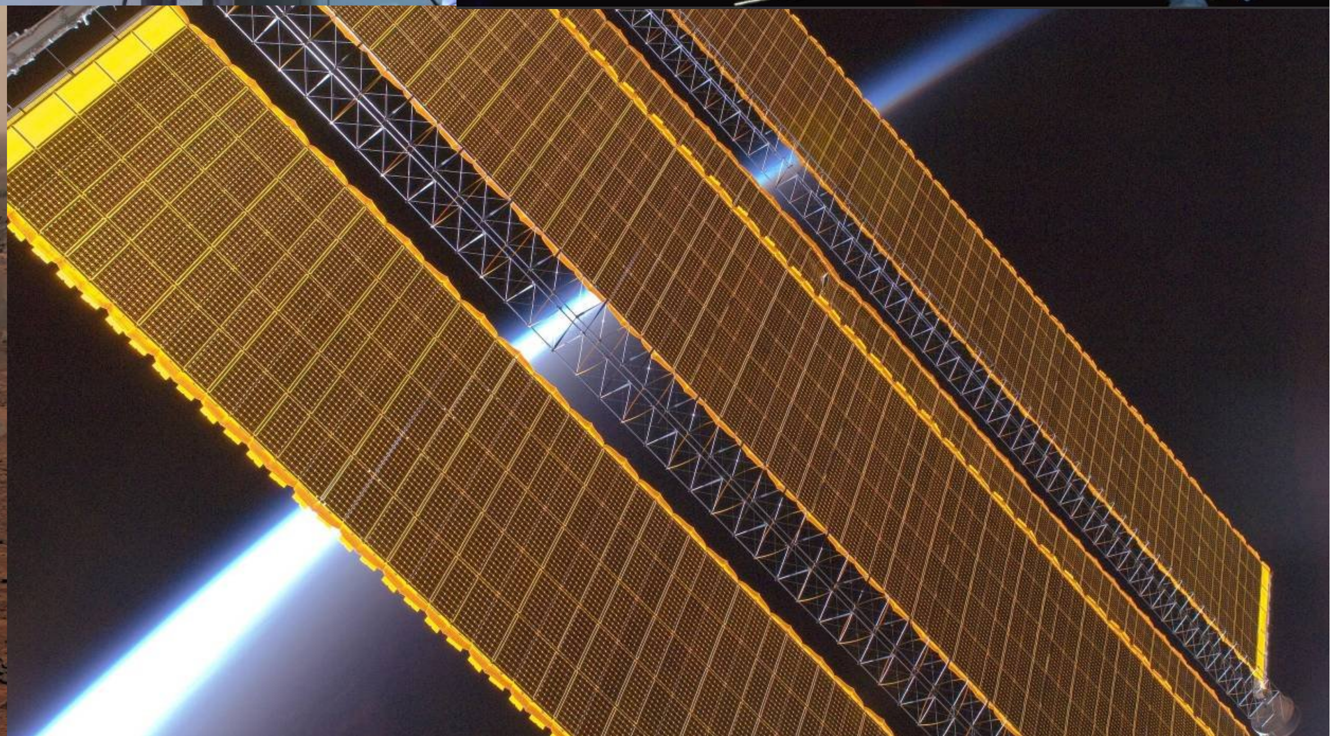
i. Balancing energy supply/demand
ii. Lower GHG emissions
iii. Lower pollution from coal, risks from nuclear
iv. Energy independence

Off-grid applications

Canada a large country with many remote communities

Space, the ultimate off-grid application

Space-based Applications



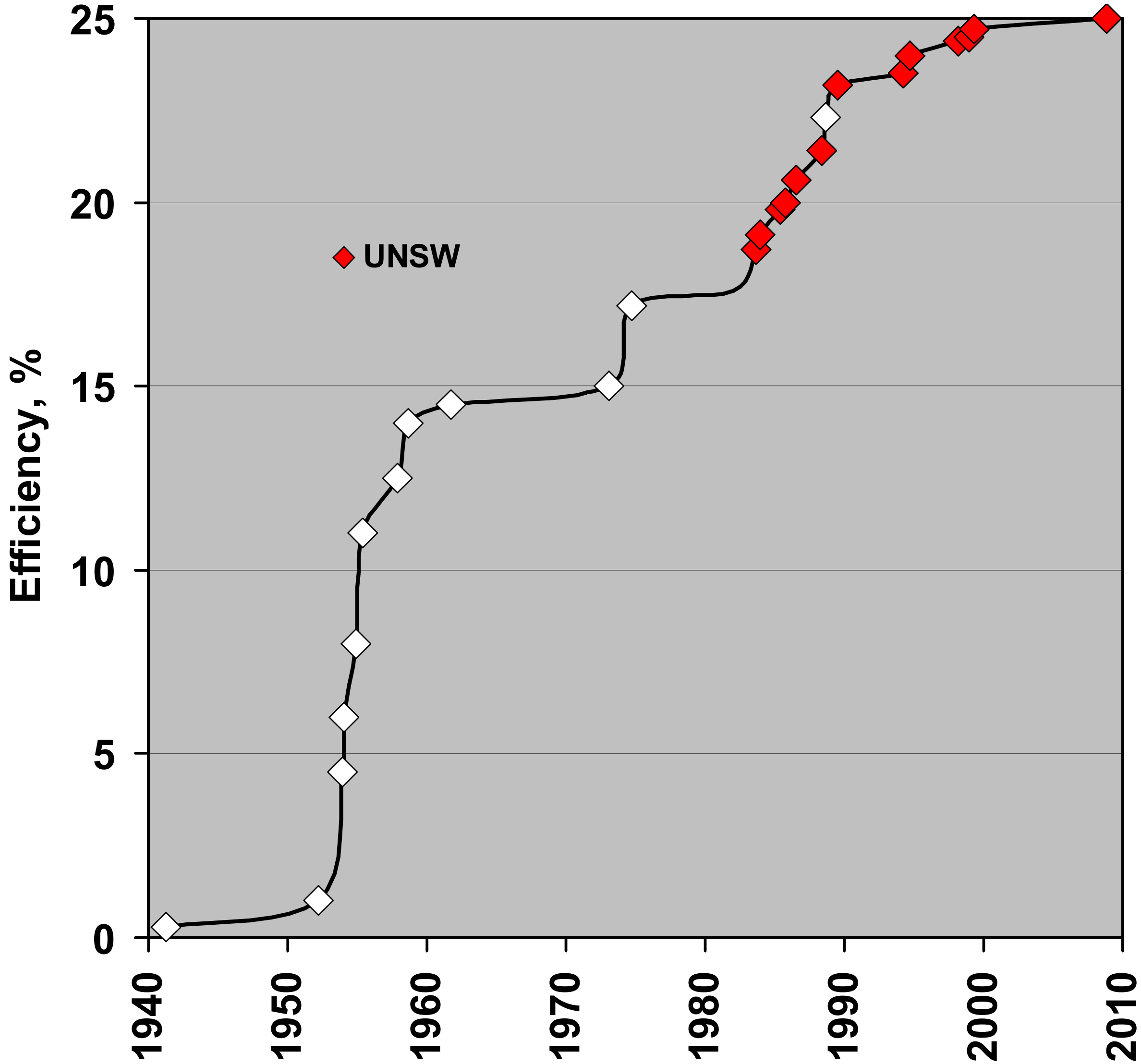
Grid connected applications

Started in a serious way in ~2000, with Germany's subsidy program

Rooftop – decentralized

Solar farms – utility scale production

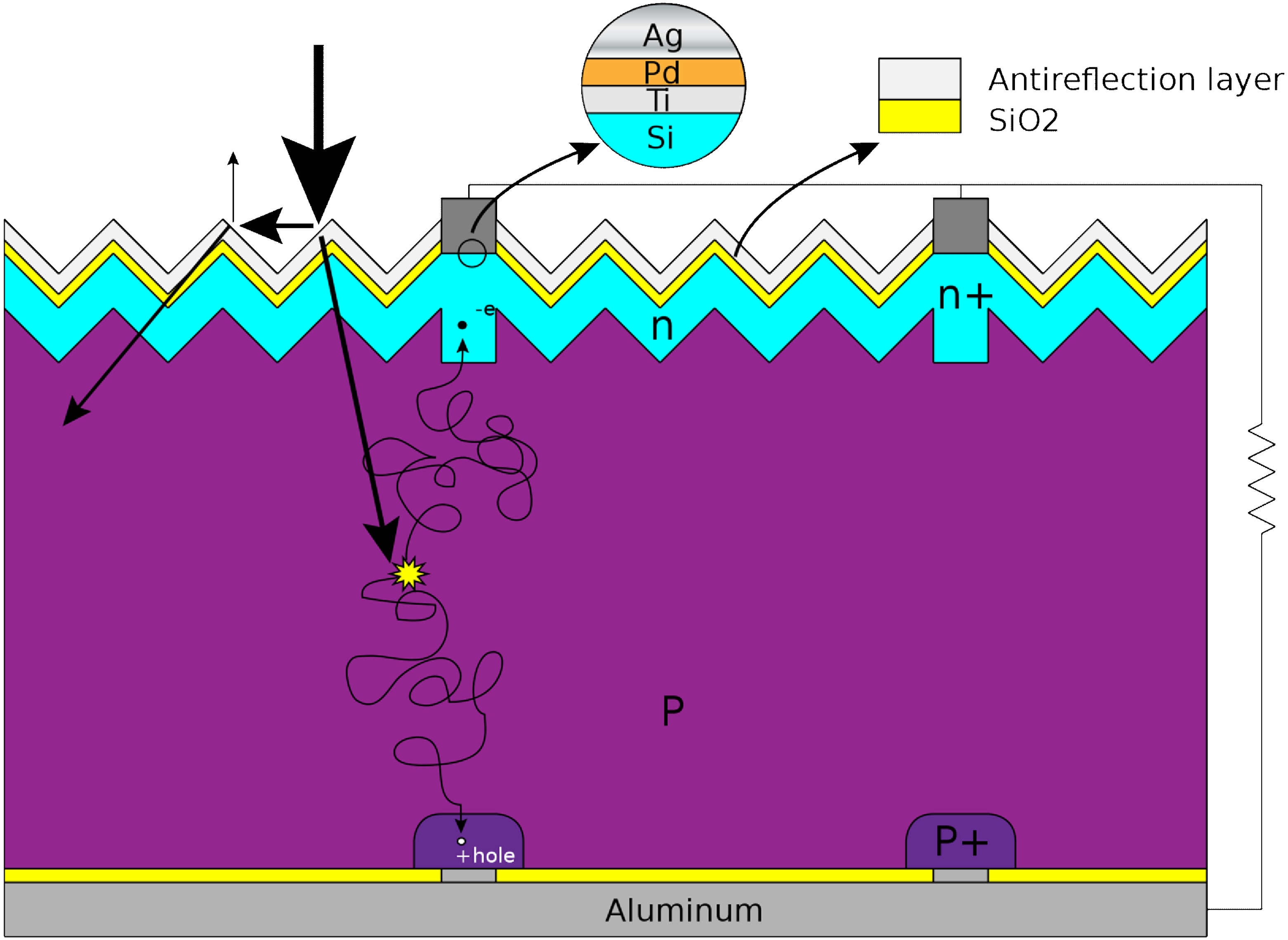
Silicon Solar Advances



Efficiency of Silicon solar cells *vs*. time

Theoretical limit is ~30%

Silicon Solar Cell Structure



Typical Silicon Cell Performance

Typical Silicon solar cell in operation (at 1 sun)

V_{op} = 0.55V

I_{op} = 32 mA/cm^2

P_{op} = 17 mW/cm^2 = 170 W/m^2

1 sun = 1kW/m^2

Efficiency = 170/1000 = 17%

Typical Silicon Cell Performance

Typical cell is 6” X 6” = 232 cm2

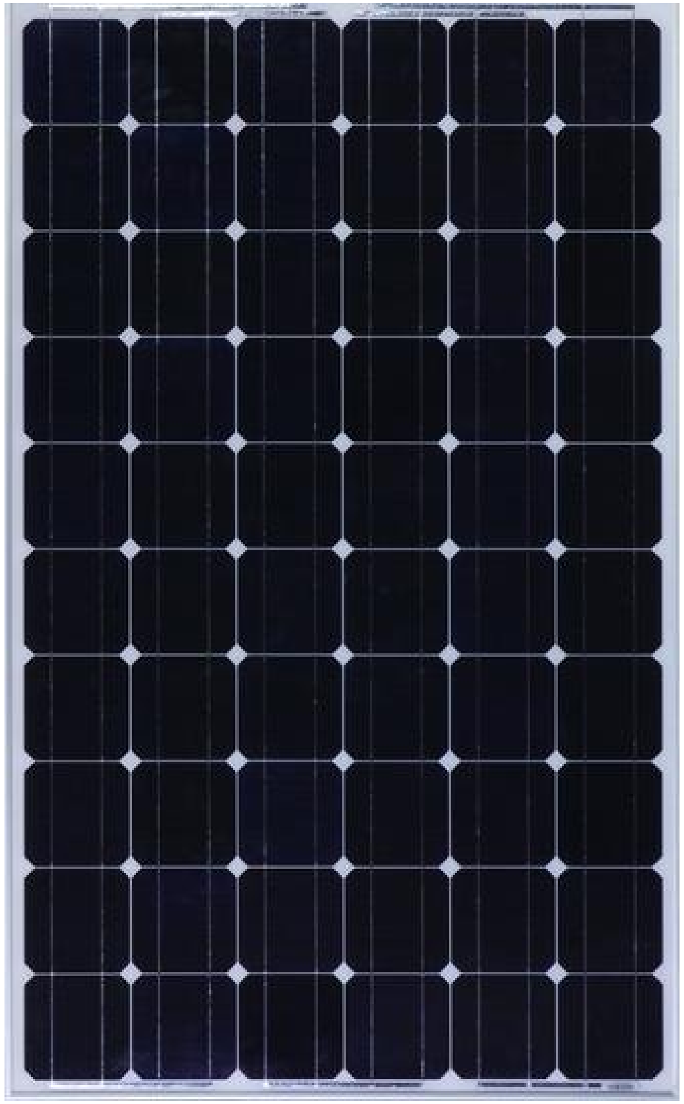
Operating Power = 0.55V X 7.2 A = 4.0W

Typical Silicon Cell-based Module Performance

Most common modules are
6 X 10 cells = 60 cells

Series connected

- I = 7.2A
- V = 33 V
- P = 240 W

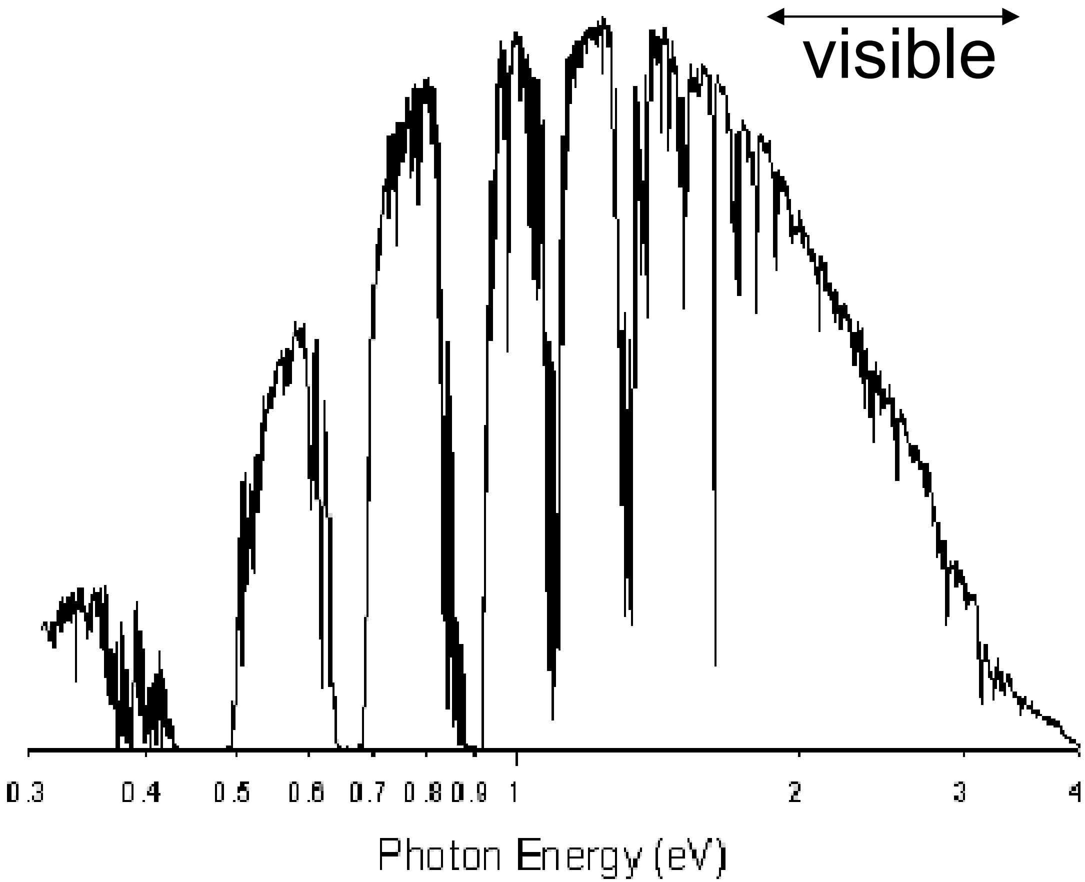


Efficiency Targets

Silicon solar cells now have efficiency ~17-18%, potential to increase to ~25%, but physical limitations beyond that

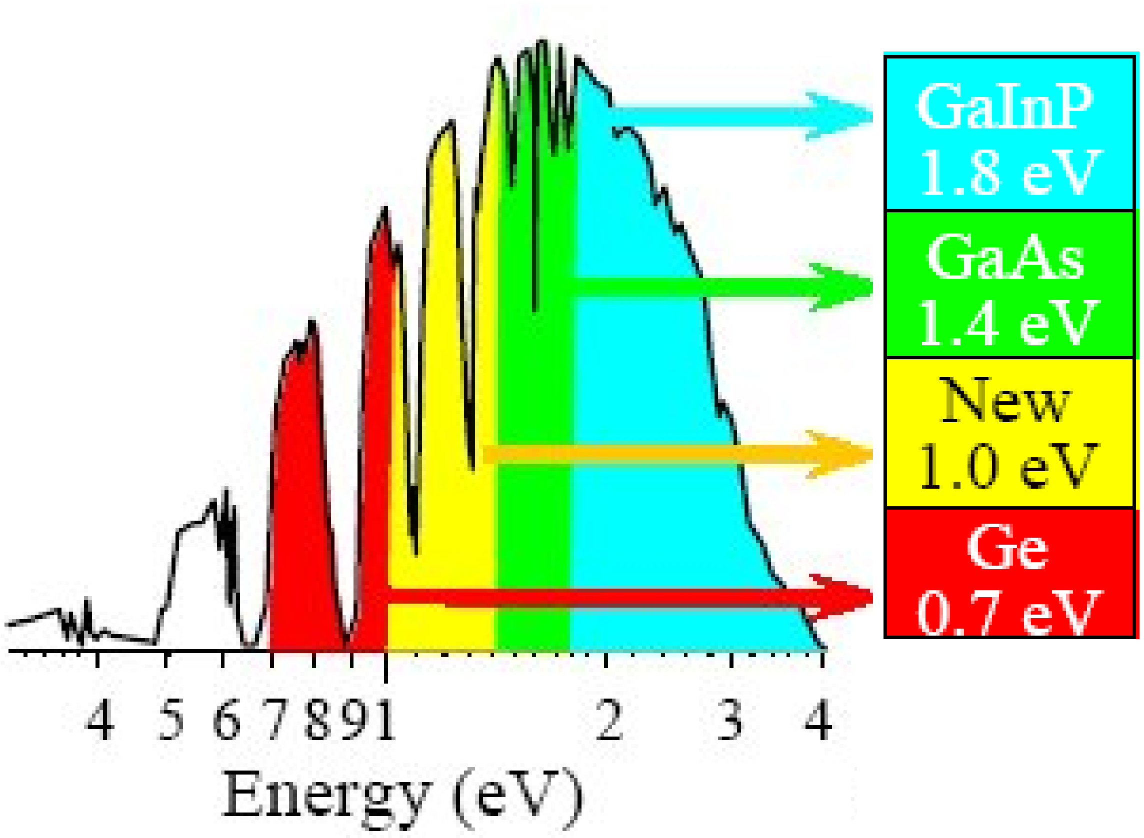
We should be aiming much higher in terms of efficiency → new technologies

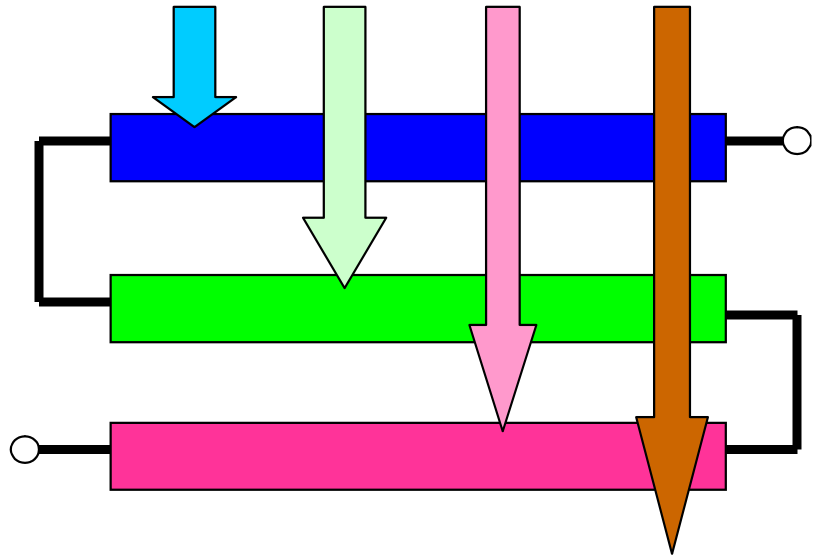
The Central PV (Technical) Challenge



99% of the energy in the solar spectrum spans the wavelength range of 340 < λ < 3500 nm (0.35 to 3.7 eV).

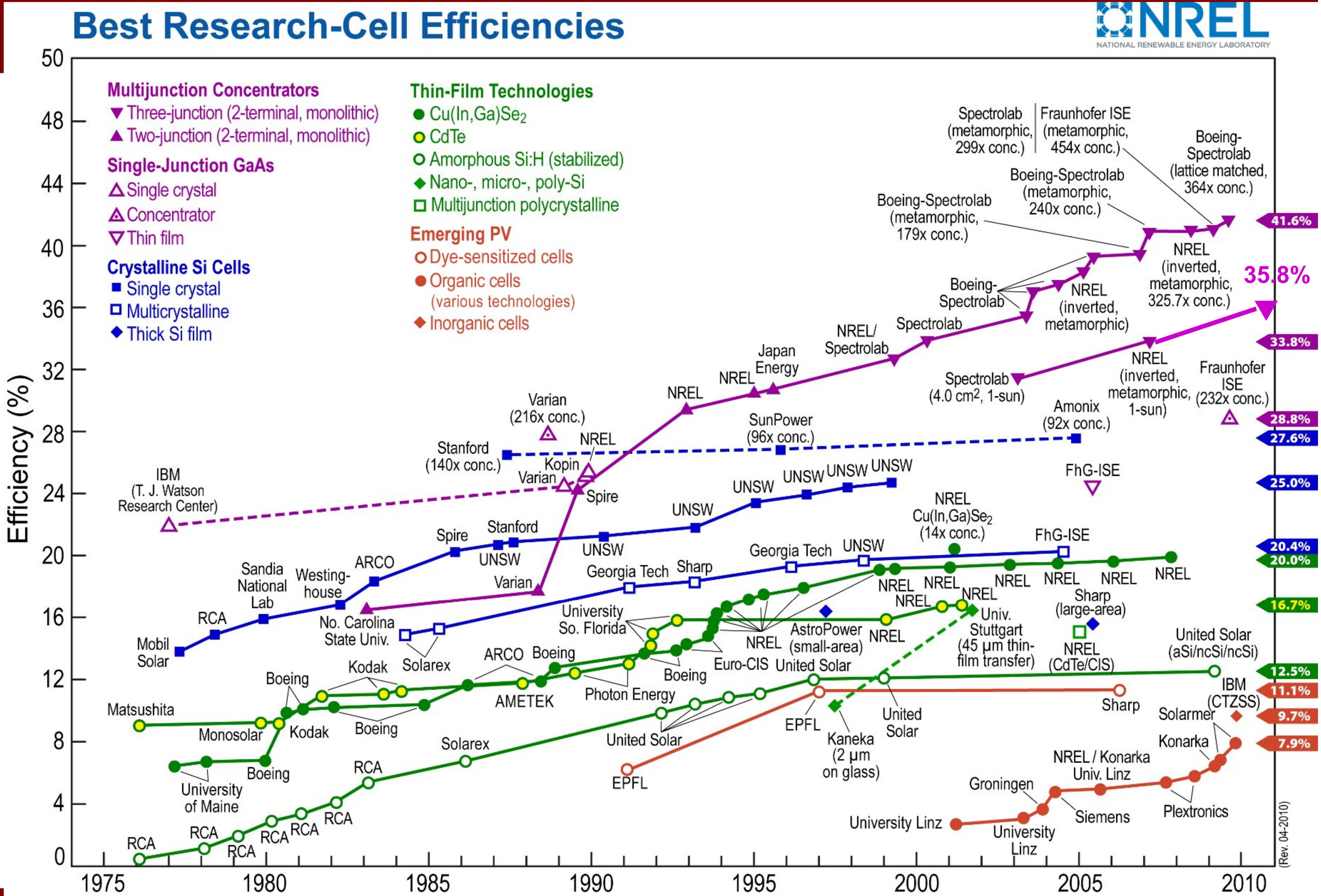
Multi-junction device Technology





Cells are in parallel optically and in series electrically

Best Research Cell Efficiencies



High Efficiency devices

Single junction cell at 1 sun;

Theoretical efficiency ~ 31% max

Multi junction cell at maximum concentration;

Theoretical efficiency ~ 83% max

Record performance today;

36% at 1 sun (3J cell, lab record 2010)

43% at 250 suns (3J cell, lab record 2010)

The Central PV (Commercial) Challenge

High efficiency and low cost

Common metric is $/W

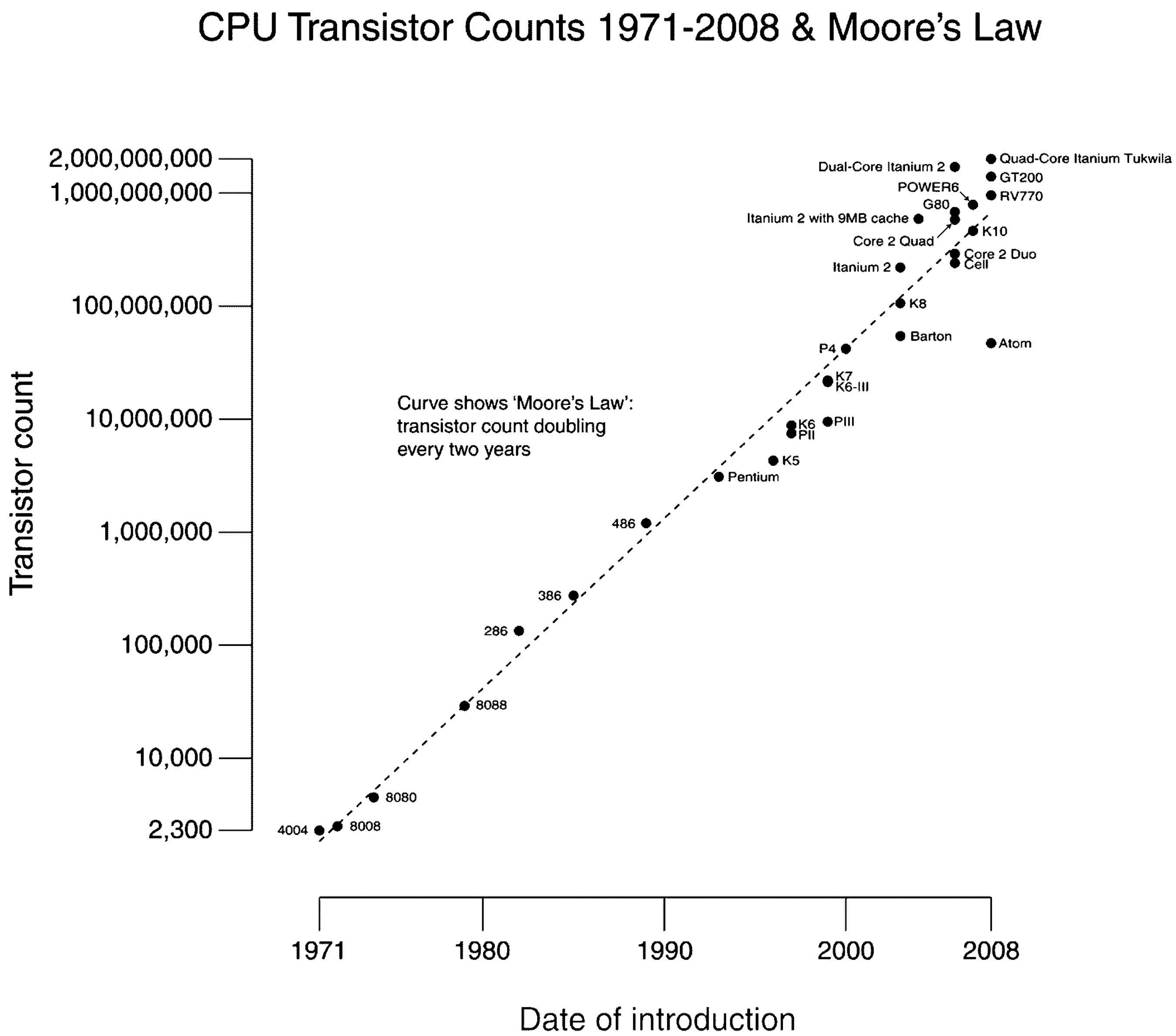
Also need:

- reliability, 20 – 30 years
- environmental impact of material usage

Materials availability – an issue for global scale deployment

Low cost manufacturing methods

Moore's Law


CPU Transistor Counts 1971-2008 & Moore's Law
Transistor count
2,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
2,300
Date of introduction
1971
1980
1990
2000
2008
Curve shows 'Moore's Law': transistor count doubling every two years
4004
8008
8080
8088
286
386
486
Pentium
K5
K6
PII
PIII
K7
K6-III
P4
Barton
K8
Itanium 2
Atom
Cell
Core 2 Duo
K10
Core 2 Quad
Itanium 2 with 9MB cache
G80
POWER6
RV770
GT200
Dual-Core Itanium 2
Quad-Core Itanium Tukwila

Quote (R. Kleiman)

"Moore's law is exponential, but so is compound interest"

i.e. even linear gains in efficiency and cost have a major financial impact

Conclusion

- Extraordinary amount of R&D activity currently under way to improve device efficiency and lower cost
- Leading to gradual improvement in efficiency and rapid reduction in cost
- Large global build-out underway in solar energy and other renewables
- Expected to continue due to limited energy resources and GHG/pollution issues

Longer term view

Many research devices will pave the way to higher device efficiencies

- many will not be economically practical for large scale deployment

Silicon and organic materials abundant

-build new technologies on Silicon platform

-organic materials attractive as degradation issues resolved