Physics of Sustainability

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Can we run the planet in a sustainable fashion, while maintaining our standard of living, and allowing other nations to reach ours?

… and what does physics have to do with that?

The public is optimistic …

In a globescan poll (Nov 2011)

71% thought their country "could almost entirely replace coal and nuclear energy within 20 years by becoming highly energy-efficient and focusing on generating energy from the Sun and wind".

http://www.globescan.com/news_archives/bbc2011_energy/

Even banks are optimistic …

HSBC advertisement in Edinburgh airport

“0.3% of solar energy on the Sahara could power Europe”

True, False, or Fantasy ?

Principles of physics: How to be an armchair expert

- The right kind of theory is better than large amounts of incomplete data
  - Global versus detailed modelling – not losing the wood for the trees
  - Linear response + corrections
- Thermodynamics
  - The global climate is well mixed – “equipartition”
  - Sources of renewable energy are dispersed and all have about the same (low) energy density
  - Free energy is not “free” --- the role of entropy
- Cost
  - The importance of money
  - Money is really energy in disguise

What this lecture is about … and what not

1. Thermodynamics of the planet
   - the large scale physics of the environment
2. Sources and sinks of renewable energy
   - why renewables have to be deployed on country-sized scales
3. Headroom for innovation on transformative energy technologies
   - generation, storage, use, and transmission

No nuclear

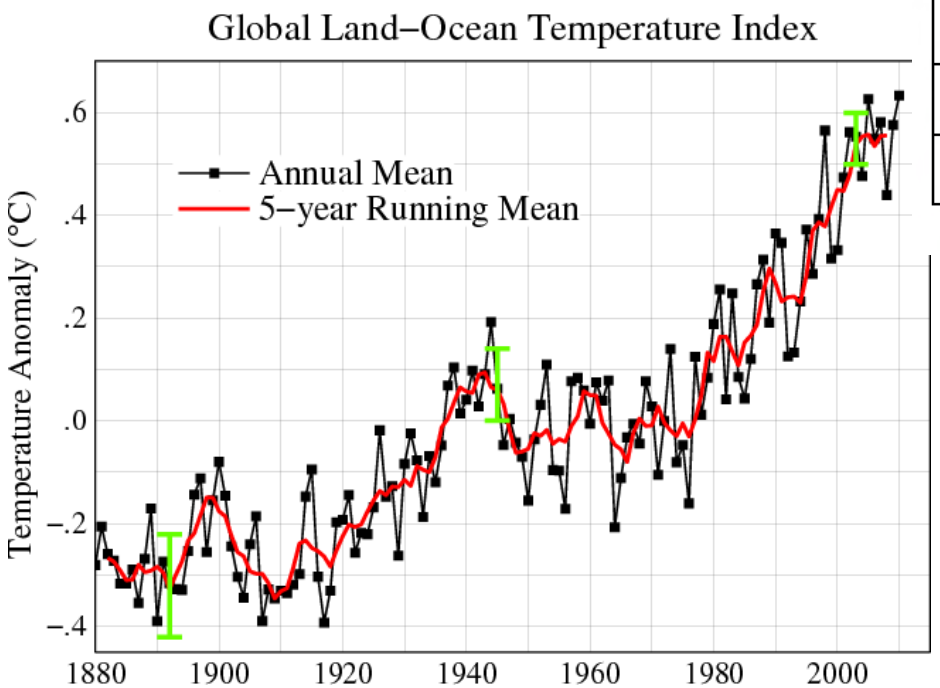
No resource use, water

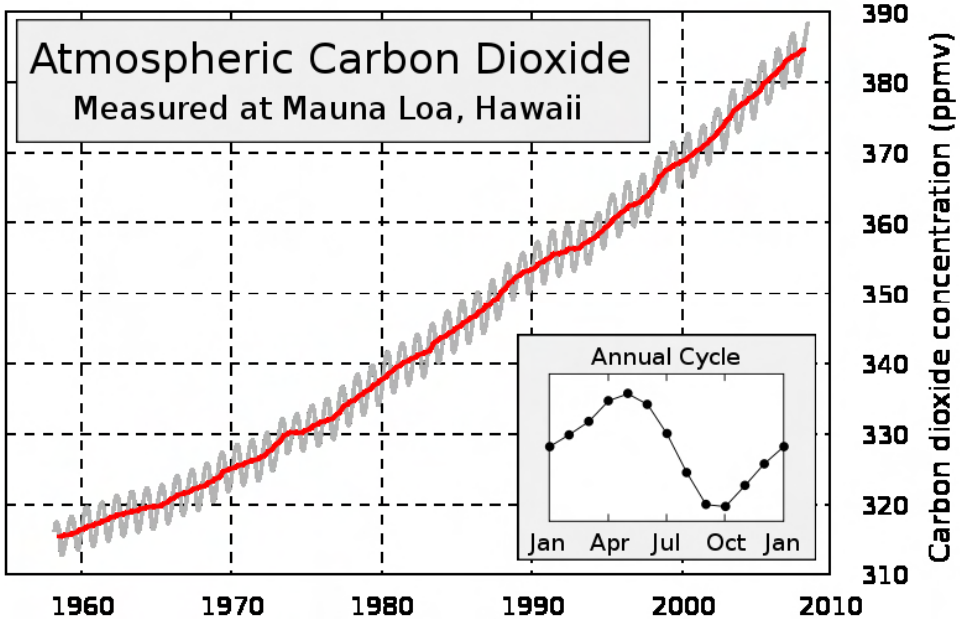
No policy

No climate change ....

Do you believe in global warming?

Fluctuation? Correlated ? Causal ?





Source: NASA Goddard Inst.
http://data.giss.nasa.gov/gistemp/

A good theory is always the best thing to have

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

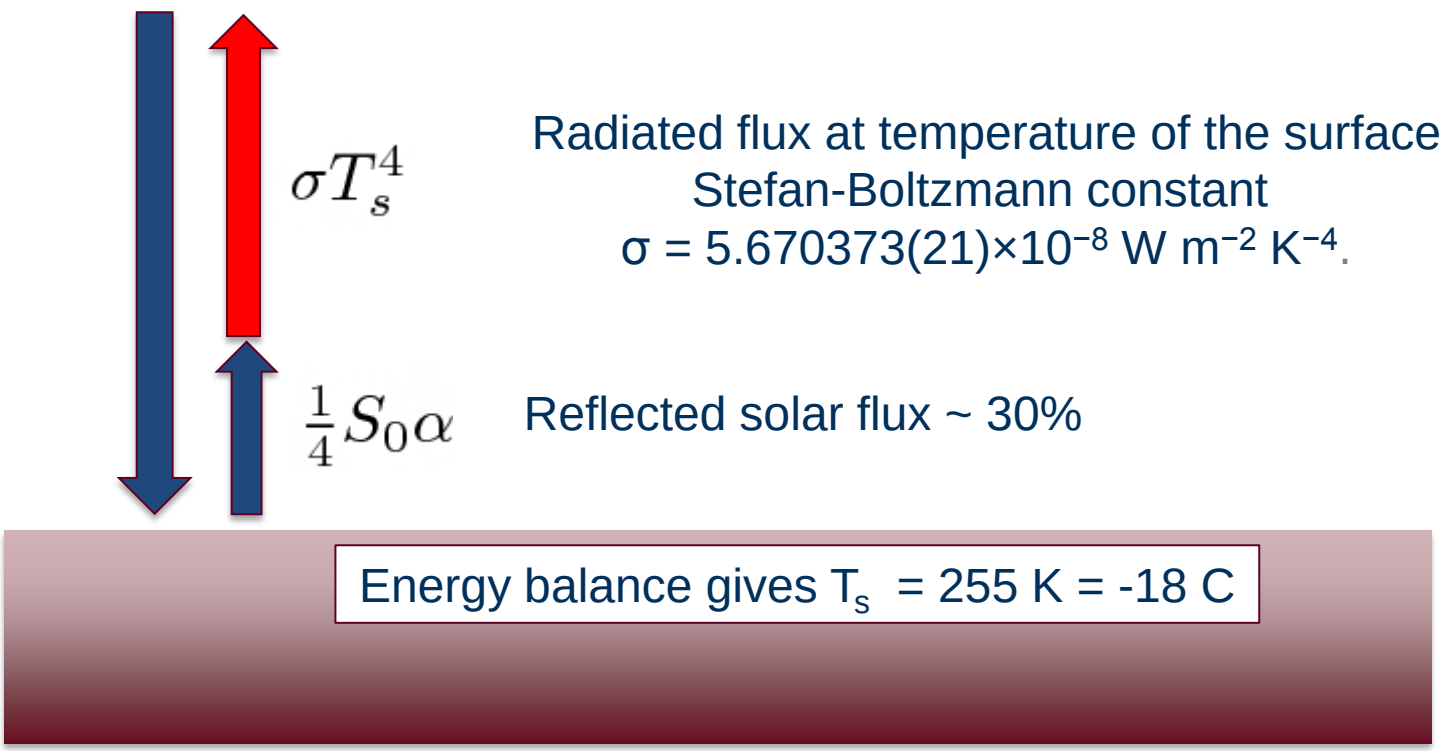
APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

Svante Arrhenius

Arrhenius's model for the greenhouse effect (a) No atmosphere

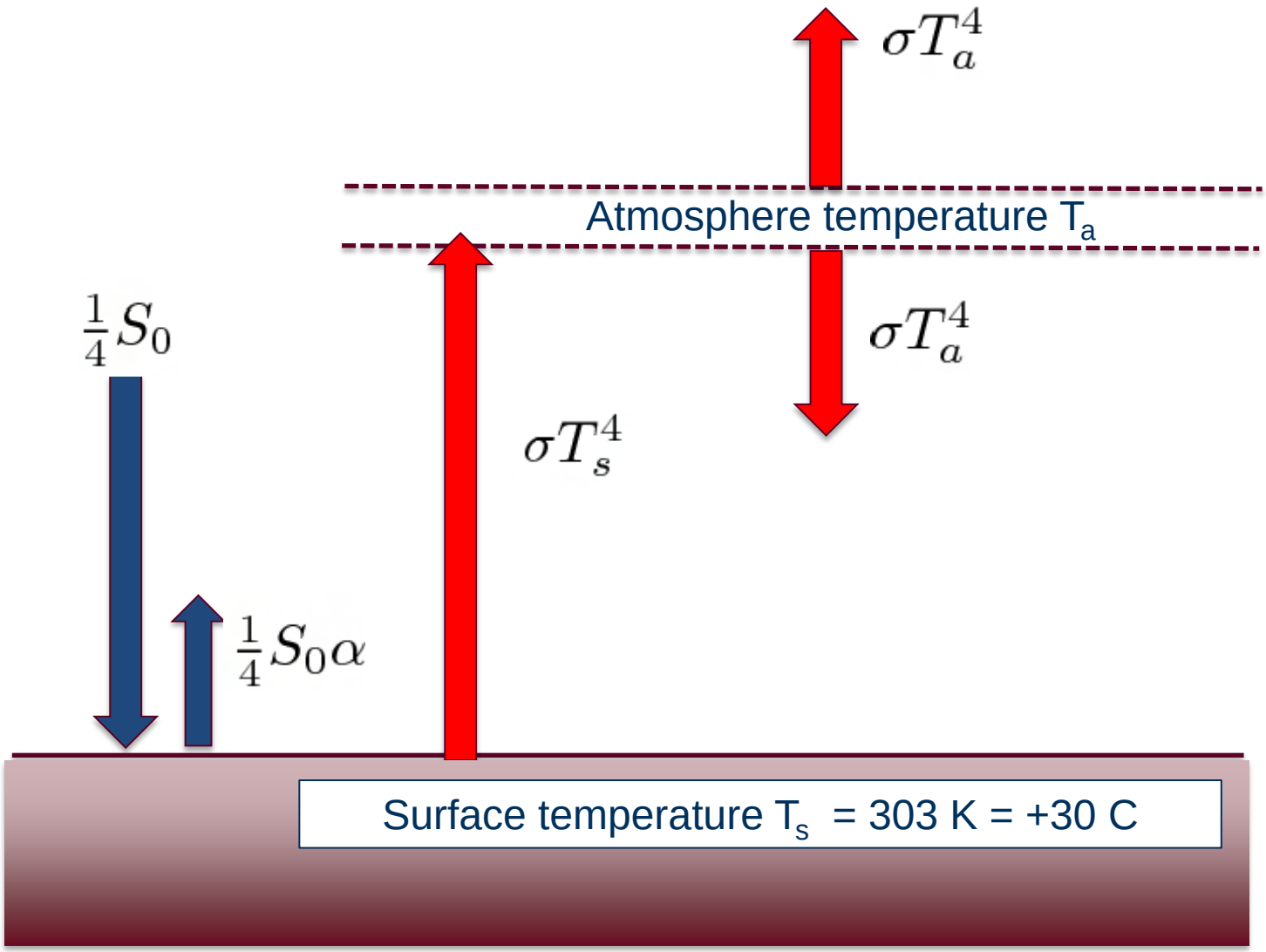
$\frac{1}{4}S_0$ Incident flux 341.5 Wm^{-2} in the "hot" solar spectrum



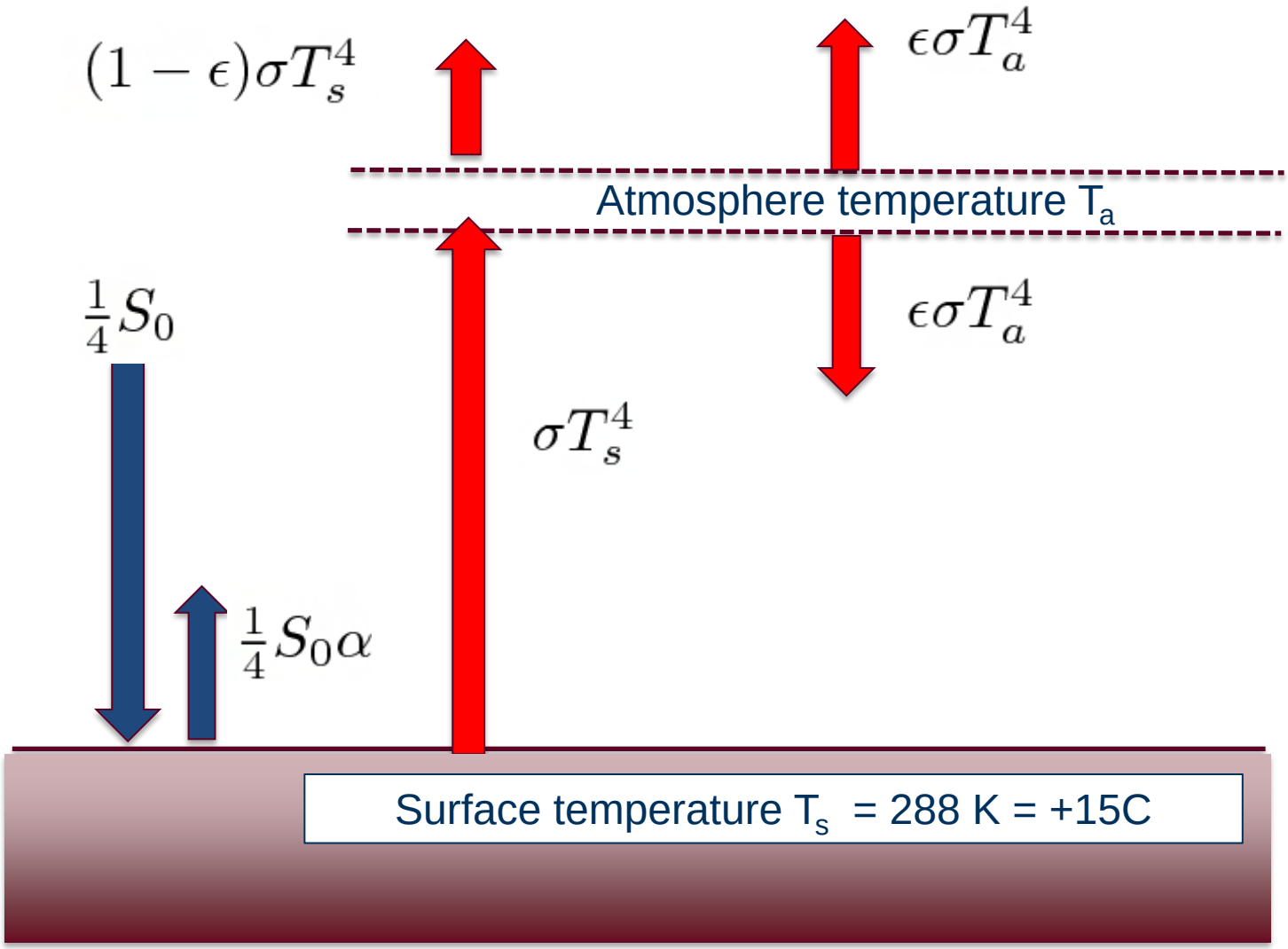
Radiated flux at temperature of the surface
Stefan-Boltzmann constant
$\sigma = 5.670373(21)\times10^{-8}$ W m^{-2} K^{-4}.

Reflected solar flux ~ 30%

Arrhenius's model for the greenhouse effect (b) Opaque atmosphere ["Venus"]



Arrhenius's model for the greenhouse effect (c) Partially transparent ["Earth": ε = 0.78]



Greenhouse gases

- Model is vastly simplified but it is very good because it depends on “sum rules”
- Atmosphere is “well-mixed”
- Few parameters α, ε, σ are very well known
- Doubling CO_2 changes $\Delta\varepsilon$ by 0.02
- Changes radiative “forcing” by 3.7 Wm^{-2} (~1%)
- Predicts ΔT_s = 1.2 K (assuming the system is linear)
- Nonlinearities (“feedback”) appear to be largely positive
  - mostly H_20 , some albedo, possibly methane, clouds?
- Consensus ΔT_s = 3 K from modern global climate models

Sources of renewable energy and the needs of the planet

Solar: the energy input

- Solar insolation is the major energy input to the planet
- Mean radiative solar flux =341.5 W/m^2
- This energy gets redistributed into other degrees of freedom
  - thermalised into infra-red --- “heat”
  - wind energy
  - wave energy
  - rainfall

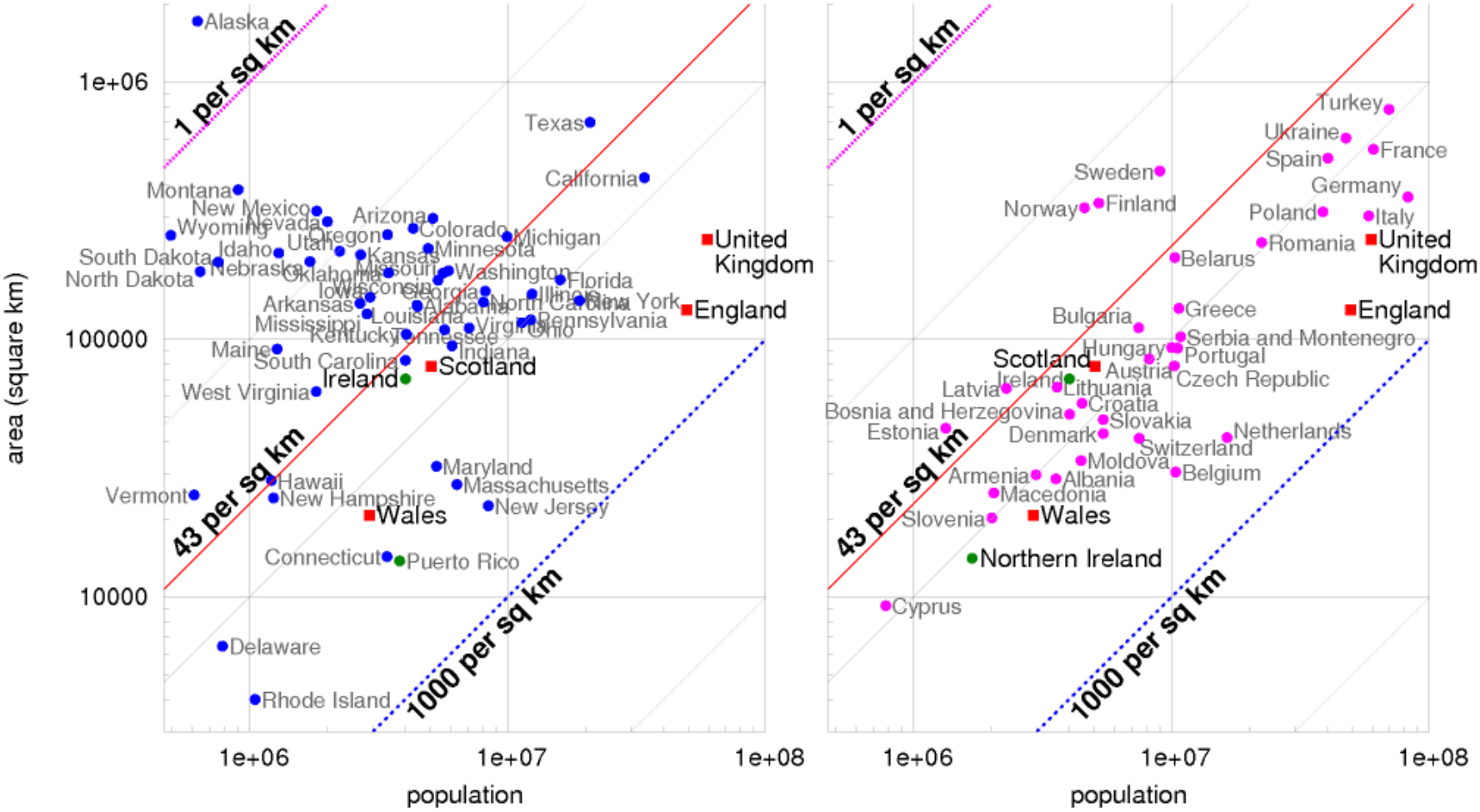
How much do we need ?

USA average power consumption = 3 TeraWatt

5 billion microwave ovens

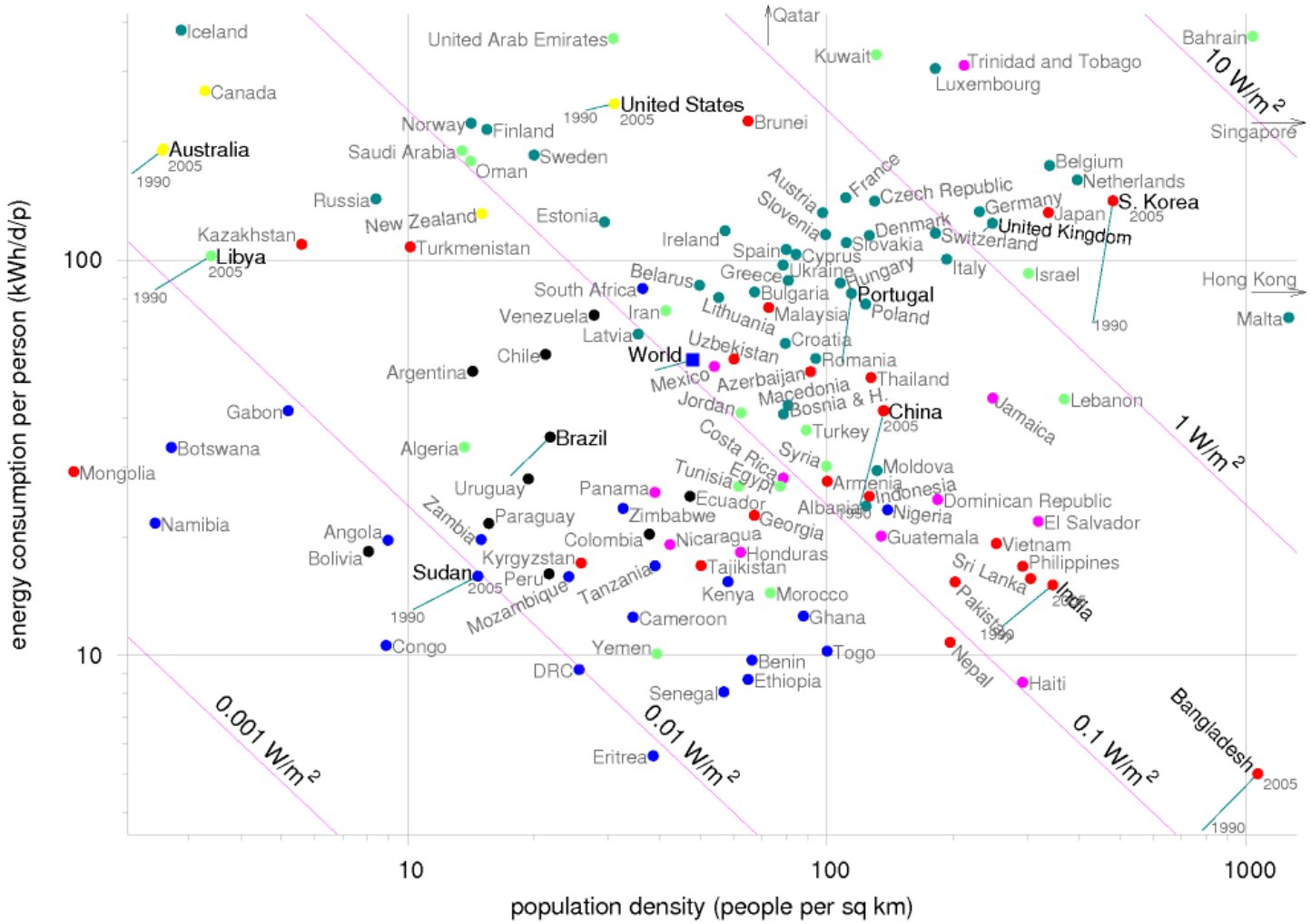
Solar flux on 10,000 km^2 = Delaware + Rhode Island

Population densities



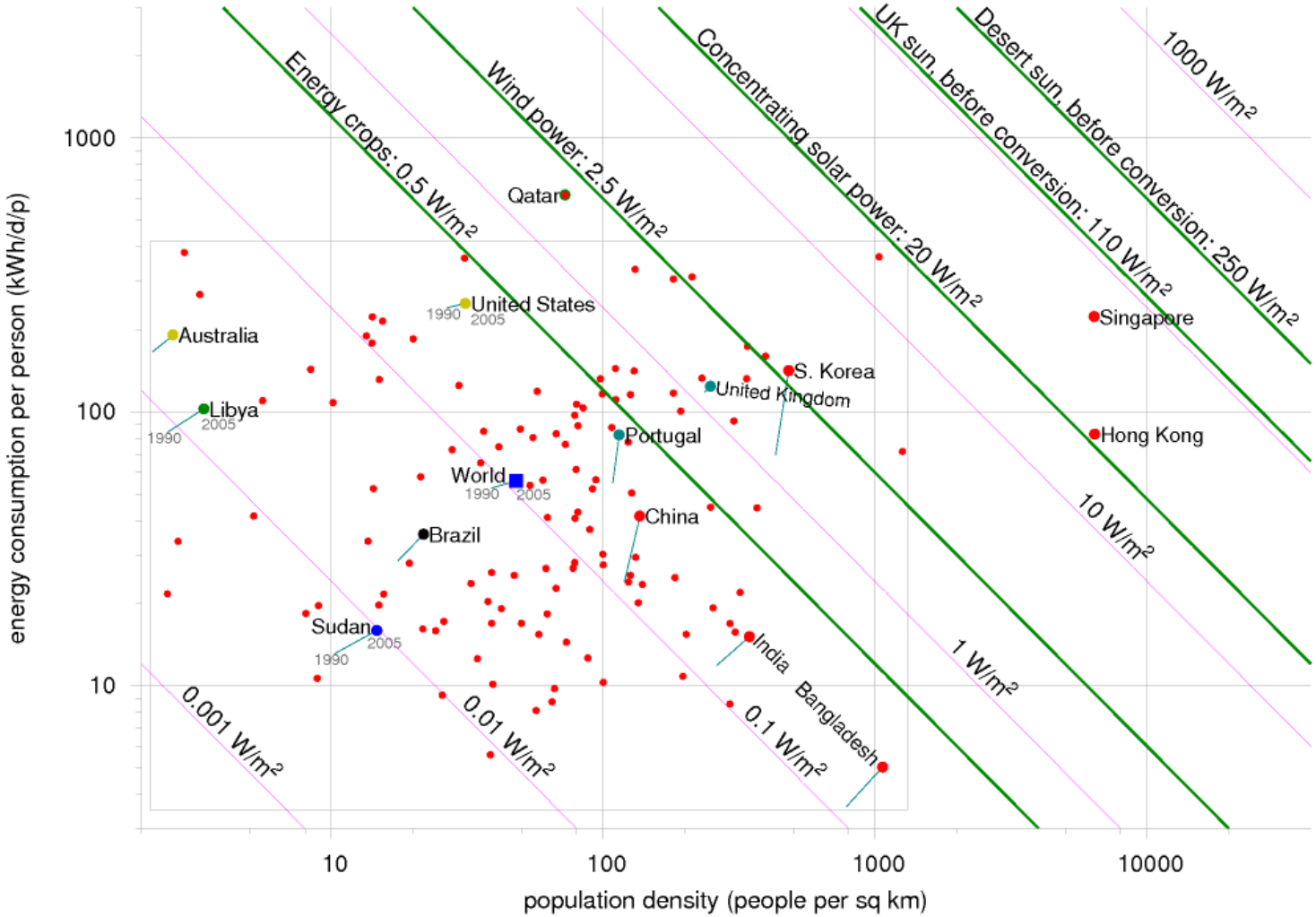
Courtesy D J Mackay, UK DECC

Energy usage per m²

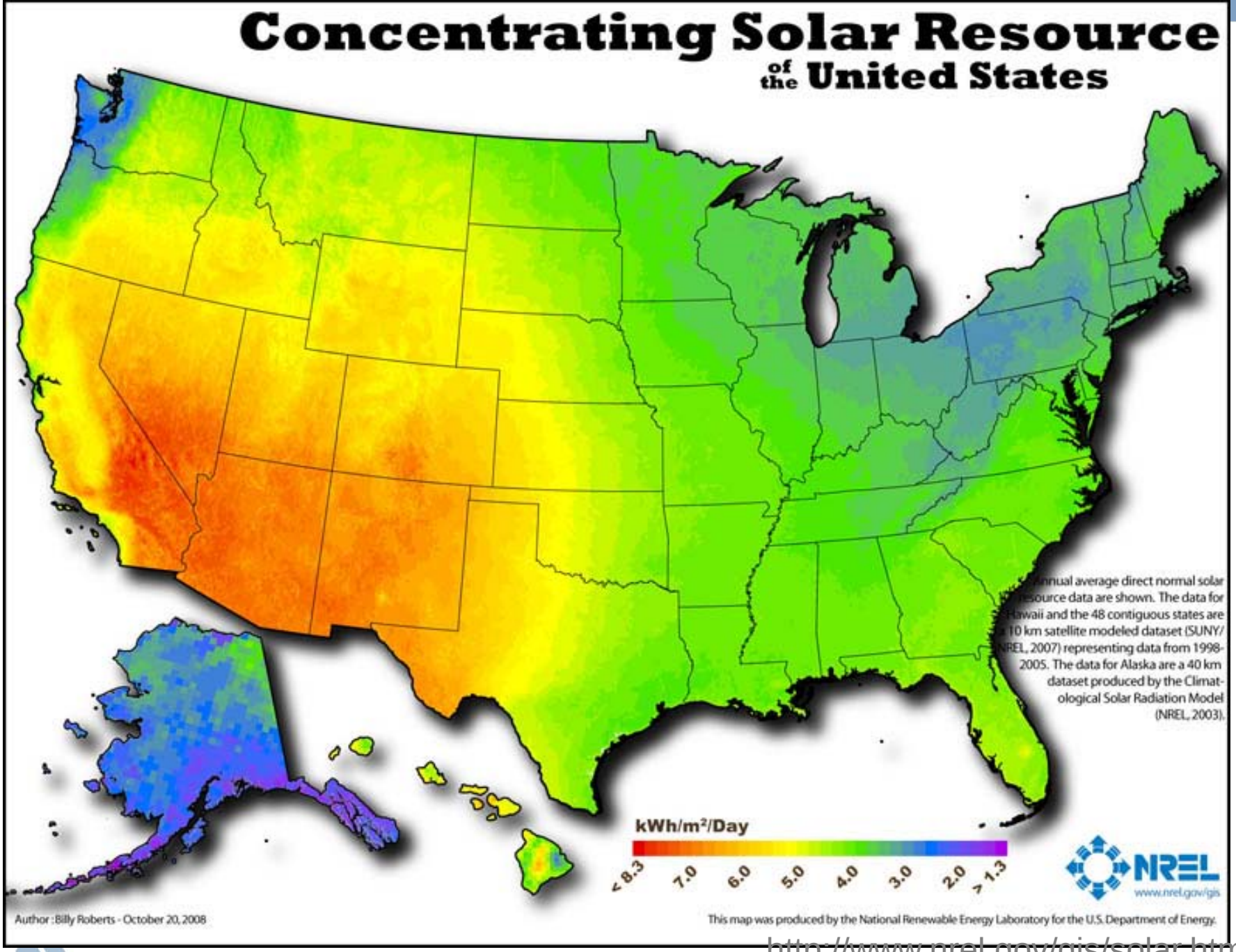


Courtesy D J Mackay, UK DECC

Renewables must be deployed on country-sized scale



Courtesy D J Mackay, UK DECC

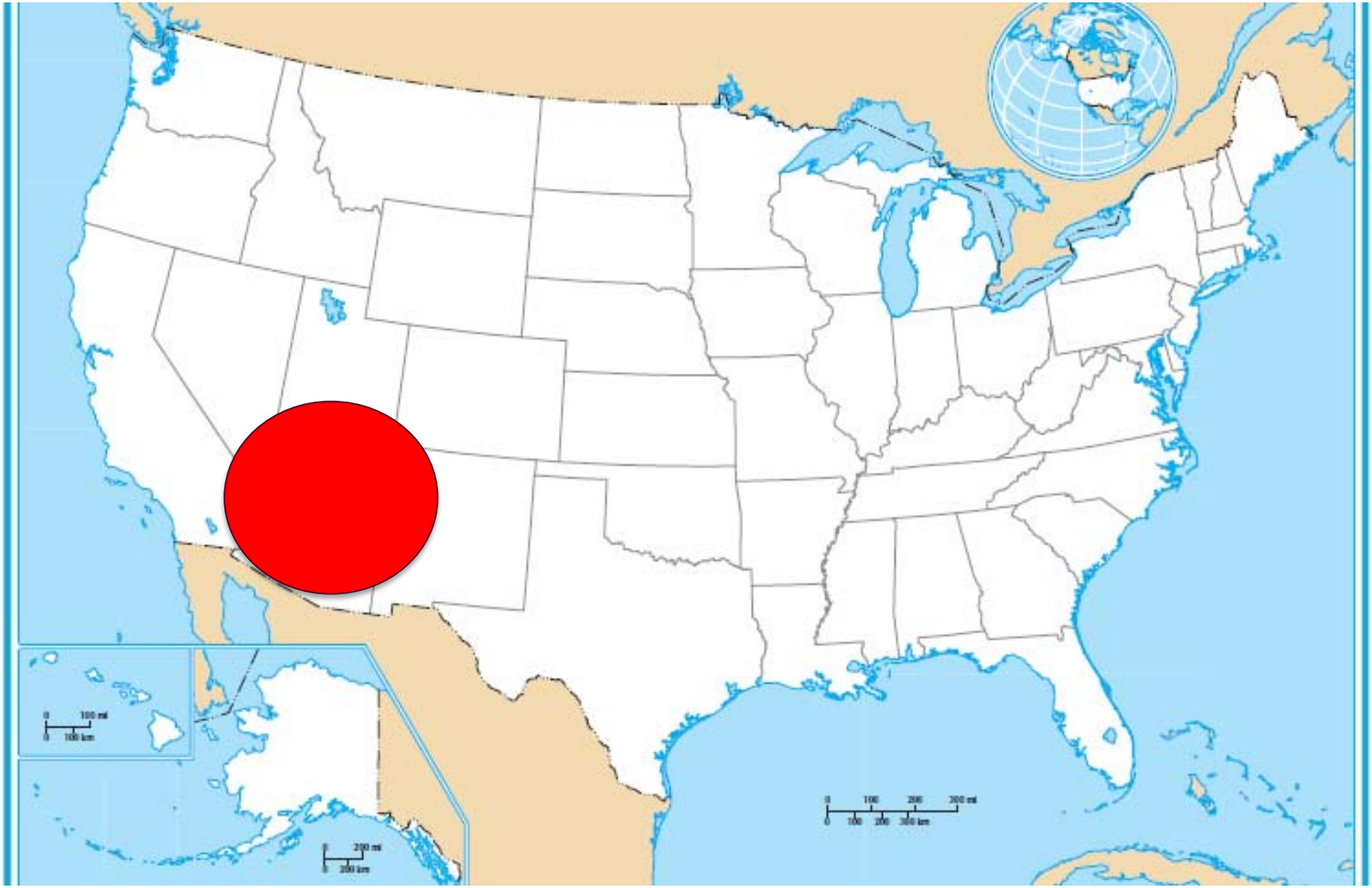


http://www.nrel.gov/gis/solar.html

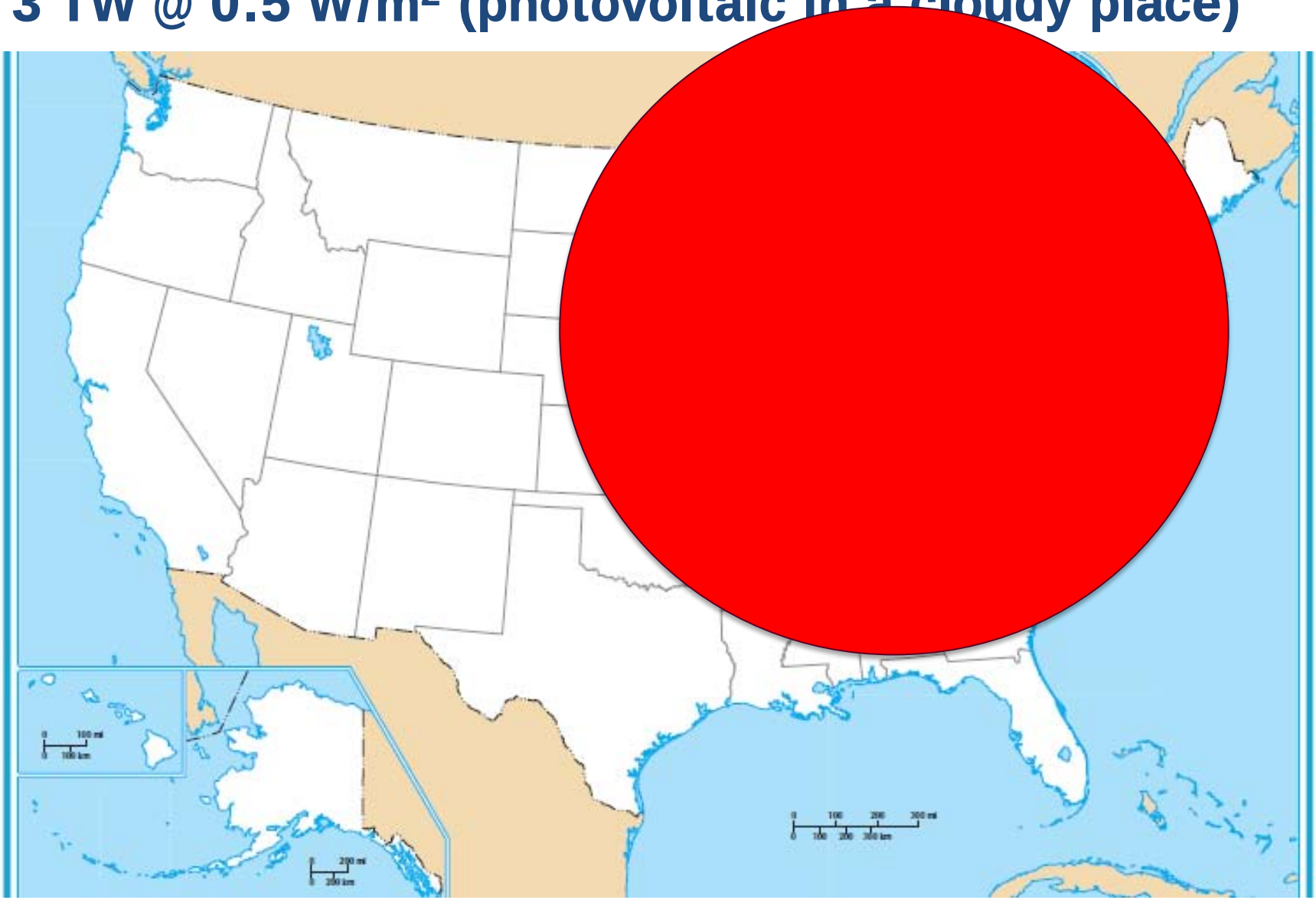
3 TW @ 300 W/m^2 (Full insolation in AZ)

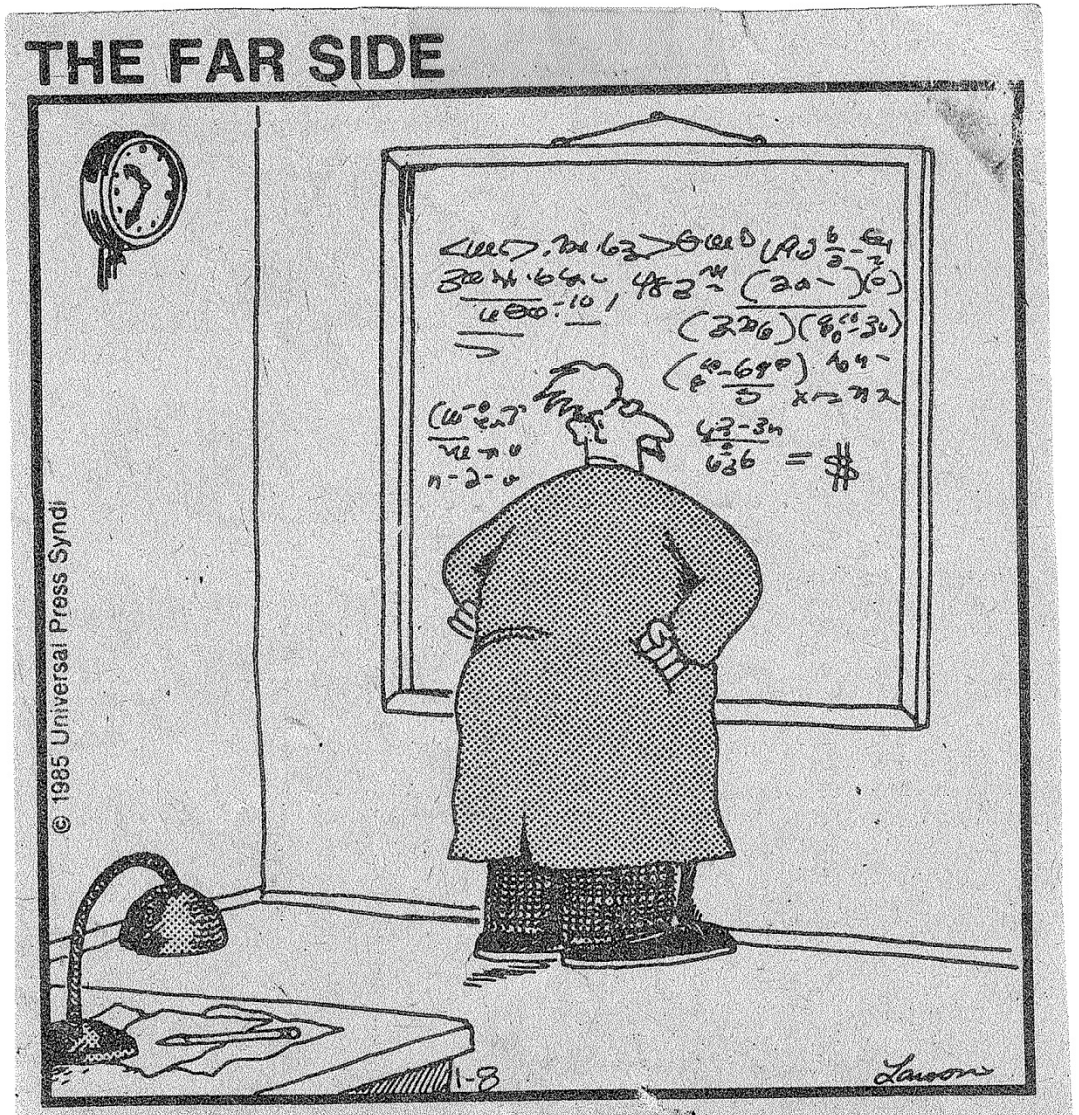
3 TW @ 20W/m² (Concentrated solar in desert)

3 TW @ 5W/m^2 (photovoltaic)



3 TW @ 0.5 W/m^2 (photovoltaic in a cloudy place)





Einstein discovers that time is actually money.

Lesson:
Renewables need country-sized deployment

- Premium on efficiency, manufacturability and cost and geography

- What about wind, hydro, wave .....

Wind energy

- Enercon E-126 7.58 MW / 6000 Tonnes
- Spacing 6-10 times rotor diameter (126 m for E-126; radius then 360m) [Spacing is a consequence of fluid dynamics]
- Area/rotor = 4×10^5 m^2
- Power /area = $7.58 \times 10^6 / 4 \times 10^5 = 18$ Wm^{-2}
- Best practical capacity 35% = 6 Wm^{-2}

Hydro is a "point source"

Hoover dam: annual energy generation 4.2×10^9 kWh (1)

- How much power available?
  - Annual Rainfall: 300 cm in Colorado = 300 kg/cm^2
  - Energy stored = mass x g x height = 300x10x1000 = 3×10^6 Jm^{-2}
  - Annual average power/area = 0.3 Wm^{-2}
- How much generated?
  - Area of Colorado : 270000 sq km = 2.7×10^{11} m^2
  - Power generated per unit area of Colorado by hoover dam = $4.2 \times 10^9 \times 3 \times 10^6 / (2.7 \times 10^{11} \times 3 \times 10^7)$ $= 1.5 \times 10^{-3}$ W m^{-2}
- Cost ?

(1) Data from Bureau of Reclamation. http://www.usbr.gov/lc/hooverdam/faqs/powerfaq.html.

Renewable sources are diffuse

	Power density W/m^2
Concentrated solar power (desert)	15-20
Solar photovoltaic	5-20
Biomass	1-2
Tidal pools/tidal stream	3-8
Wind	2-8
Rainwater (highland)	0.3

... and of course they all require energy to construct

The (energy) cost of making things

The “hamburger rule”

Ground beef - $10 / kg

Honda Civic 1.8
Price $16000
Weight 1210 kg

$13/kg

The cost of things is their energy input

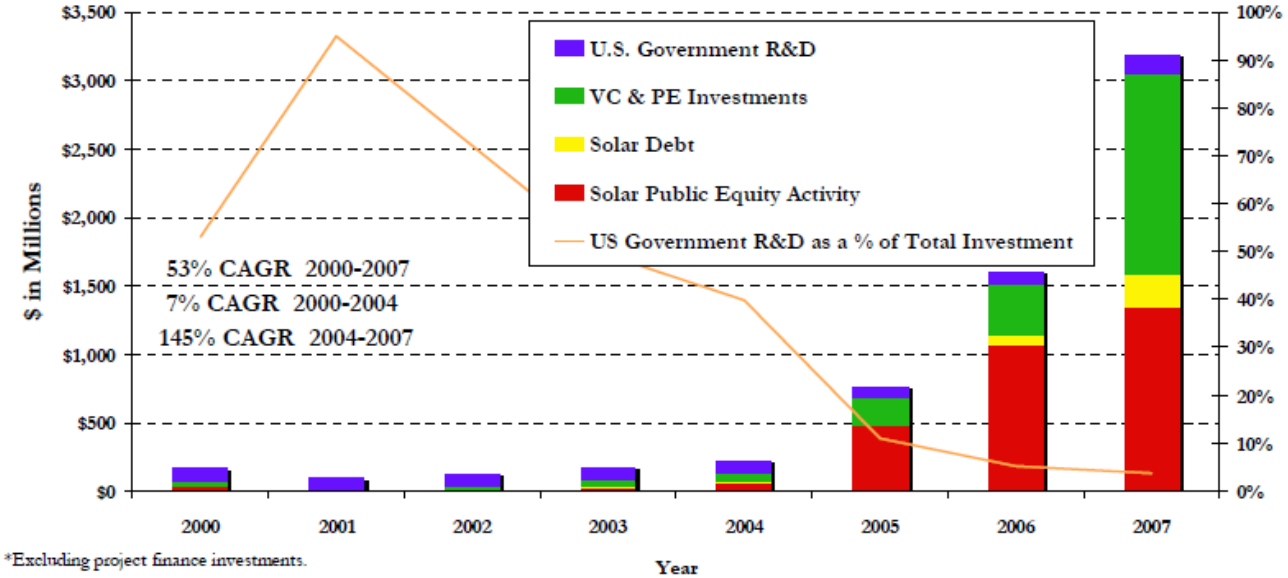
	Price/$	Energy consumed kWh	Implied cost of energy $/kWh	Time to breakeven at 10c/kWh
1 kg Steel*	1.00	7.5	0.13	
1 kg Al	2.50	16.2	0.15	
1 kg hamburger	10.00	1.9X50(1)	0.11	
1 liter Diesel	0.80	10	0.08	
1 kg wheat flour	1.00	4.3	0.23	
E-126 wind turbine (2)	$10M/6000 ton= 1.50			3.5 years
Solar panel	$1/Watt			4 years

*1/3 of the cost of steel is the energy input

(1) Energy factor – David Pimentel 1997
(2) Bloomberg New Energy Finance's Wind Turbine Price Index 7 Feb 2011

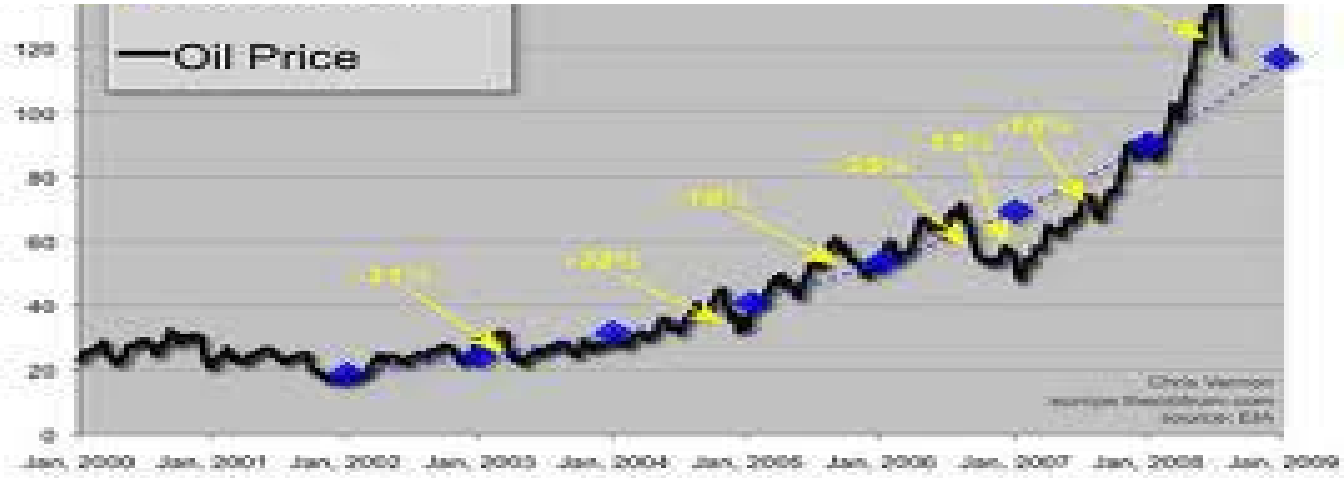
The "S-curve" for solar

Figure 4: U.S. Capital Investments in Solar Energy*



*Excluding project finance investments.
No new equity was raised from solar M&A in the U.S. during this period.

Source: NEF / NREL / FACC



Recap ….

- Equipartition of energy amongst sources
  - Power densities for renewables are all very similar
  - Payback time for energy used in construction is a substantial fraction of the lifetime
- Energy is really money

This is the 2nd law of thermodynamics, the “no-free-lunch” theorem

We will never (again) make energy cheap

However, the financial conditions are now in place for a transition to a sustainable energy economy

Money is really energy

And now to technology …

- Renewable sources must be country-sized

  Premium on Cost, Manufacturability, Efficiency
- Energy uses are typically point source

  People, cars, factories, computers ....
- Clusters of technologies have societal advantages

  photovoltaics + storage => no power grid

  photovoltaics + storage + refrigeration => food storage, vaccination

  photovoltaics + storage + refrigeration + lighting => education

How much headroom for new technologies ?

Transformative technologies

- Photovoltaics for electricity generation
- Ultracapacitors/batteries for electrical storage
- Thermoelectrics, magneto/electro-calorics for electrical refrigeration
- Light emitting diodes for electrical lighting
- Superconductors for electrical transmission/ motors

If these technologies are cheap and efficient we have the best possible local solutions for energy use

Why electricity?

By 2100 (say) we will be relying principally on the cheapest and most abundant source of energy: direct solar

Renewable energy sources are diffuse, and solar to electric is the most efficient in principle with global impact (there are many special cases that can have local impact)

Solar to fuel? – why introduce an extra source of inefficiency into the energy cycle?

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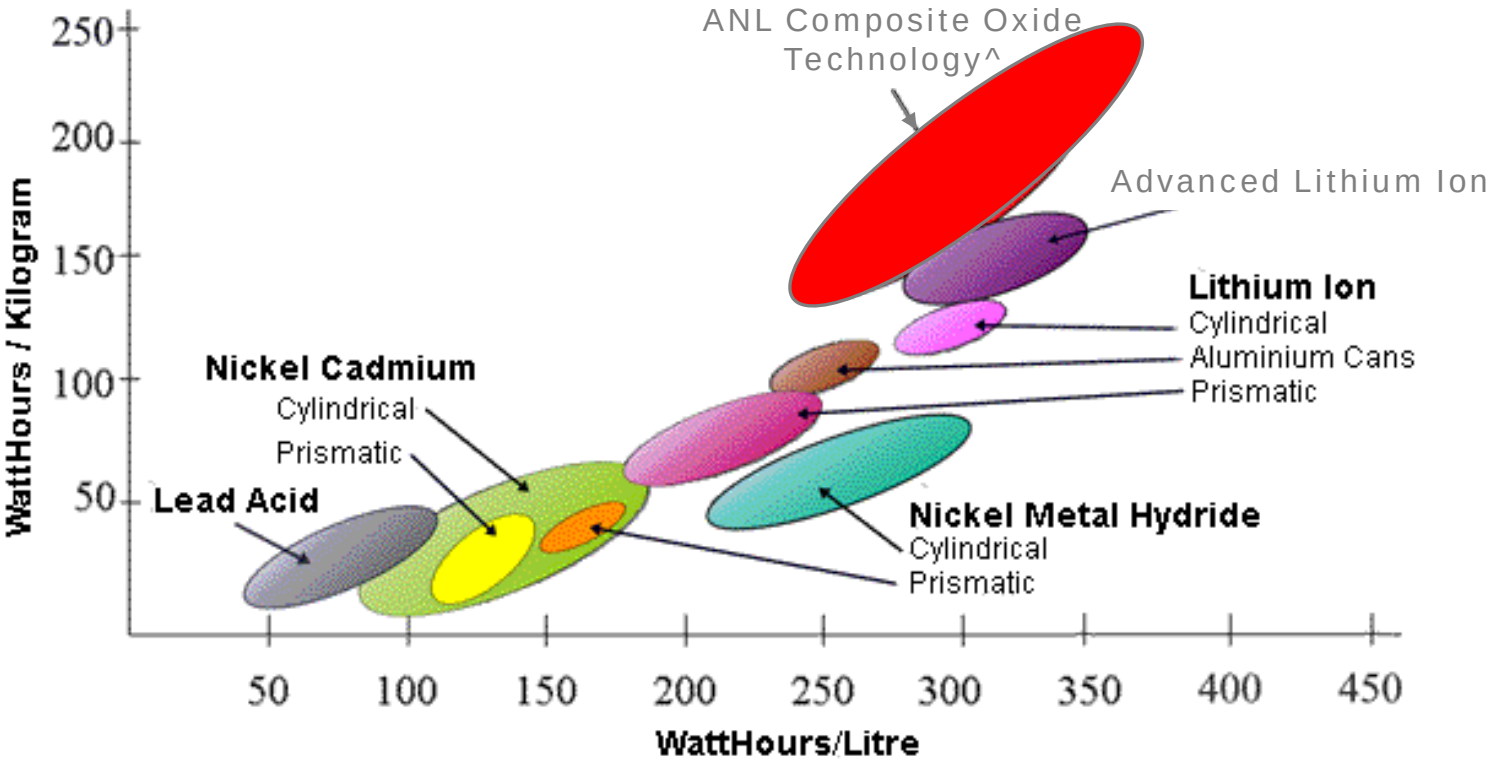
Chevy Volt - The first Plug-in Hybrid Electric Vehicle

Battery System

Size	5.5-foot-long T-shaped;
Mass (kg)	**198.1**
Cells	288 prismatic
Combined electric/extended driving range	Up to 350 miles (~40 miles by battery only)
Warranty	Eight years/100,000 miles
energy	16 kWh
battery price	**~$8,000 (~$500/kWh)**

Energy storage density of advanced batteries



gasoline is 12000 Wh/Litre
about a factor of 60 by weight

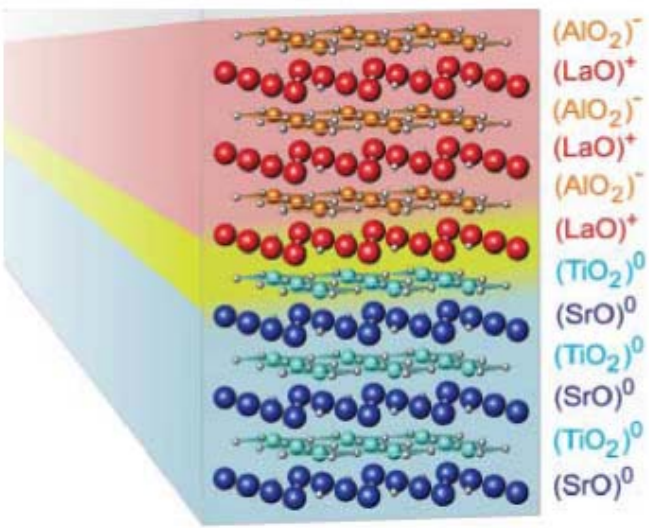
Fundamental Limits for Electrical Energy Storage

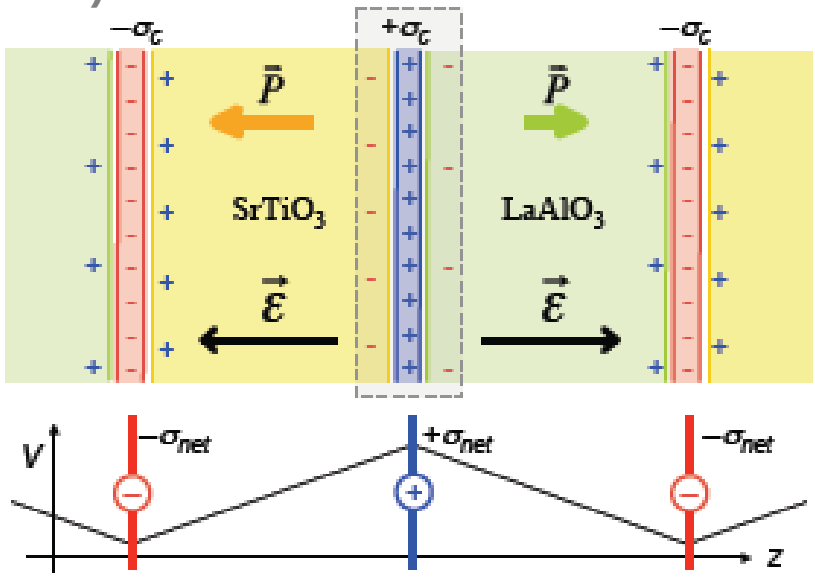
- What is the limit: measure storage energy in eV/Angstrom^3
- 1 eV A^3 = 1.6 10^{11} Jm^{-3} = 160 MJ/L (megaJoules per liter)
- Li ion battery 7.5 10^8 Jm^{-3} = 0.75 MJ/L
- Diesel : 38 MJ/L
- Liquid H_2 : 10 MJ/L

Since there are problems with moving ions around (speed, material changes, etc.) what can you imagine with the smallest convenient particle – the electron ?

Polar heterostructures demonstrate there is a possible solution?

A Ohtomo & H Hwang, Nature **427, 423 (2004)**





- Once voltage offset = bandgap, chemical potential of carriers controlled by external circuit
- Carriers are lattice-constant sized, so in principle density high
- There are a few issues with materials growth, defects, reconstructed surfaces etc ... currently a fictional and extremely expensive device

Science fiction continued ….

One can imagine a structure of a combined PV/storage device in a material with $m^*=1$ and $\varepsilon = 2$ that will

- efficiently absorb photons
- dissociate the resulting excitons instantly
- store charge at a density approaching that of gasoline

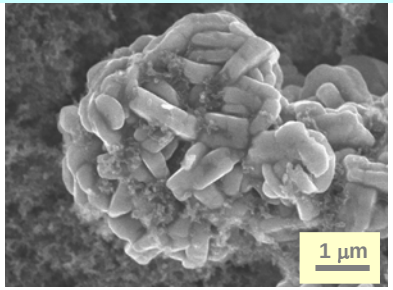
So we solved PV and storage ....

Next ?

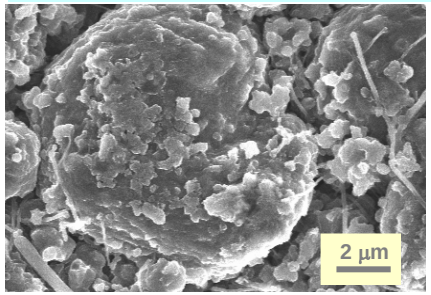
What is the path forward?

- At least two orders of magnitude below optimal performance and too costly
- Devices are unnecessarily complicated, operation is poorly understood, and manufacturing difficult to control
- Major discoveries of new materials classes are rare and random
- Transformational technologies depend on better understanding and control of materials at scales ranging from the atomic to the mesoscale

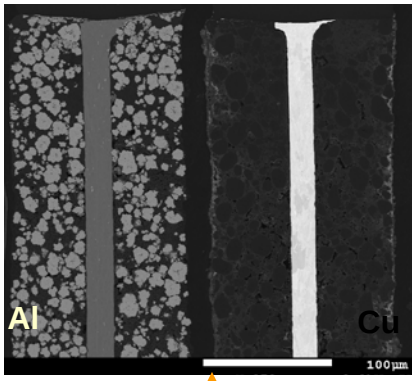
The cathode contains an oxide, carbon additives and PVdF binder



The anode contains graphite, carbon additives and PVdF binder



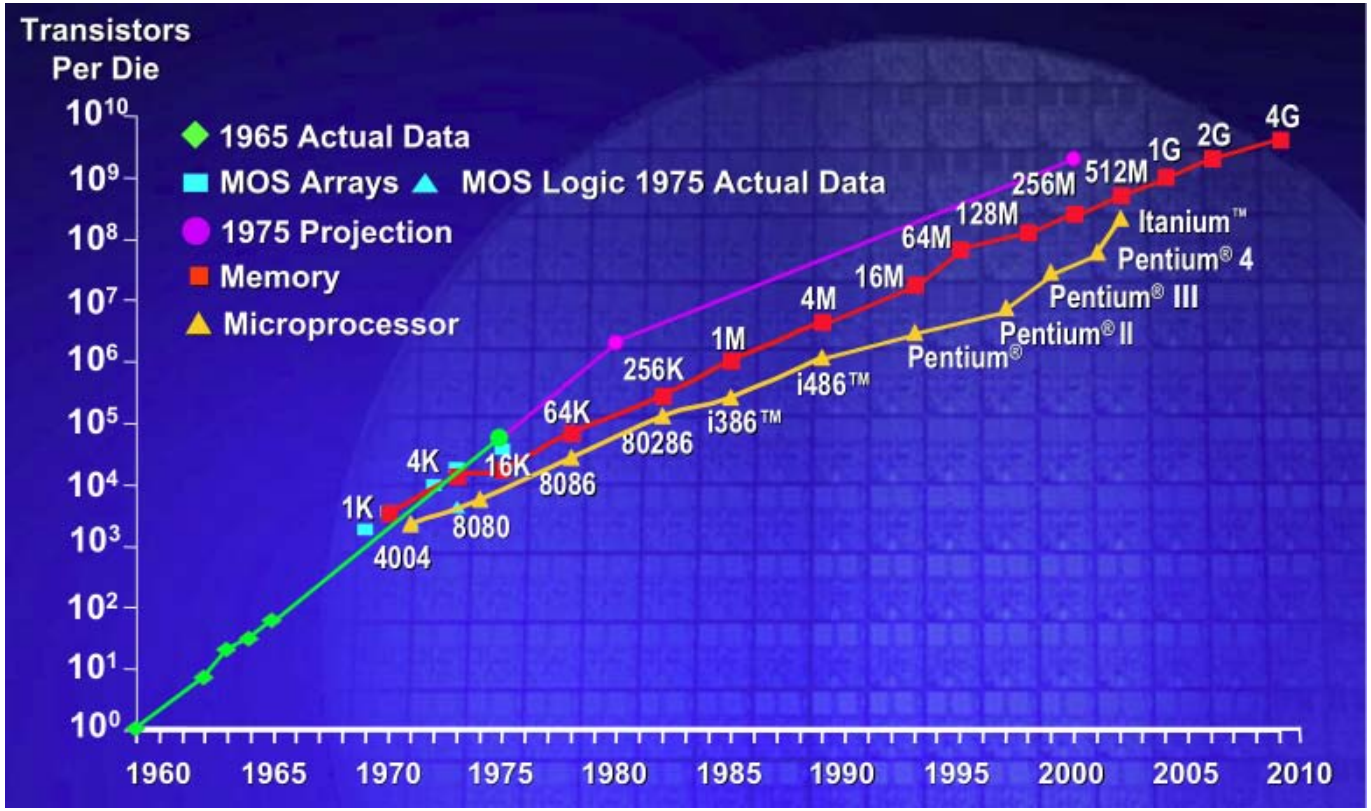
The cathode comprises an Al current collector coated on both sides. The anode comprises a Cu current collector coated on both sides.



Cathode **Separator** **Anode**

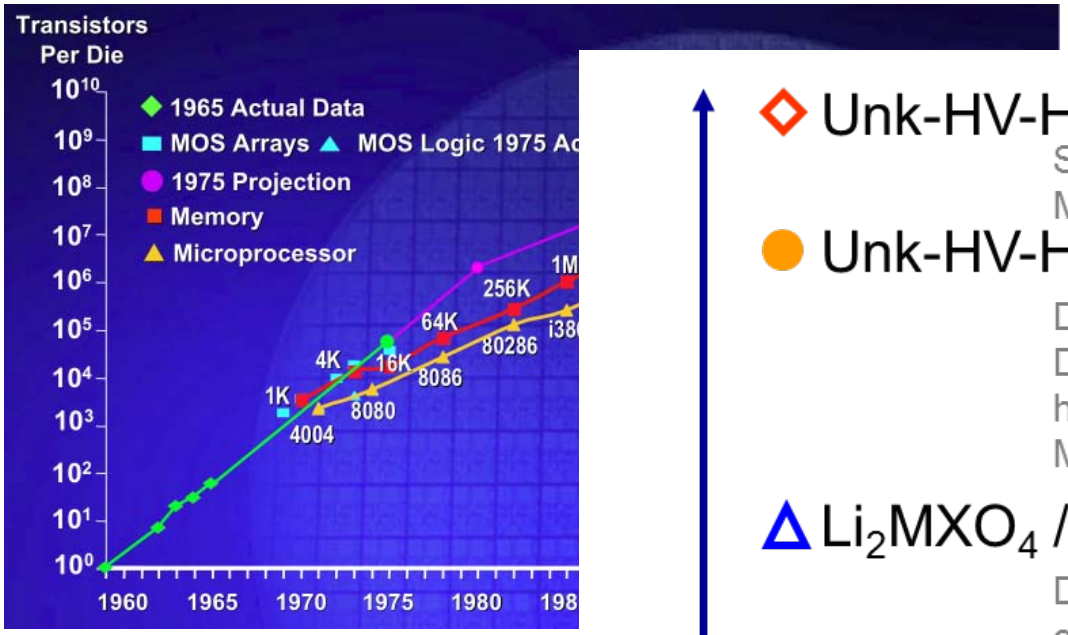
Photo image of an 18650 cell

So we need a roadmap: Moore's Law for materials ?



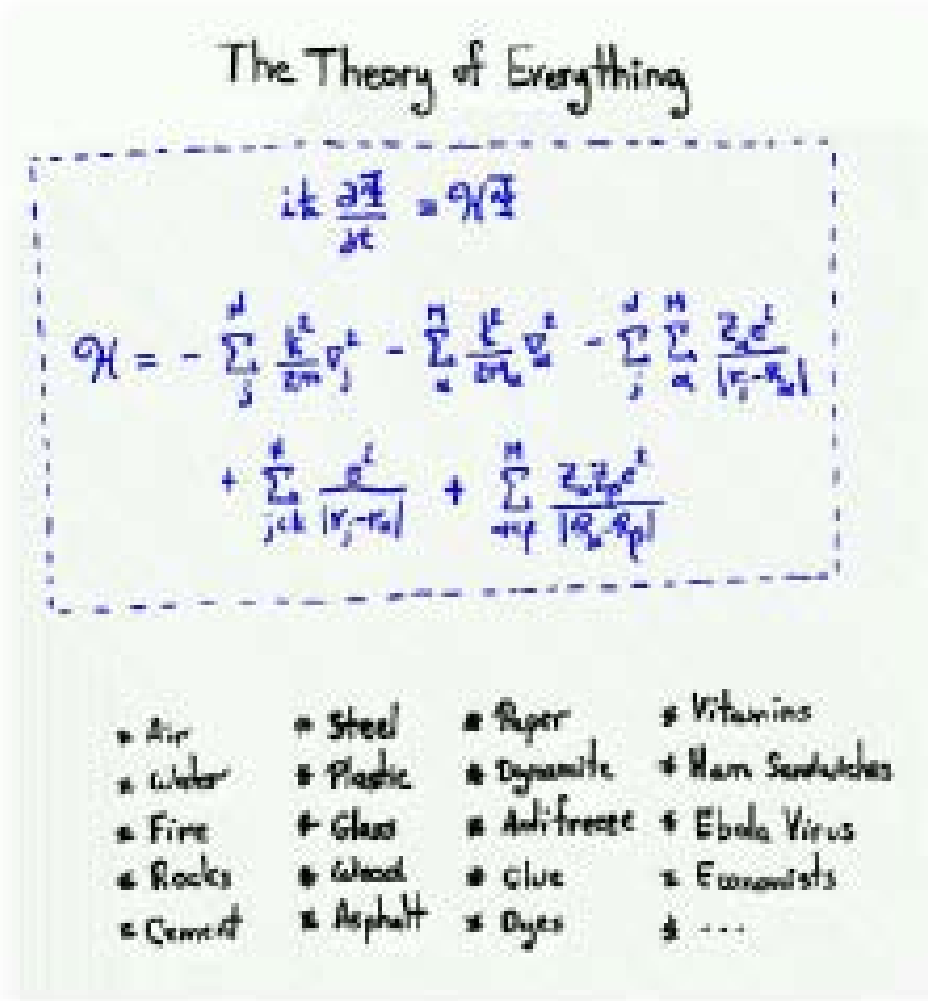
Not so much the logarithmic scale, but the predictability
Also, a single metric defines performance and cost

The consequence of understanding is prediction: Moore's Law for Si *vs*. current strategy for Li-ion batteries



- ◇ Unk-HV-HC / Li metal
  - Safe and reversible cycling of Li metal
  - Market entry >2021
- ● Unk-HV-HC / Gr-Si
  - Discovery of high voltage electrolyte >4.8 V
  - Discovery of reversible unknown high-voltage high-capacity cathode: 250 mAh/g @ 4.8 V
  - Market entry > 2019
- △ Li_2MXO_4 / Gr-Si
  - Discovery of path to reversible multi-electron cathode material with 4V cell voltage
  - Market entry > 2017
- ■ LMR-NMC / Gr-Si
  - Stabilization of silicon
  - Market entry > 2015
- ◇ LMR-NMC / Gr
  - Stabilization of LMR-NMC
  - Market entry > 2013
- ● LMO / Gr

Modelling – its in here somewhere ….



Robert Laughlin (Nobel lecture)

Nanoscience by the ton

We need a road map for materials development that enables us to escape primitive technologies and have a predictable path forward – this is the science challenge of the next few decades

"Top –down" engineering is not the solution - for example:

- 2/3 of the weight of a PHEV battery is "packaging" – control electronics, safety engineering, casing etc.
- Most of the cost of solar panel installation is *not* the module – power electronics and packaging, installation costs, permit fees etc.

Can we learn how to construct functional materials whose properties are defined by precisely controlled interfaces on the nanoscale and which may be manufactured at low cost in enormous volume ....

Nanotechnology fabs of the future …

Final remarks: Science, Economics and Geopolitics

Science: Modest Optimism

There are enough renewable sources of energy and enough space for new technology that the problems are containable

Economics: In balance

All installations will require >billion $ investments on very uncertain technology paths

Energy is now expensive enough that renewable technologies may not all get strangled at birth

Geopolitics: Questionable

Those countries with the greatest embedded capacity (e.g grid, natural gas, roads, oil) will be the slowest to innovate