Energy and Sustainability Challenges

Peter Littlewood
pblittlewood@anl.gov

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 ?

Efficient, sustainable transportation

Efficient sustainable transportation ???

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

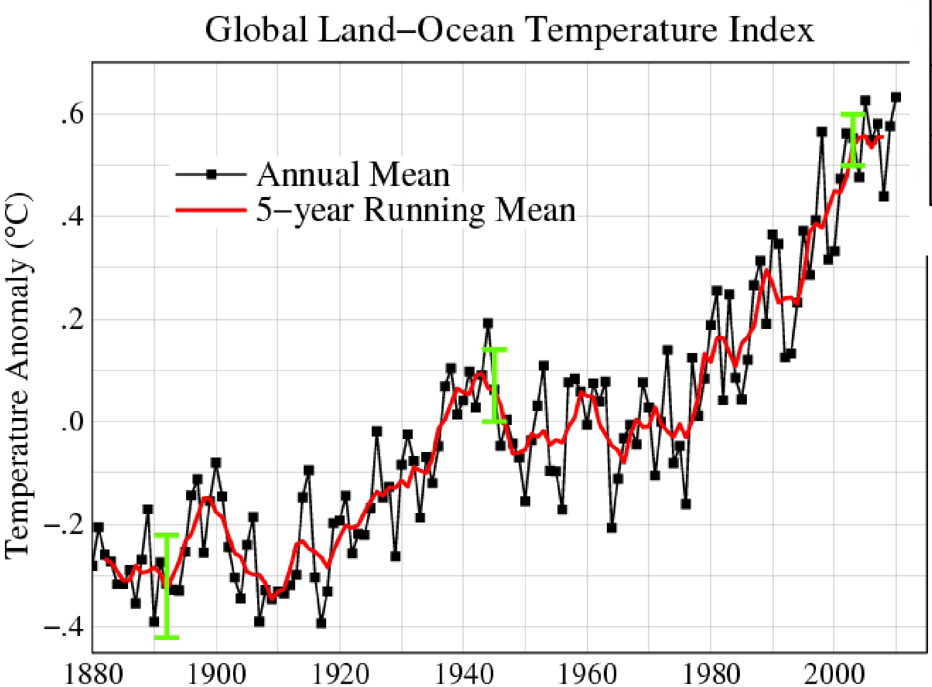
No resource use, water

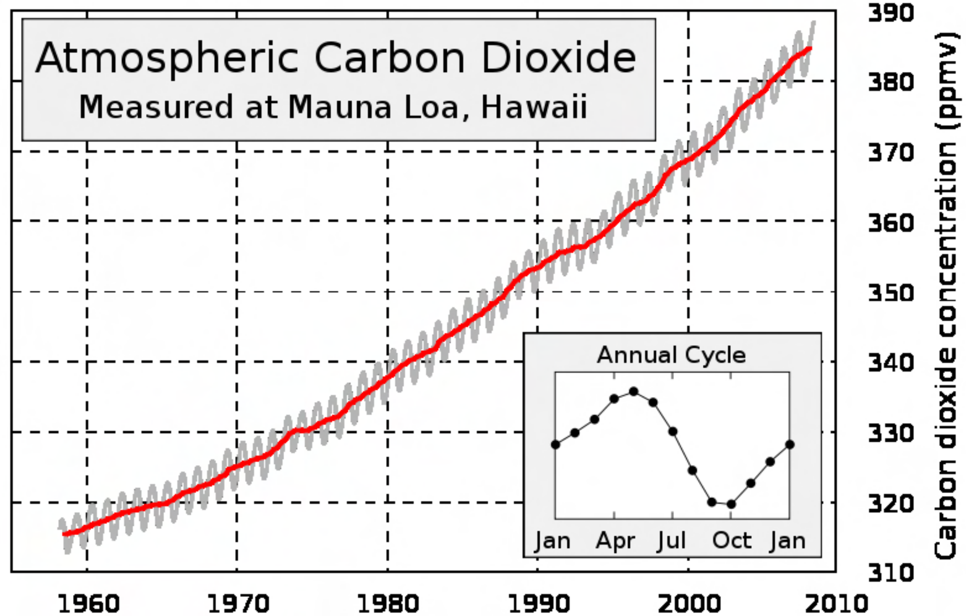
No policy

No climate change ....

Do you believe in anthropogenic climate change?

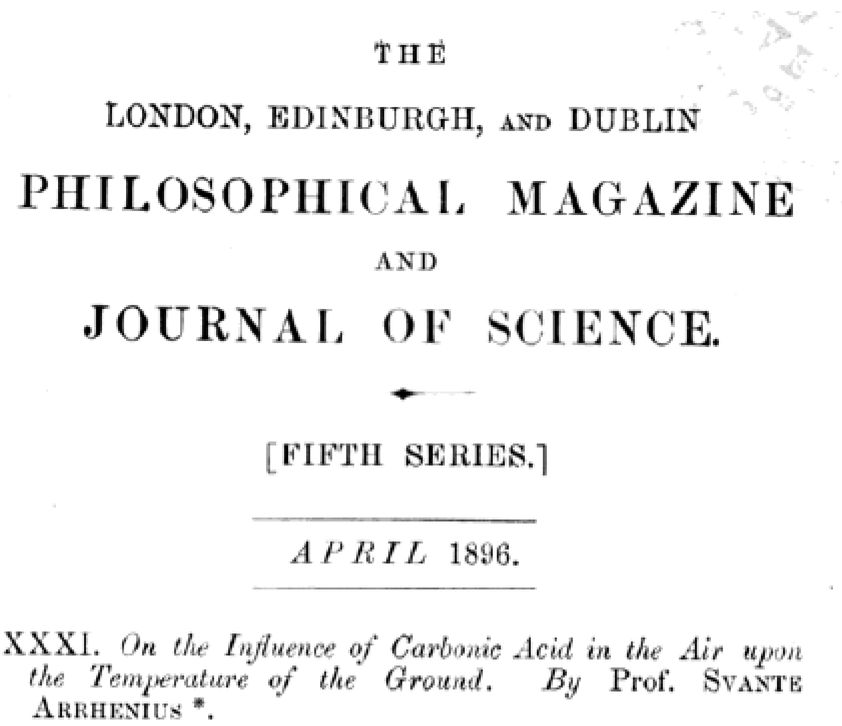
Fluctuation? Correlated ? Causal ?





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.]

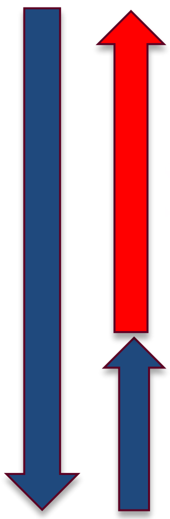
APRIL 1896.

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 ["Mars"]

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



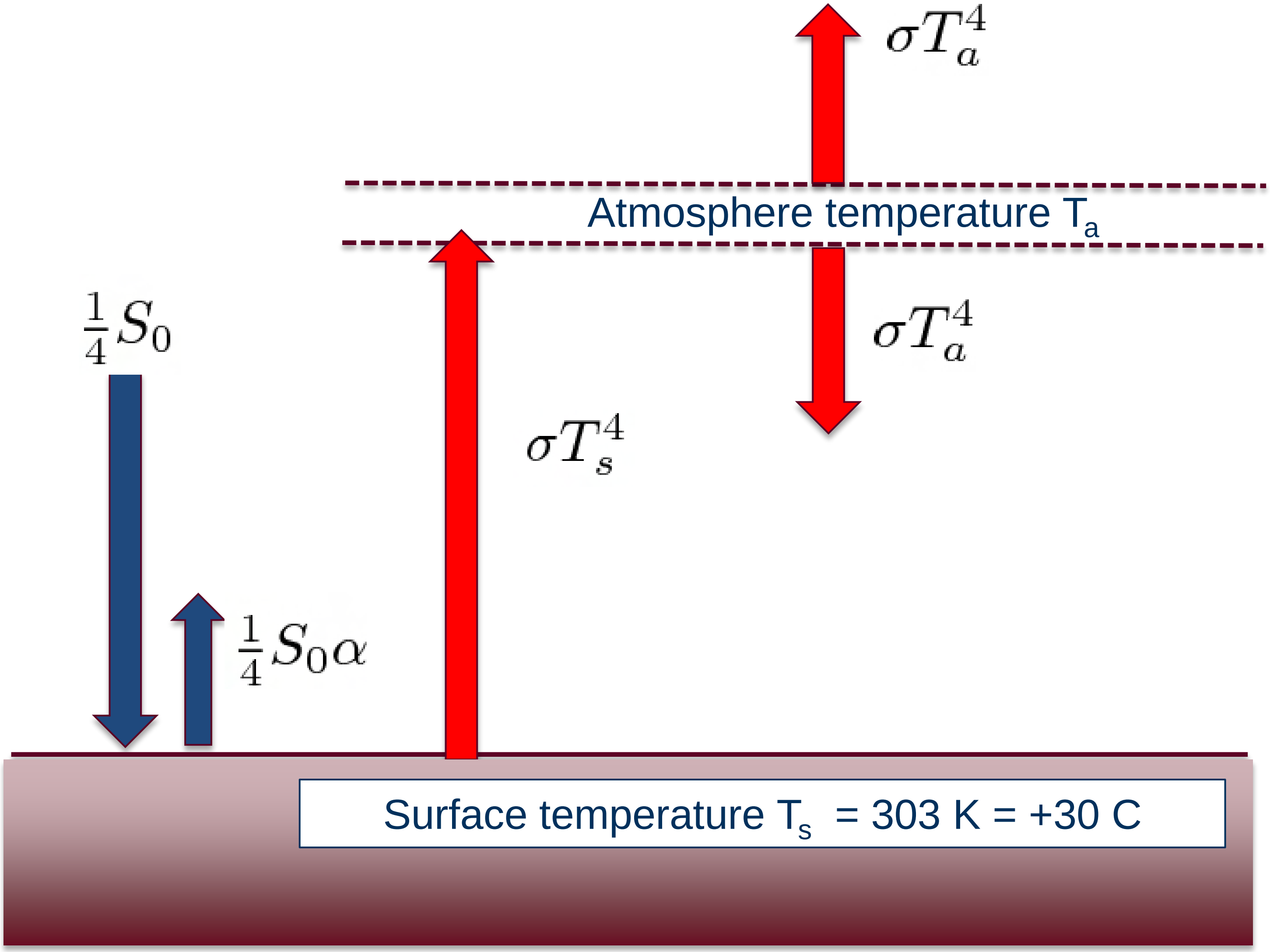
σT_s^4

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

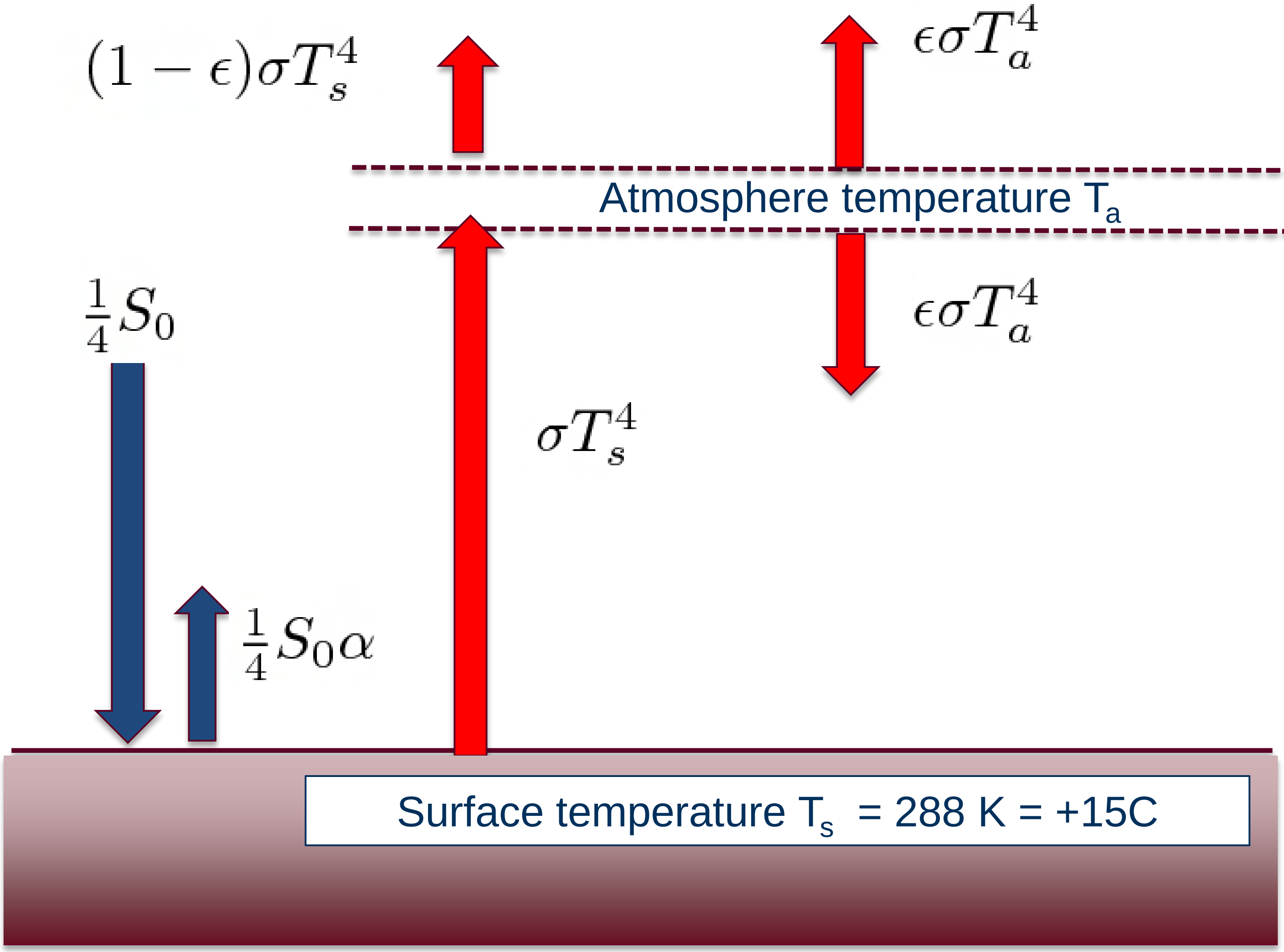
$\frac{1}{4}S_0\alpha$ Reflected solar flux ~ 30%

Energy balance gives T_s = 255 K = -18 C

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

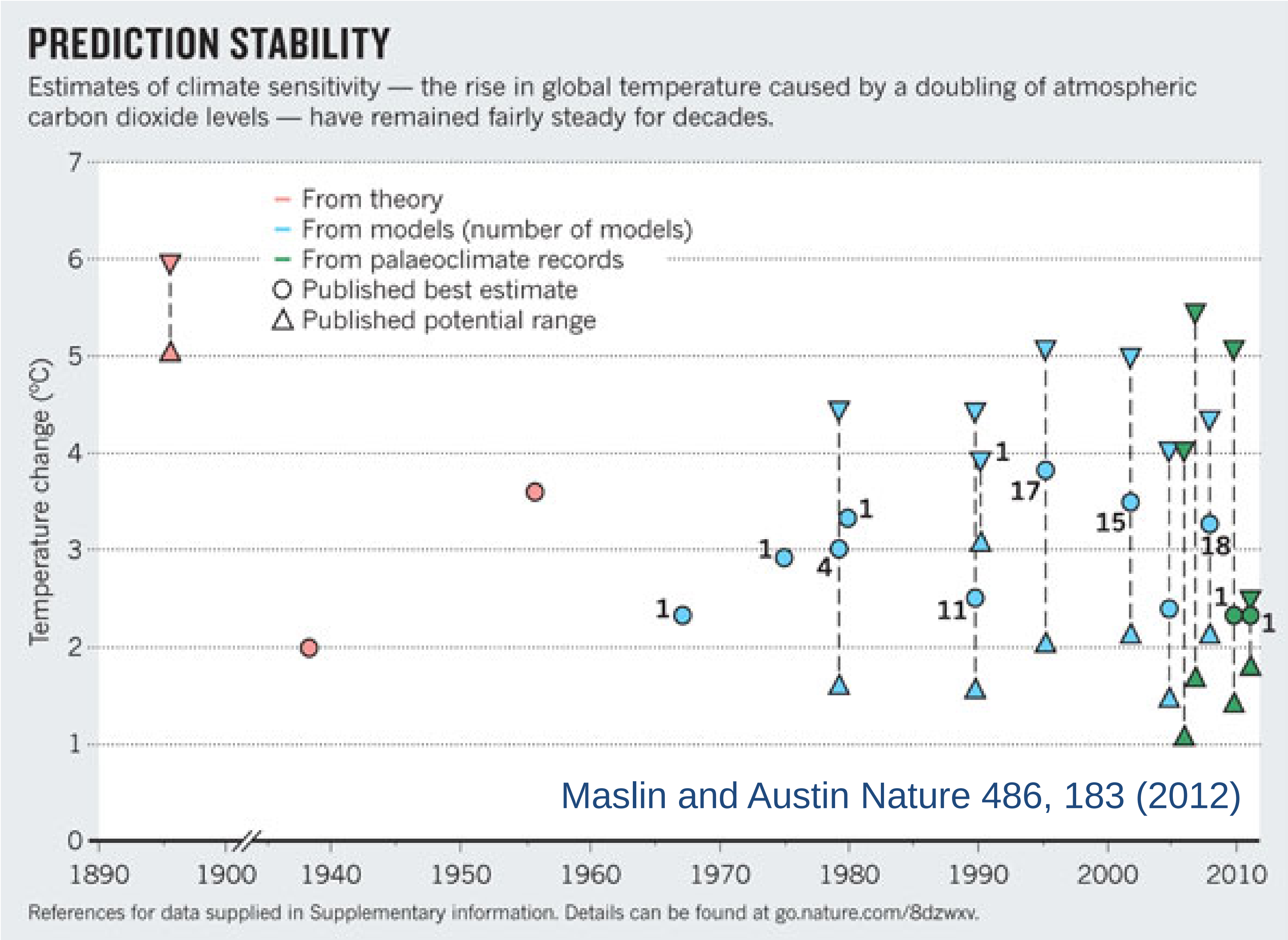


Arrhenius's model for the greenhouse effect
(c) Partially transparent ["Earth": ε = 0.78]



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 Δε 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 $H_2 0$, some albedo, possibly methane, clouds?
- Consensus ΔT_s = 3 K from modern global climate models



Maslin and Austin Nature 486, 183 (2012)

Outline

- Scale : generation, storage and transmission of energy from renewable sources
- Cost : technology measured in $/kg
- Science : a product as well as a driver for technology
  - 20th century physical sciences have evolved along with technologies --- transistor, laser, display --- to maximise information capacity in dense packages for consumption
  - how will our science evolve along with 21st century technology pulls?
- How much headroom, and how?

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

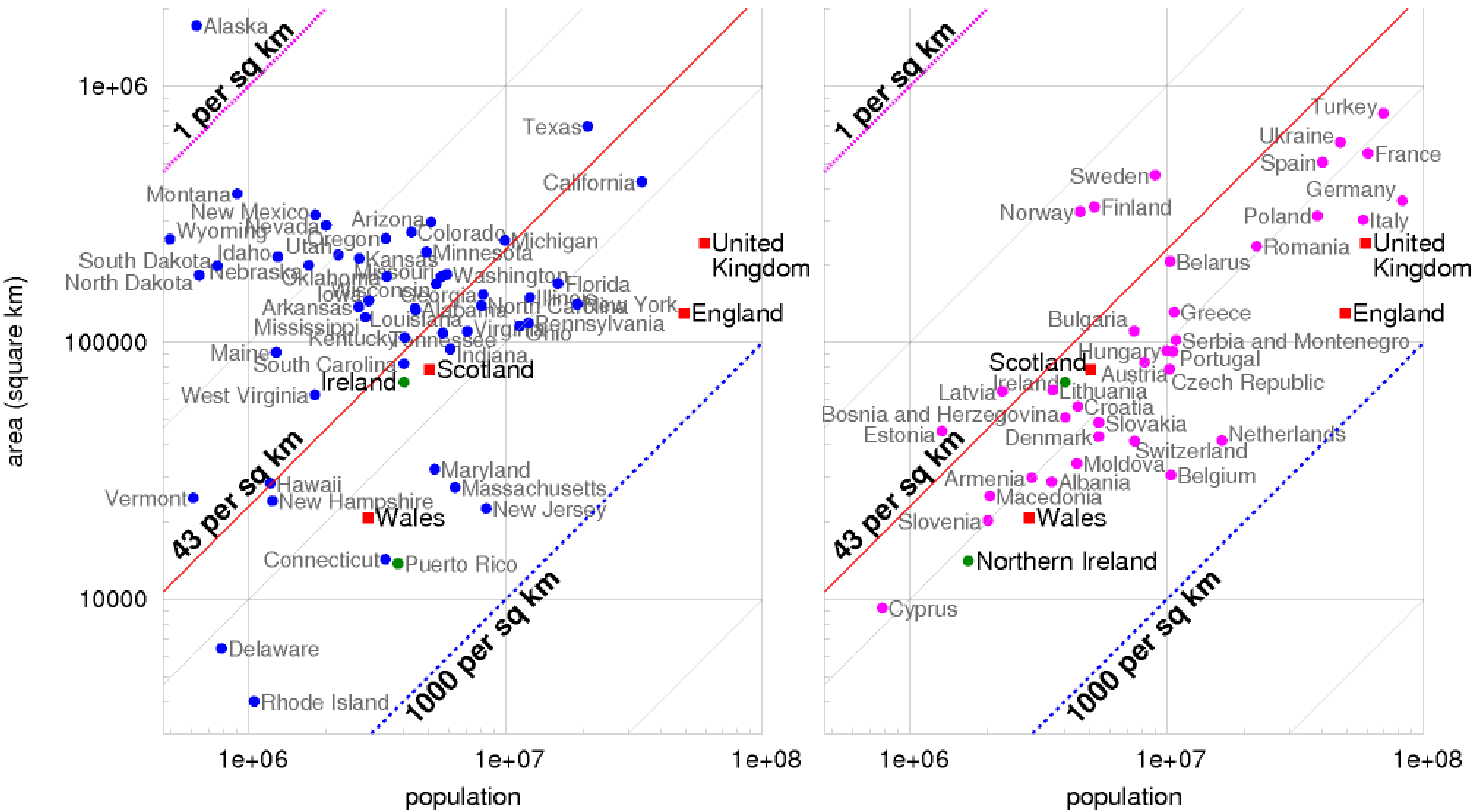
How much do we need ?

USA average power consumption = 3 TeraWatt

5 billion microwave ovens

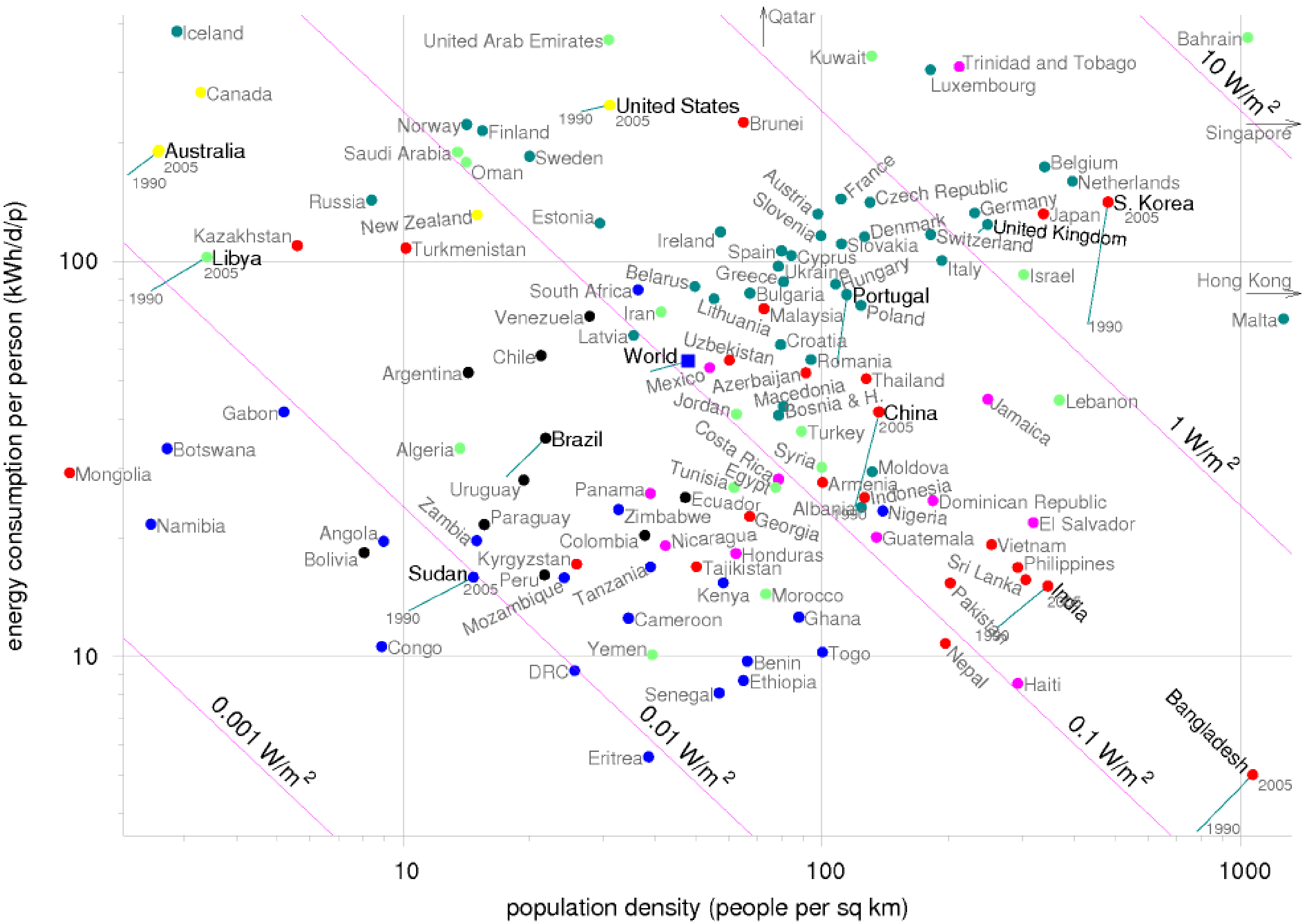
Solar flux on 10,000 km^2 = Delaware + Rhode Island

Population densities



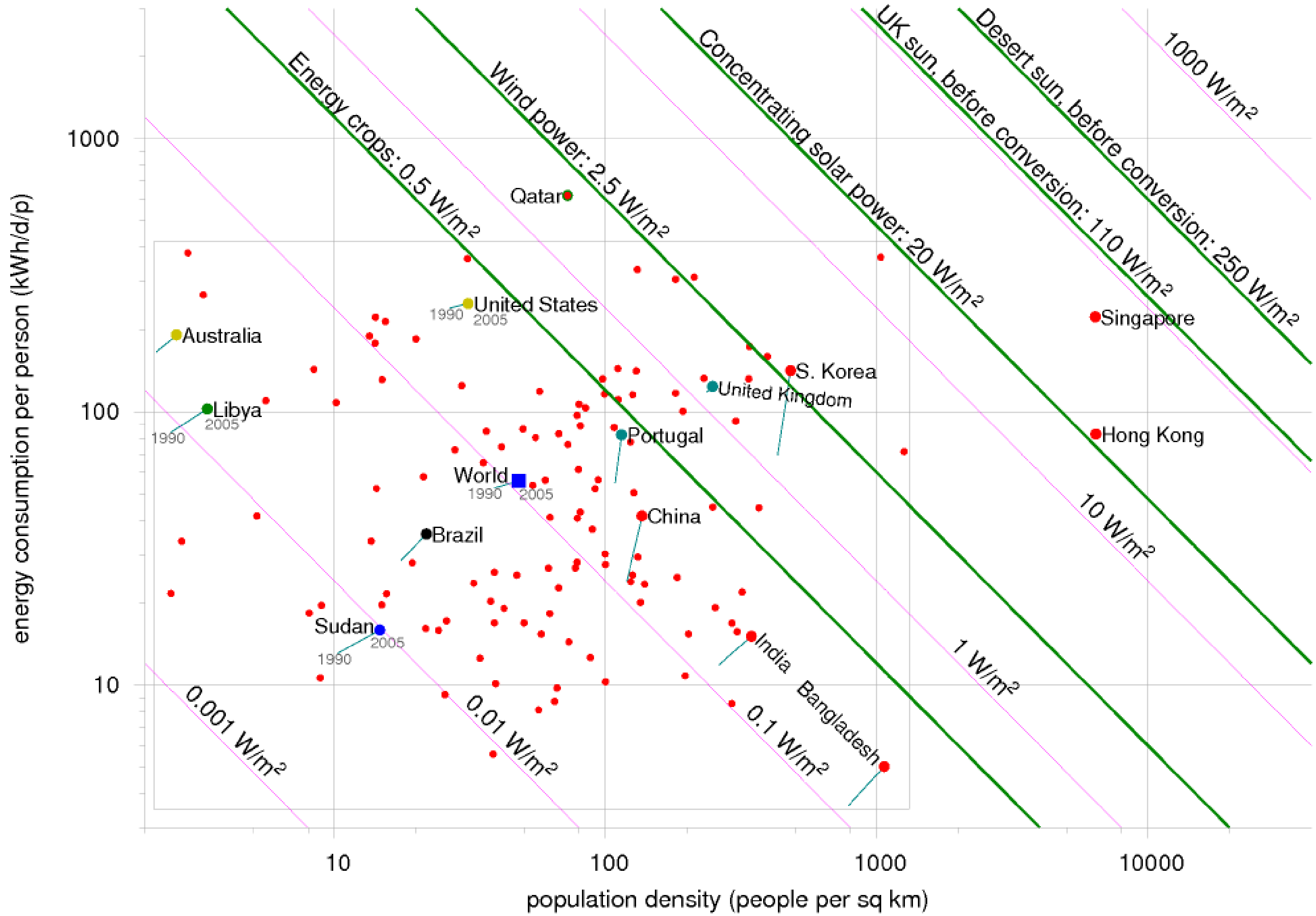
Courtesy D J Mackay, UK DECC

Energy usage per m²

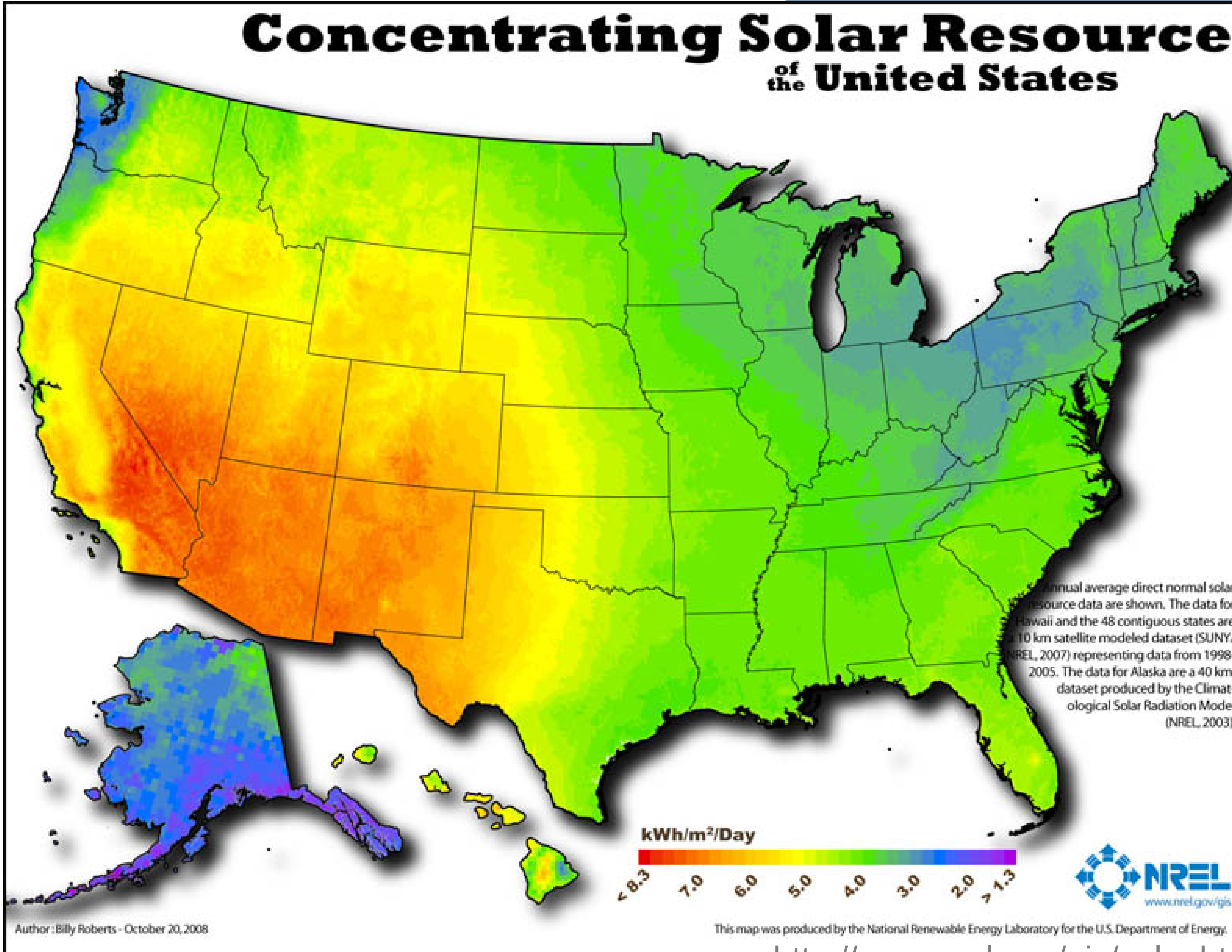


Courtesy D J Mackay, UK DECC

Renewables must be deployed on country-sized scale



Courtesy D J Mackay, UK DECC



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

Solar photovoltaics in the United States

Solar Electric Power Association

- By end of 2014, 6.6 gigawatts (peak) installed in U.S.
  - About 40 GW worldwide
- Rating assumes 1kW/m^2 insolation (mid-day in Arizona)
- In practice, average power ~20-30% of peak (at best)
  - So this is ~ 0.1% of demand…
- Can we scale this up ?

https://financere.nrel.gov/finance/content/calculating-total-us-solar-energy-production-behind-the-meter-utility-scale

Technologies by volume

1Q 2014 global shipments of silicon wafers:

- 2,364 million square inches

http://www.semi.org/MarketInfo/SiliconShipmentStatistics

1.2 square kilometers

GlobalFoundries Fab 8 campus, in Malta NY

2014 Solar PV Capacity in USA – 6.6 GW (peak)
~ 30 square kilometers

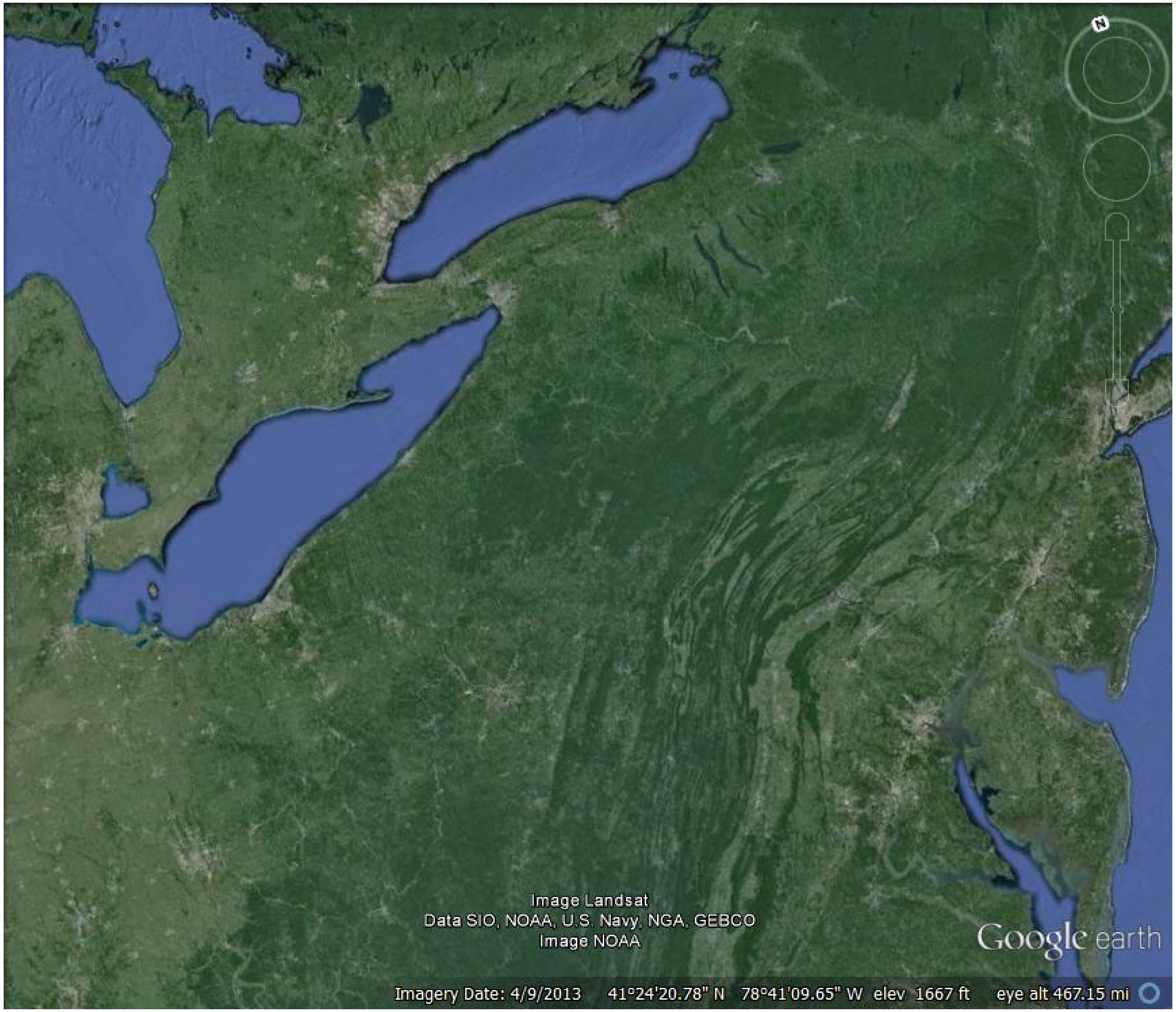
3 TW @ 300 W/m^2 (Full insolation in AZ)

10,000 km^2

3 TW @ 80 W/m^2 40,000 km^2
State-of-the-art PV – 30% efficient

3 TW @ $30 W/m^2$ 100,000 km^2
Typical solar PV installation: ~ 10% efficient

3 TW @ 5W/m² 600,000 km²
Typical installed PV under cloudy conditions



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 = $4x10^5$ m^2
- Power /area = $7.58 \times 10^6 / 4x10^5$ = 18 Wm^{-2}
- Best practical capacity 35% = 6 Wm^{-2}
- 5% of US land area generates 3 TW

Hydro is a "point source"

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

- How much power available?
  - Annual Rainfall: 100 cm in Colorado catchment = 1000 kg/m^2
  - Energy stored = mass x g x height = 1000x10x1000 = 1×10^7 Jm^{-2}
  - Annual average power/area = 1 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 = $4.2 \times 10^9 \times 3 \times 10^6 / (2.7 \times 10^{11} \times 3 \times 10^7)$ = 1.5×10^{-3} W m^{-2}
- Cost ?

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

Challenges of geography, efficiency, and cost

	Power density Watt/m^2
Full insolation Arizona desert	300
Concentrated solar power (desert)	15-20
Solar photovoltaic	5-80
Biomass	1-2
Tidal pools/tidal stream	3-8
Wind	2-8
Rainwater (highland)	1-2
US energy consumption (all sources)	0.3

In the US:
Solar + wind + storage + grid infrastructure = Sustainable economy

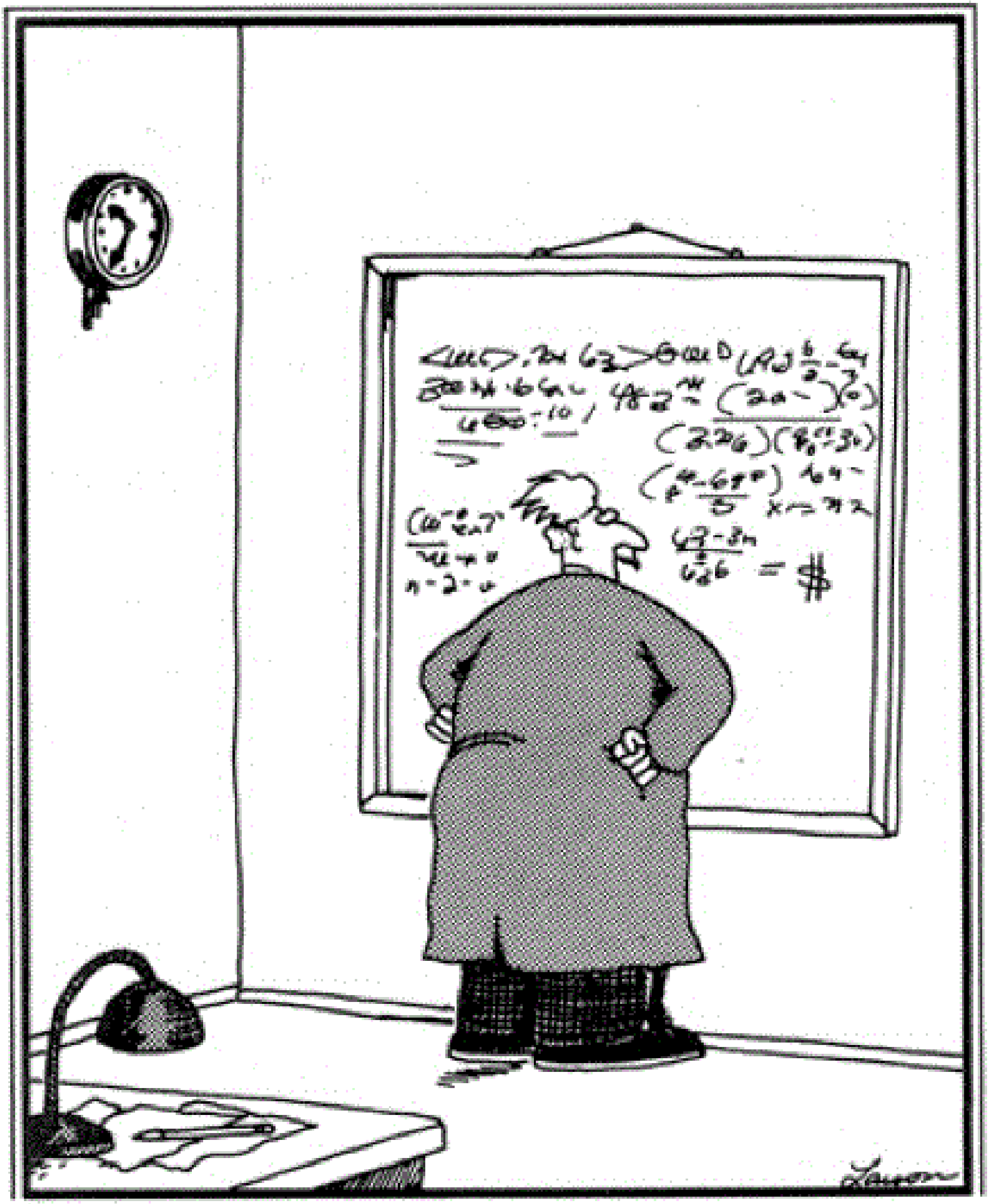
In the Global South:
Solar + storage+ refrigeration+ lighting = Education and healthcare

Backing up grid renewables with storage

3 Terawatts x 12 hours equals:

9 times the **annual** energy generated by the Hoover Dam

10^8 tons of Li-ion batteries: ~ 10^3 times current production



Einstein discovers that time is actually money

The (energy) cost of making things

Materials are energy, and energy is money

Energy input accounts for:
- 1/3 cost of steel ($1/kg)
- 1/2 cost of aluminum ($2.50/kg)

iPad
Cost: $500
Weight: 0.6 kg
$1,000/kg

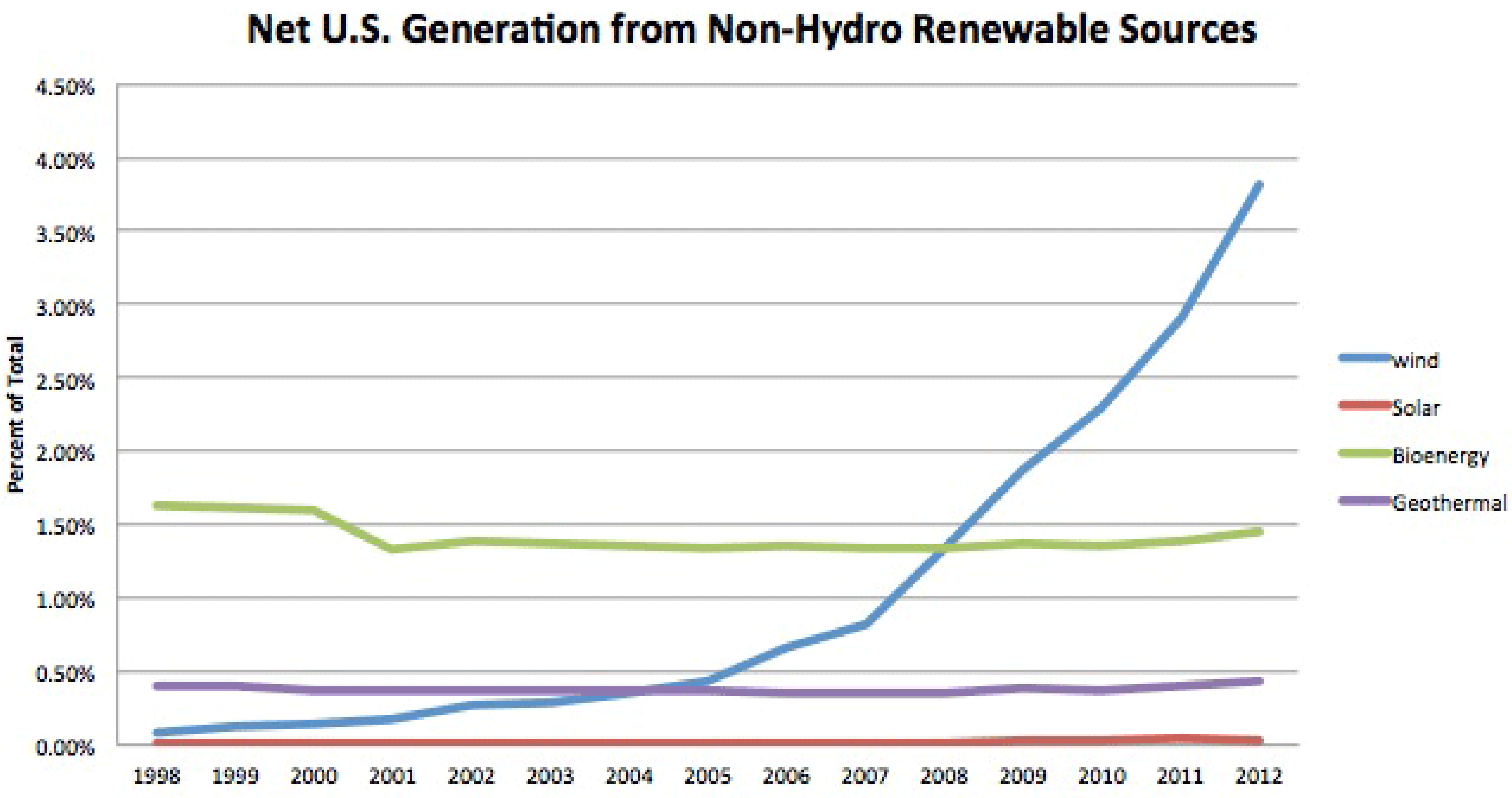
Boeing 787-9
$243M
180,000kg
$1,500/kg

Honda Civic 1.8
$16,000
1,210 kg
$13/kg

Ground beef
$10/kg

Wheat flour **$1/kg**

Enercon E-126
7.58 MW
$10M
6,000 tons
$1.5/kg
Payback
in 3-4 years
at 10¢/kWh



Source NREL
https://financere.nrel.gov/finance/content/calculating-total-us-solar-energy-production-behind-the-meter-utility-scale

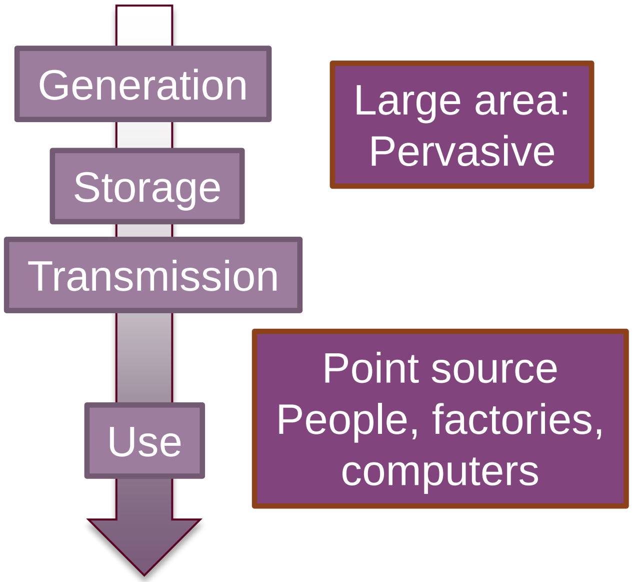
And now to technology …

- 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 materials technologies for the electrified economy

- Solar PV for electricity generation
 (or solar to fuel)
- Ultracapacitors/batteries for electrical storage
- Superconductors for electrical transmission/ motors
- Thermoelectrics for refrigeration/scavenging
- Light emitting diodes for electrical lighting
- Membranes for water purification/desalination

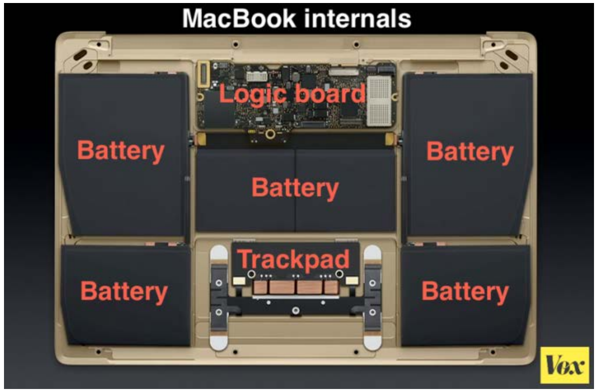


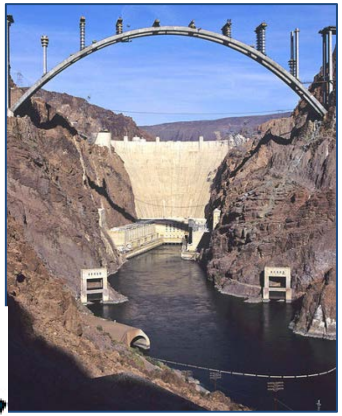
Point use is easier: Smaller scale for fabrication, straightforward path to introduction.
Large-scale disruptive technologies are very hard

Aside from the grid, we have no examples of implementing wide-scale ‘by the ton ’ electrical materials technology

Why electrical storage?

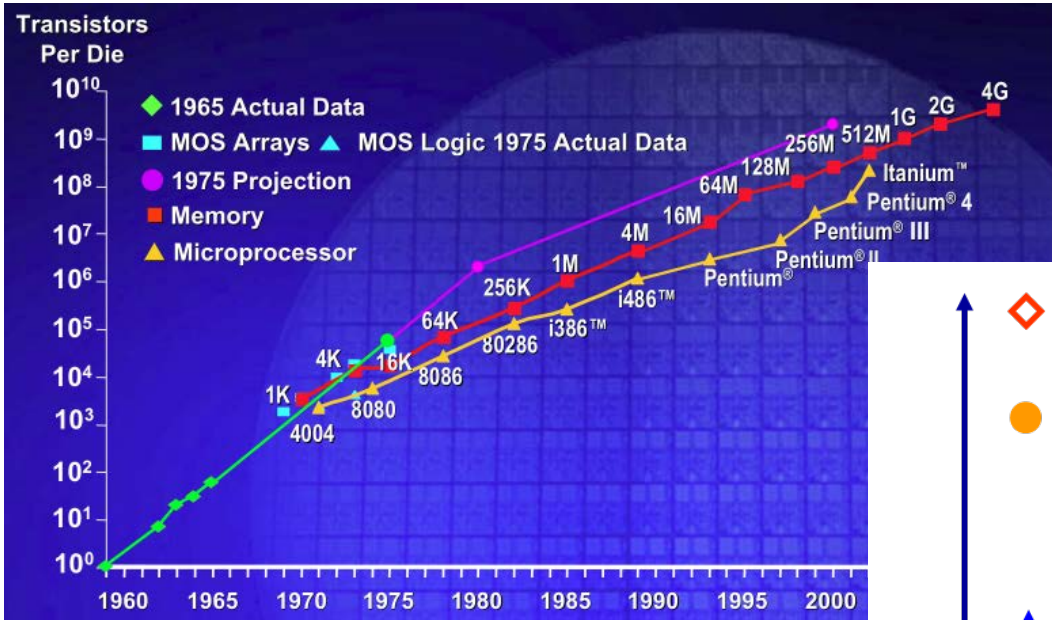
- Market – lithium-ion batteries already a $10B business
  - Improving at few percent per annum
  - **Can we do this faster?**
- Laggard technology
  - Around 1% theoretical capacity; (lighting ~80%, solar PV ~30%)
  - **Can we do this much better?**





- Scale – To back up US for 12 hours takes:
  - 9x annual energy production of the Hoover Dam
  - 1,000x the annual production of Li-ion batteries
  - **Can we do this at scale?**
- Impact – an efficient battery is a bank for electrons
  - **Can we turn energy into money?**

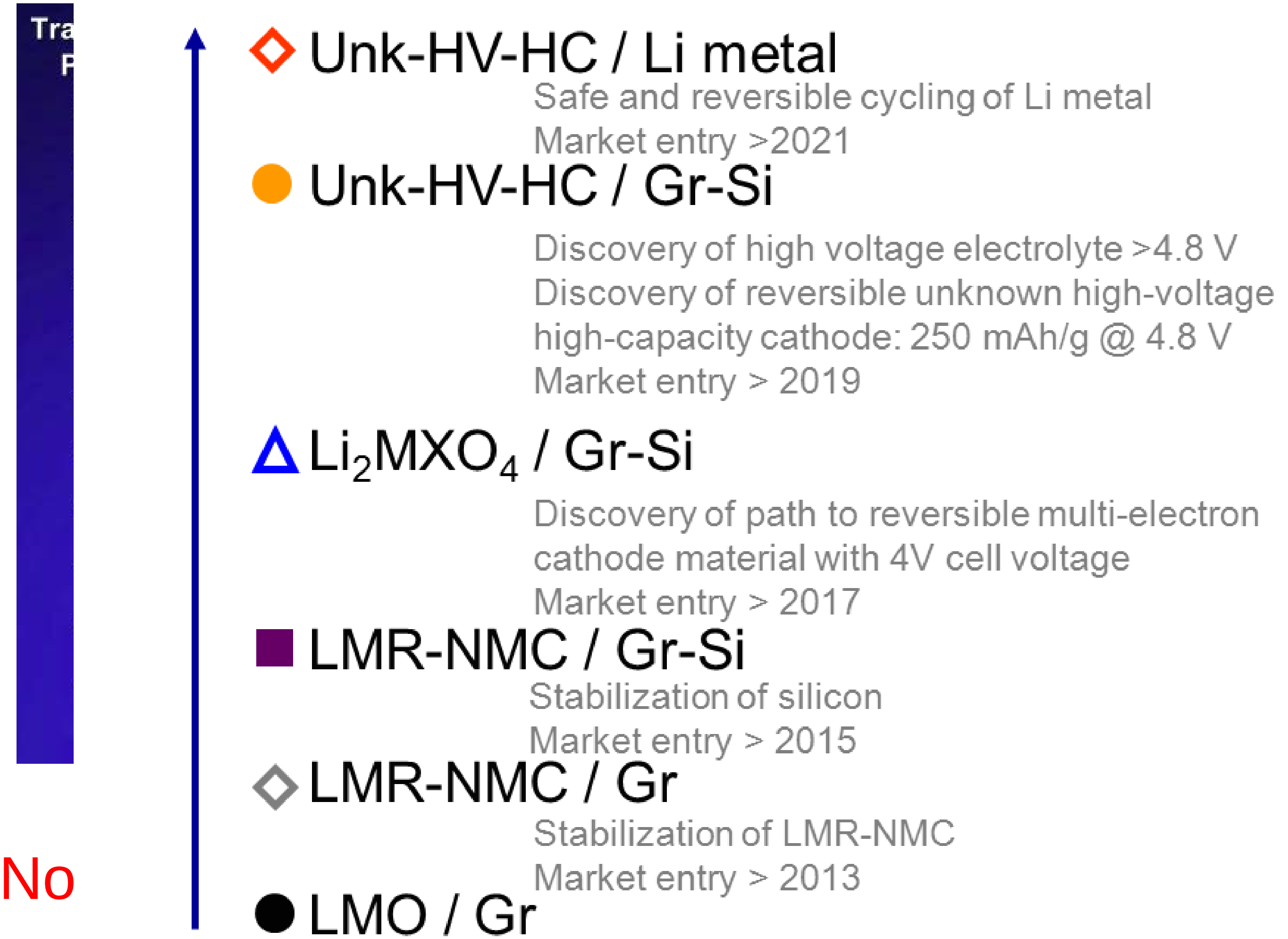
The consequence of understanding is prediction: Moore's Law for Si *vs*. current strategy for Li-ion batteries



Transformational technologies depend on reliable understanding and control of materials at scales ranging from the atomic to the mesoscale

- ◇ **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**

So we need a roadmap: Moore’s Law for batteries?

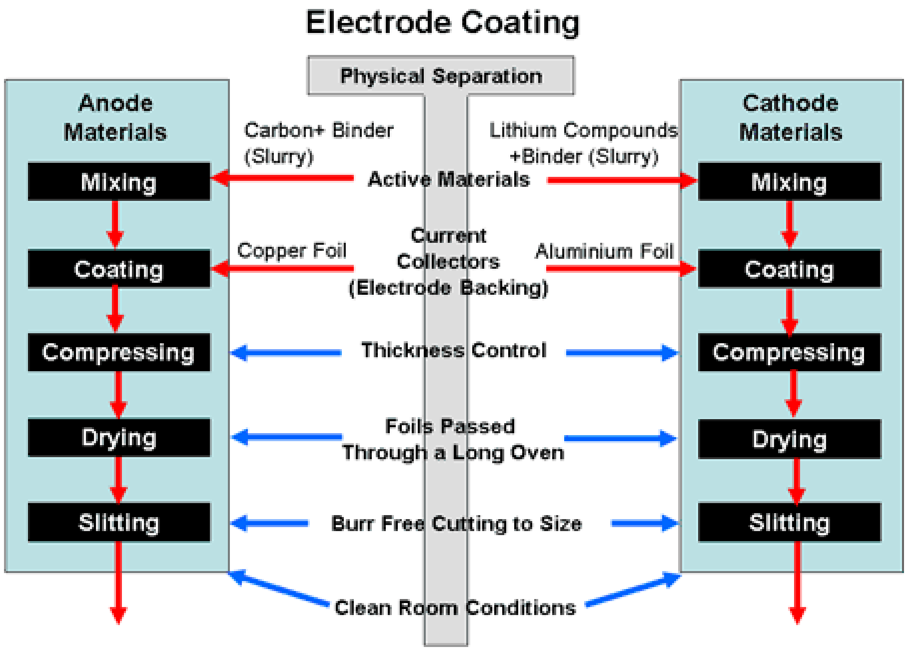


No … tability

… cost

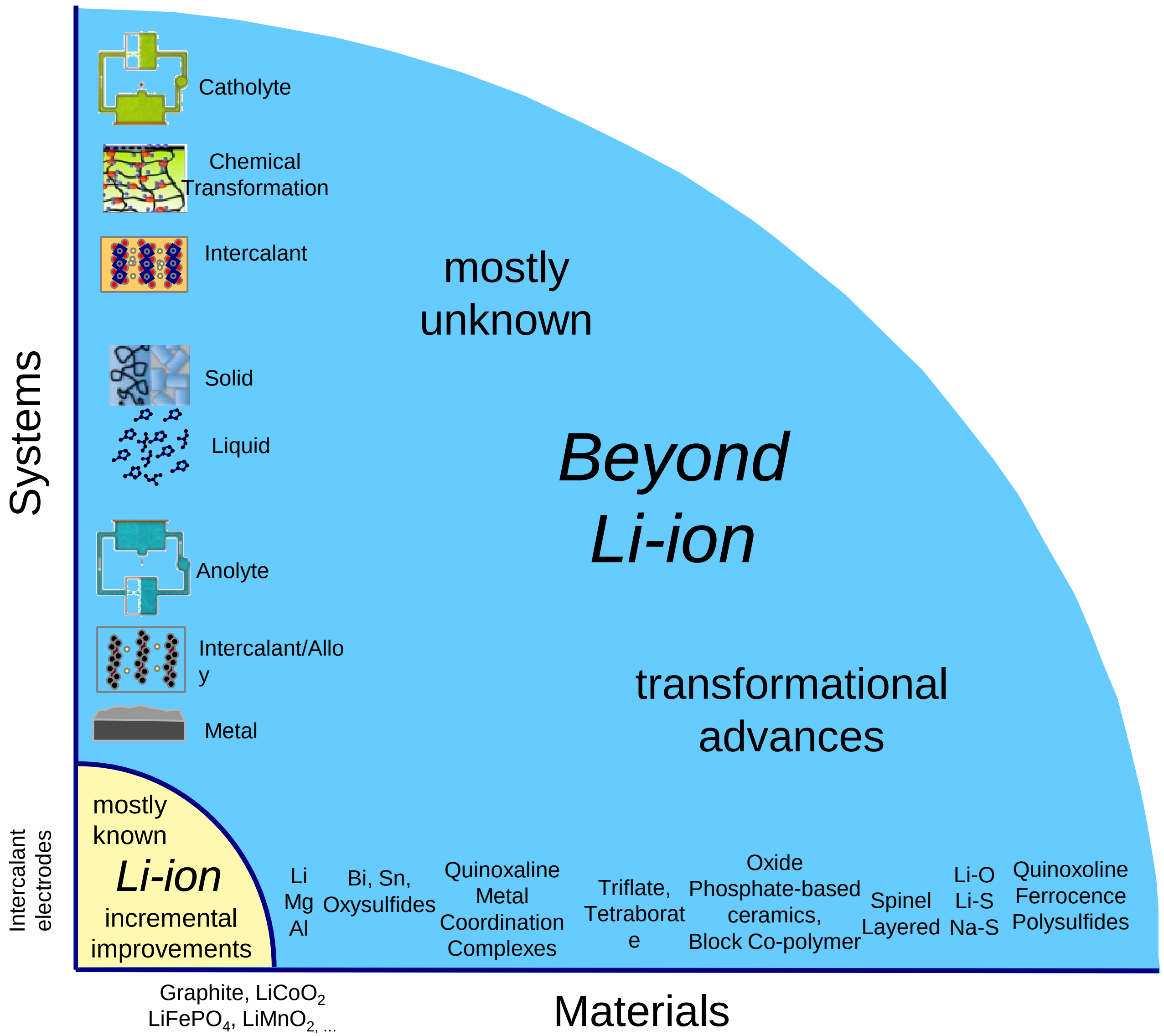
Gallagher, Nelson, Dees, 2010

Battery manufacturing employs a tape casting process inherited from a deceased industry

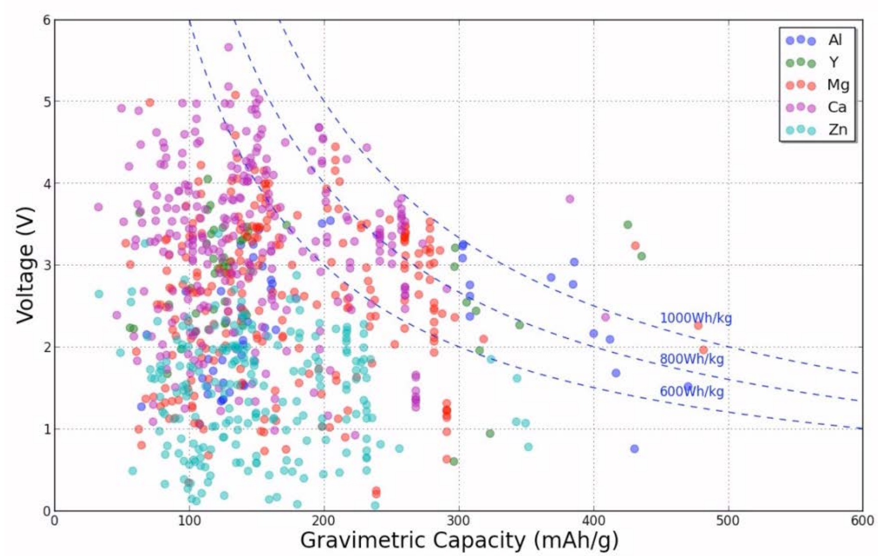


JCESR: Joint Center for Energy Storage Research

New research paradigm to explore vast space

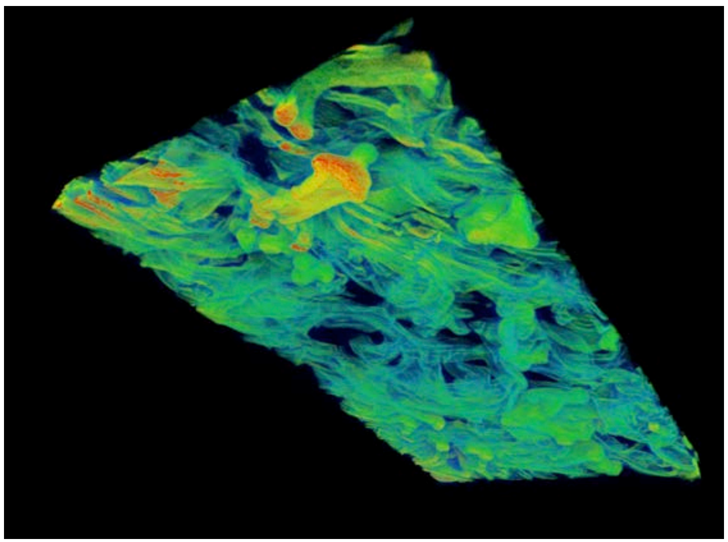


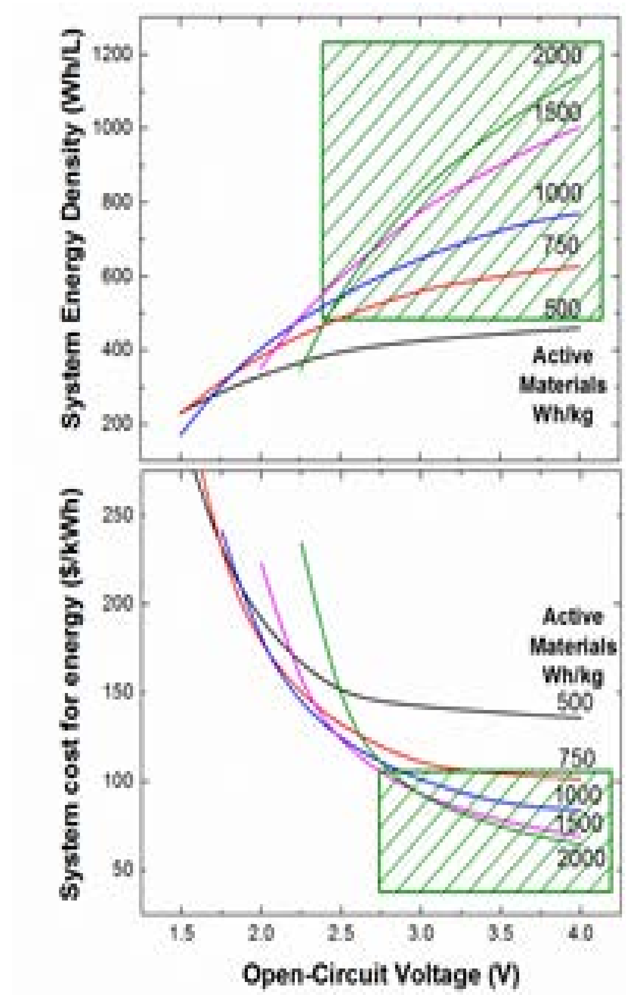
Pruning the search tree



Screening of 1,800 intercalant hosts

In operando
X-ray





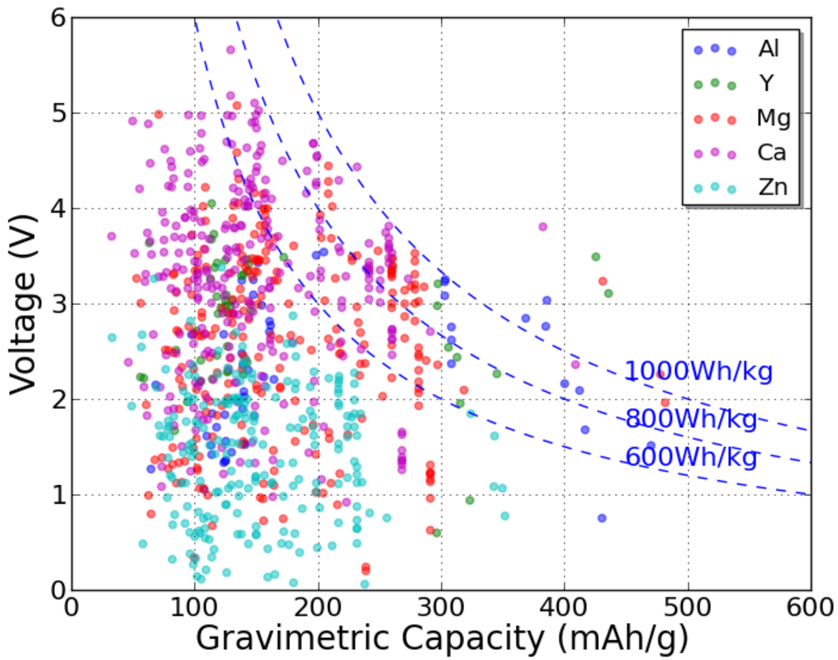
Systems analysis and
techno-economic modeling

Overall goal: ***systematically*** design breakthrough multivalent cathodes using computing

"[The Chevrel] discovery resulted from a lot of unsuccessful experiments of Mg ions insertion into well-known hosts for Li+ ions insertion, as well as from the thorough literature analysis concerning the possibility of divalent ions intercalation into inorganic materials."

-Aurbach group, on discovery of Chevrel cathode

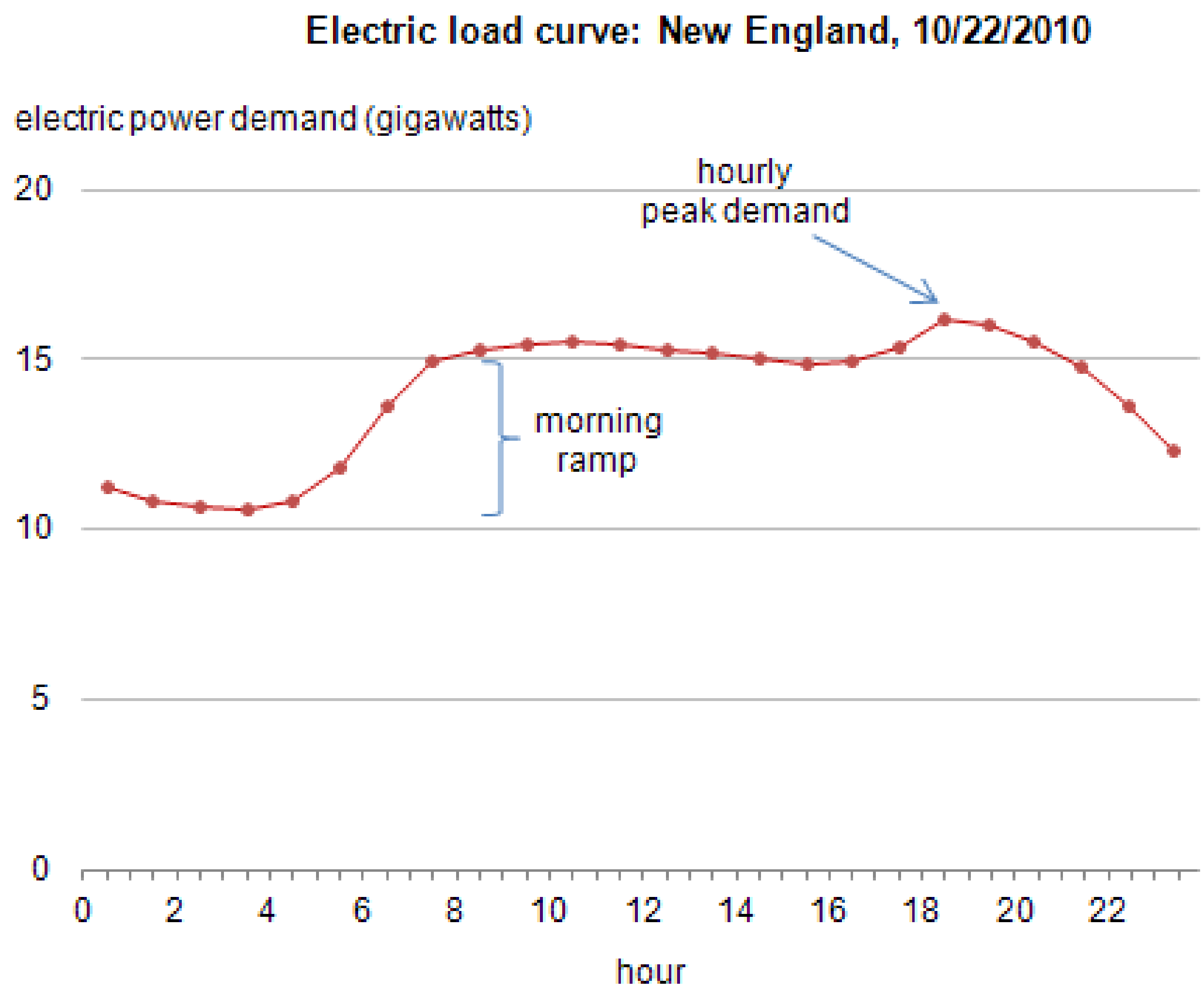
Levi, Levi, Chasid, Aurbach J. Electroceramics (2009)



Compound	E (V)	mAh/g	ΔV	Structures
CaV2O5	3.16	242	7.0%	Layered
CaV2O5	3.04	242	6.7%	
MgMn2O4	2.82	270	14.0%	Spinel
CaMn2O4	3.15	251	27.9%	
CaMn2O4	3.24	251	23.0%	Post-spinel (Marokite)
Mg(CoO2)2	2.95	260	4.1%	
Ca(CoO2)2	3.39	242	12.5%	
CaMn4O8	2.76	138	2.8%	Hollandite
Ca(MnS2)4	1.83	104	9.4%	Layered CoO2-type
MgMoO3	2.09	319	0.8%	ReO3-type perovskite
CaWO3	2.19	197	14.6%	
Ca2MoWO6	2.52	235	10.8%	
CaCr2(PO5)2	4.90	146	3.2%	VOPO4-type
CaV2(PO5)2	4.21	147	3.0%	
MgVPO5	2.40	288	0.0%	
Mg2V2O6	2.58	217	3.0%	Layered

Liu, et al. Energy & Environmental Science (2015)

Research target: turning energy into a currency



Technology will drive our science

Much 20th century science has evolved along with its technologies --- transistor, laser, display --- to maximise information capacity in dense packages for consumption

Will 21st century science be driven by problems of scale?

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 multibillion $ 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