Energy for the 21st Century

Professor G. R. Tynan
Center for Energy Research
UC San Diego
La Jolla CA 92093 USA

Rutherford Appleton Laboratory
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What time is it in the world…

…and where are we going?

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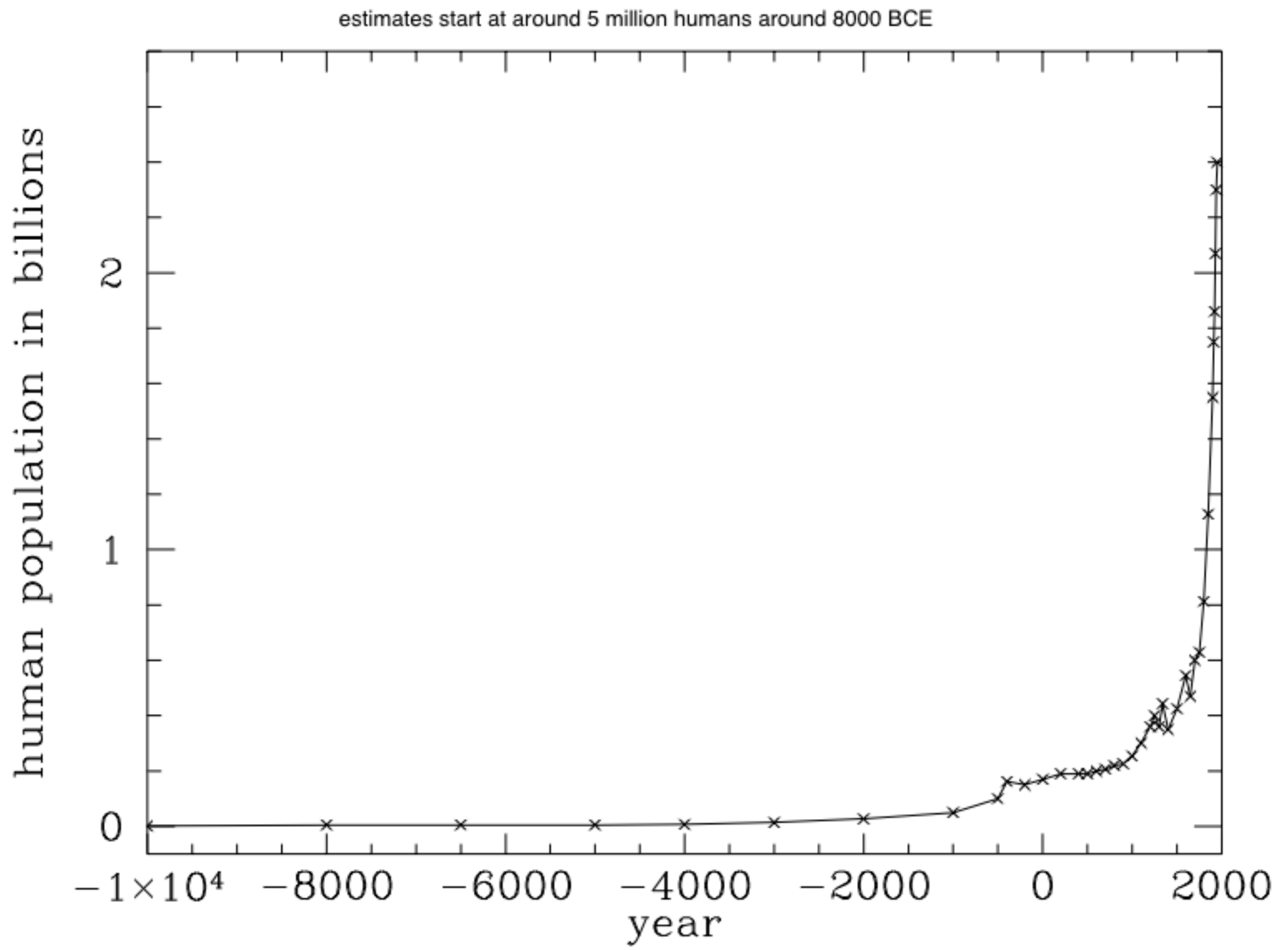
This is THE question facing humanity today…

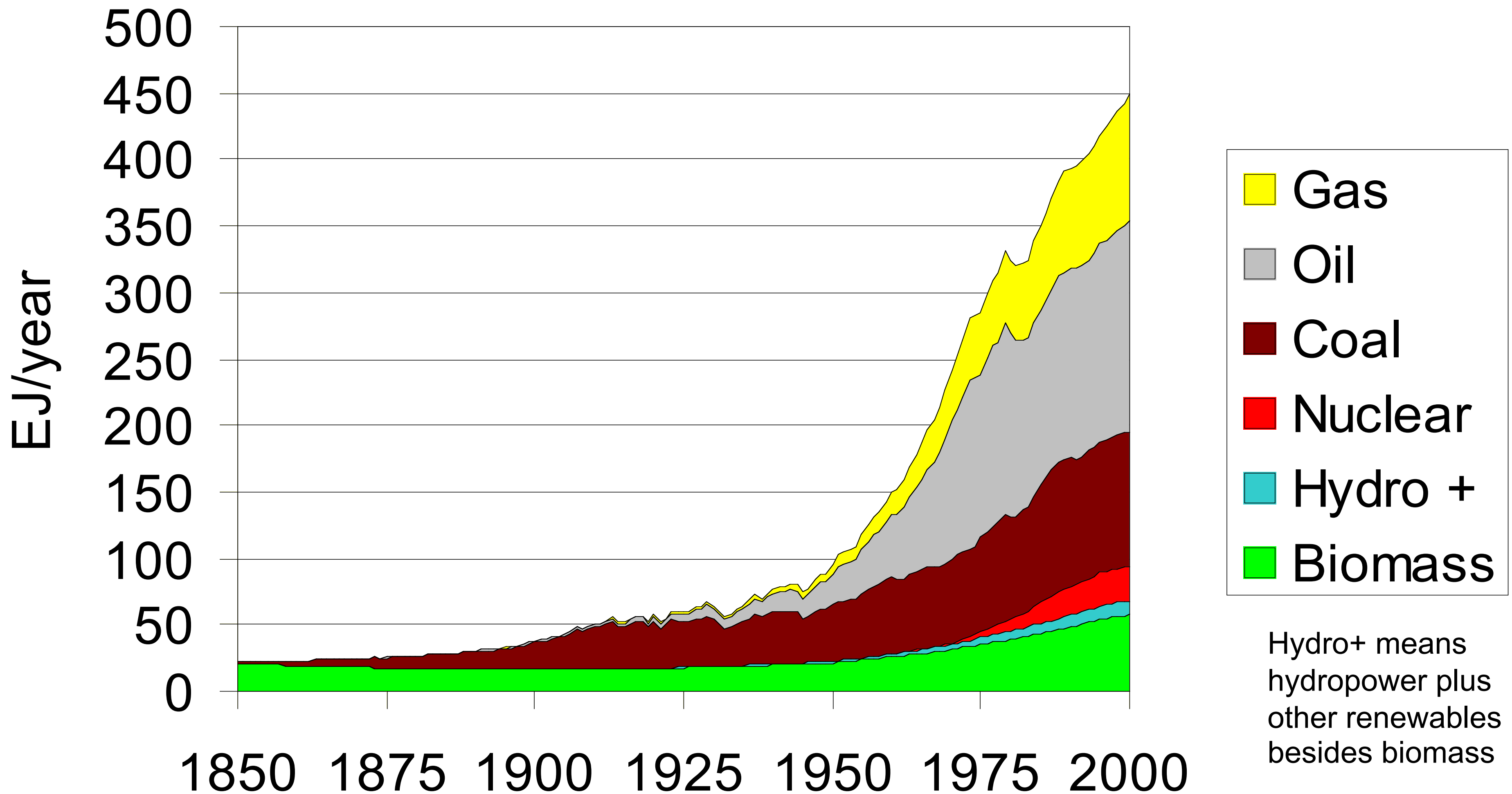
…and energy access places a key role in the answer.

Part I: What Drives our Energy Demand, and Why Should We Care?

Human Population Since Last Ice Age



World primary energy demand since 1850



Hydro+ means hydropower plus other renewables besides biomass

Energy supply grew 20-fold between 1850 and 2000. Fossil fuels supplied 80% of the world's energy in 2000. **From Holdren (2007)**

Population & Resource Availability

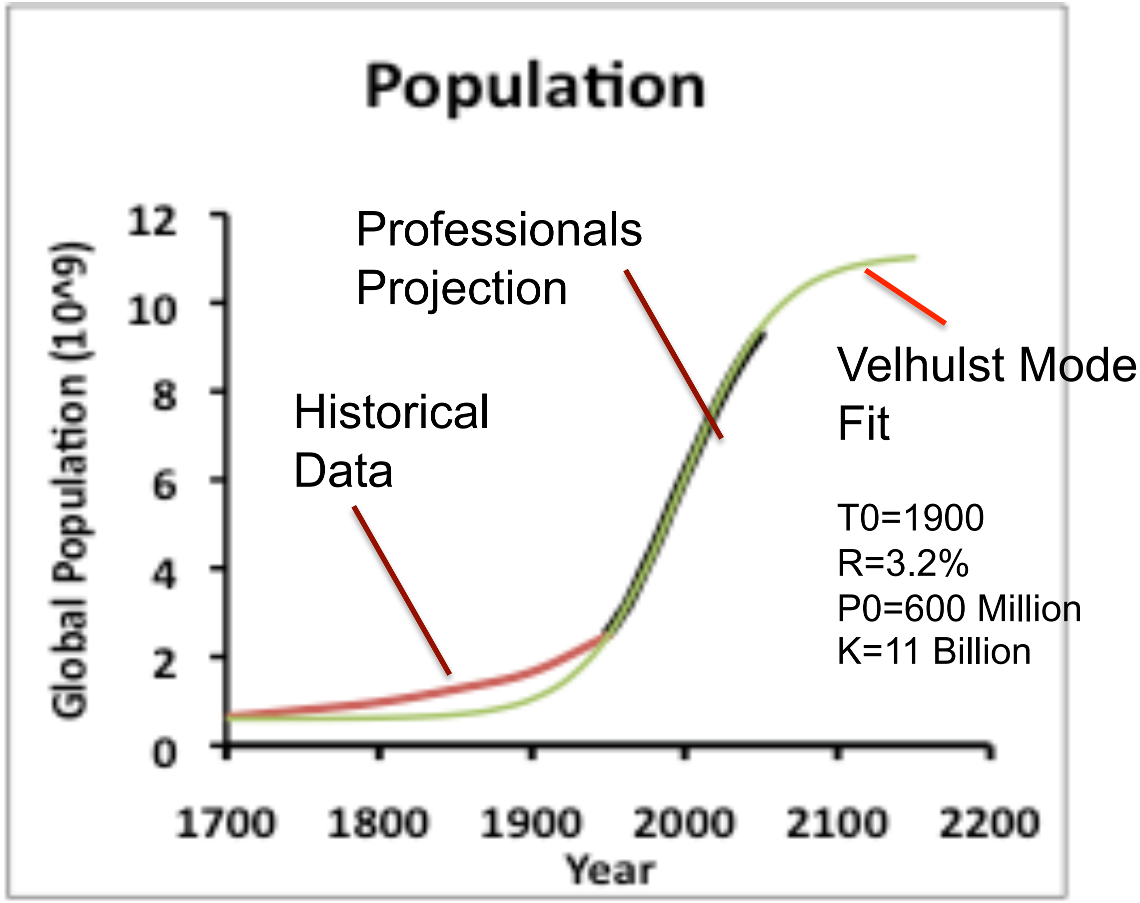
Pierre Velhulst

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right)$$

P – Population

R – early time growth rate

K – CARRYING CAPACITY



ENERGY ➔ FOOD, WATER, …
➔ INCREASE IN CARRYING CAPACITY

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Why Care About Energy?

"All ancient civilizations, no matter how enlightened or creative, rested on slavery and on grinding human labor, because human and animal muscle power were the principal forms of energy available for mechanical work. ***The discovery of ways to use less expensive forms of energy than human muscles made it possible for men to be free."***

R. Revelle, Science ***192****, 969 (1976).*

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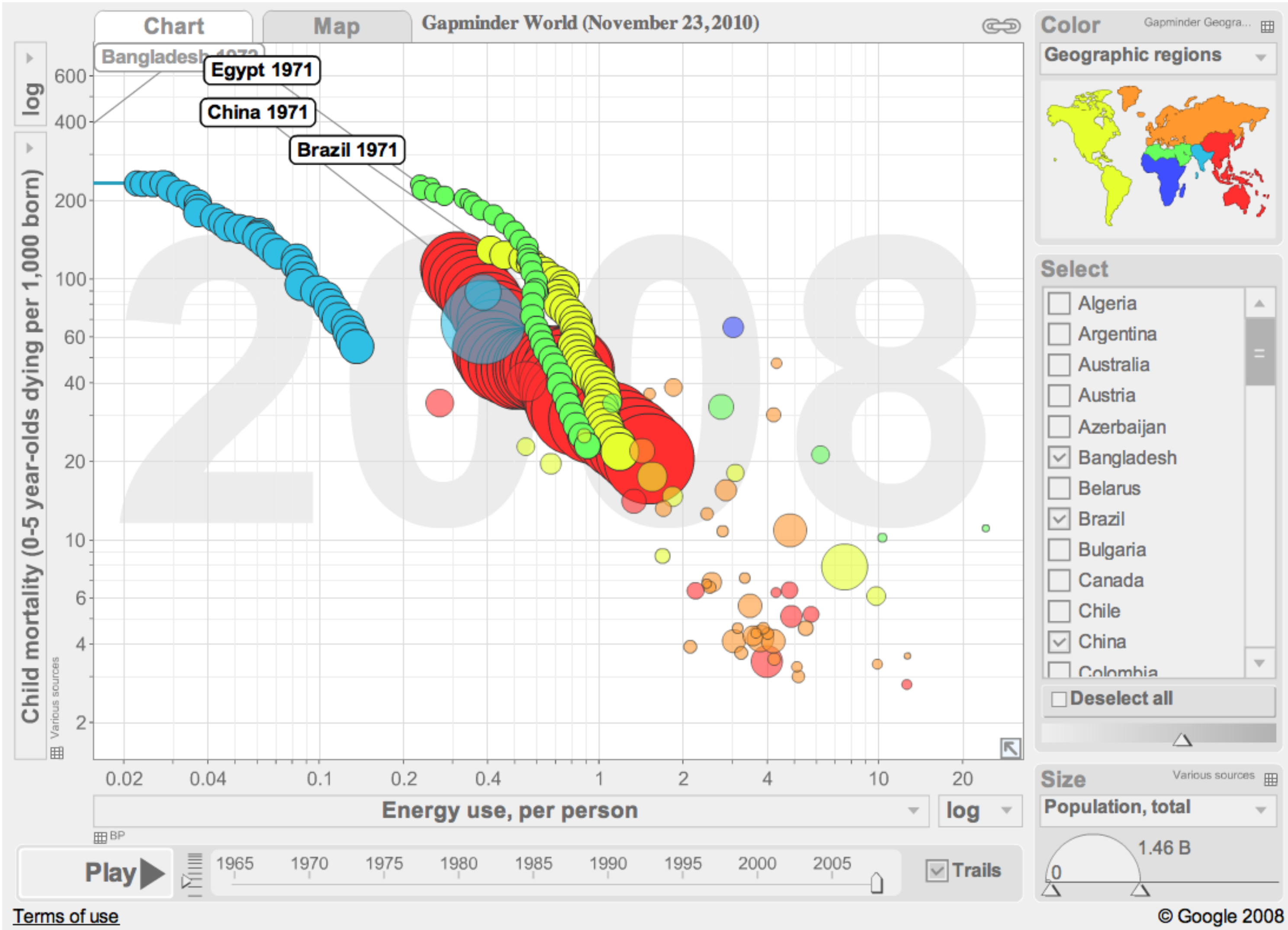
Child Mortality Correlated to Energy Access



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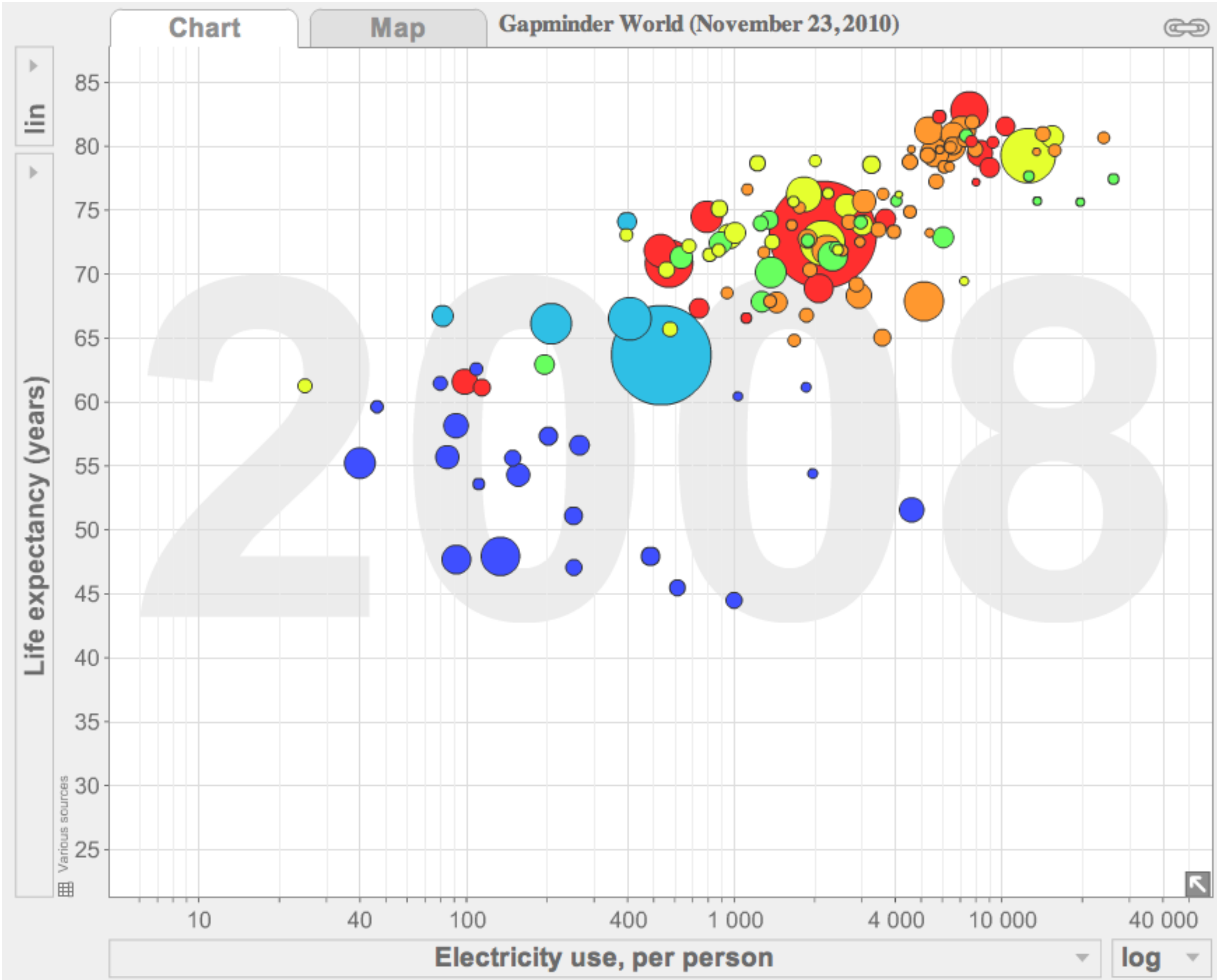
Life Expectancy Correlated w/ Energy Access



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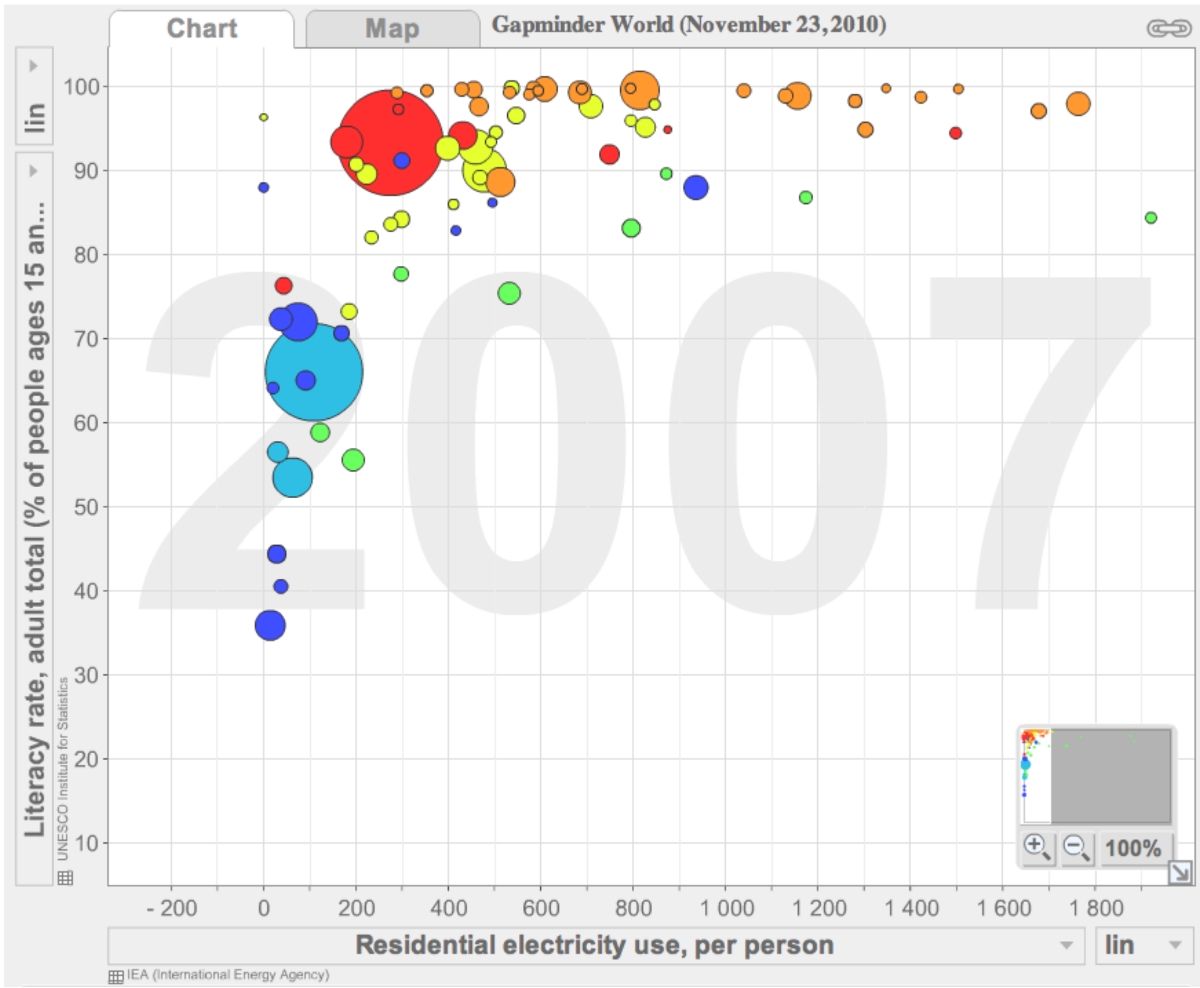
Literacy Correlated to Energy Access



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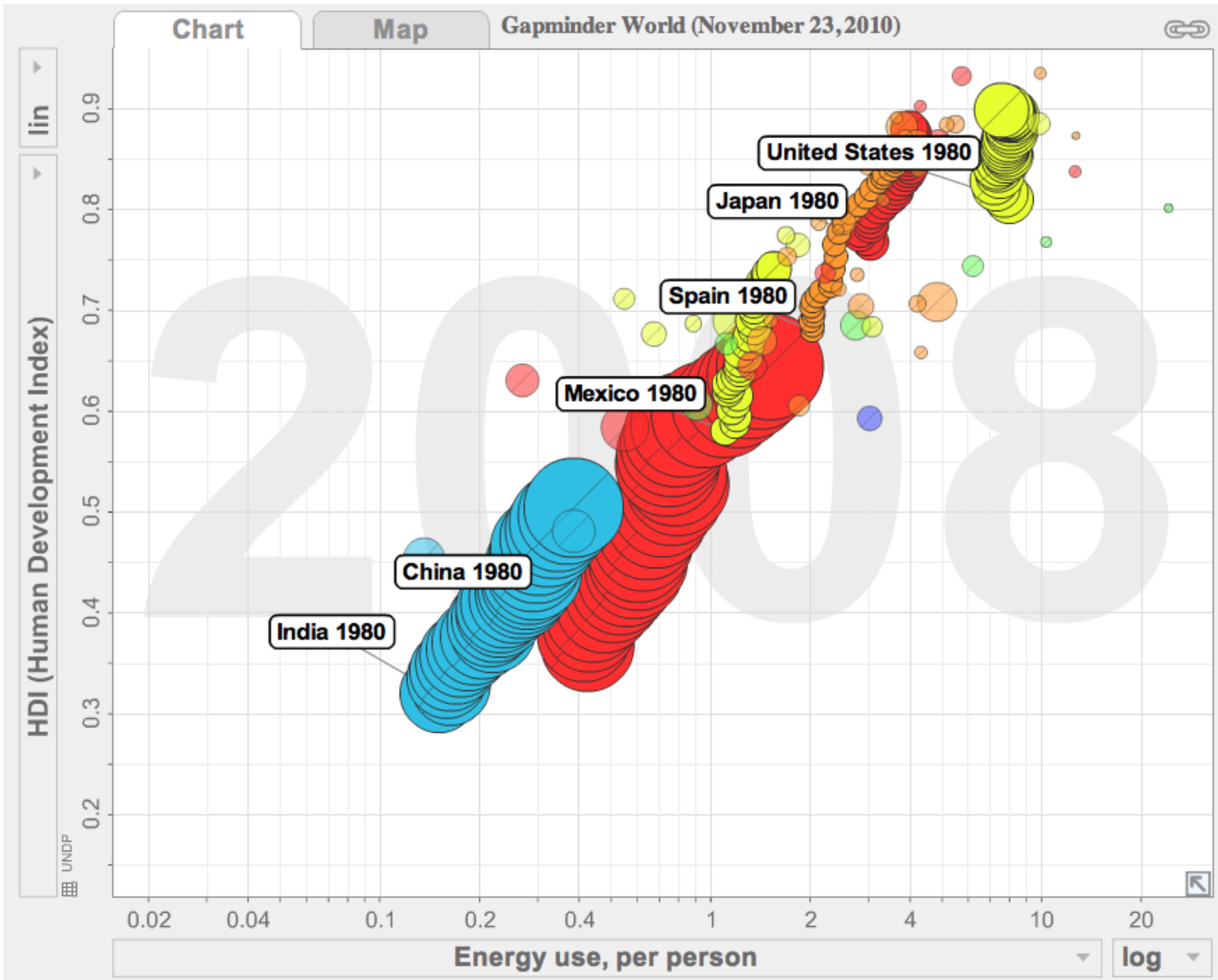
Human Development Index & Energy Access



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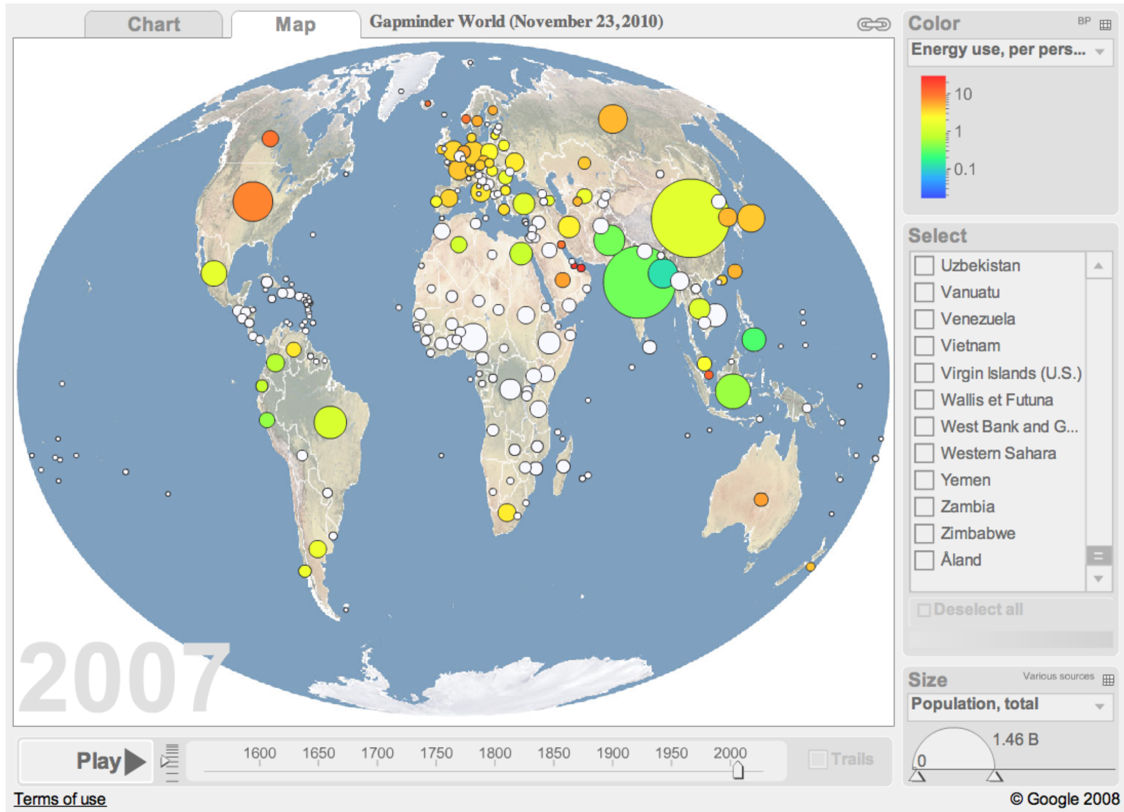
LARGE Variations in *per-capita* Energy Access

Indicators: Color= Log (Energy/per-capita); Size: Population



~3.5 Billion People Live w/o Adequate Access to Energy
~2 Billion are Climbing the Energy Ladder
~1.5 Billion Have More than Enough

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Most of Humanity Needs **MORE** Energy

"The test of our progress is not

whether we add more to the

abundance of those who have much;

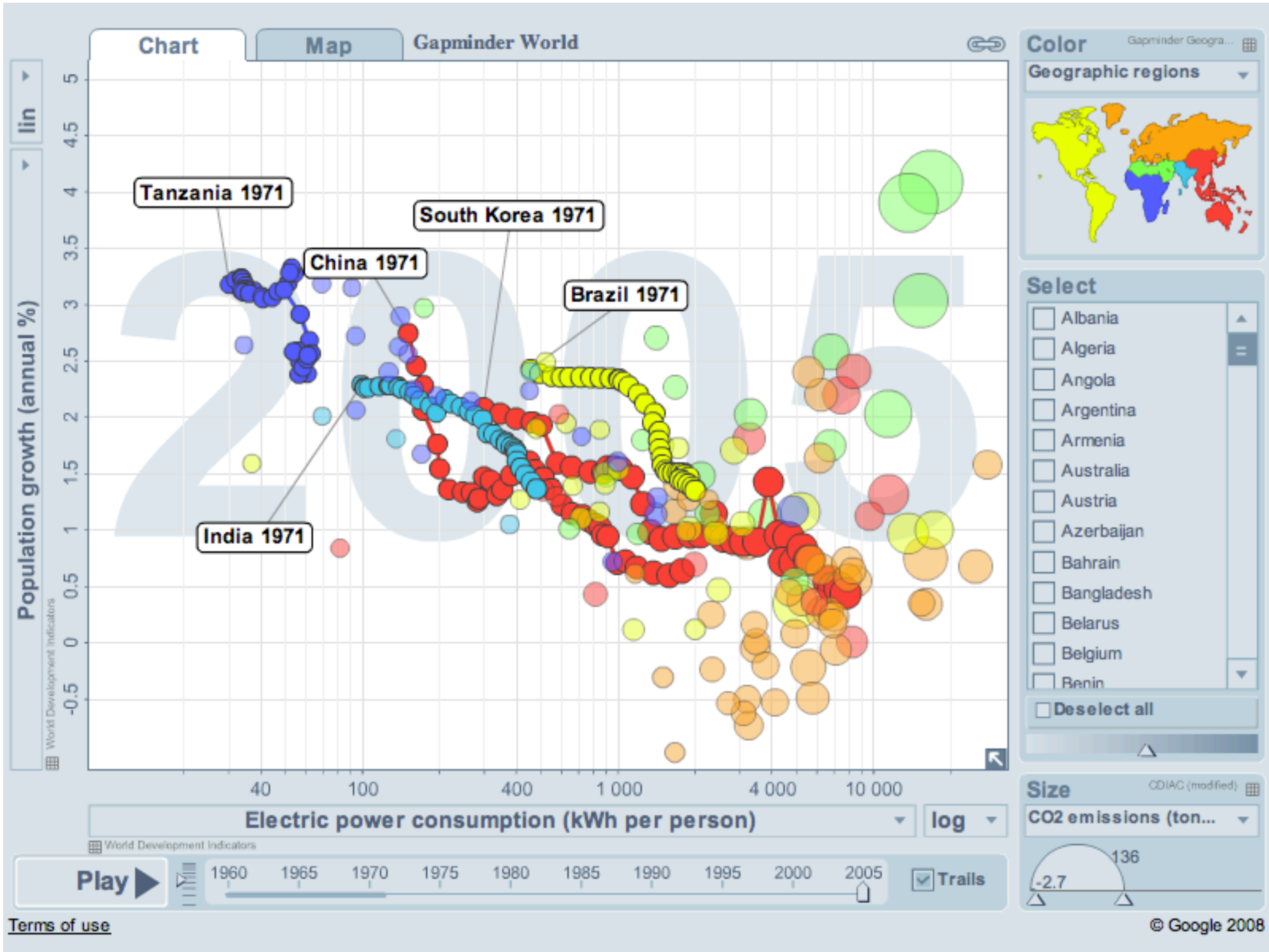
it is whether we provide enough for

those who have too little."

F.D.Roosevelt, 1937

Energy Access is also Correlated With Population Growth Rates & Thus is Linked to Stabilizing Global Human Population

Energy Access Linked to Population Growth Rate



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Implication for Stabilization of Population Growth

Let Population at t=0 be P_0

Annual population growth rate *decreases* by factor, *f<1*, each year, i.e.

$$r_1 = fr_0$$

$$r_2 = fr_1 = f^2 r_0 \ldots$$

$$r_n = f^n r_0$$

Then Population after i years is given as

$$\begin{aligned} P_i &= P_0 + \Delta P_0 \left(1 + f + f^2 + \ldots + f^{i-1}\right) \\ &= P_0 + r_0 P_0 \left(1 + f + f^2 + \ldots + f^{i-1}\right) \\ &= P_0 \left(1 + r_0 \sum_{j=0,i} f^j\right) \end{aligned}$$

Implication for Stabilization of Population Growth

For $i \to \infty$ can note that the infinite series is given as

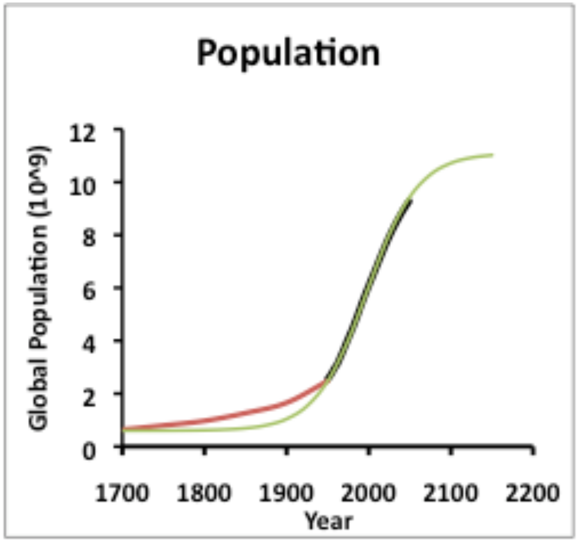
$$\sum_{\substack{j=0,i \\ \lim i \to \infty}} f^{j} = \frac{1}{1-f}; \quad f < 1$$

Thus for given P_0 and r_0 can solve for growth rate decrement, f, needed to Yield a final population as $n \to \infty$

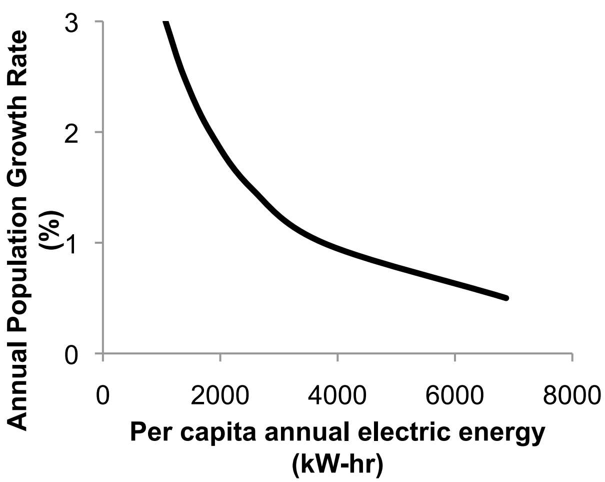
$$f = 1 - r_0 \left(\frac{P_\infty}{P_0} - 1 \right)^{-1}$$

Apply to current global situation, for stable population of 11 Billion, require f~0.97 Which implies 2-4x increase in per-capita energy access,

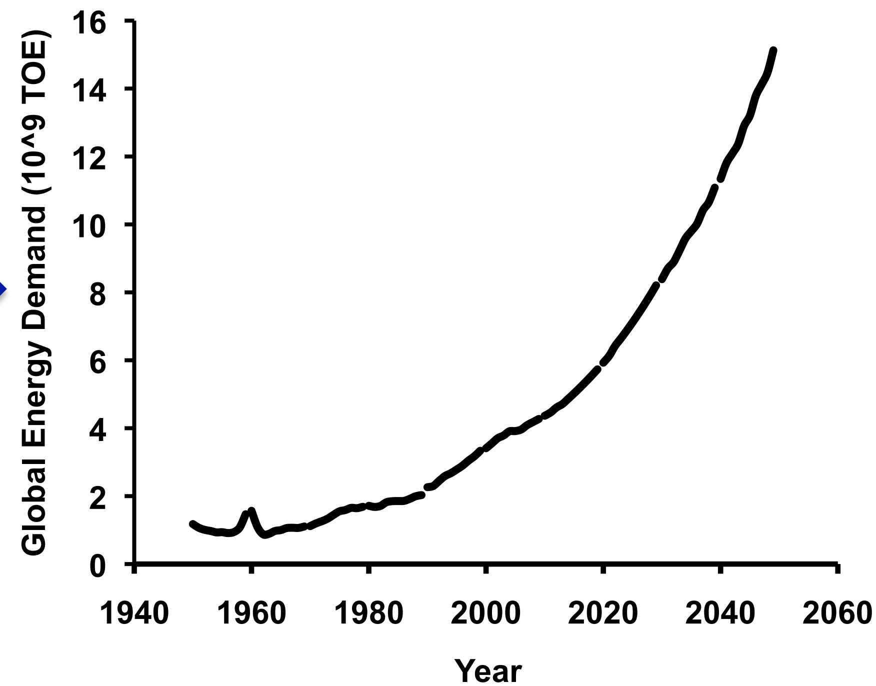
Implication: Energy Demand will Increase!



Population Growth Rate vs. Per-capita energy



Global Effective Energy Demand (TOE)



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Part II: Our Current Energy Economy is Unsustainable…

due to both **Resource Limits** &
Global Climate Change

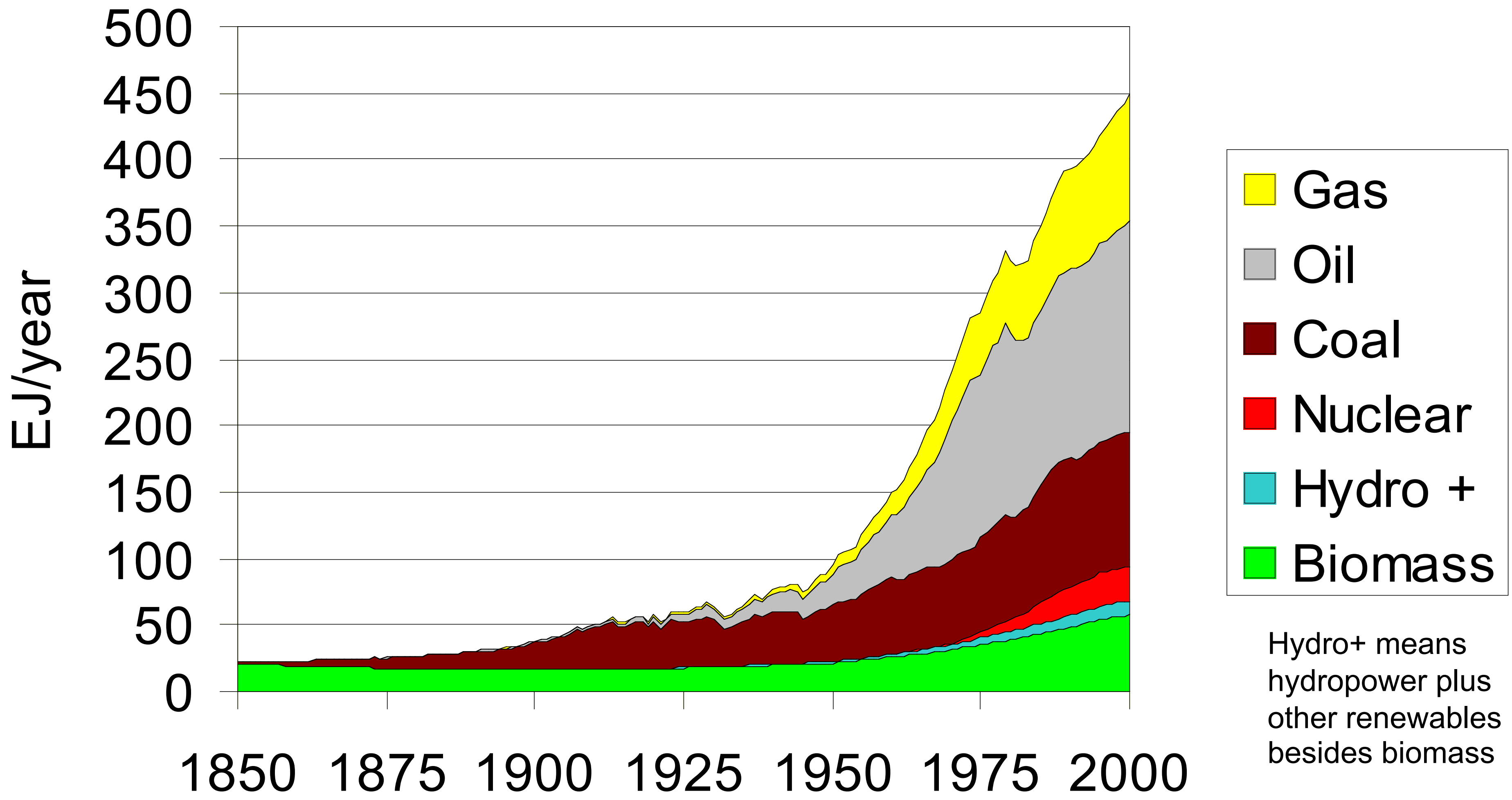
Where Does This Energy Come From?

Source	10^{18} Joules/yr	Percent of Total
Petroleum*	158	40.0
Coal*	92	23.2
Natural Gas*	89	22.5
Hydroelectric*	28.7	7.2
Nuclear Energy	26	6.6
Biomass (burning)*	1.6	0.4
Geothermal	0.5	0.13
Wind*	0.13	0.03
Solar Direct*	0.03	0.008
Sun Abs. by Earth*	2,000,000	then radiated away

* Ultimately derived from our sun

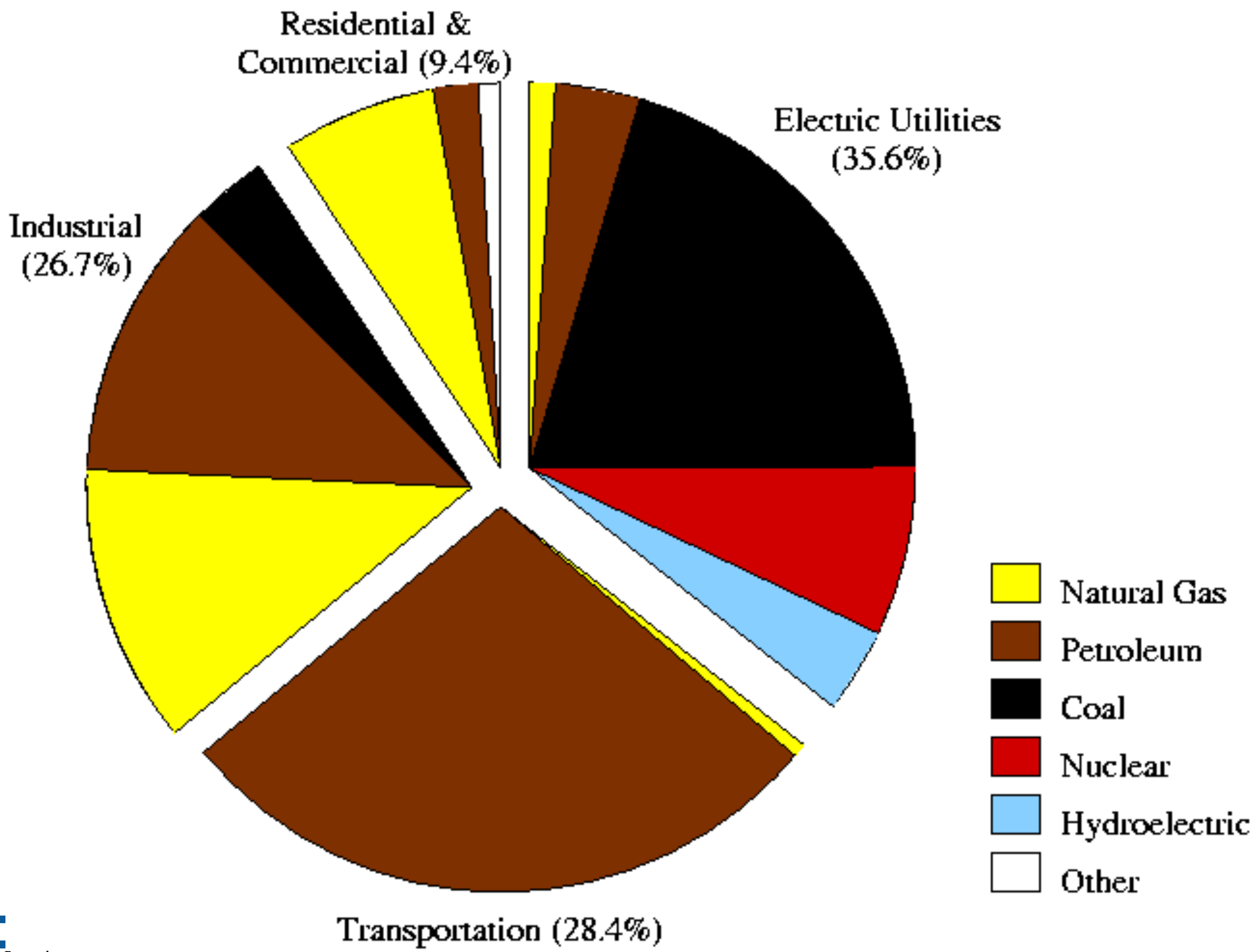
Courtesy David Bodansky (UW)

History of world supply of primary energy: continuous growth



Energy supply grew 20-fold between 1850 and 2000. Fossil fuels supplied 80% of the world's energy in 2000. From Holdren (2007)

How do we use energy?



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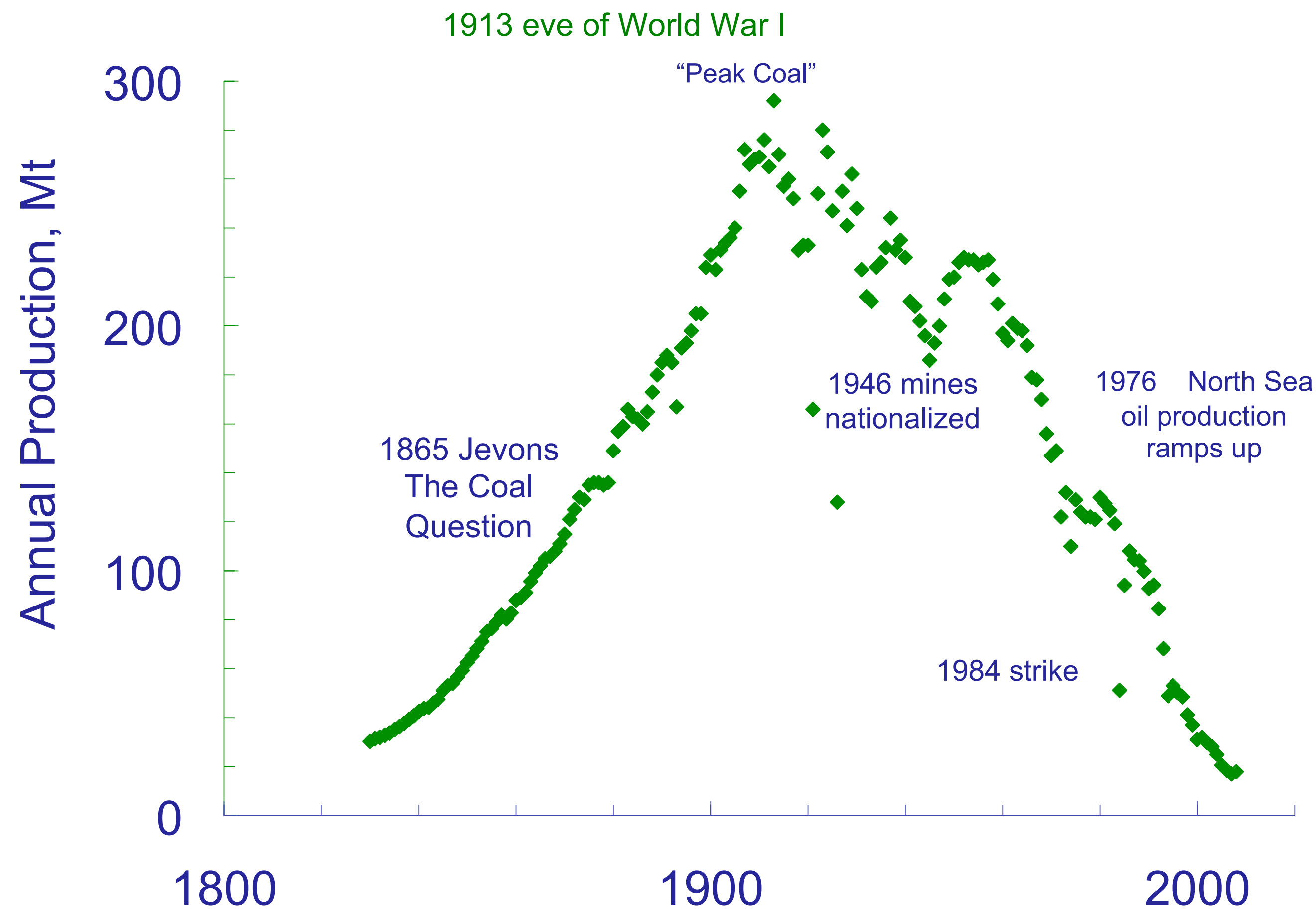
Fossil Fuels are a Finite Resource

An Example from History: British Coal Production 1800-2000



D. Rutledge, CalTech http://rutledge.caltech.edu/

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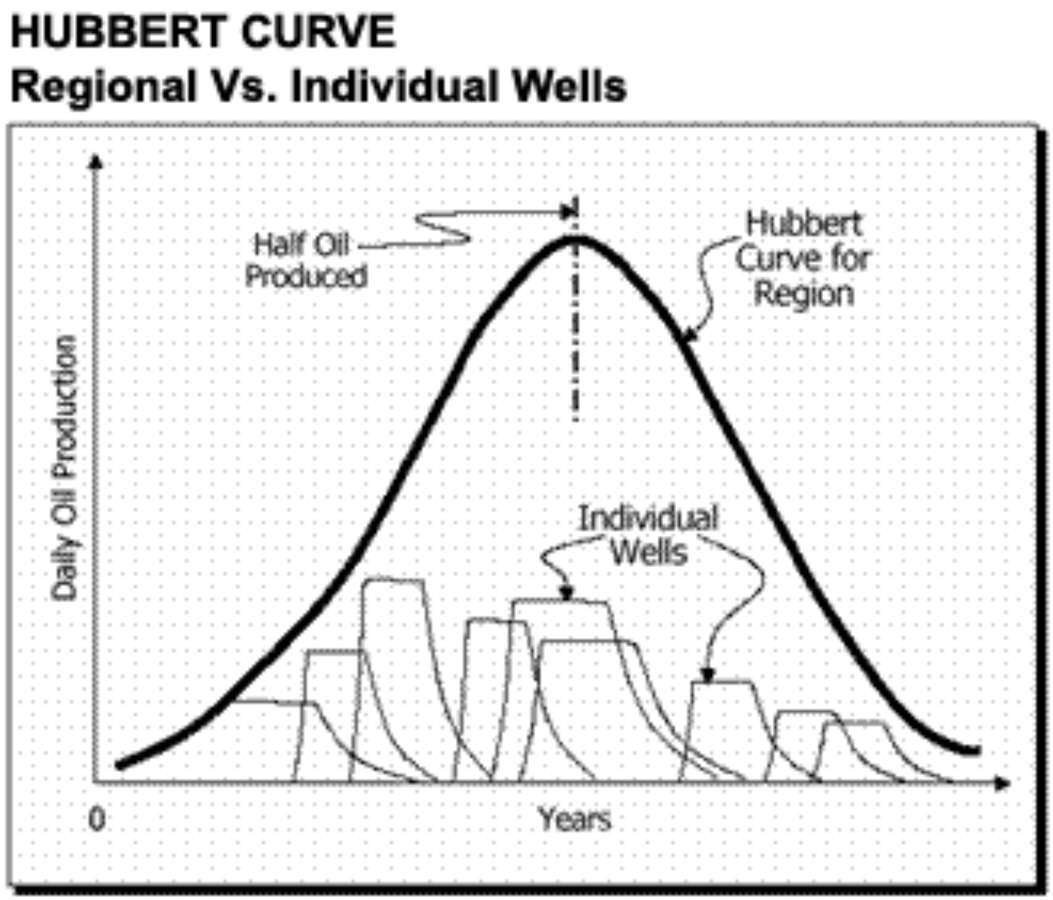
The Hubbert Curve



Looks at Production v. Resource – US Data

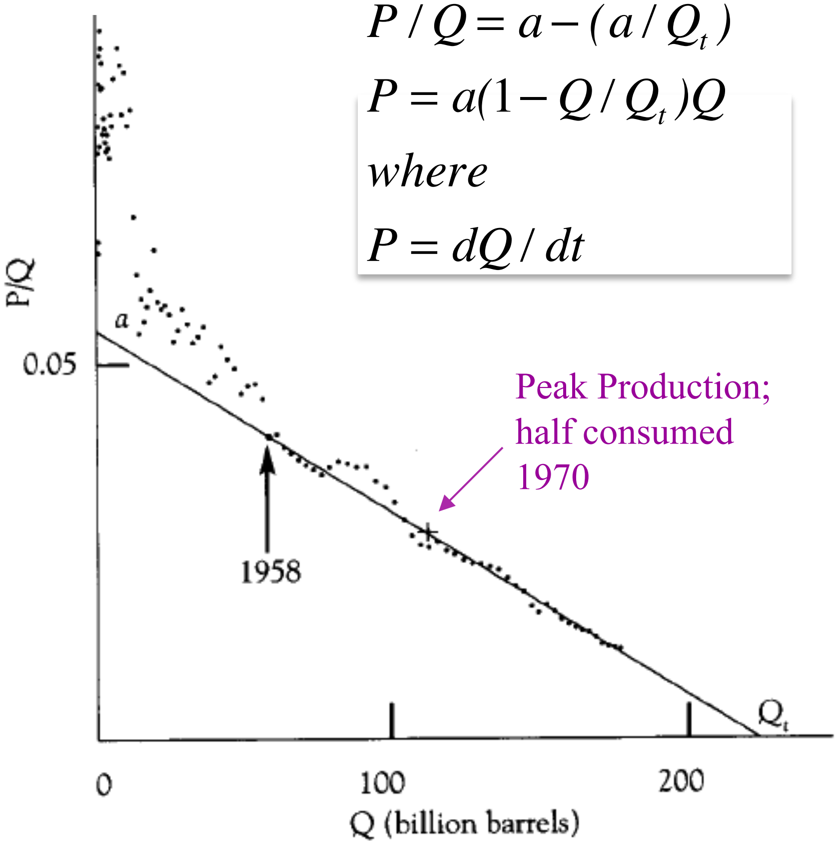
$$Y = a + mX$$

$$P / Q = a - (a / Q_t)$$

$$P = a(1 - Q / Q_t)Q$$

where

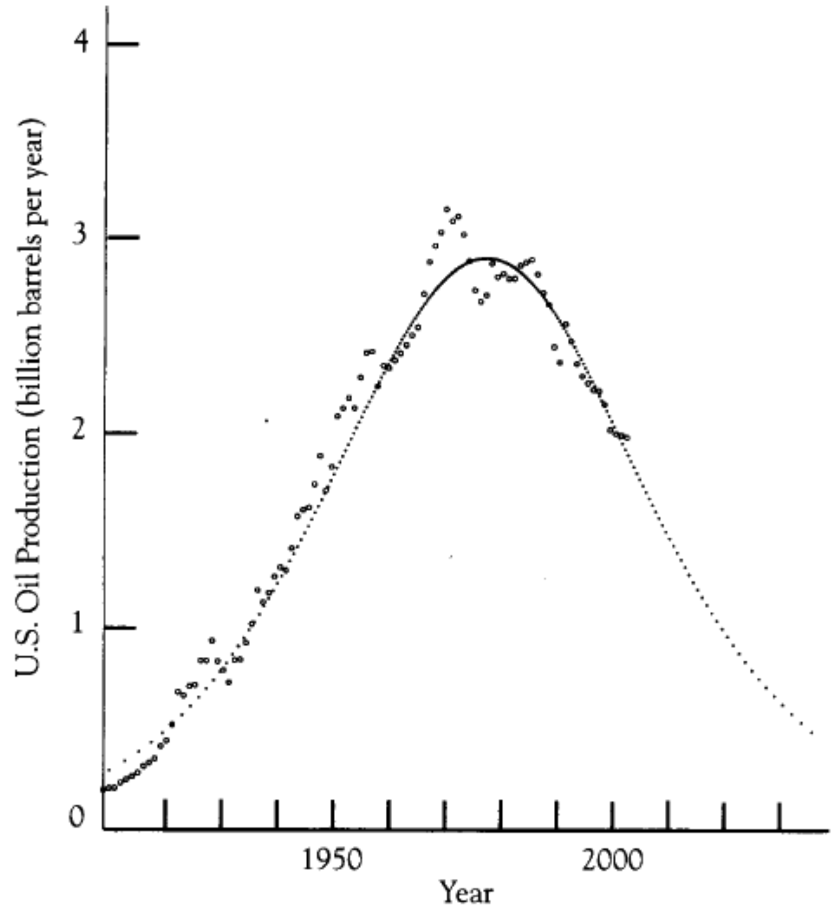
$$P = dQ / dt$$



- Plot rate of production (P: annual production) divided by resource (Q: total produced to date) against total resource, Q
  - P/Q is like an interest rate: fractional increase per year
- A “logistic” or S-curve would follow a straight line sloping down
- U.S. oil production does so after 1958
- When you get to zero P/Q, you’ve hit the end of the resource: no more production

Same fit, in Production v Time plot for U.S.

- The best-fit line on the previous plot produces a decent fit to the rate history of oil production in the U.S.
- Supports the peak position well, and implies a total resource of about 225 Gbbl



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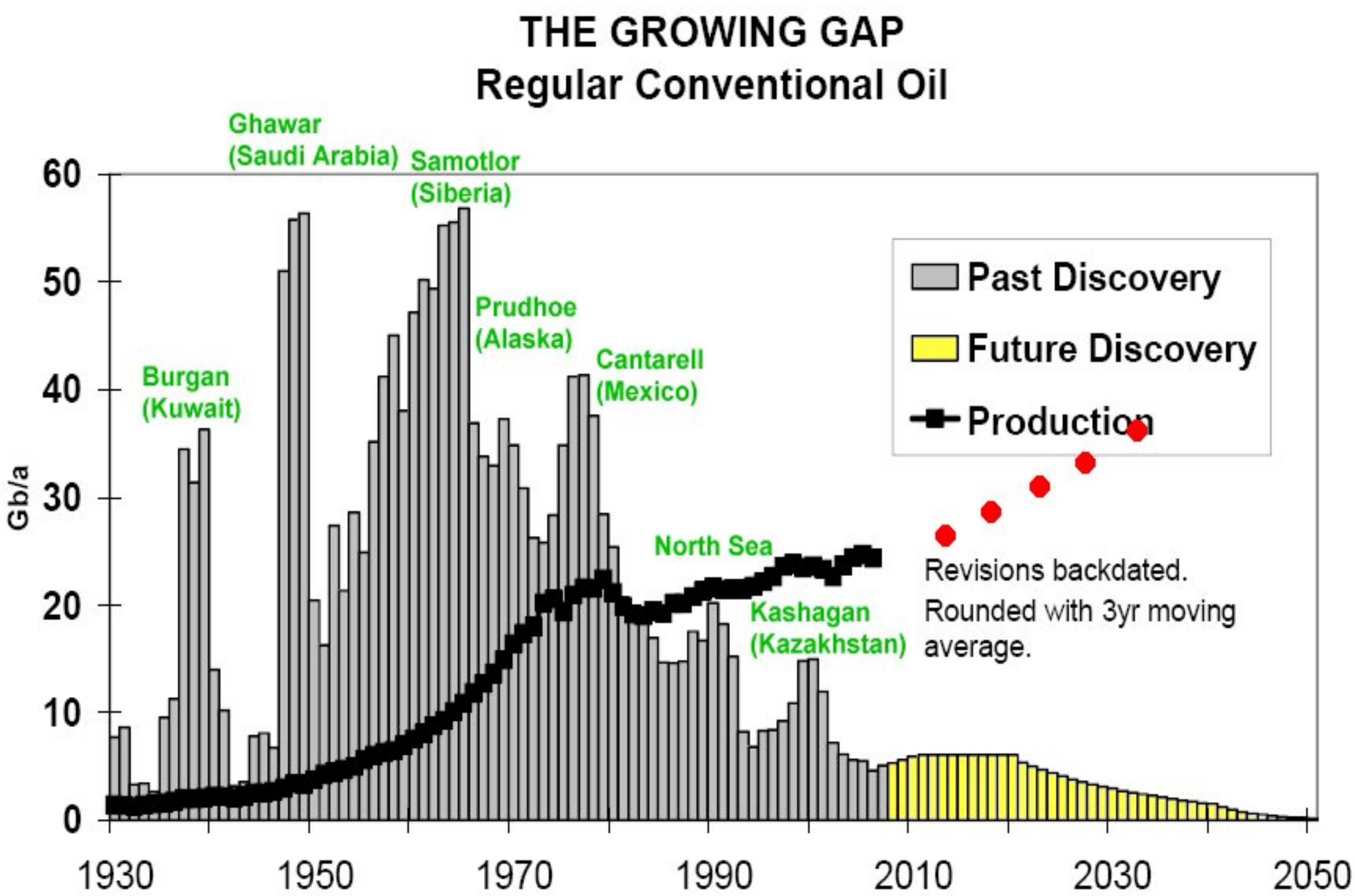
Global Annual Discovery & Production – Conventional



Sources: BP Stat. Energy Review & www.oilposter.org

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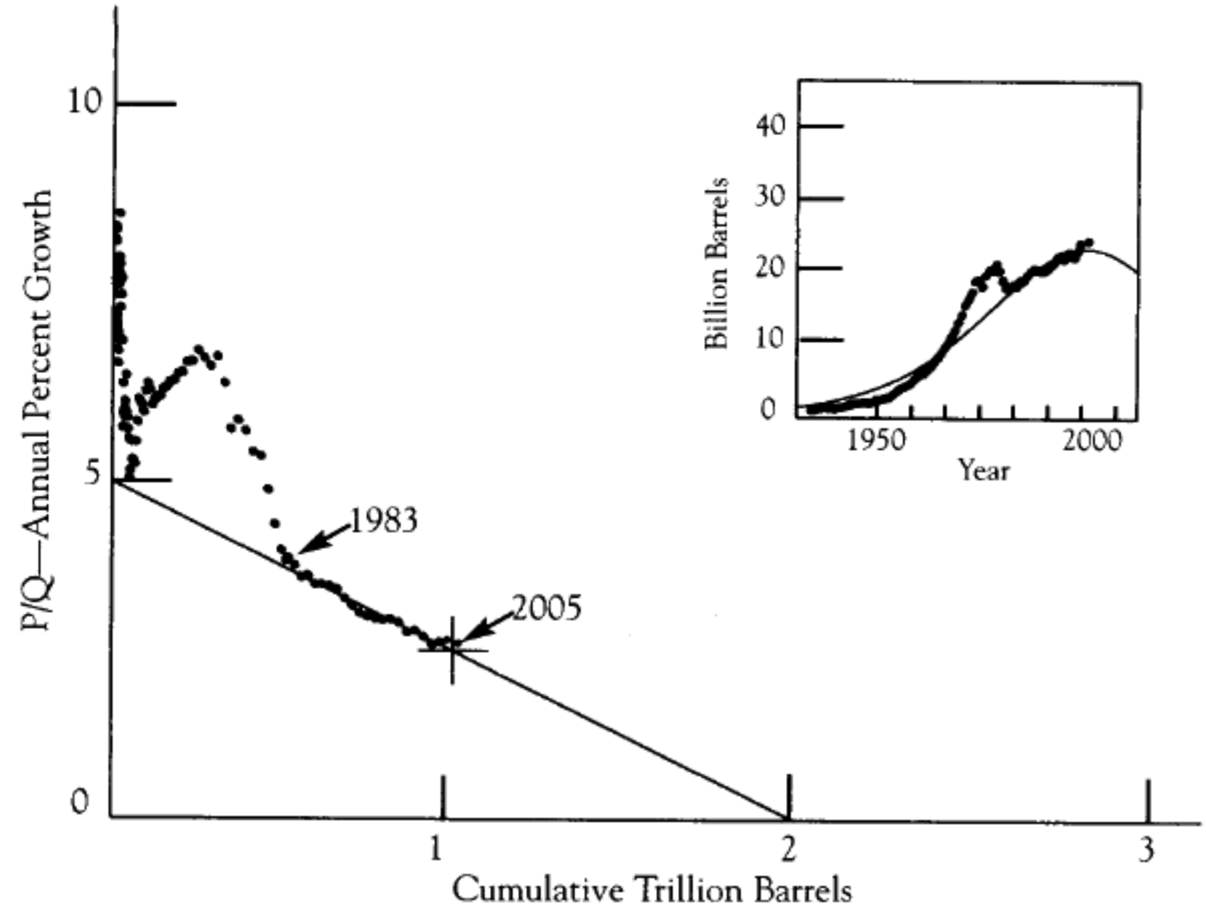
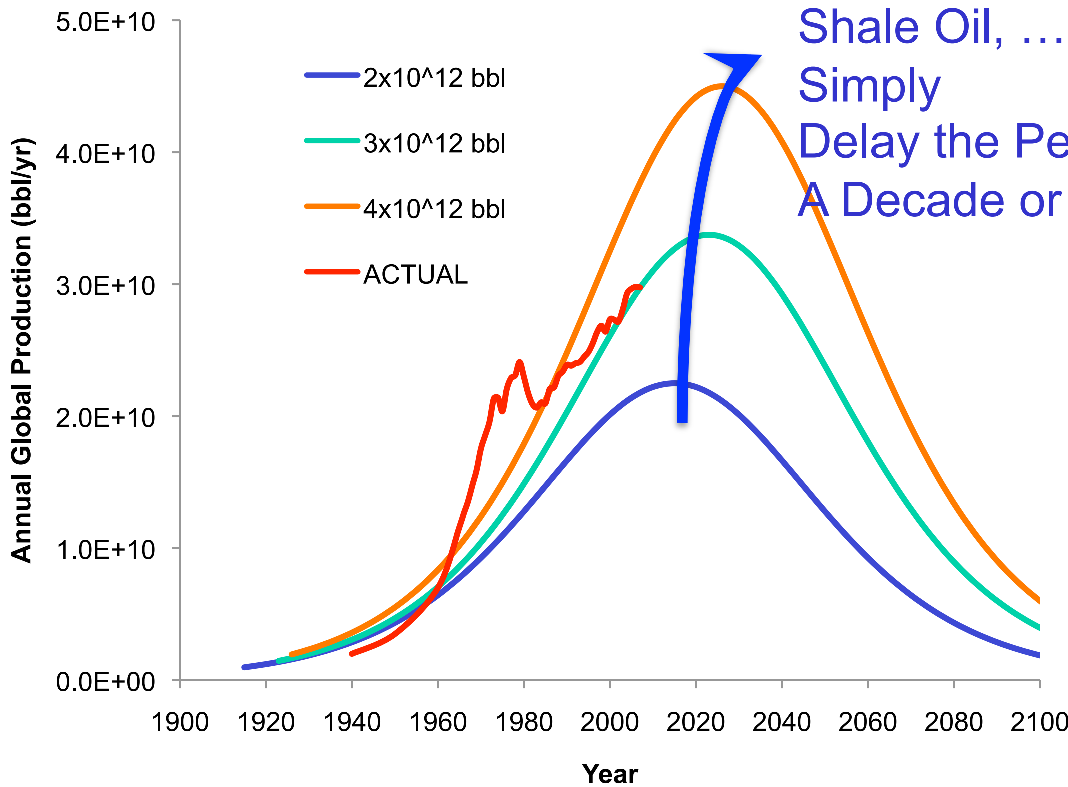
Production v. Resource – Global



- About halfway along 2,000 Gbbl at 2005 implies we're roughly at the peak (for conventional oil)

Petroleum Production Likely Peaks in 2015-2025



Unconventional Resources (Tar Sands, Shale Oil, …) Simply Delay the Peak by A Decade or Two

Gas & Coal will Follow Similar Trends Later in Century

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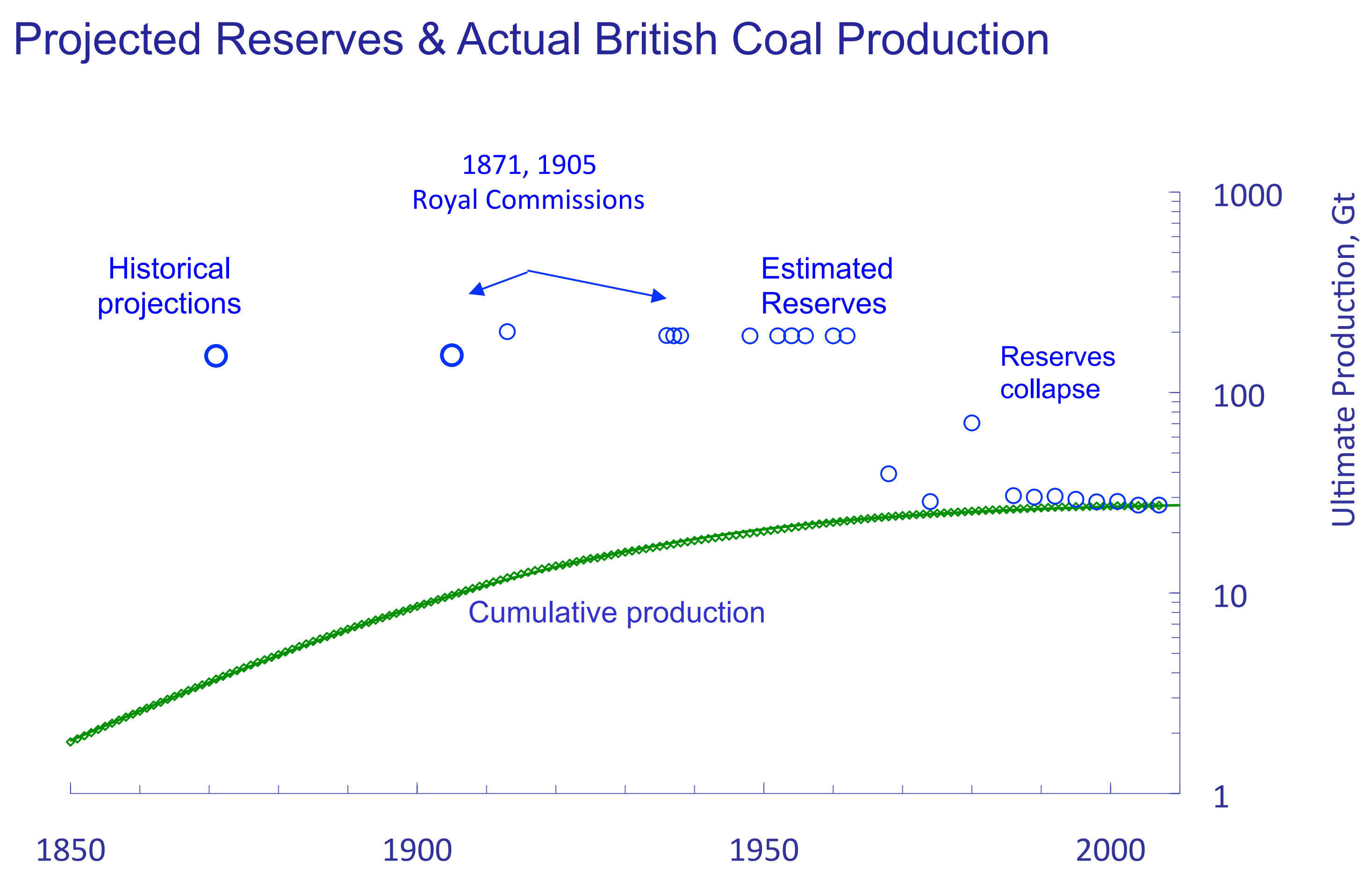
We’ve Been Here Before!



Ref: D. Rutledge, CalTech http://rutledge.caltech.edu/

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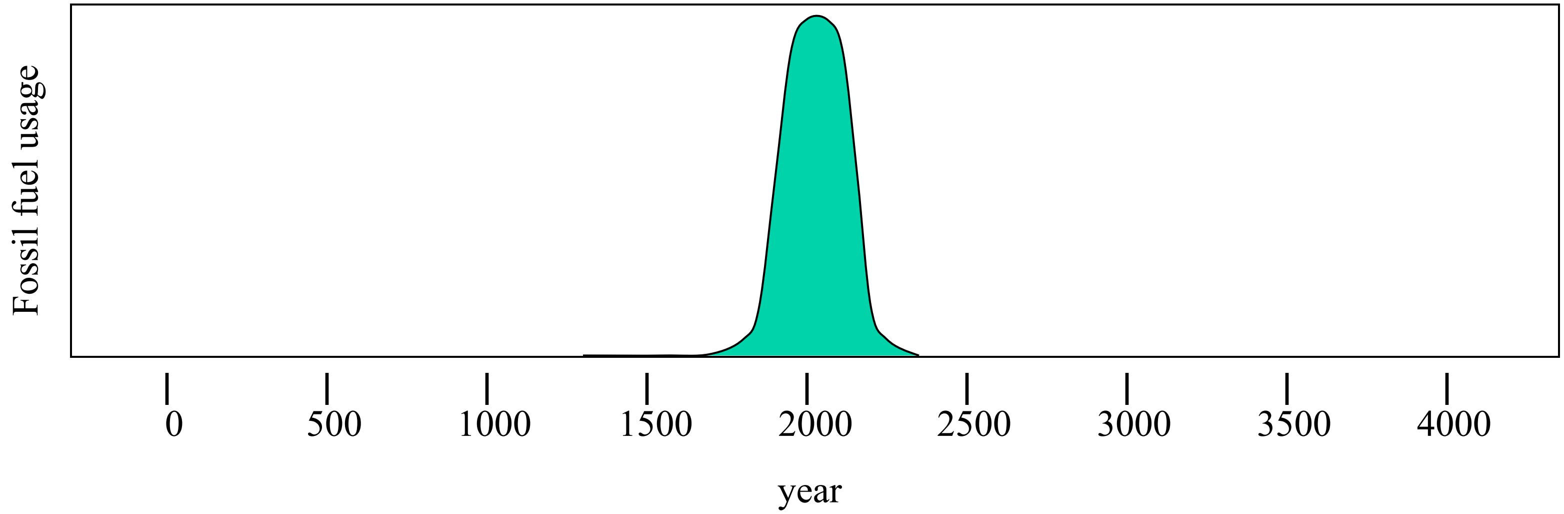
We live in a special time and place…

- Most of history we used < 100 Watt per human; currently we use ~10000 Watt per human continuously! Big change makes big change in lifestyle possible
- This phase has only lasted for the last century or so
- Most of our resources come from fossil fuels presently, and this has a short, finite lifetime
- Access to this resource is HIGHLY variable around the world!



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Part II: Our Current Energy Economy is Unsustainable…

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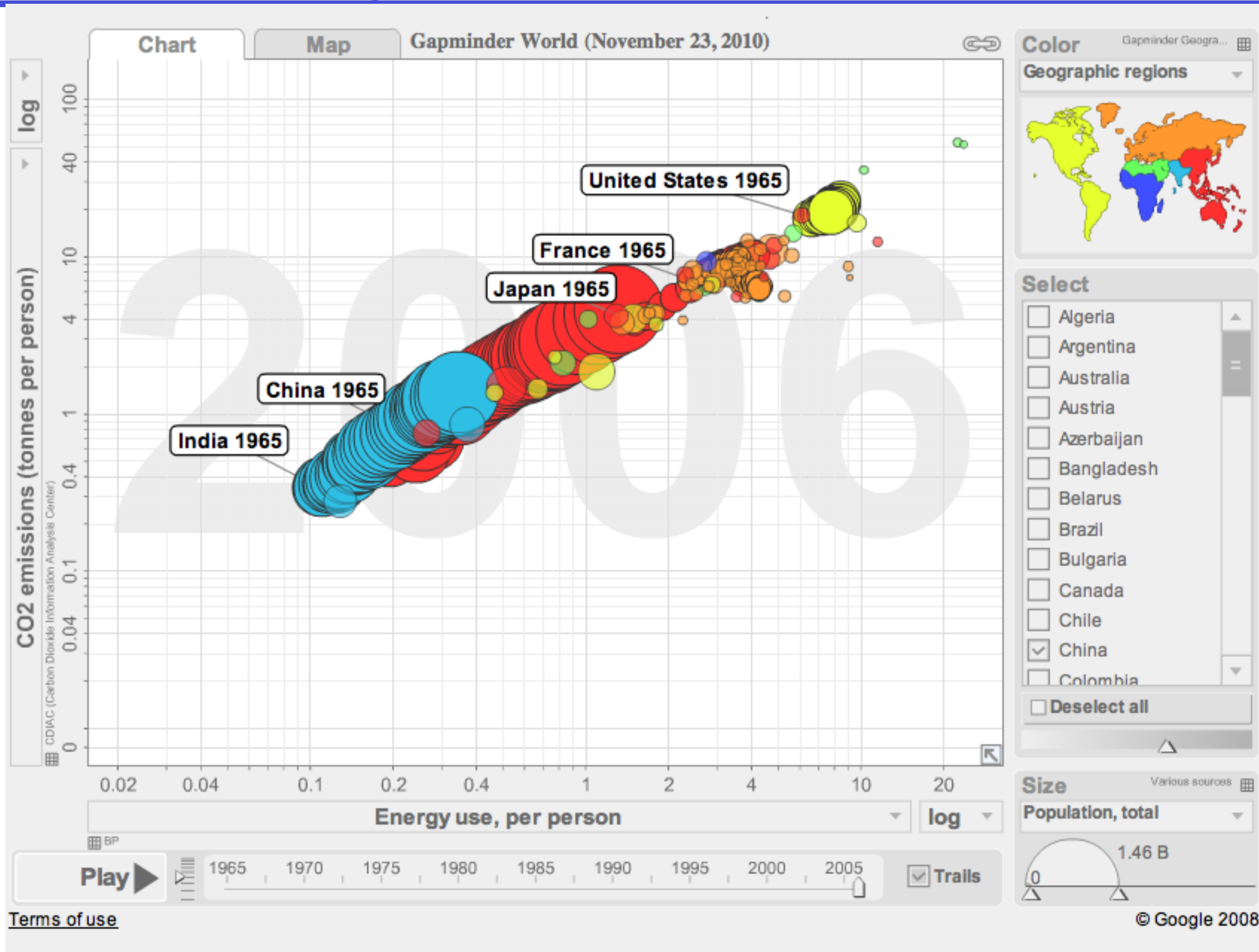
So far… Energy Access = CO2 Emissions



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Earth’s Thermal Balance

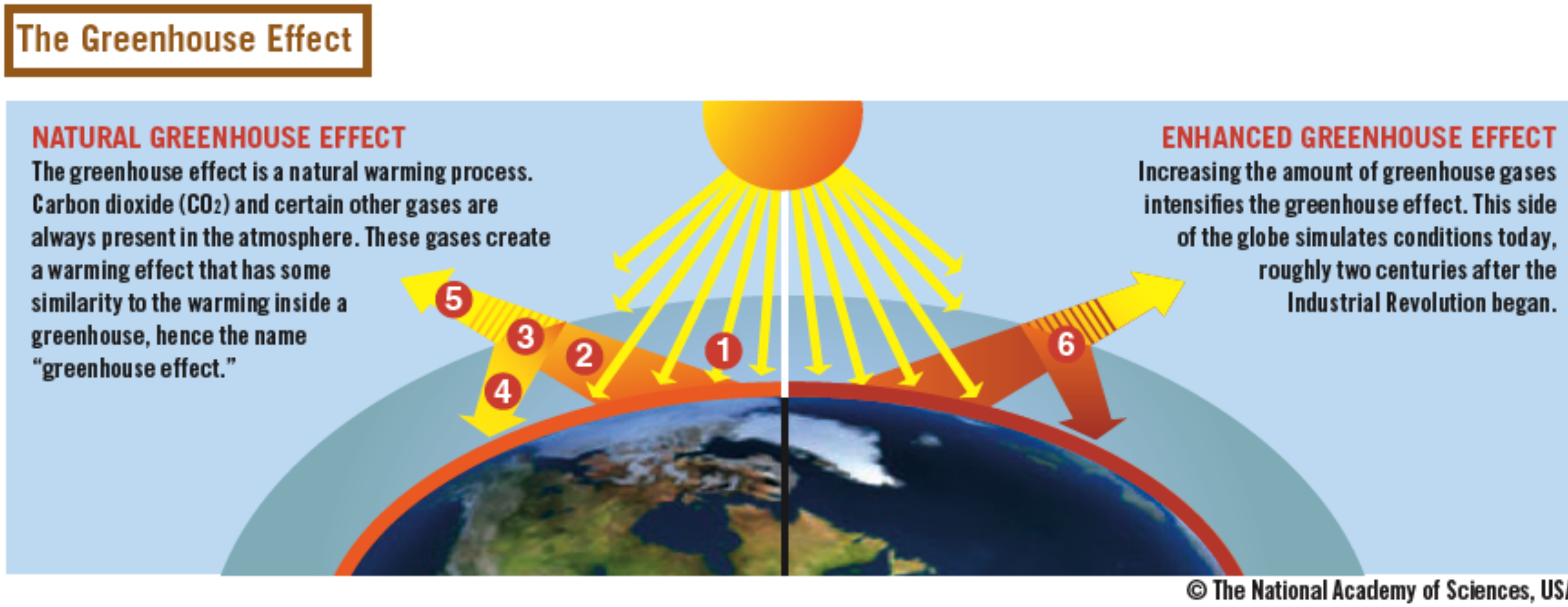

Illustration of the greenhouse effect (courtesy of the Marian Koshland Science Museum of the National Academy of Sciences). Visible sunlight passes through the atmosphere without being absorbed. Some of the sunlight striking the earth ❶ is absorbed and converted to heat, which warms the surface. The surface ❷ emits heat to the atmosphere, where some of it ❸ is absorbed by greenhouse gases and ❹ re-emitted toward the surface; some of the heat is not trapped by greenhouse gases and ❺ escapes into space. Human activities that emit additional greenhouse gases to the atmosphere ❻ increase the amount of heat that gets absorbed before escaping to space, thus enhancing the greenhouse effect and amplifying the warming of the earth.

www.pewclimate.org & National Academy of Sciences

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The Carbon Cycle ref: Schimel, Nature 393, 208 (1998)

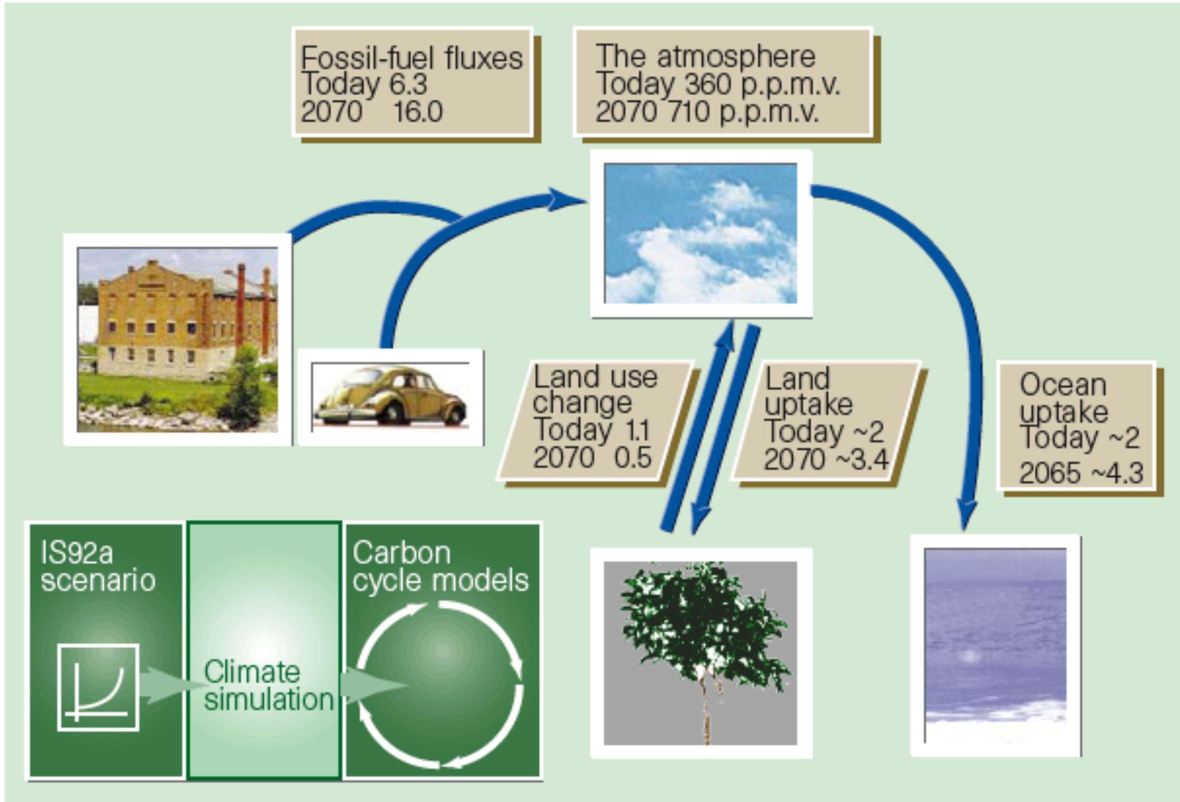
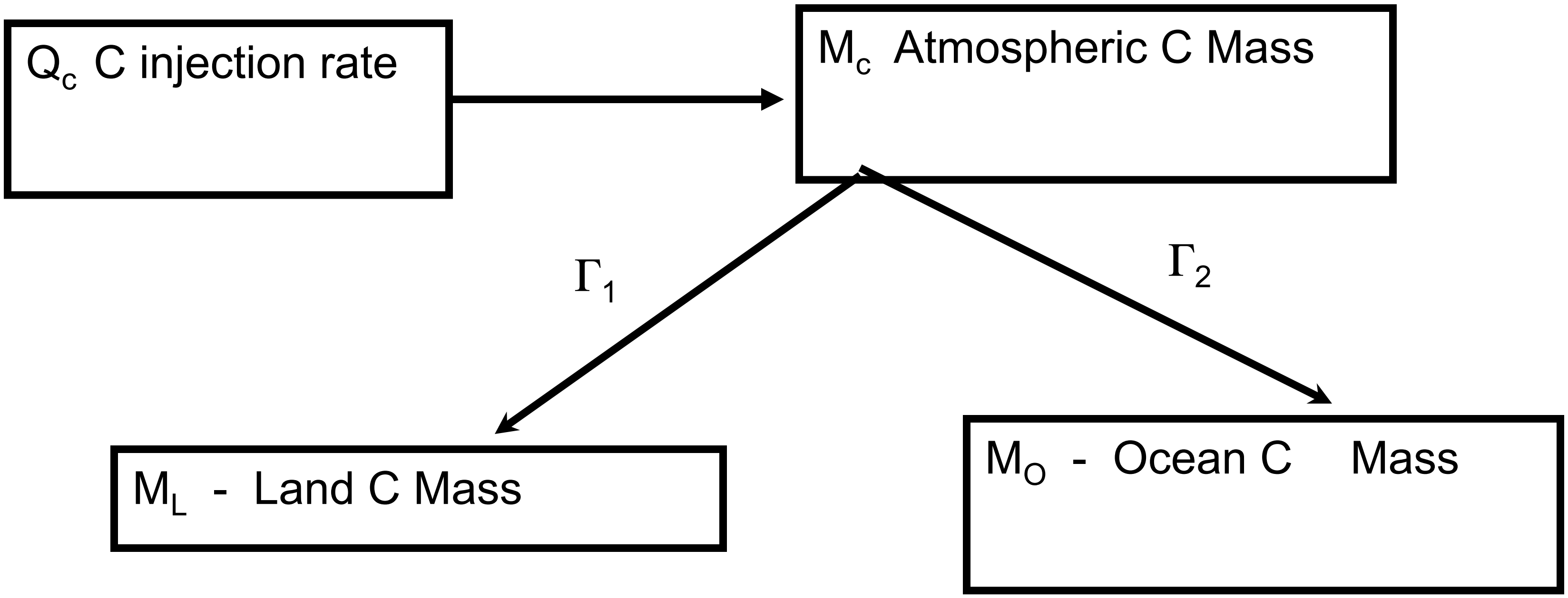


Figure 1 Present-day fluxes of anthropogenic CO_2 compared with estimated fluxes for the year 2070 (or 2065 in the case of Sarmiento *et al.*[3]). Units are 10^{15} g yr^{-1} unless stated otherwise; p.p.m.v., parts per million by volume. The estimates for 2070 (2065) are taken from IPCC IS92a figures, or in the case of land uptake[4] and ocean uptake[3], are from models of the response of land and oceans to climate change using IS92a as input; IS92a, or IPCC Scenario 92a, gives projections of increasing emissions of CO_2 from use of fossil fuels, assuming moderate growth rates. The inset at bottom left indicates how scenarios of increased anthropogenic emissions of CO_2 feed into climate simulations and then models of the carbon cycle.

Simple Carbon Balance Model Illustrates the Problem



Atmospheric C Mass Balance: $\frac{d\Delta M_c}{dt} = Q_c - \frac{\Delta M_c}{\tau_{eff}}$

with: $\tau_{eff} \equiv \frac{\tau_L \tau_O}{\tau_L + \tau_O}$ ~ 100's years

Assume Diffusive-like Fluxes: $\Gamma_{L,O} = \frac{M_C(t) - M_{C0}}{\tau_{L,O}}$

Response to Step-function Q_c=const for t>0:

$$\Delta M_C = Q_{C_0} \tau_{eff} \left(1 - exp\left(-t / \tau_{eff}\right)\right)$$

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0-D Globally Averaged Carbon Balance (cont'd)

Response to Step-function Q_c=const for t>0:

$$\Delta M_C = Q_{C_0} \tau_{eff} \left(1 - exp\left(-t / \tau_{eff}\right)\right)$$

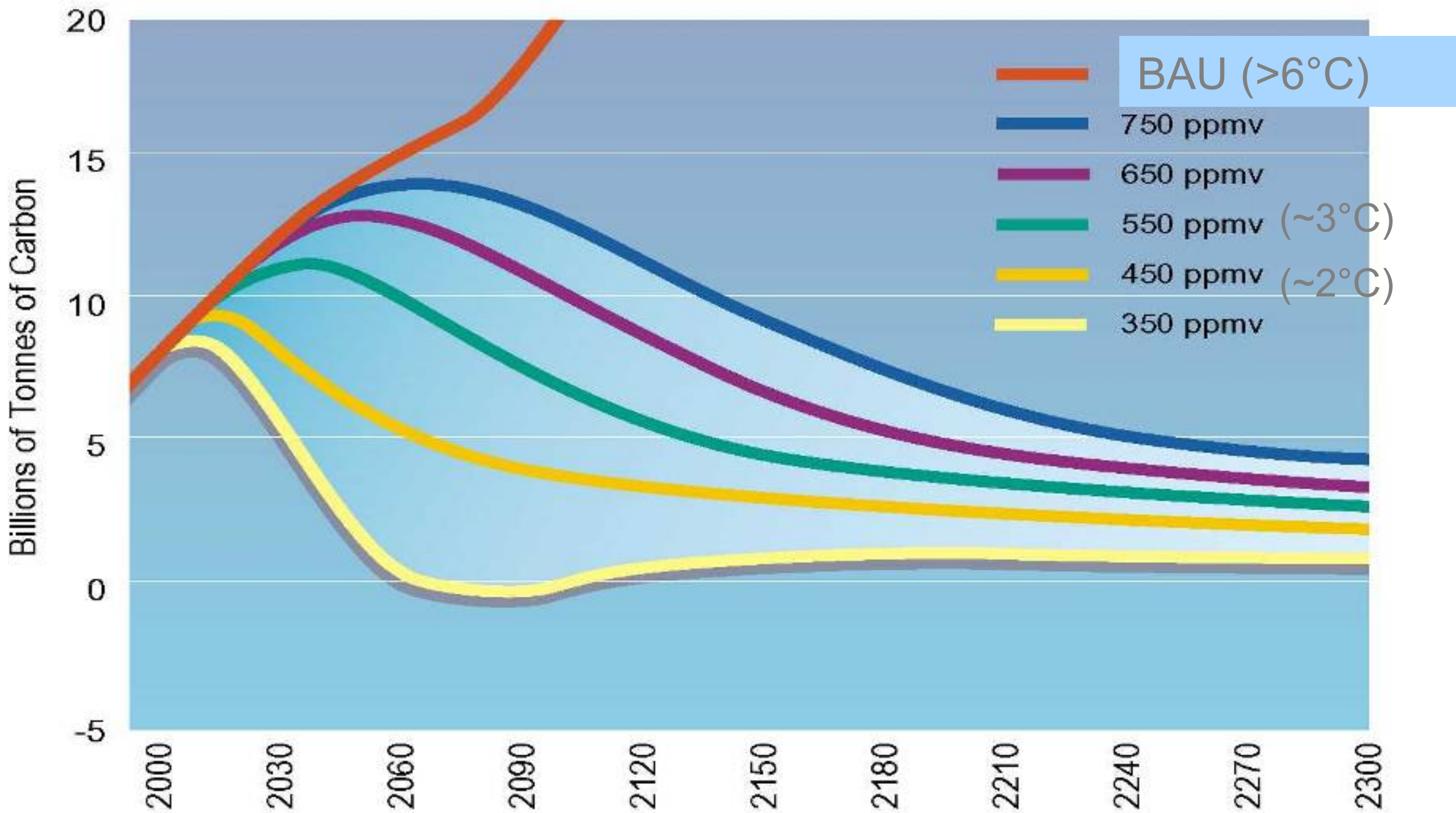
Solution for timescales short compared to τ_{eff} (~100's years)

$$\Delta M_C = Q_{C_0} t$$

➔ **The Atmosphere Simply Accumulates the CO_2 We Inject**

➔ ***IF WE WANT TO STOP ACCUMULATING CO_2 BEFORE 100'S YEARS PASS THEN Q_C ➔ 0 !***

Emission paths for stabilizing CO_2 concentrations



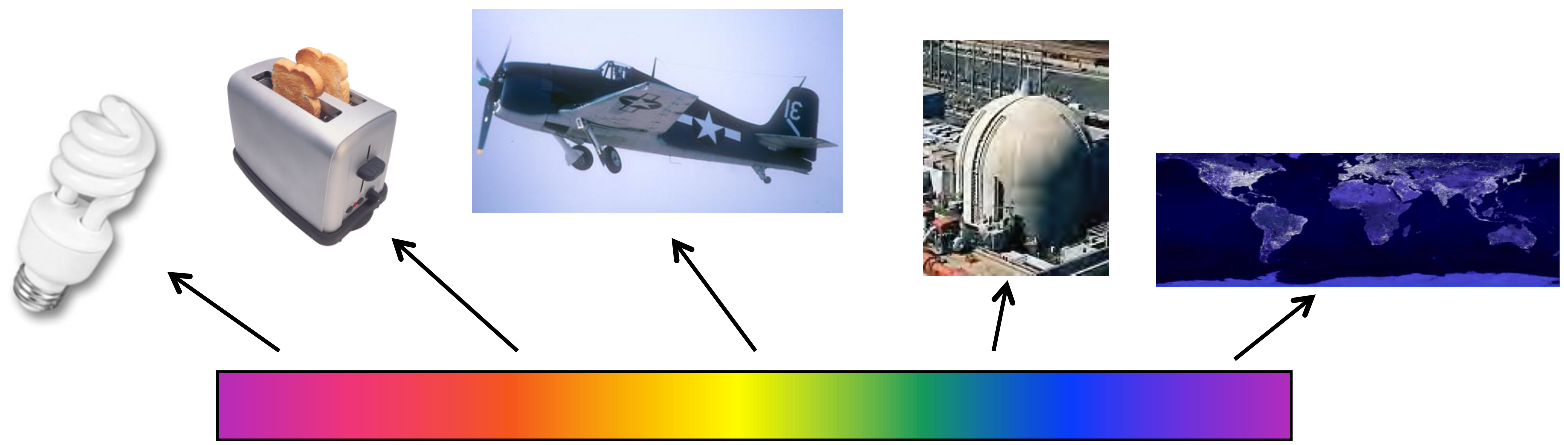
The path to avoid ΔT_{avg} >2°C (gold) requires much earlier, more drastic action than path to avoid >3°C (green).

Source: IPCC & J. Holdren 2007 AAAS Plenary Lecture

Part III: What Will It Take to Meet Human Energy Needs **AND** Avoid Unacceptable Global Climate Change?

Scale Matters

Current Global Total Power Demand:
About 14,000 Nuclear or Coal Power Plants, or 20,000 bbls/sec
14,000,000 Wind Turbines or 40,000 sq miles PV



	1	10^3	10^6	10^9	10^{12}
Power	1 W	1 kW	1 MW	1 GW	1 TW

Source: *Powering the Planet*, Nathan S. Lewis.

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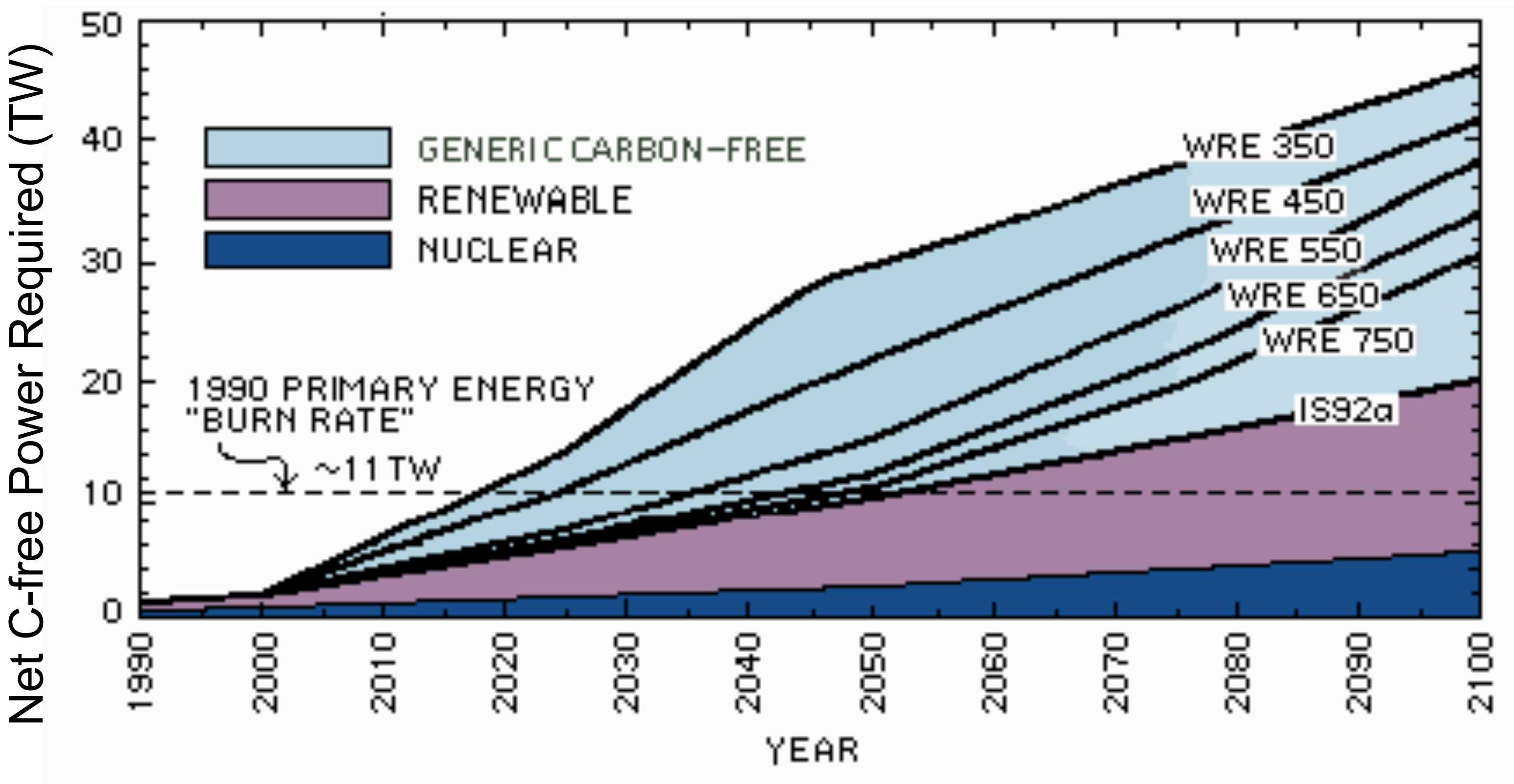
Need to Meet Demand & Stabilize CO_2 Levels

- Key Factors in Projections
  - Population Stabilizes at 10 Billion
  - Energy Access Gradually Spreads to Majority of Population,
  - Energy Intensity Decreases 1%/yr
  - Carbon Intensity Decreases to CH4 Level in 2030 & Keeps Decreasing(!)
- Model Carbon Cycle
  - Human & Natural Emissions, Biosphere & Physico-Chemical Uptake
- Solve for Total Energy Demand & Fraction that Must be Carbon Free

Projected Carbon-free Power Required



Hoffert et al, Nature 395, 881 (1999)

The Challenge and Opportunity

- Quality of Life & Sustainability Both Imply Increased Global Energy Demand
- Current Fossil Fuel Sources are Finite & Have Serious Global Environmental Impacts

➔ **WE NEED CLEAN ENERGY SOURCES AT <u>RELEVANT</u> (10's TW-yr) SCALES**

Part IV: **What are our options, which ones scale,** and how long will the needed transition take?

Many Potential Options are Discussed…

- Waves
- Tides
- Ocean Currents
- Ocean Thermal
- Conventional Geothermal
- Deep Geothermal
- Food-to-Ethanol
- Unconventional Fossil Fuels w/ CCS
- "Negawatts"
- Solar PV
- Solar Thermal
- Wind
- Advanced Biofuels
- Synthetic Photosynthesis
- Nuclear Fission
- Nuclear Fusion

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THESE DON'T SCALE

- "Negawatts"
- Solar PV
- Solar Thermal
- Wind
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- Nuclear Fusion

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Many Potential Options are Discussed…

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THESE DON'T SCALE

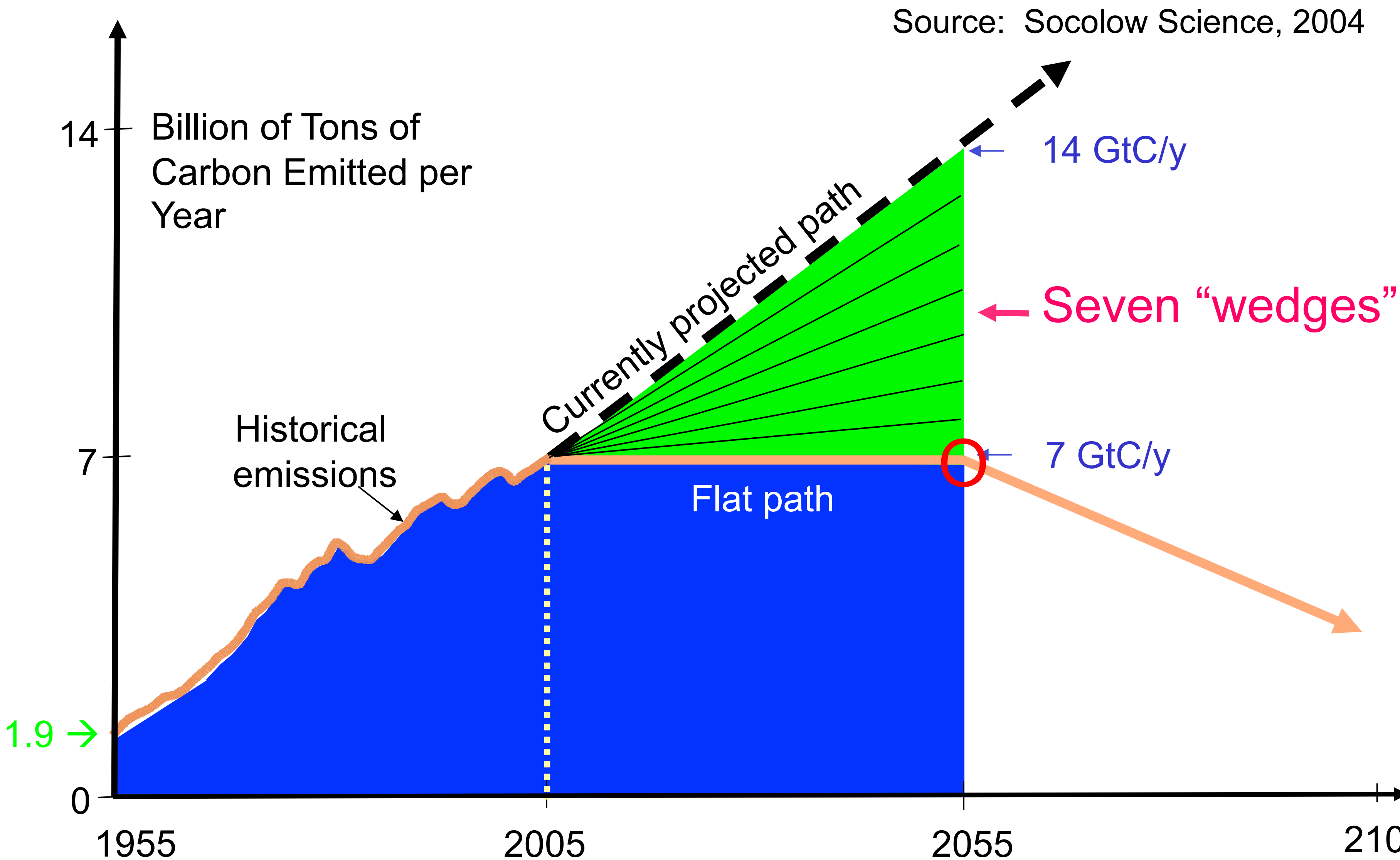
EARTHQUAKES

- "Negawatts"
- Solar PV
- Solar Thermal
- Wind
- Advanced Biofuels
- Synthetic Photosynthesis
- Nuclear Fission
- Nuclear Fusion

Options That Could Scale:

- Efficiency, Usage, & Carbon Intensity Improvements
  - Can Slow Rate of Increase But Not Reverse Trends
- Carbon Sequestration (G-tonnes/yr)
  - Large Potential … but Undemonstrated at Scale
- Solar & Wind
  - Requires Large Land Area (10^4-10^6 km^2) in Remote Locations with Large-scale transmission)
  - Intermittency Forces Massive Storage, Accurate Forecasting, Backup Power & Will Limit Maximum Market Penetration
- Next-gen Bio-Fuels or Synthetic Photosynthesis
  - Requires Large Land & Water Resources,
- Nuclear Fission
  - Long term – requires closed fuel cycle or
  - Requires Pu Economy or Th-based reactors)
  - Public Acceptance?
- Nuclear Fusion
  - Large Resource (>>1000 years)
  - No Long-lived Actinides
  - Potential Safety Advantages w/r/t Fission
  - Potential (w/ Adv. Mat'ls) for Low Level Waste Disposal

Solution Requires "Cocktail Approach"



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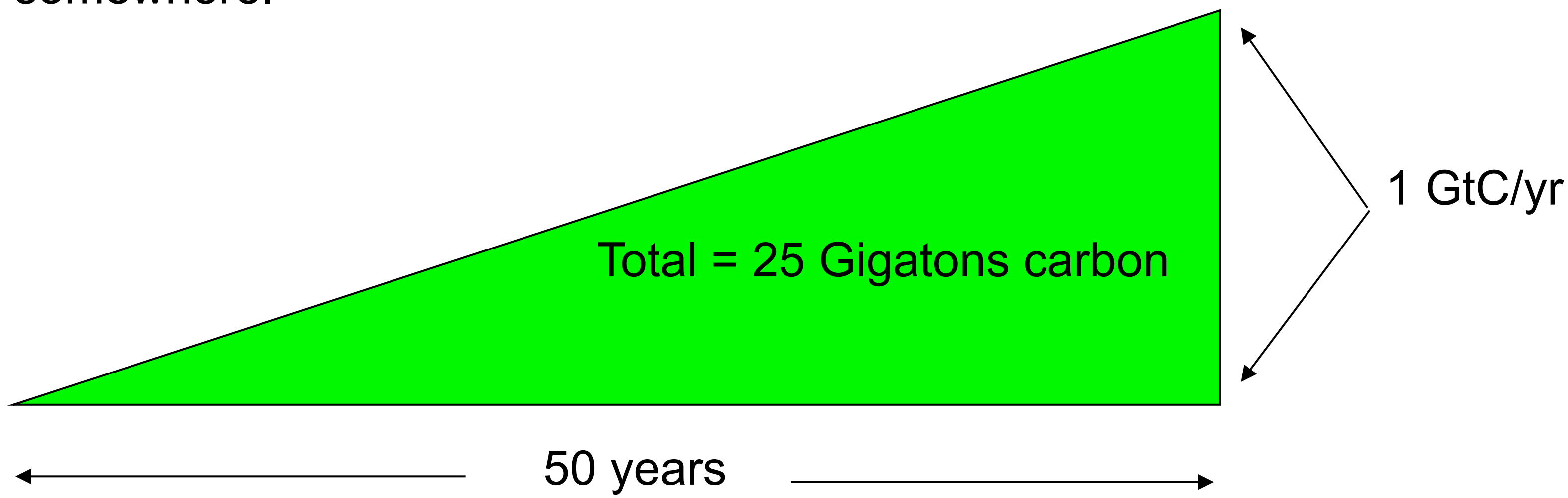
What is a "Wedge"?

A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.



Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. This is 2.5 trillion dollars at $100/tC.

A "solution" to the CO_2 problem should provide at least one wedge.

Source: Socolow, Science 2004

Meeting Demand & Stabilizing C-Emission Requires

- 5M Acres of PV (1000x today's installed capacity)
- 1M 2MW Turbines (~2M km^2)
- 800 "Clean Coal" Plants (none today)
- 700 New Nuclear Power Plants (~2x current fleet)
- Record Efficiency Improvements
- Replace Petroleum fuels w/ Biofuels
- 2-3x Increase in Vehicle Fuel Efficiency

Will Require ~100km x 100 km PV installation or ~100 Million Rootops

Will Lead to ~1M Large (~3MW) Wind Turbines Covering ~10^6 km^2

Efficient Use of Electricity

industry

buildings

power

Effort needed by 2055 for 1 wedge:

.

25% - 50% reduction in expected 2055 electricity use in commercial and residential buildings

Socolow, Science 2004

Efficient Transportation

Effort needed by 2055 for 1 wedge:

2 billion cars driven 10,000 miles per year at 60 mpg instead of 30 mpg.

1 billion cars driven, at 30 mpg, 5,000 instead of 10,000 miles per year.

Source: Sokolow, Science 2004

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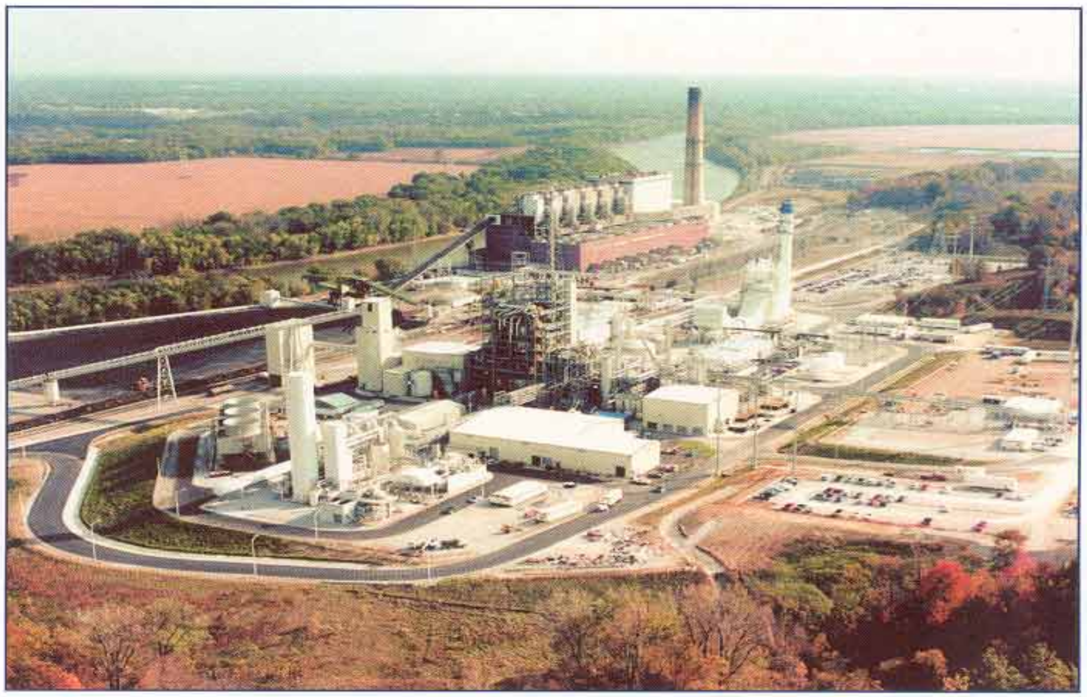
Carbon Capture and Storage



The Wabash River
Coal Gasification Repowering Project

Effort needed by 2055 for 1 wedge:

Carbon capture and storage at 800 GW coal power plants.

Sokolow, Science 2004

Graphics courtesy of DOE Office of Fossil Energy

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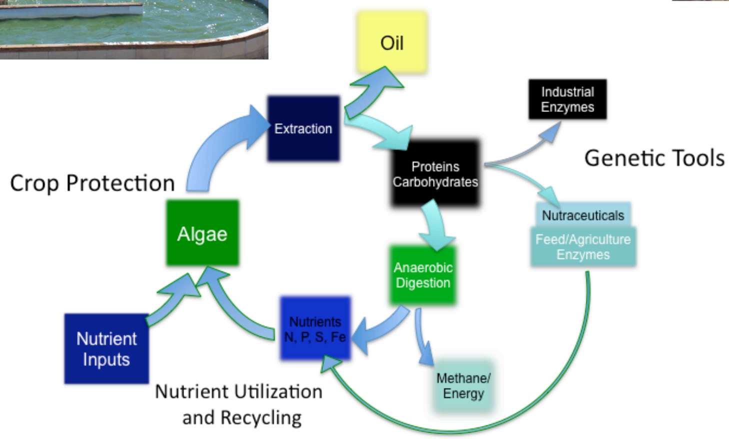
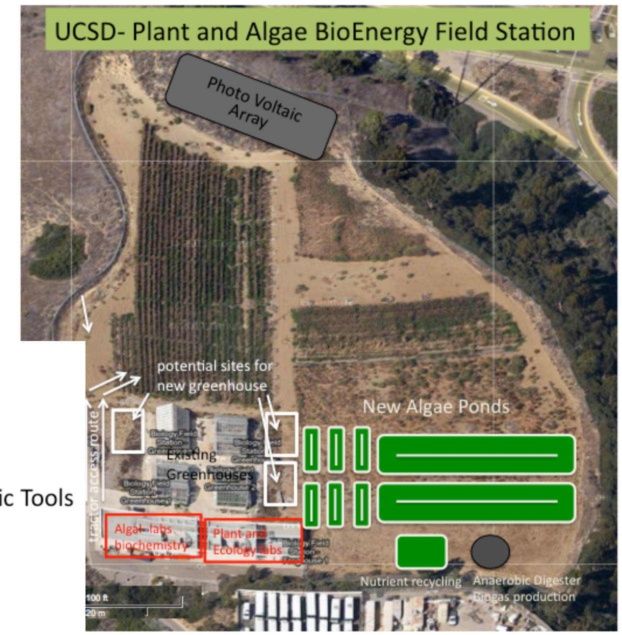
Next-generation biofuels





Will need 100’s of km^2 of Algae biofuel production…

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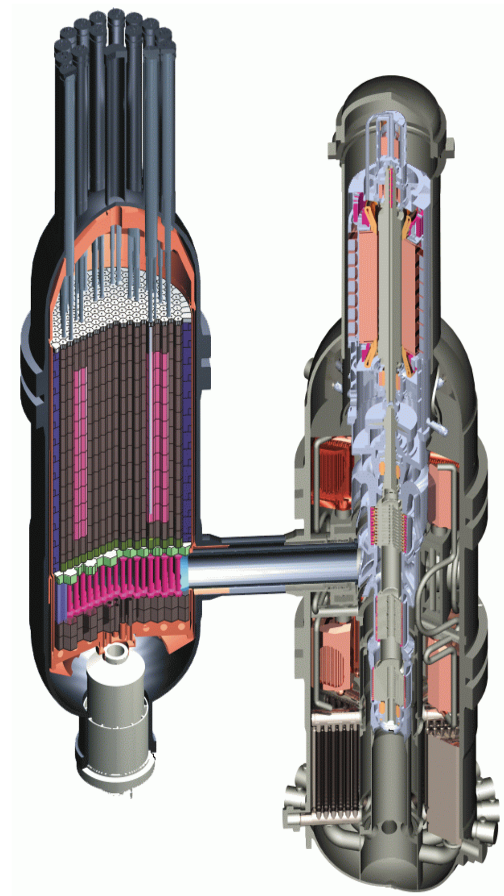
Next Generation Nuclear Fission

- Passively Safe Reactor Core
- Proliferation Resistant Fuel Cycle w/ Reprocessing
- Process Heat, H Production
- Electricity
- Geological Waste Disposal

Effort needed by 2055 for 1 wedge:

700 GW (twice current capacity) displacing coal power

Source: Sokolow Science 2004



Graphic courtesy of General Atomics

Part IV: How long does it take to grow these new energy source technologies **to the required scale**?

Look at How New Technologies Supplant Older Technologies in the Marketplace

This is a Well-studied Subject…

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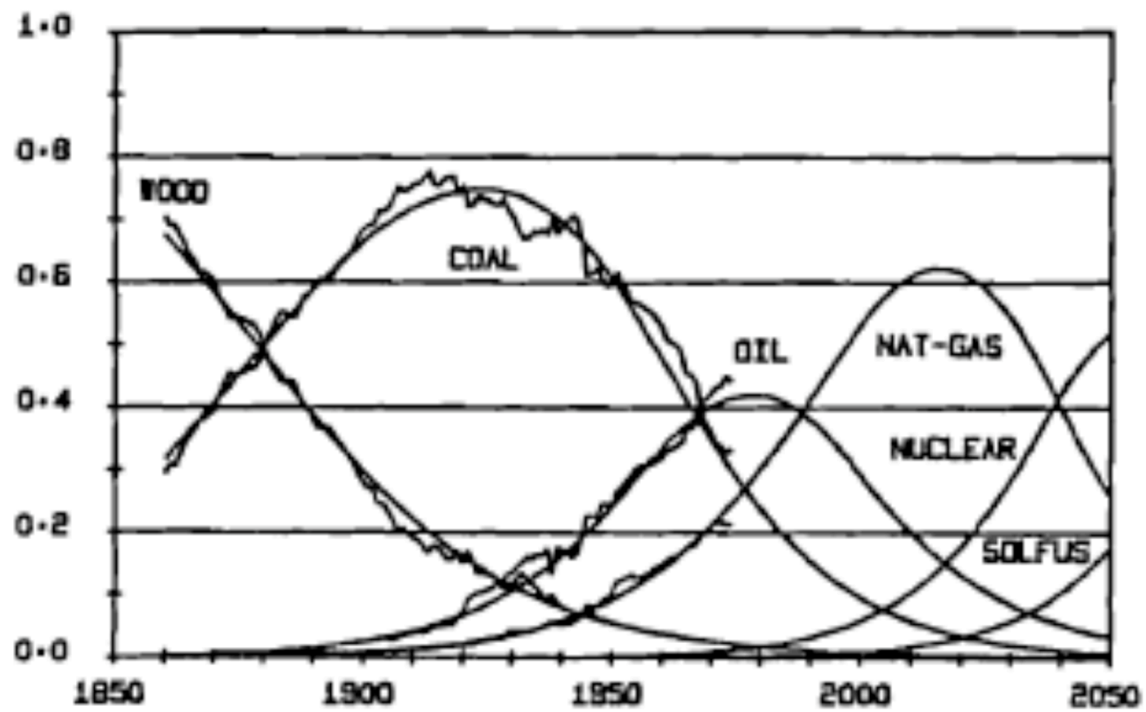
Methodology

- Take Historical Data for Absolute Energy Use
- Find Total Energy Demand v. Time
- Find f(t) for Each Energy Source
- Use Fischer-Pry Approach to Model Data
- Result…

Source: Marchetti, Tech. Forecasting and Social Change 10, 345-356 (1977)

Market Fraction - Primary Energy Sources - 1860-1980



Here the contributions of the various primary sources are shown as fractions of the total market. The smooth curves are two-parameter logistics assembled in a system of equations as described in the text. *The fitting appears perfect for historical data.*

Source: Marchetti, Tech. Forecasting and Social Change 10, 345-356 (1977)

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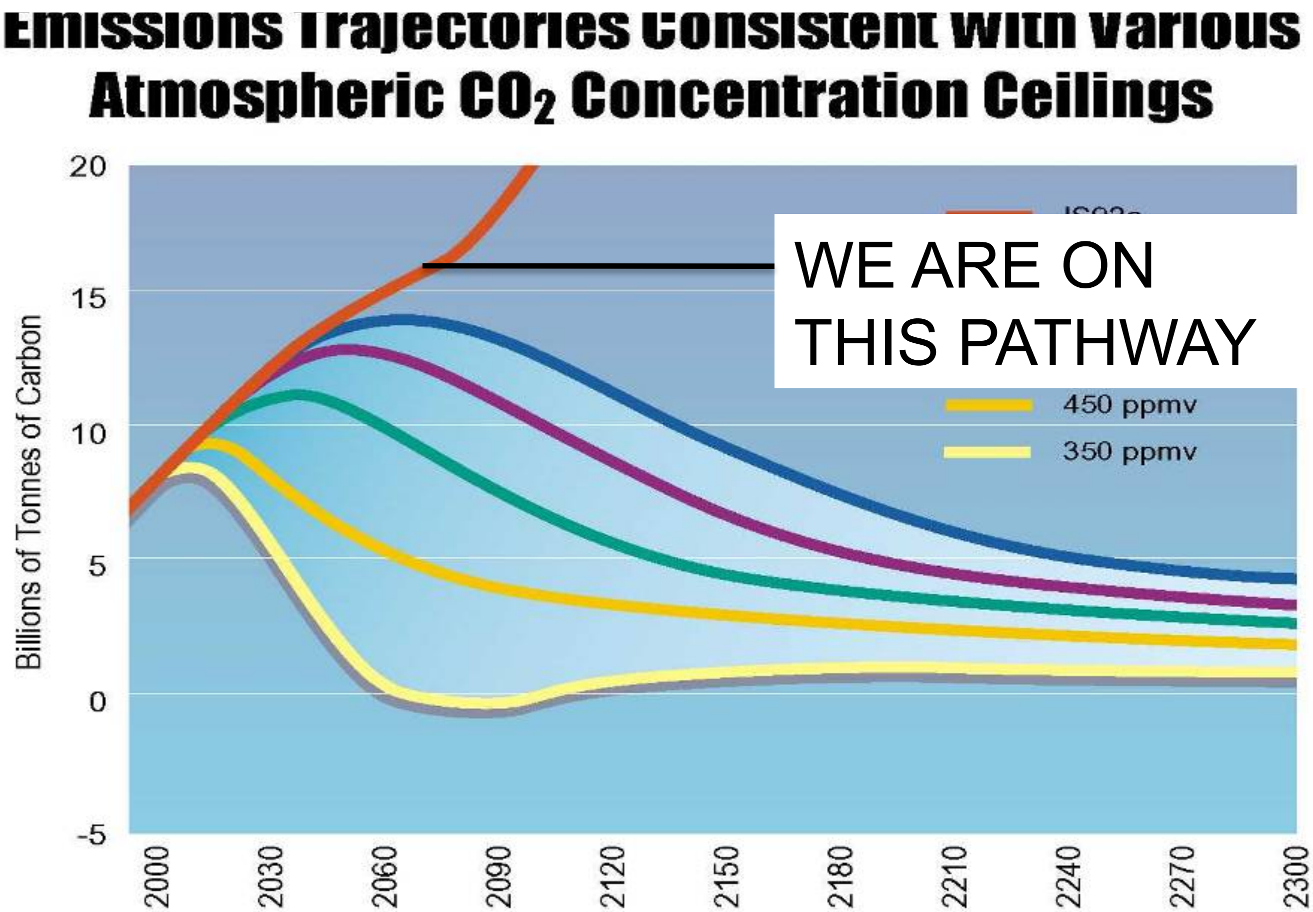
Takeover Times - Primary Energy Sources - 1860-1980

- Time to go from 1% to 50% of Energy Market Is Long (>50years!)

Primary Source	Penetration Time (years)
Wood	-60 years
Coal	66 years
Oil	52 years
Gas	95 years

Source: Marchetti, Tech. Forecasting and Social Change 10, 345-356 (1977)

But It's 2012 and our C Emissions are Still Growing(!)



Source: IPCC & J. Holdren 2007 AAAS Plenary Lecture

Q: What Can Be Done NOW?

Reduce Short Lived Climate Change Gases

project surya
Fighting Climate Change Now

3+ Billion Rely on Biomass Fuel

CER Center for Energy Research

V. Ramanathan, SIO

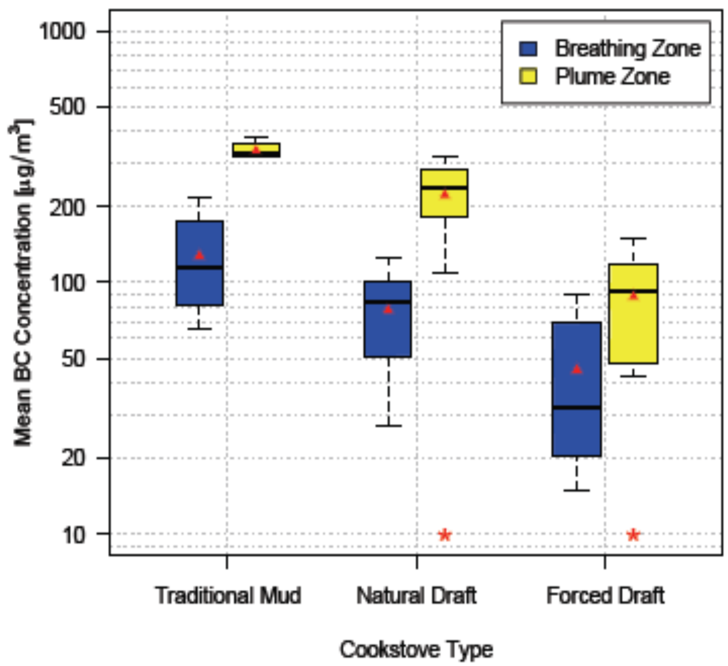
UC San Diego

The Surya Experiment

Mud Stove

For ~1000 Families

Improved Cookstove



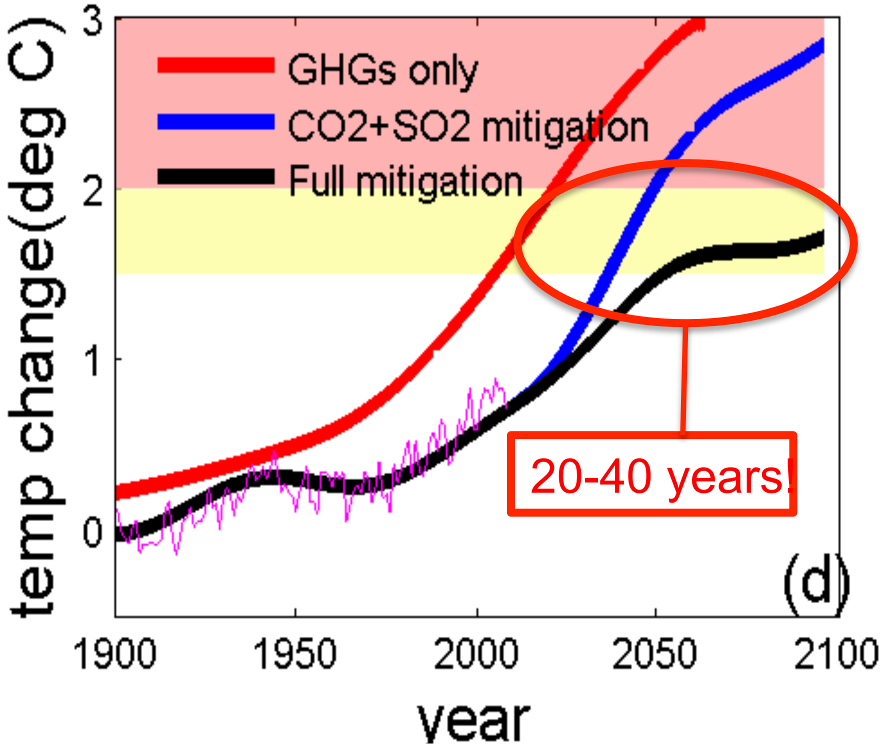
Measurements Demonstrate Large Pollutant Reductions with Global Implications…

V. Ramanathan, SIO

CER Center for Energy Research

UC San Diego

Wide-spread Adoption Delays >2deg C Warming



Ramanathan and Xu, PNAS 2010

HOW TO ENABLE RAPID SPREAD?

- Create Profit Incentive for Adopters
- Drive Down Costs
- **Enable Widespread Community-led Social Uptake**

Buys Critical Time for Energy Technology Transition & avoids 3M premature deaths/Year

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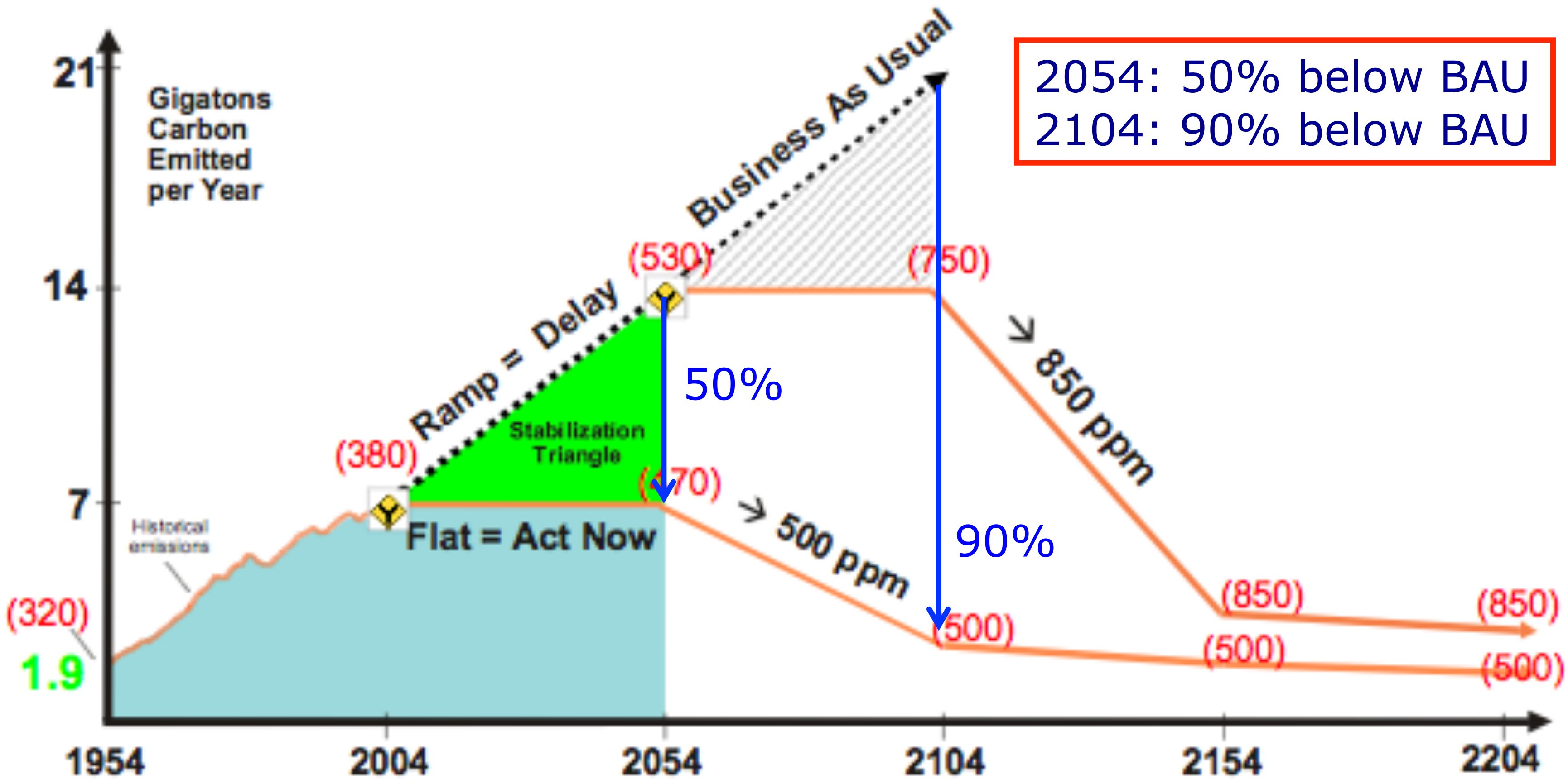
But Long-term, Carbon Emissions Must **Vanish**

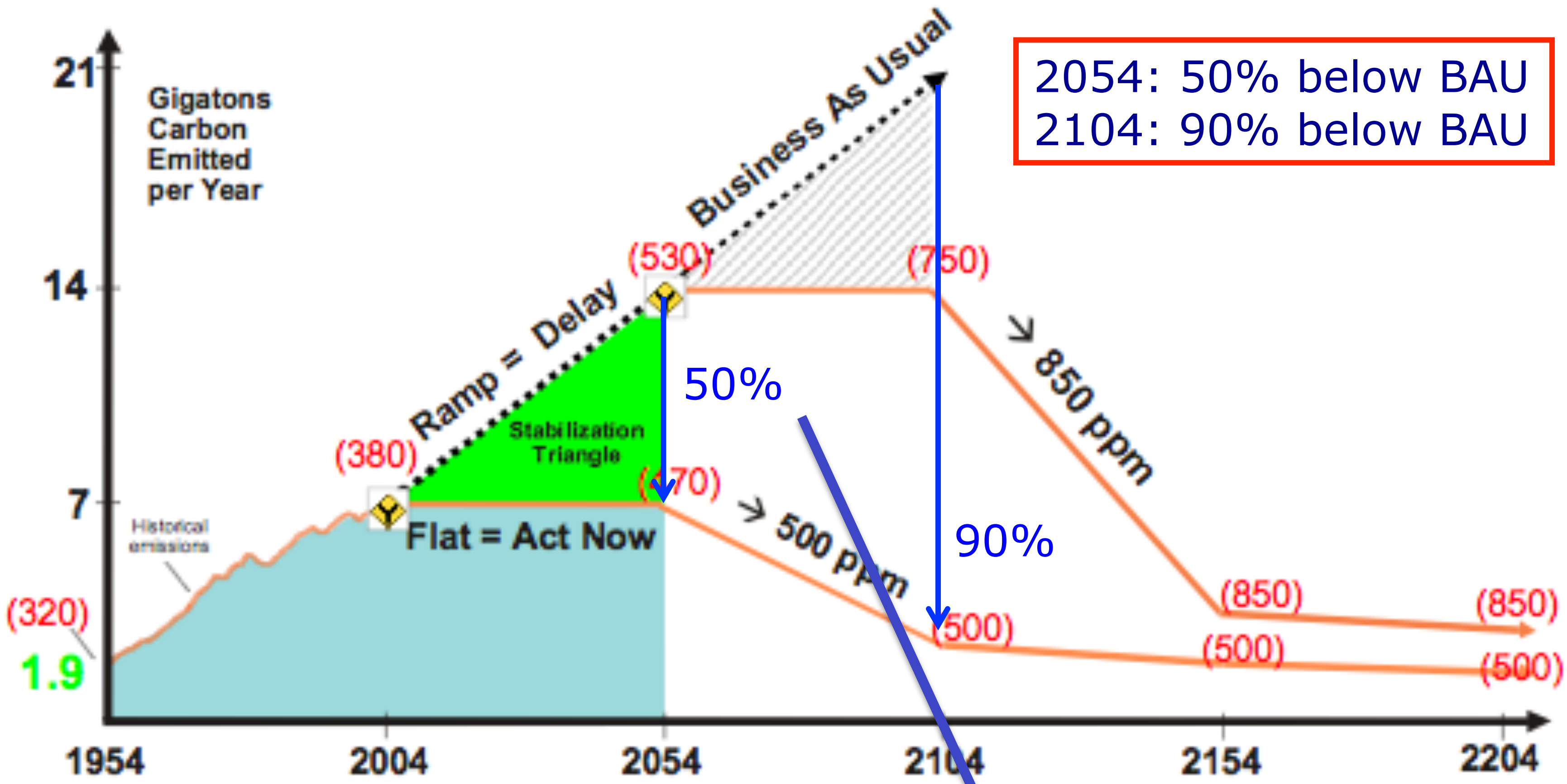
Source: Socolow, Princeton Univ.



Must Transition to a nearly C-free Energy Economy during Second Half of 21st Century!

BUT… Long-term Carbon Emissions Must **Vanish**

Source: Socolow, Princeton Univ.



2054: 50% below BAU
2104: 90% below BAU

This is where fusion Could play a role

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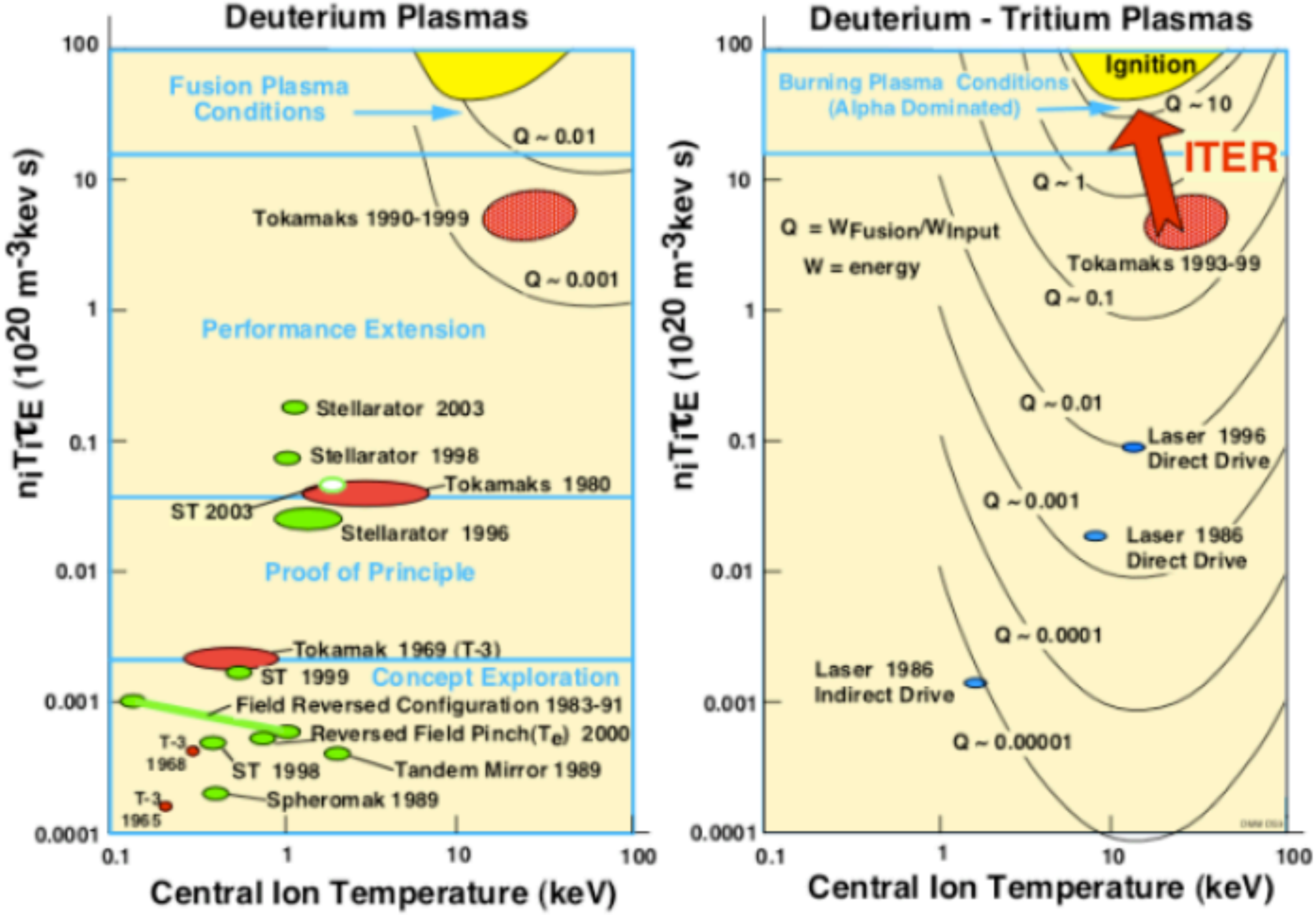
Progress towards fusion energy



Ref: Greenwald Report

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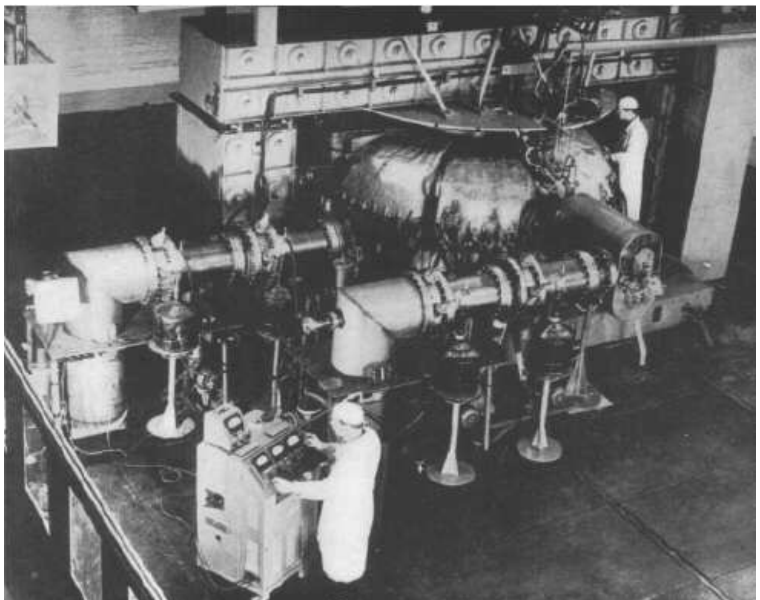
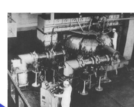
Tokamak evolution

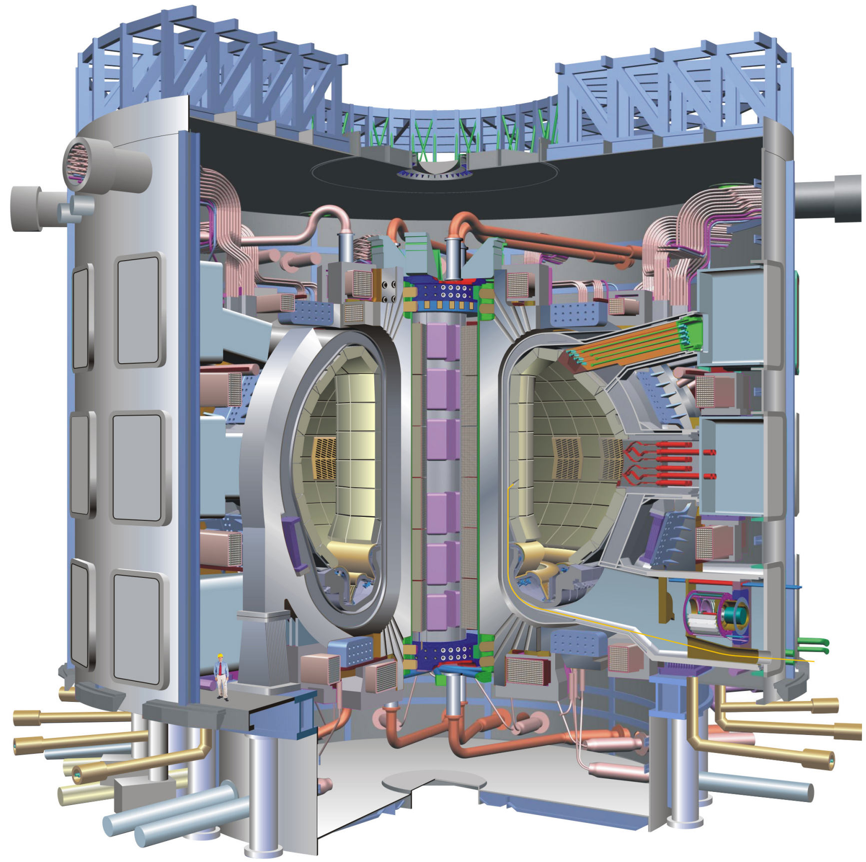
$Q \sim 10^{-7}$



T-3 (1960s USSR)



$Q \sim 10$



ITER (2020s)

to scale

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Key Issues for Fusion Energy Production

- Produce Plasmas w/ Sufficient Confinement & Pressure (Turbulence, MHD)
- Achieve Burning Status (Q>5 or so) (Fast Particle Physics)
- Produce Sufficient Tritium (Mat'ls, Nuclear Engineering)
- Maintain such a state indefinitely (Current Drive, PMI)
- Achieve very low disruption probability (<1disruption/year) & mitigate when disruption occurs
- Develop materials that survive radiation environment (Mat'l Science)

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Epilog: Why Fusion?

The World Desperately Needs An Energy Source with the Characteristics of Fusion but…

Even with Success in ITER, First Fusion Power Isn't Until ~2040 at earliest!

We CLEARLY also need all the other scaleable sources & efficiency improvements

We Need to Take the Long View

Today's Decisions Have Long Term Consequences