Combustion in a Global Environmental Context

Part Two: Stabilization Wedges

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Part Two: Stabilization Wedges

The Wedge Model

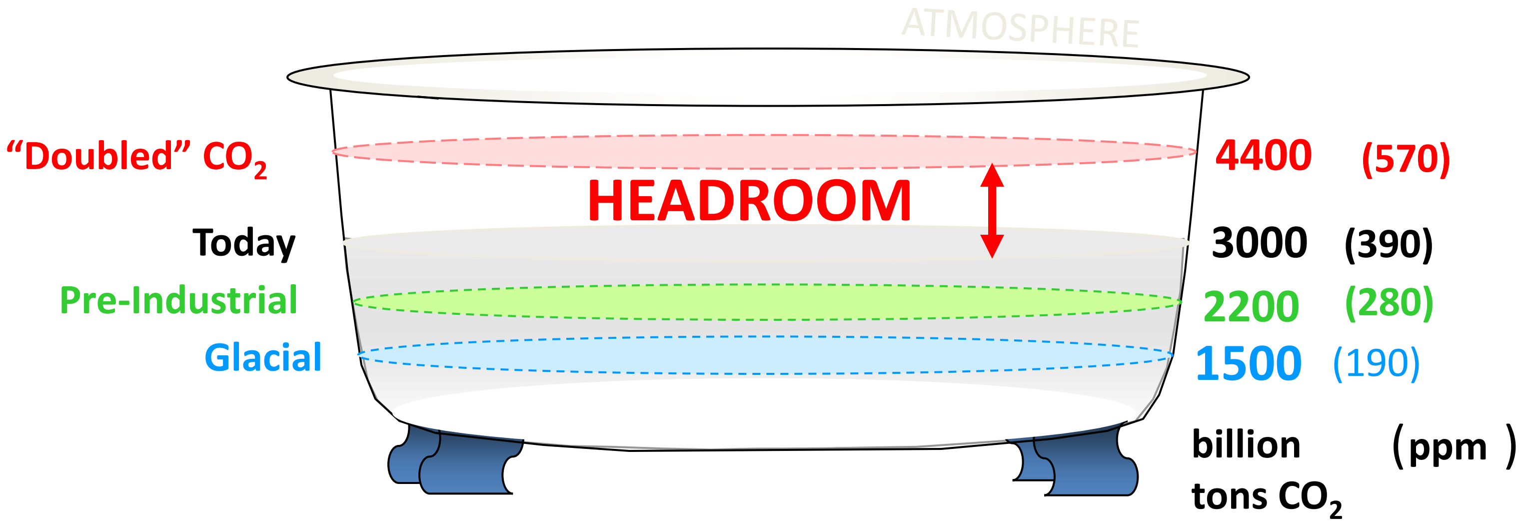
The Abundance of Fossil Fuels

Specific Stabilization Wedges

Decentralized energy conversion

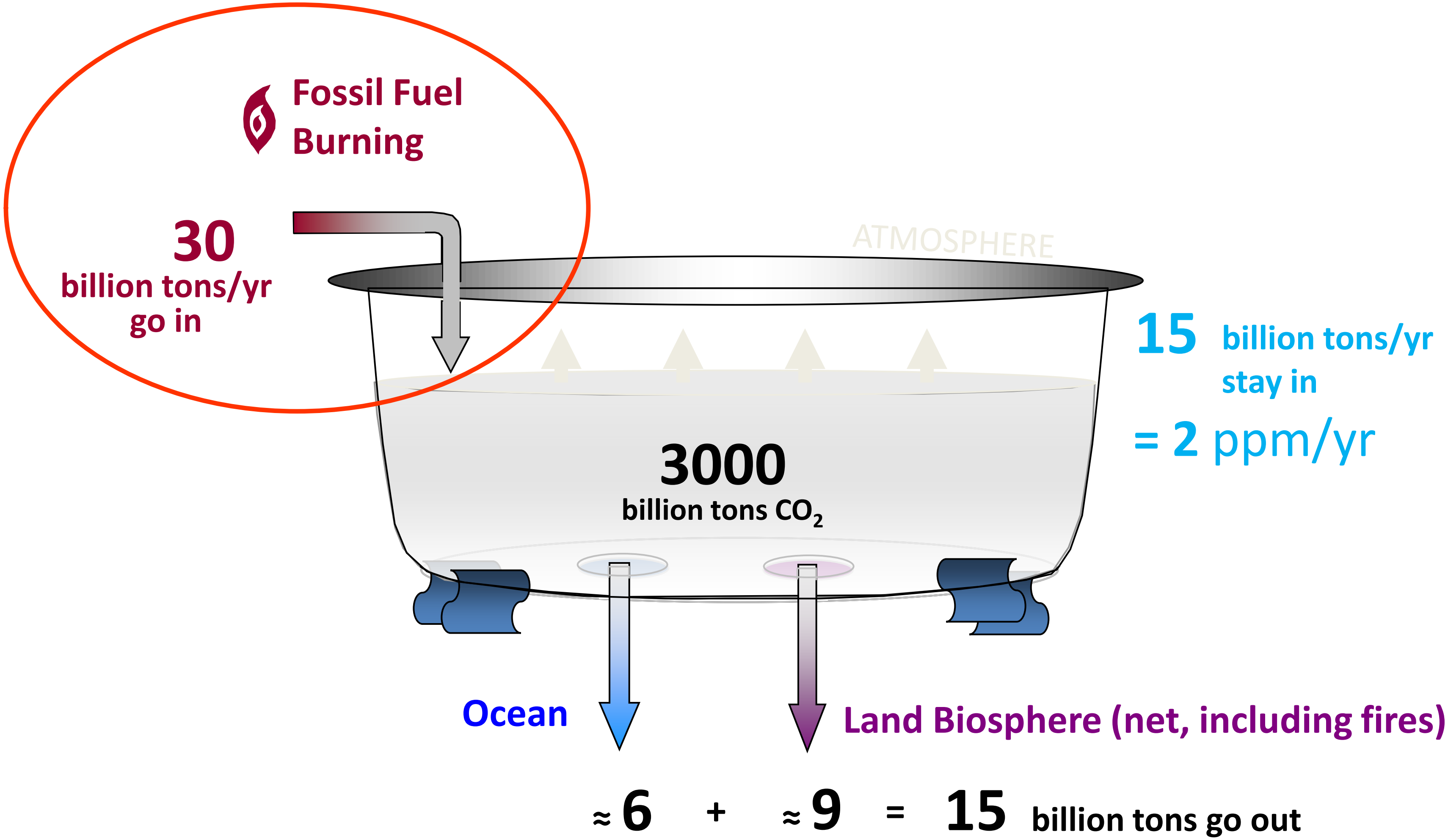
Centralized energy conversion

Past, present, and potential future levels of CO_2 in the atmosphere



In Part Two, we look at roles for technology.

Sources and sinks of CO_2



Today, global per-capita emissions are ≈ 4 tCO_2/yr.

The Wedge Model

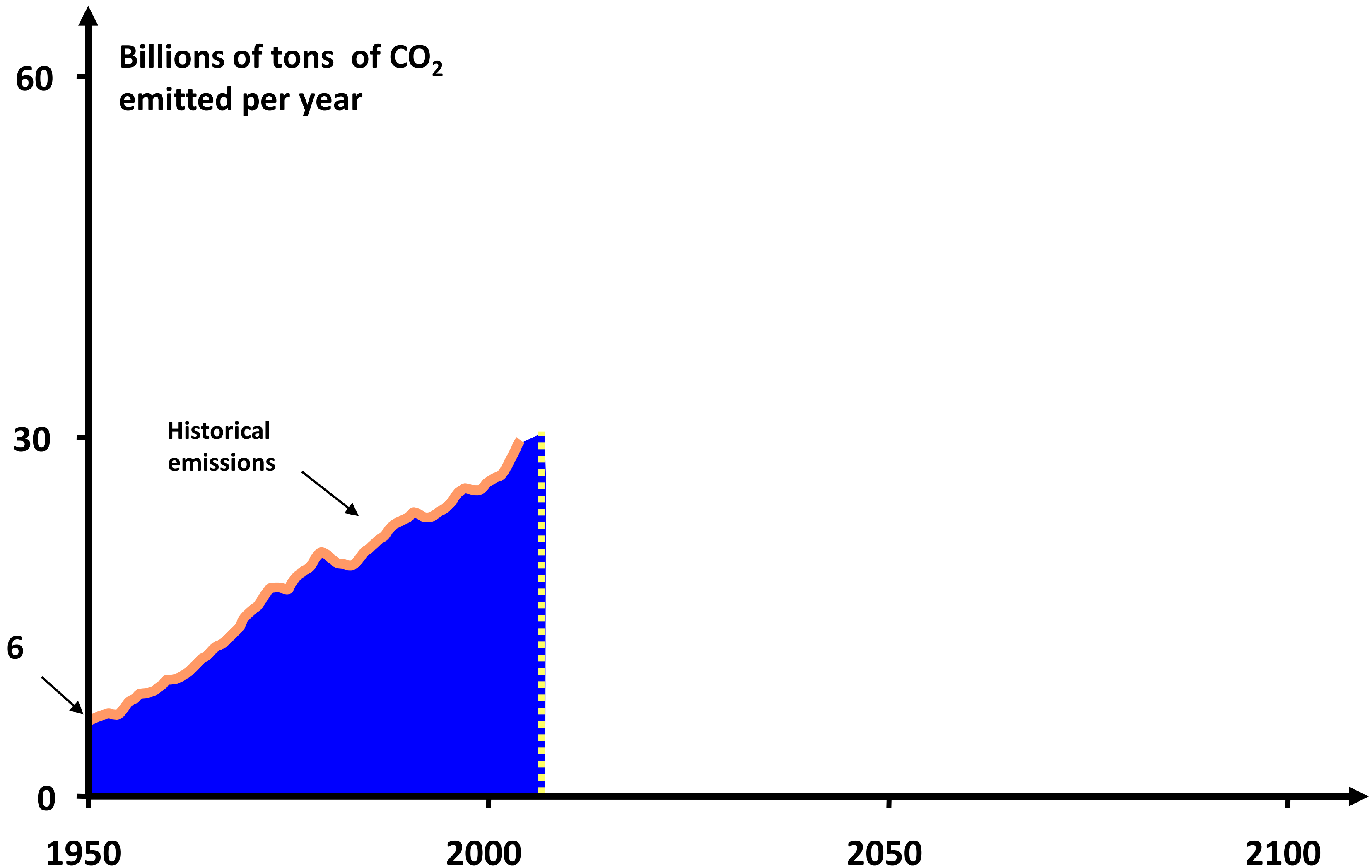
Co-author: Steve Pacala

Articles:

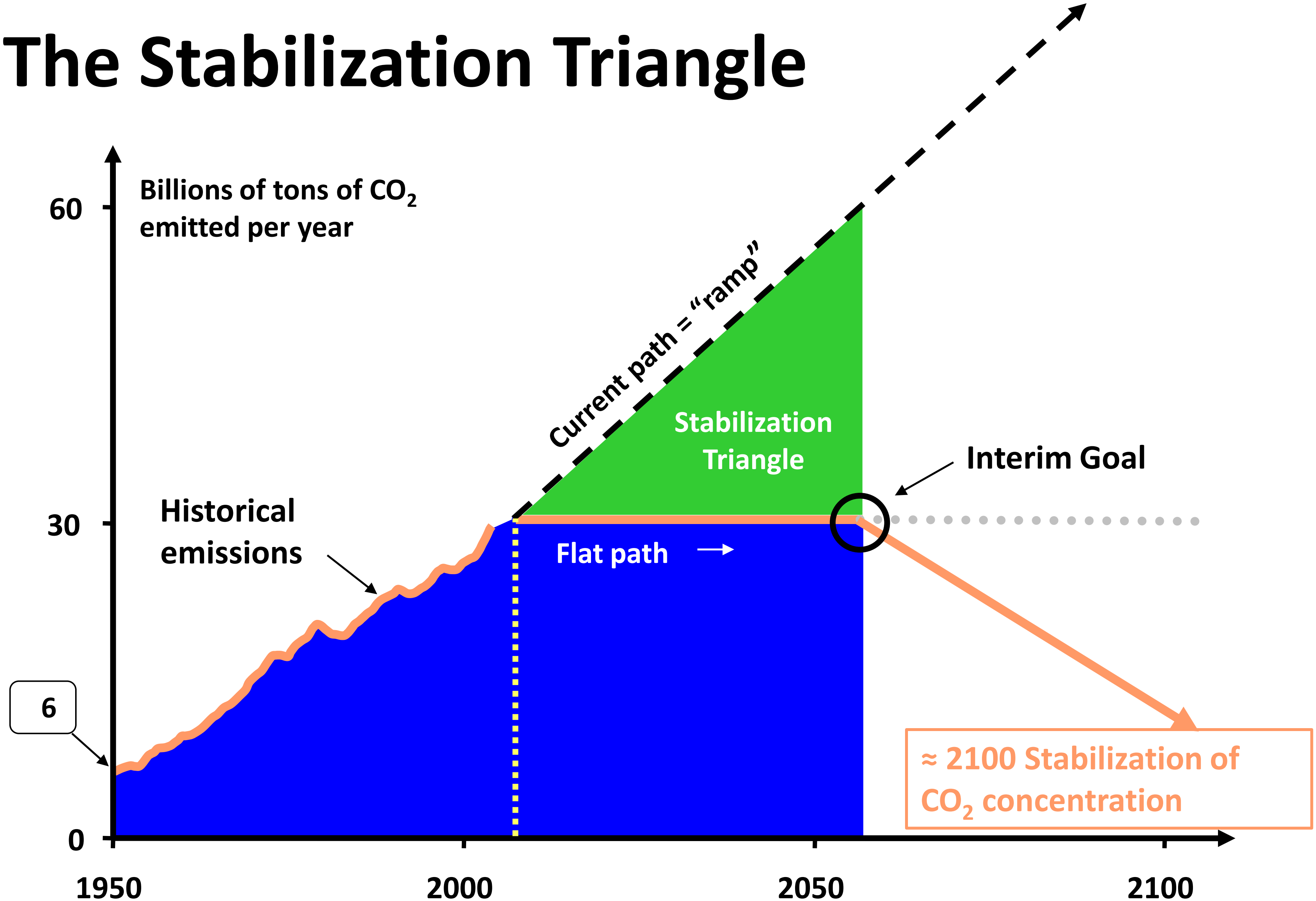
Science (2004)

Scientific American (2006)

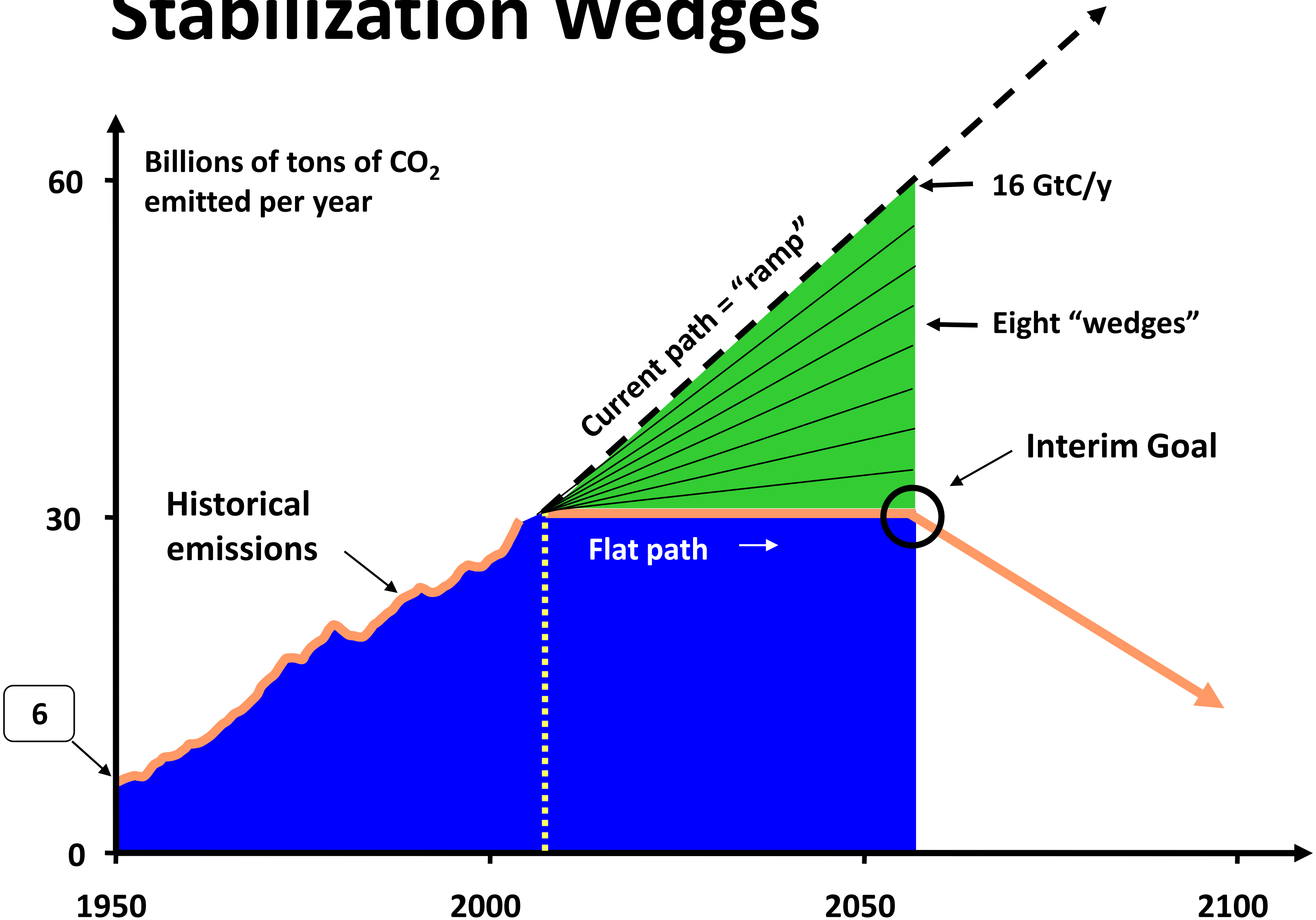
Historical Emissions



The Stabilization Triangle

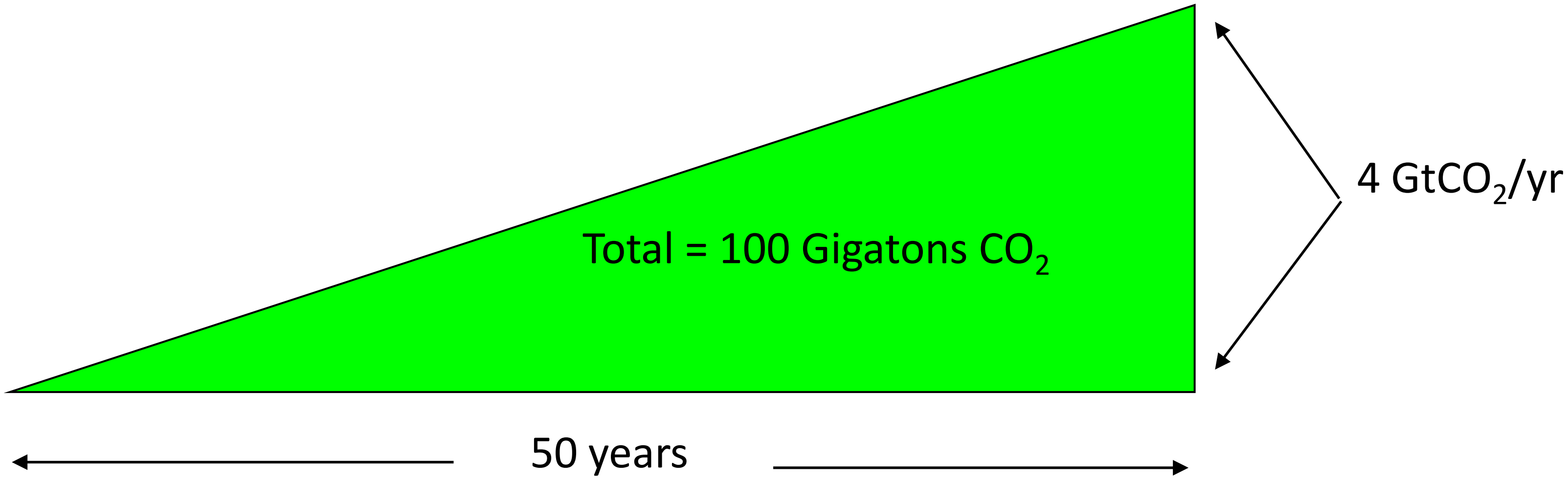


Stabilization Wedges



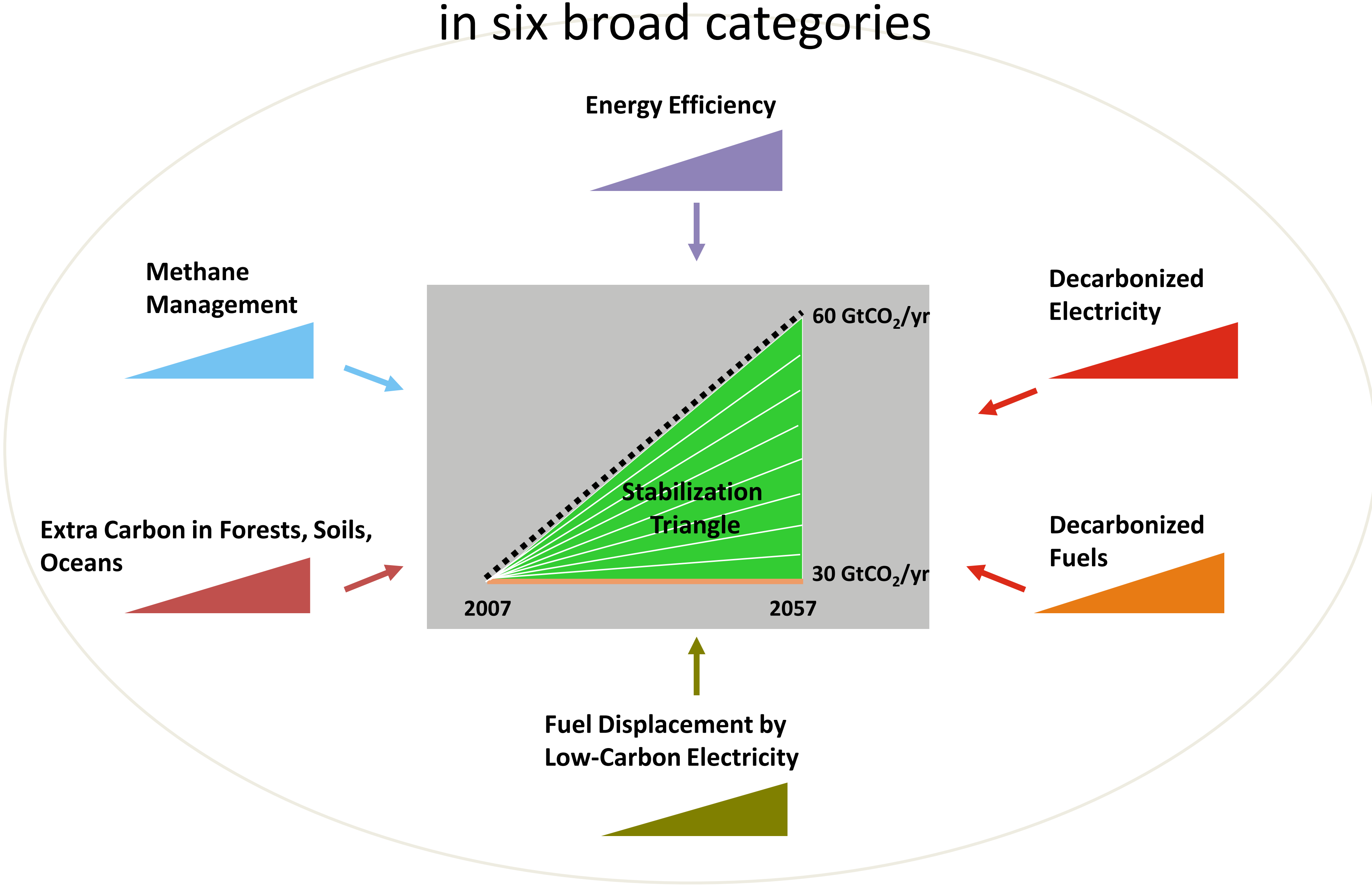
What is a "Wedge"?

A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to 4 $GtCO_2$/yr. The strategy has the potential to be commercialized at very large scale.

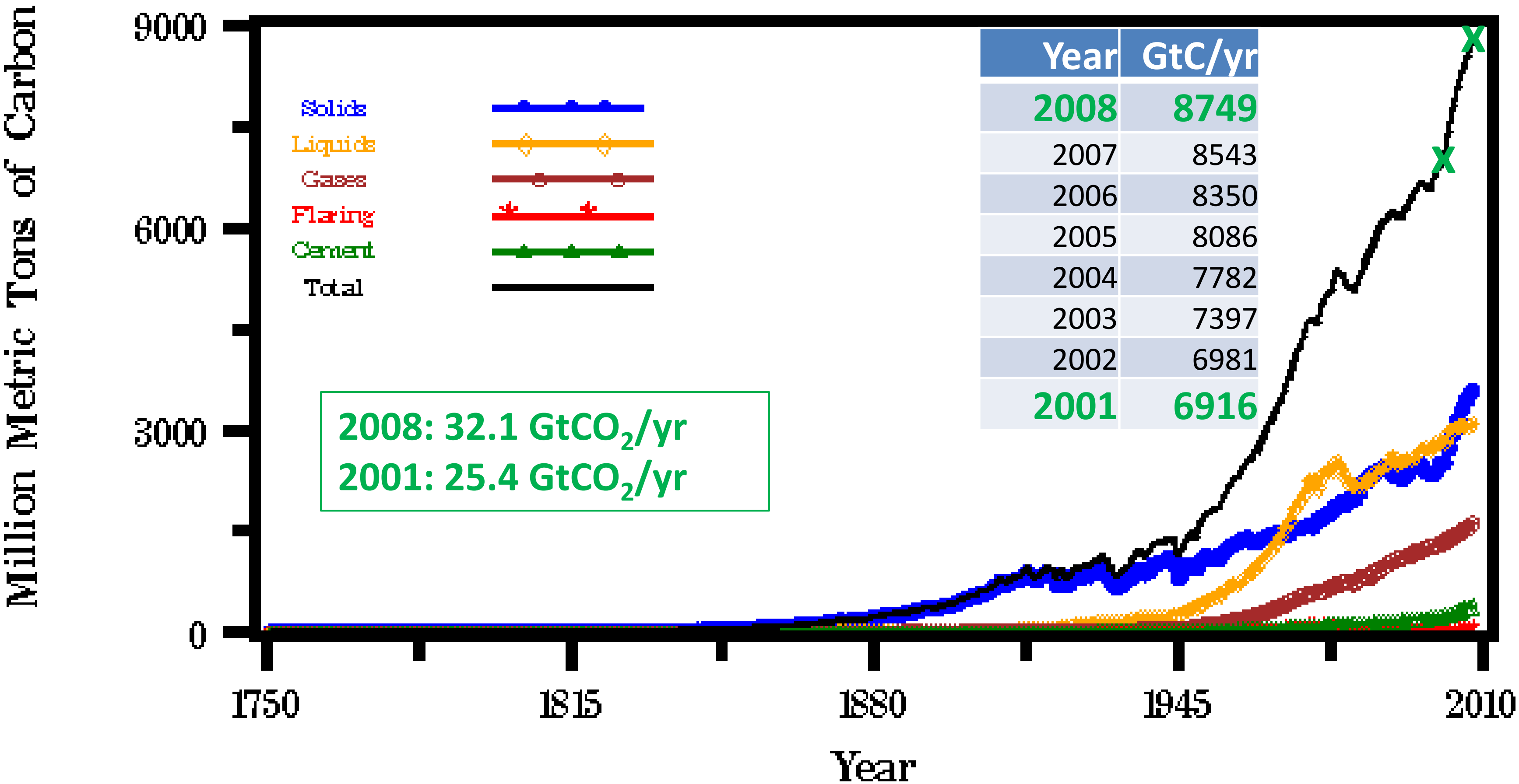


A wedge avoids the emissions of 100 $GtCO_2$. This is six trillion dollars at $60/$tCO_2$.

Fill the Stabilization Triangle with Wedges in six broad categories

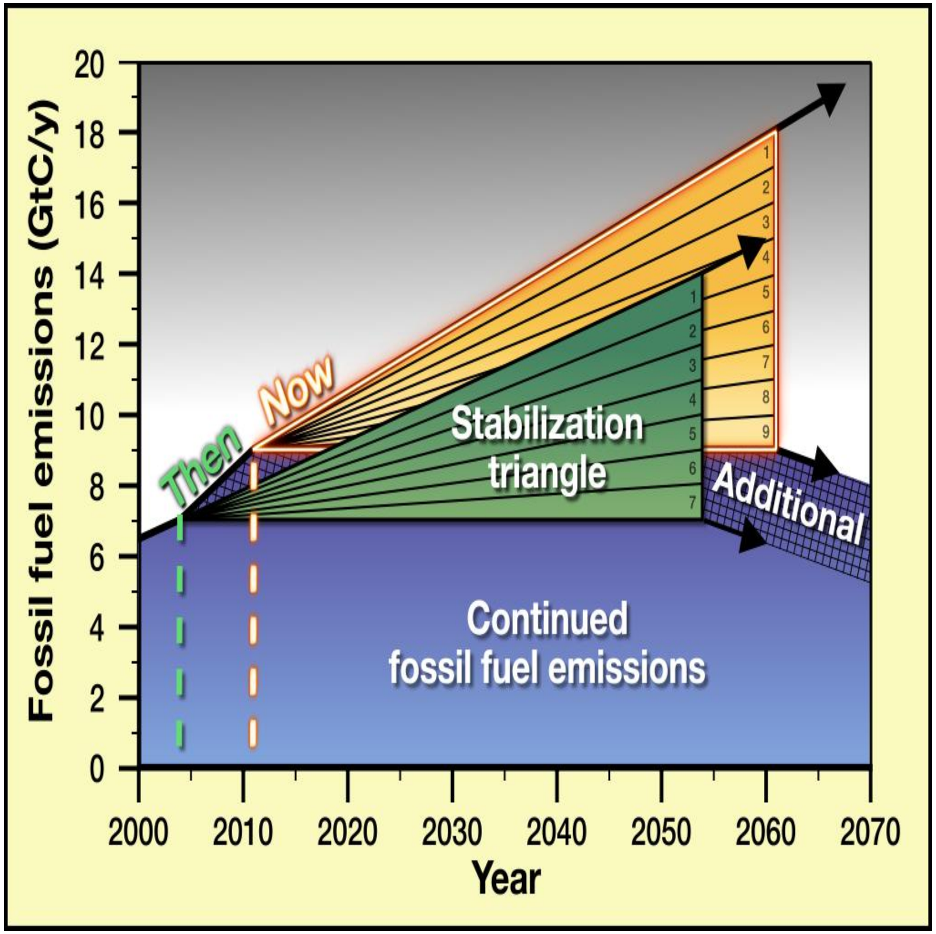


Seven, eight, nine wedges

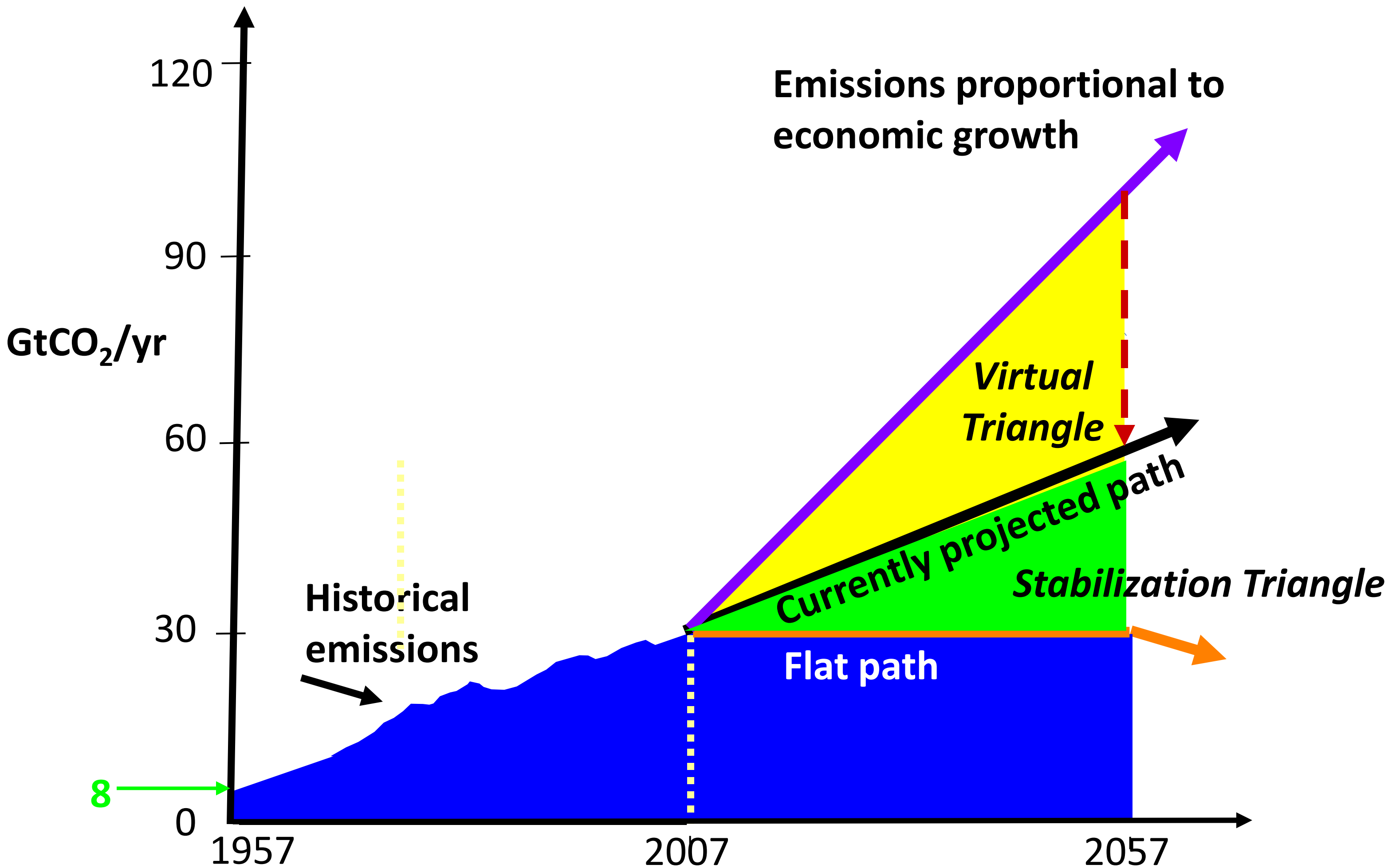


Source (accessed 10/1/11): http://cdiac.ornl.gov/trends/emis/glo.html.

2011 *vs*, 2004:
Nine wedges *vs*. seven

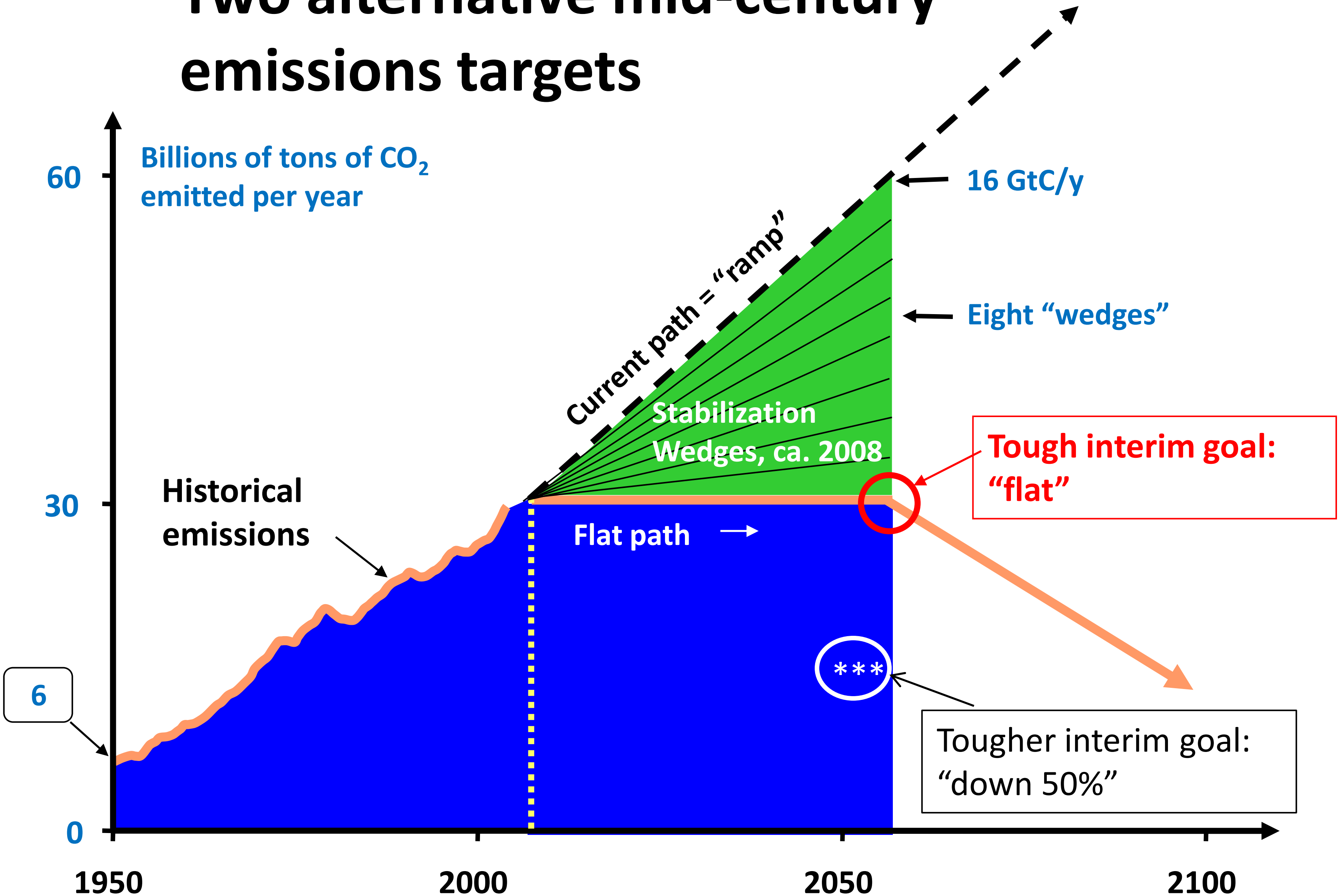


The Virtual Triangle: Large Carbon Savings Are Already in the Baseline

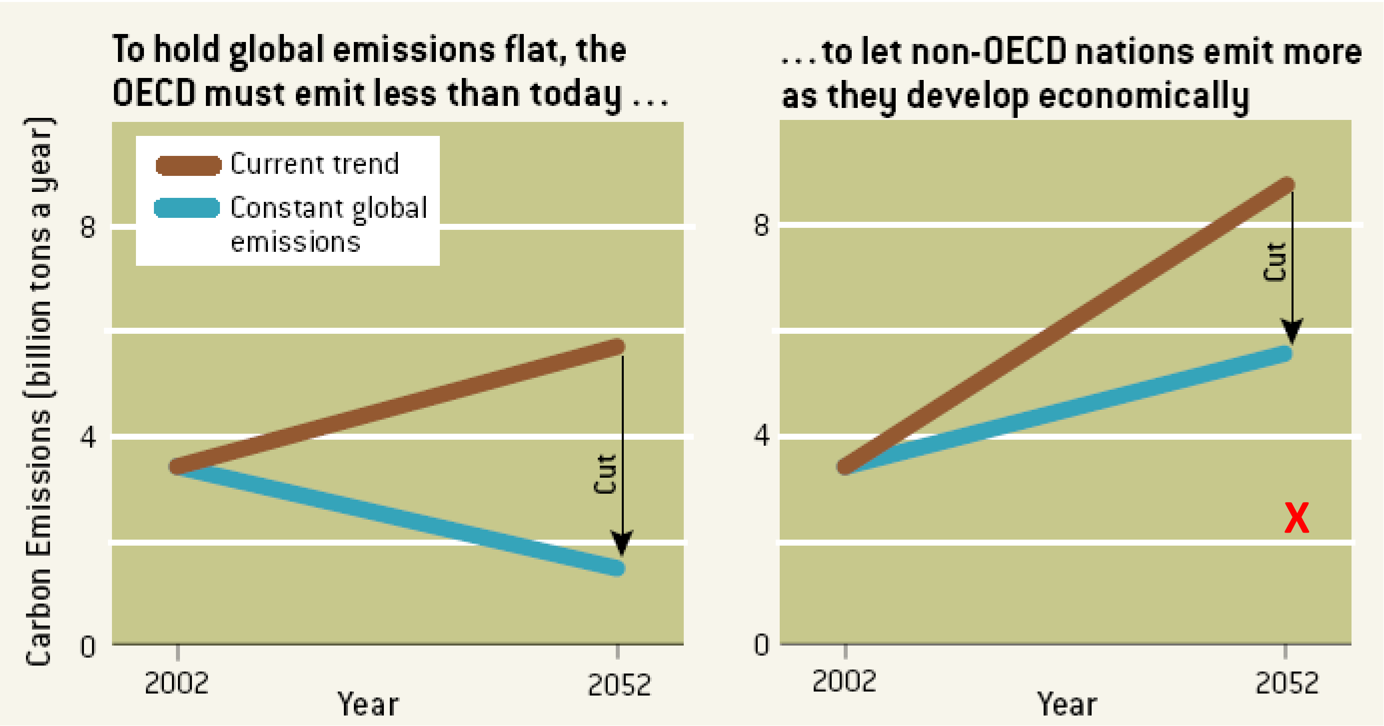


Models differ widely in their estimates of contributions to the virtual triangle from structural shifts (toward services), energy efficiency, and carbon-free energy.

Two alternative mid-century emissions targets



"Flat" vs. "down 50%" is mostly about the developing world's emissions



Up 60% or down 60%

Up 140% or up 60%, ***or down 40%***

Urgently needed: analyses of low-carbon industrialization.

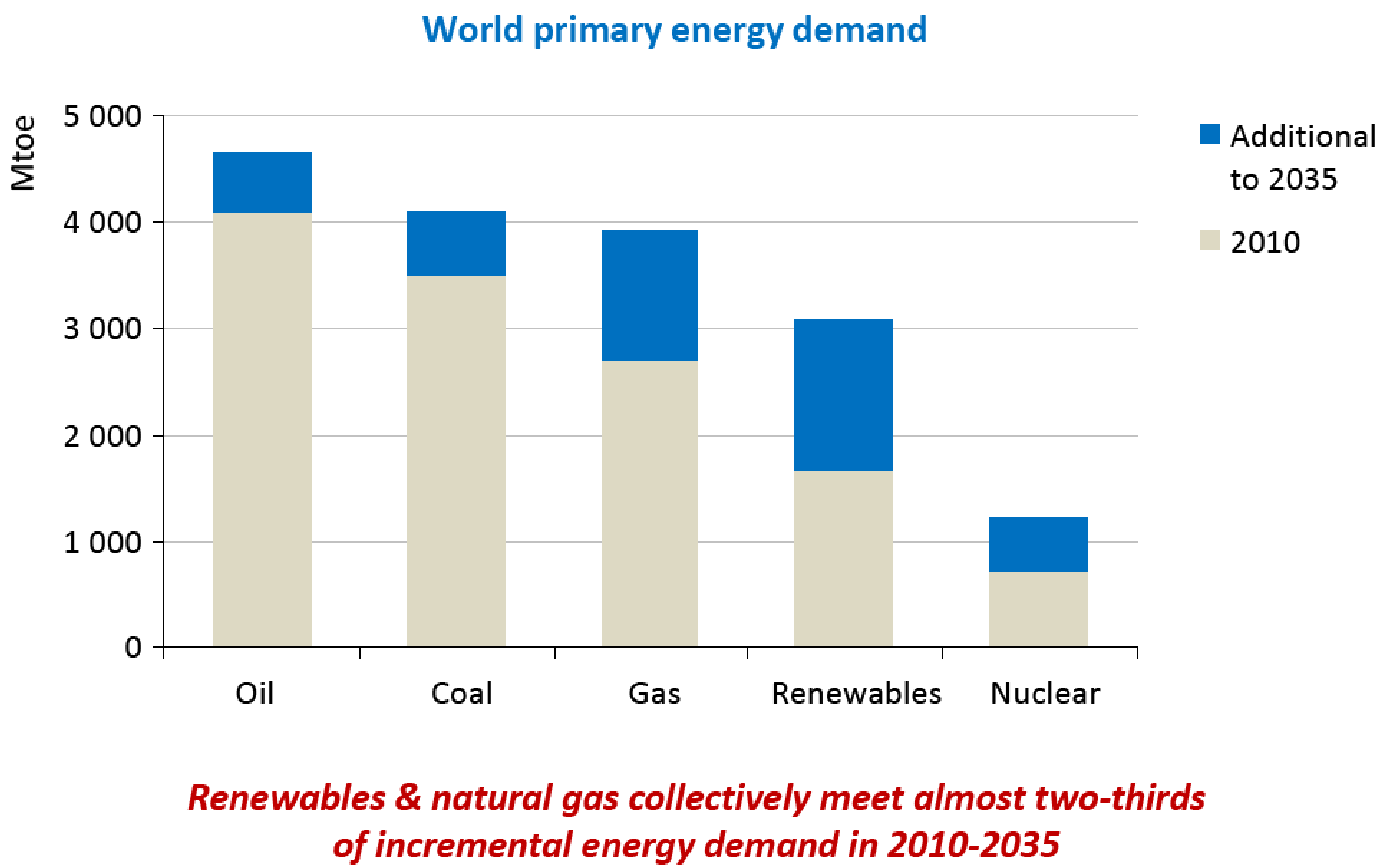
Source of Figure: Socolow and Pacala, "A plan to keep carbon in check," *Scientific American*, Sept 2006.

The Abundance of Fossil Fuels

Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO	A nuclear or renewables world unmotivated by climate.	Most people in the fuel industries and most of the public are here. **5^{o}C.**
	YES	Environmentalists, nuclear advocates are often here. **2^{o}C.**	OUR WORKING ASSUMPTIONS. **3^{o}C, tough job.**

80% of primary energy is fossil fuel today, maybe 75% in 2035



1 toe = 1 “ton of oil equivalent” = 41.86 GJ.

Source: International Energy Agency, *World Energy Outlook 2011*

Why is there energy below ground?

We are reverse ancient photosynthesis:

Simplest explanation:

In ancient times:

$$\Delta + CO_2 + H_2O \rightarrow HCO_2 + O_2$$

Now:

$$\Delta + CO_2 + H_2O \leftarrow HCO_2 + O_2$$

Δ is energy.

More accurately…

We mostly find hydrocarbons, so there were further changes:

$CH_2O \rightarrow C_xH_y$.

Also, for liquids and gases, obstructed upward movement and concentration.

Carbon intensity: Coal > oil > gas

Table 12.6 Typical carbon and energy content of fossil fuels.

C/E

Energy Source	Carbon Content (Weight %C)	Heating Value (kJ/g)[a]	Carbon Intensity (g C/MJ)[a]
Natural gas	74	54.4	13.7
Crude oil	85	44.3	19.2
Coal	59[b]	24.2	24.4

[a] Based on higher heating value (HHV). The lower heating value (LHV) is approximately 10% lower for natural gas and 5% lower for coal and crude oil. Use of the LHV would *increase* the carbon intensity value of each fuel by these percentages.

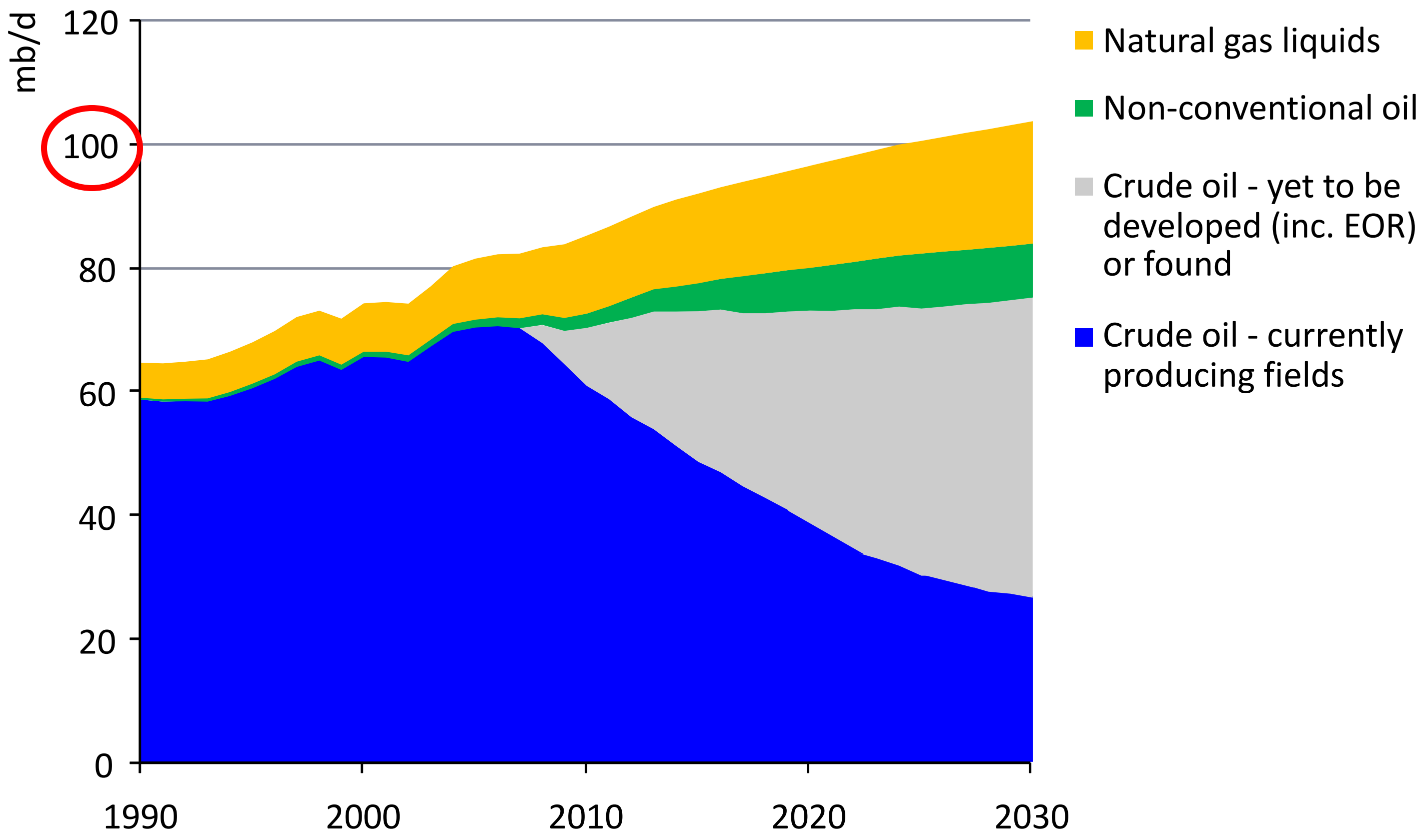
[b] Values vary by about ±30% for different coal types.

Source: USDOE, 1998; IPCC, 1996b.

***Note*: C/E ≈ 0, *nominally*, for hydro, wind, biofuels, nuclear.**
***Actual* values are situation-dependent, especially for biofuels.**

Rubin, p. 519

World oil production by source in the WEO 2008 Reference Scenario

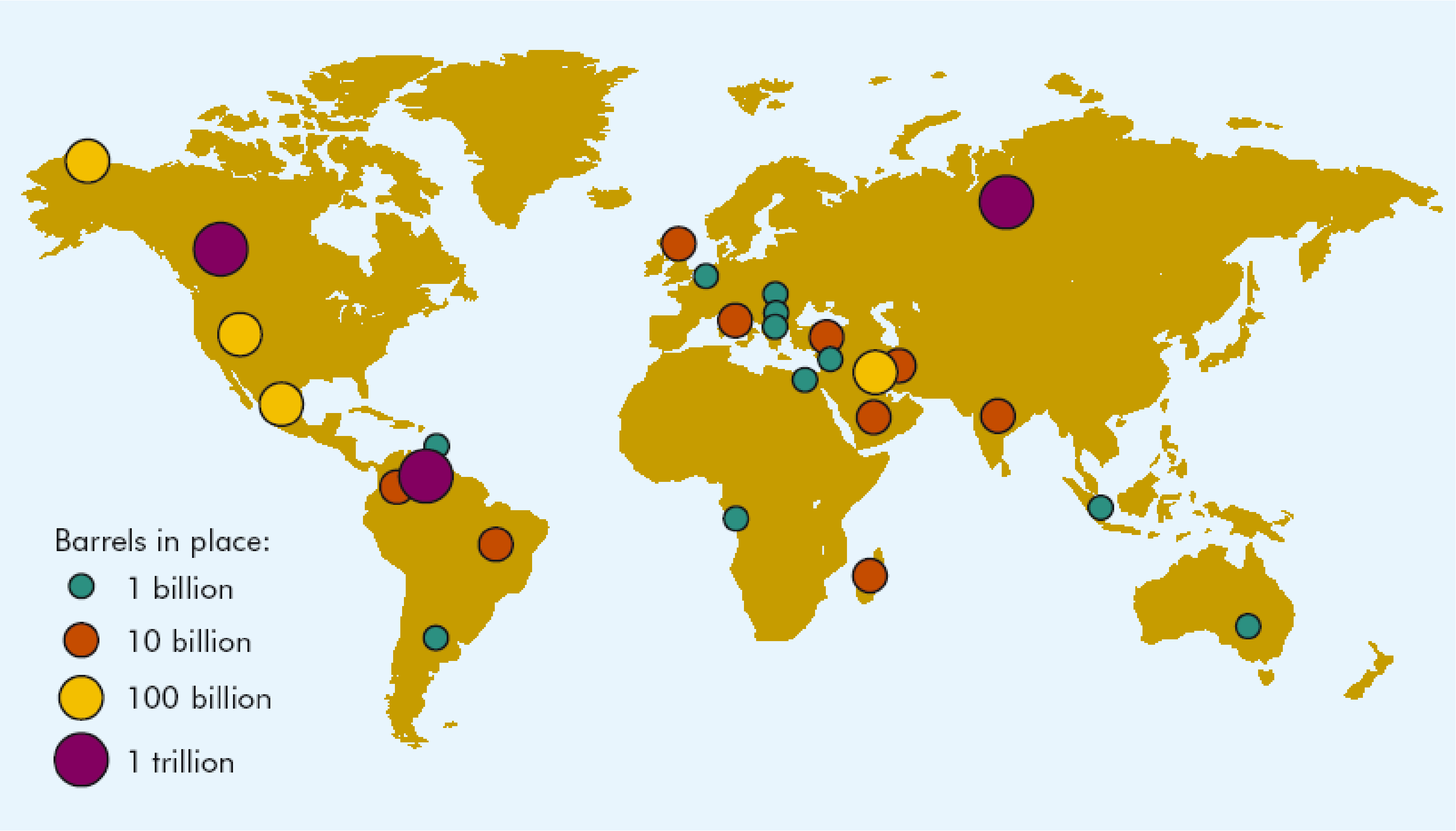


Even if oil demand was to remain flat to 2030, 45 mb/d of gross capacity – roughly four times the capacity of Saudi Arabia – would be needed just to offset decline from existing oilfields

Source: International Energy Agency, *World Energy Outlook* ***2008***

A World That Could Long Remain Dominated by Fossil Fuels: The Alberta Tar Sands

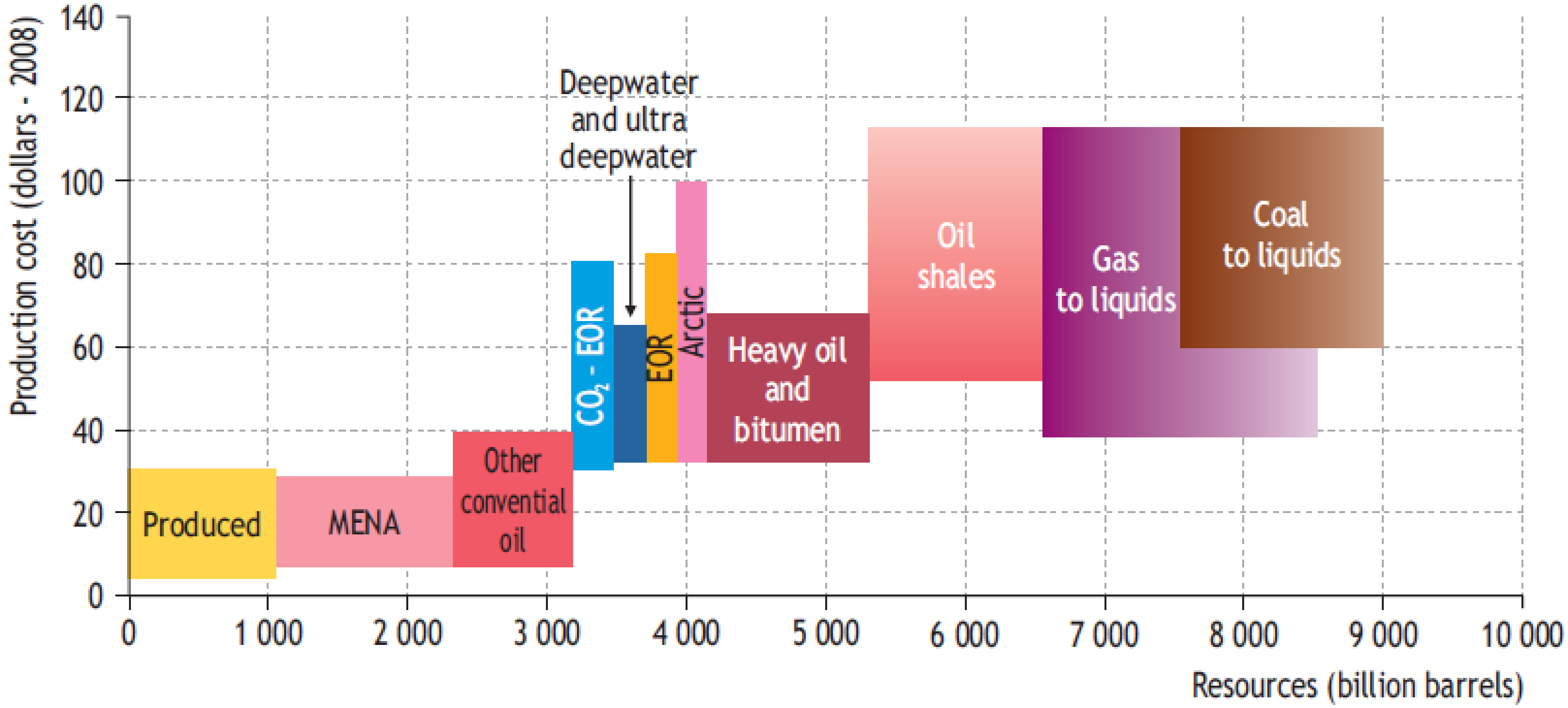
Heavy Oil Resources in the World



Reproduced in Resources to Reserves *with kind permission from the Energy Institute, originally published in* Modern Petroleum Technology (**www.energyinstpubs.org.uk**)*, with thanks also to Maurice Dusseault, University of Waterloo, Canada, for pointing out this figure.*

Source: Vierbuchen (Exxon), talk at Princeton, fall 2005

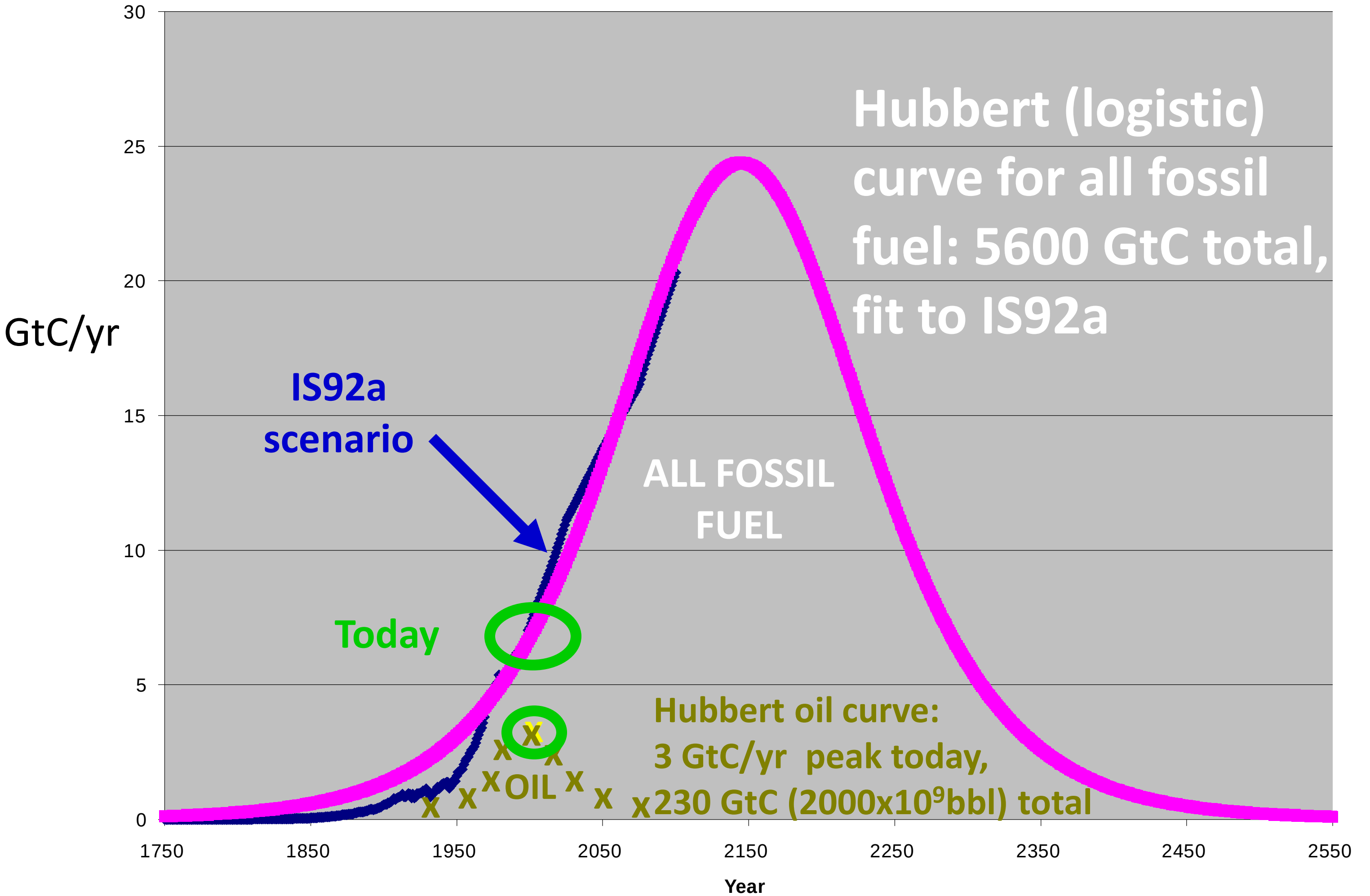
Long-term oil-supply cost curve, with GTL and CTL



The total recoverable oil-resource base is estimated at 9 trillion barrels (including 2.5 trillion barrel of GTL/CTL) of which we have so far produced 1.1 Tb

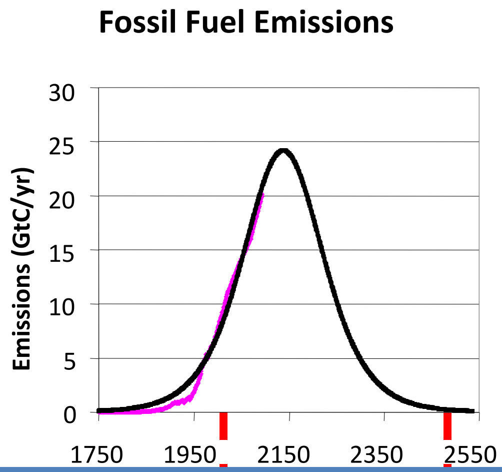
***Source*: International Energy Agency, *World Energy Outlook* 2008**

Conventional oil: a negligible fraction of fossil fuel

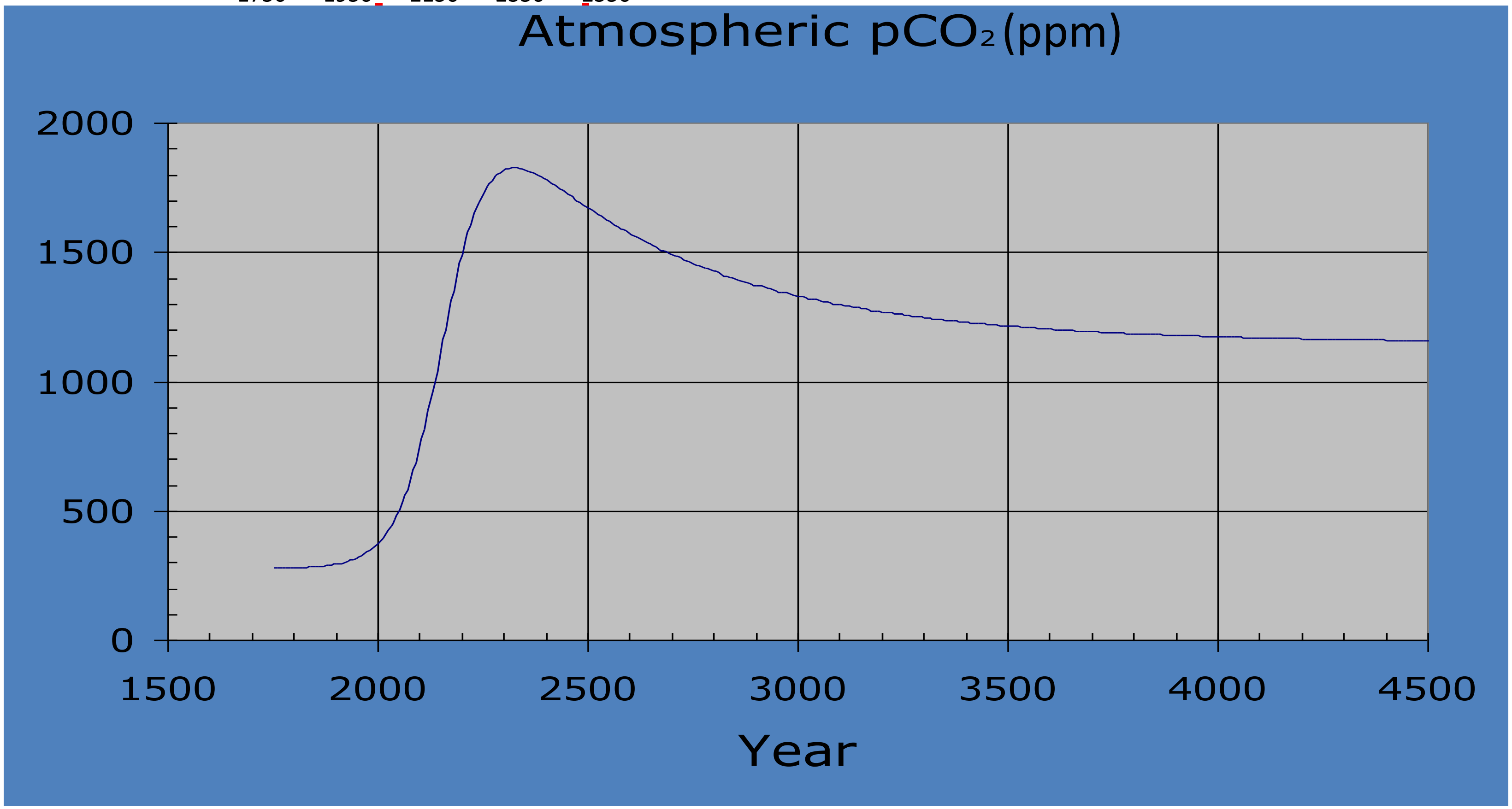


Source for "all fossil fuel": Bryan Mignone

Atmospheric CO_2 with 5600 GtC emissions

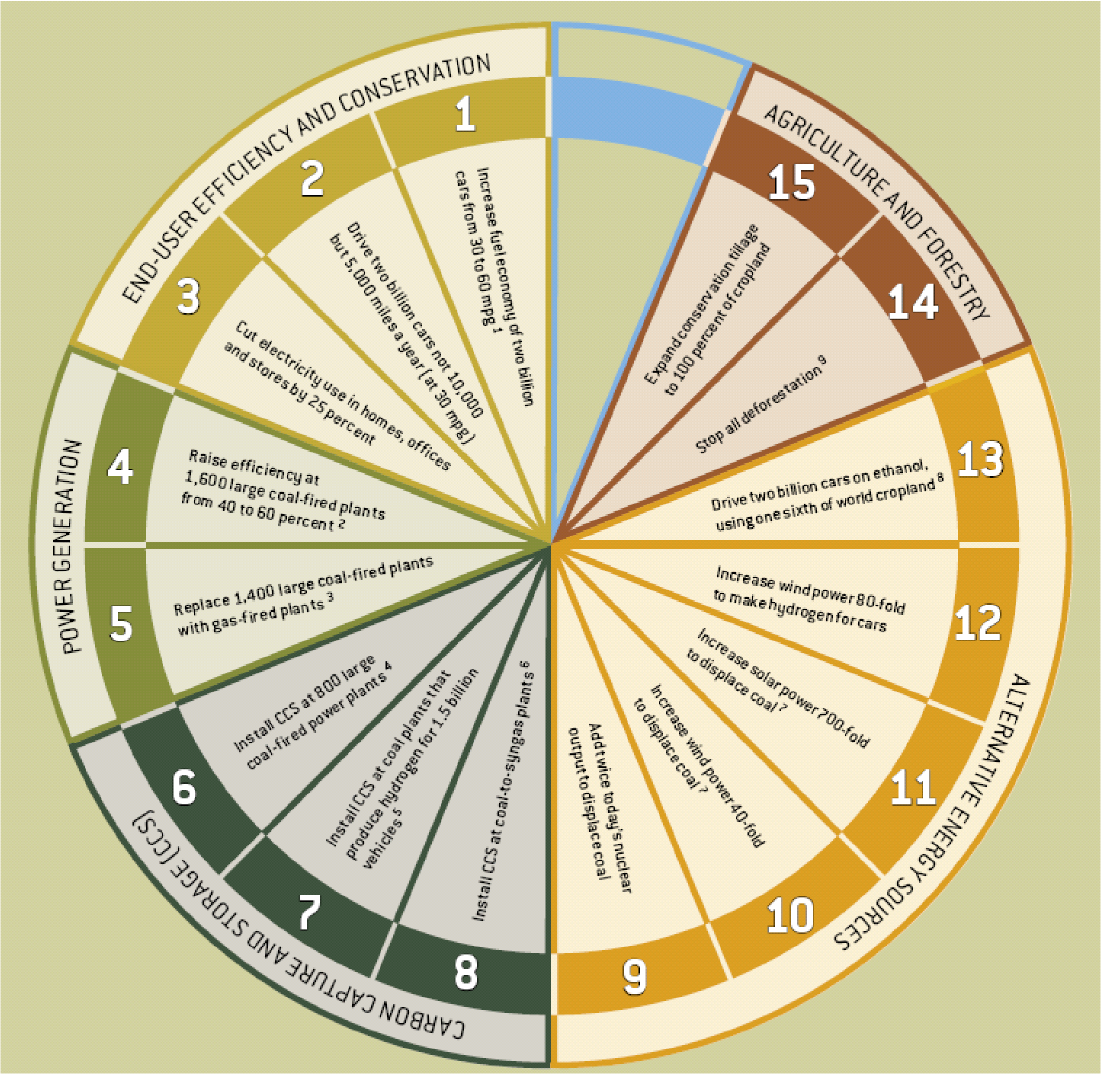


Integral ≈ 5,000 GtC ≈ 20,000 $GtCO_2$ → 10^{o}C.



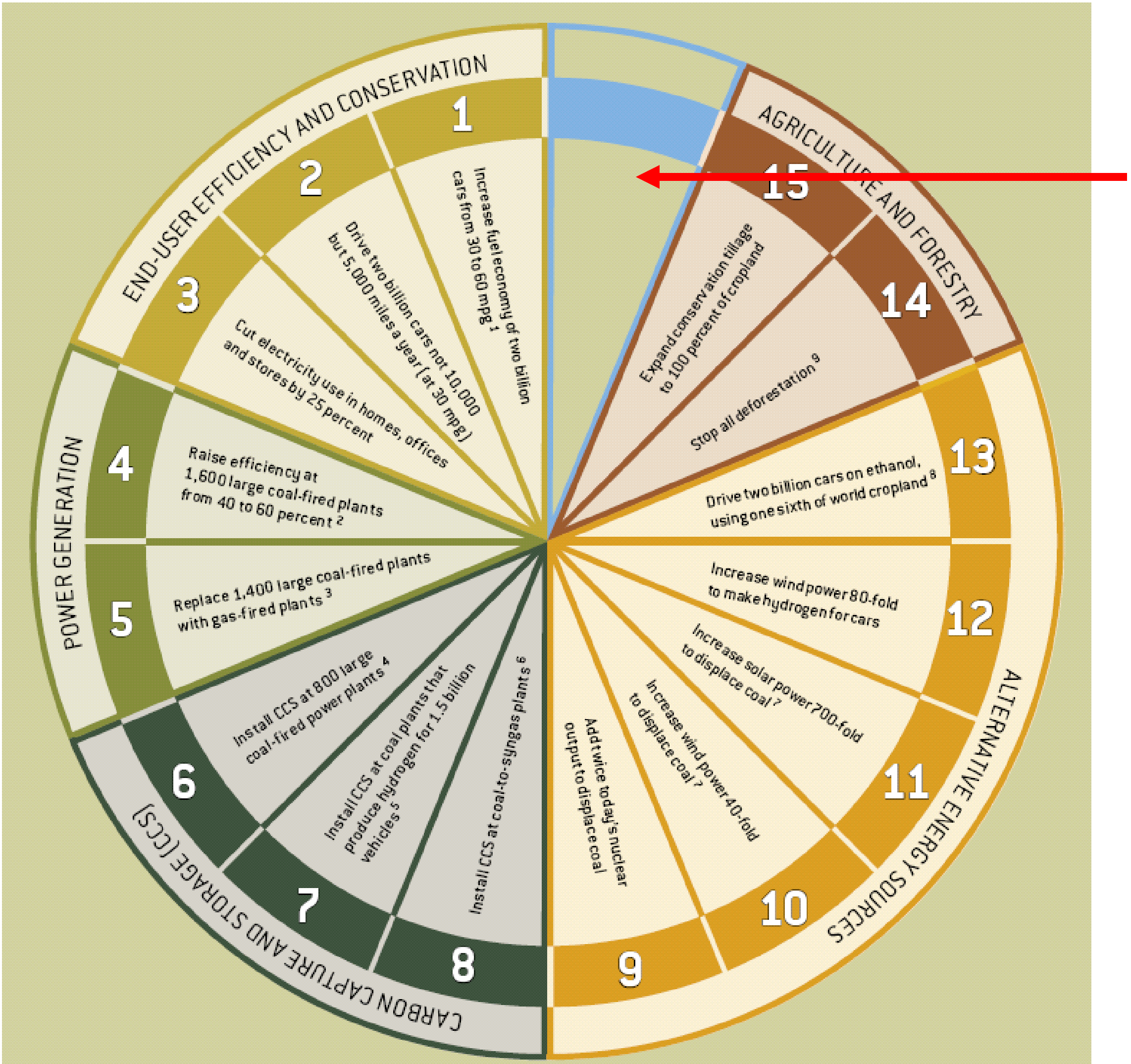
Specific stabilization wedges

15 Ways to Make a Wedge



Source; Socolow and Pacala, *Scientific American*, September 2006, p.54

15 Ways to Make a Wedge



Industrial energy efficiency
"Upstream" investment
Concentrated solar power
Methane mitigation
Population

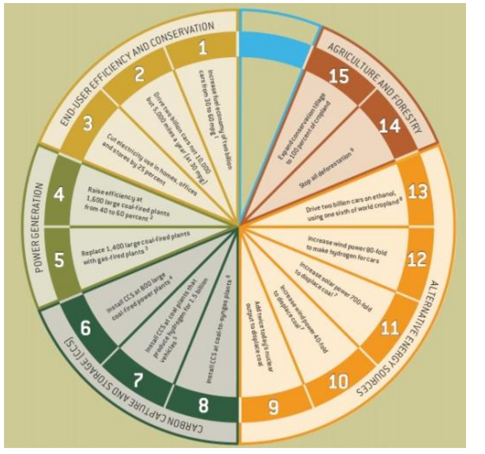
Not commercial, so not included:

Fusion

Capture of CO_2 from air

Source; Socolow and Pacala, *Scientific American*, September 2006, p.54

Dartboard notes



Notes:

1 World fleet size in 2056 could well be two billion cars. Assume they average 10,000 miles a year.

2 "Large" is one-gigawatt (GW) capacity. Plants run 90 percent of the time.

3 Here and below, assume coal plants run 90 percent of the time at 50 percent efficiency. Present coal power output is equivalent to 800 such plants.

4 Assume 90 percent of CO_2 is captured.

5 Assume a car (10,000 miles a year, 60 miles per gallon equivalent) requires 170 kilograms of hydrogen a year.

6 Assume 30 million barrels of synfuels a day, about a third of today's total oil production. Assume half of carbon originally in the coal is captured.

7 Assume wind and solar produce, on average, 30 percent of peak power. Thus replace 2,100 GW of 90-percent-time coal power with 2,100 GW (peak) wind or solar plus 1,400 GW of load-following coal power, for net displacement of 700 GW.

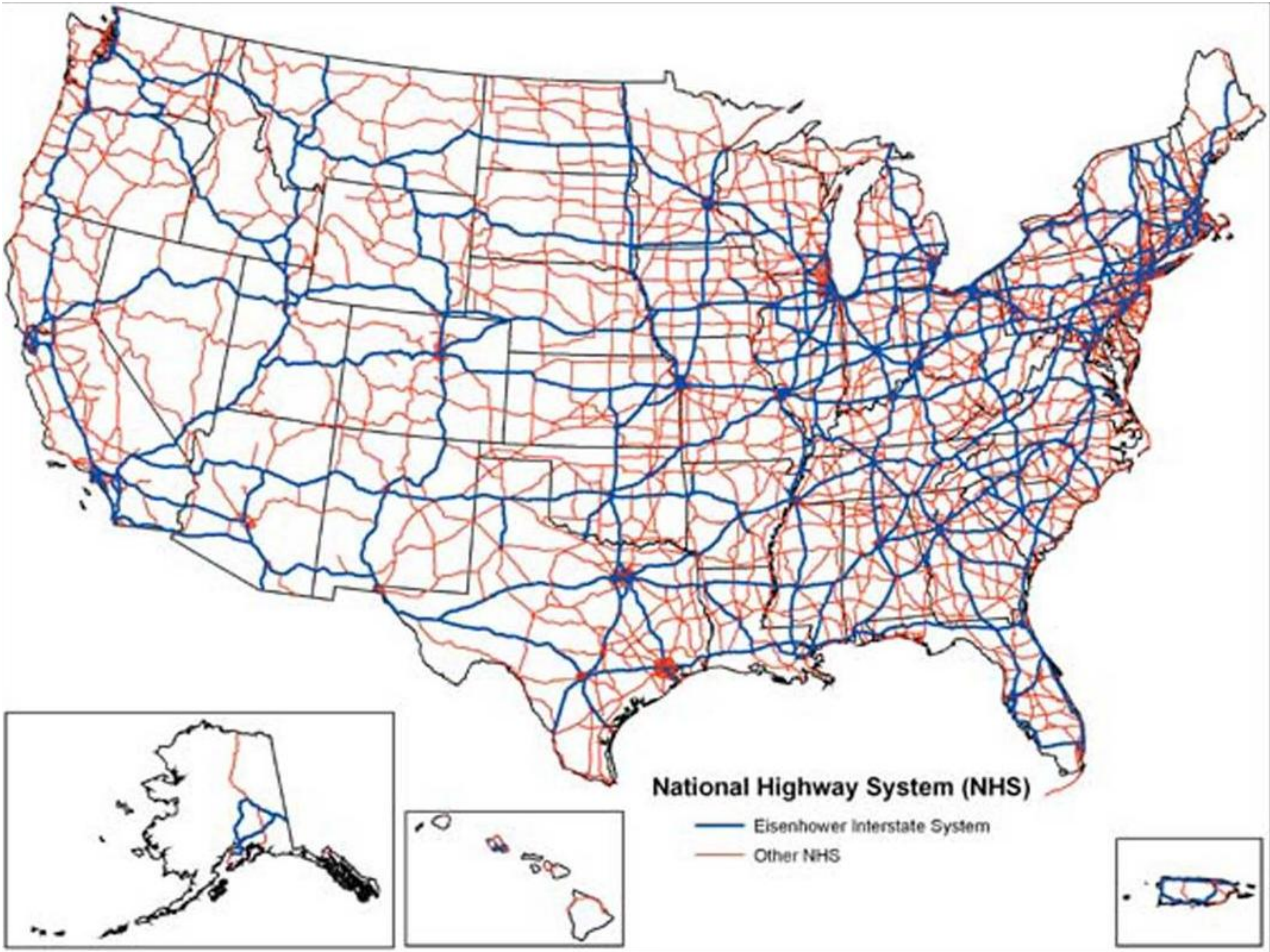
8 Assume 60-mpg cars, 10,000 miles a year, biomass yield of 15 tons a hectare, and negligible fossil-fuel inputs. World cropland is 1,500 million hectares.

9 Carbon emissions from deforestation are currently about two billion tons a year. Assume that by 2056 the rate falls by half in the business-as-usual projection and to zero in the flat path.

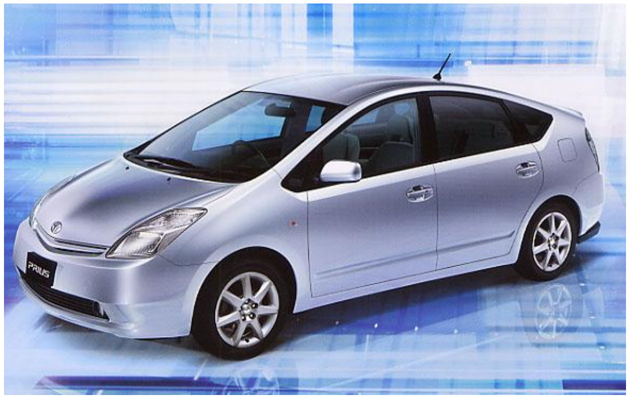
Source; Socolow and Pacala, *Scientific American*, September 2006, p.54

DECENTRALIZED ENERGY CONVERSION

Legacy: U.S. Highway System



The frontier for motive power



Efficient energy conversion

Combustion, drive train, aerodynamics, rolling resistance

Primary source for traditional fuel (gasoline, diesel, jetfuel)

“Conventional” and “unconventional” crude oil

Synthetic fuel from natural gas, coal, or biomass

Non-traditional “fuel”

Compressed natural gas

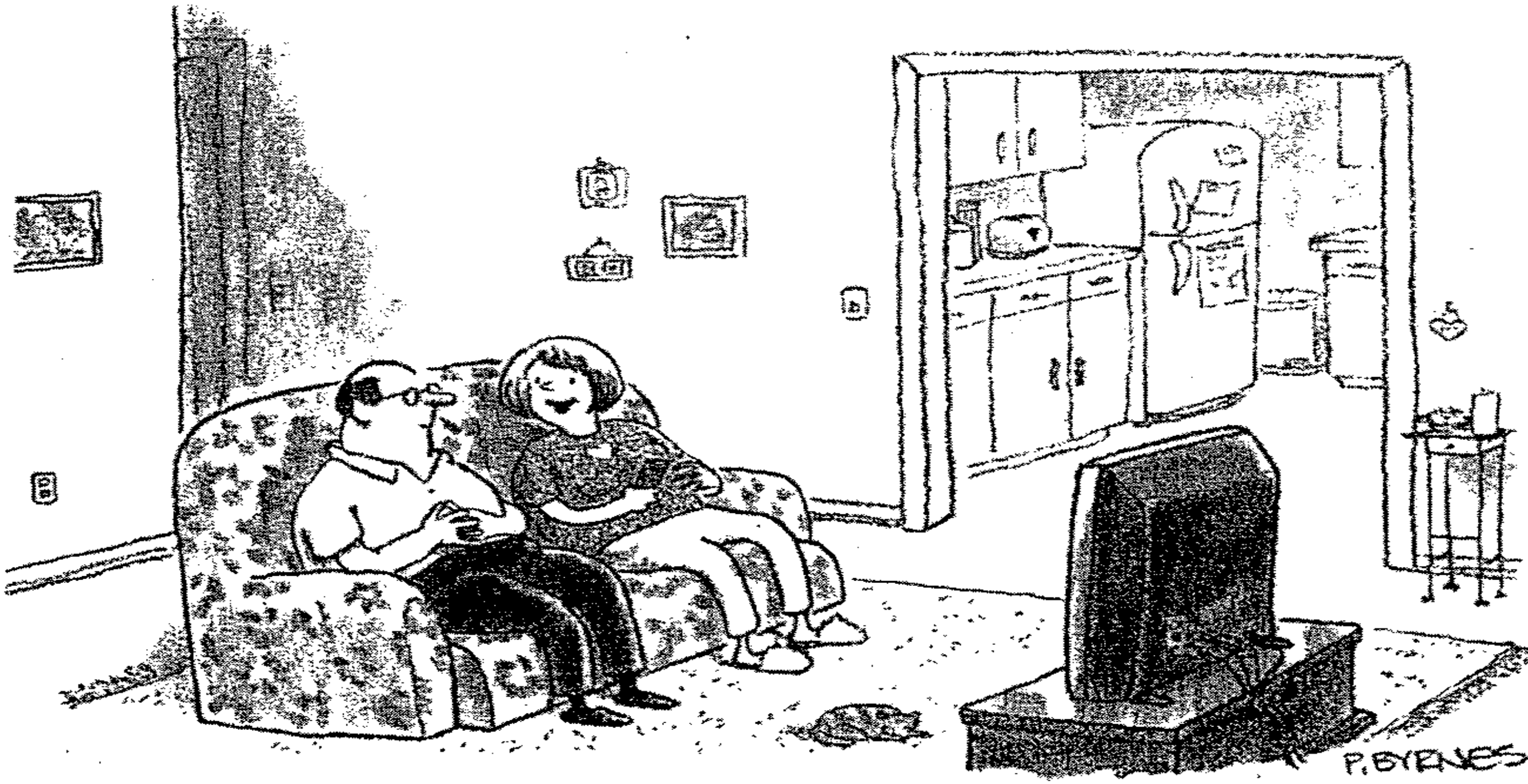
Electrochemical energy (battery or fuel cell)

System efficiency

Most cars have only one person in them most of the time.

Many trips can be replaced by information technology.

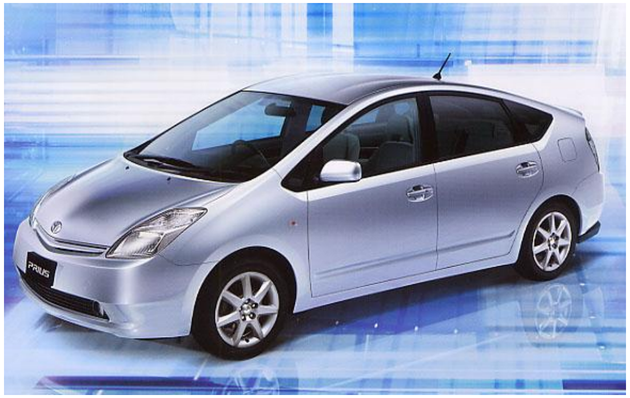
Can virtual experiences substitute for travel?



"When we retire, I want to watch travel videos."

From *The New Yorker*, April 21, 2008

Transportation Efficiency Wedges



Note: Drive 16,000 km at 8 liters/100km: emit 1 tC (≈ 4 tCO_2)

Efficiency wedge: In 2062, 2 billion cars driven 16,000 km/yr at not 8 but 4 l/100km.

Vehicle-use wedge: IN 2062, 2 billion cars at 8 l/100km, driven not 16,000 but 8,000 km/yr.

2 billion cars at 4 l/100km, driven 8,000 km/yr: 1.5 wedges.

Efficient Use of Electricity

***Three images*:**

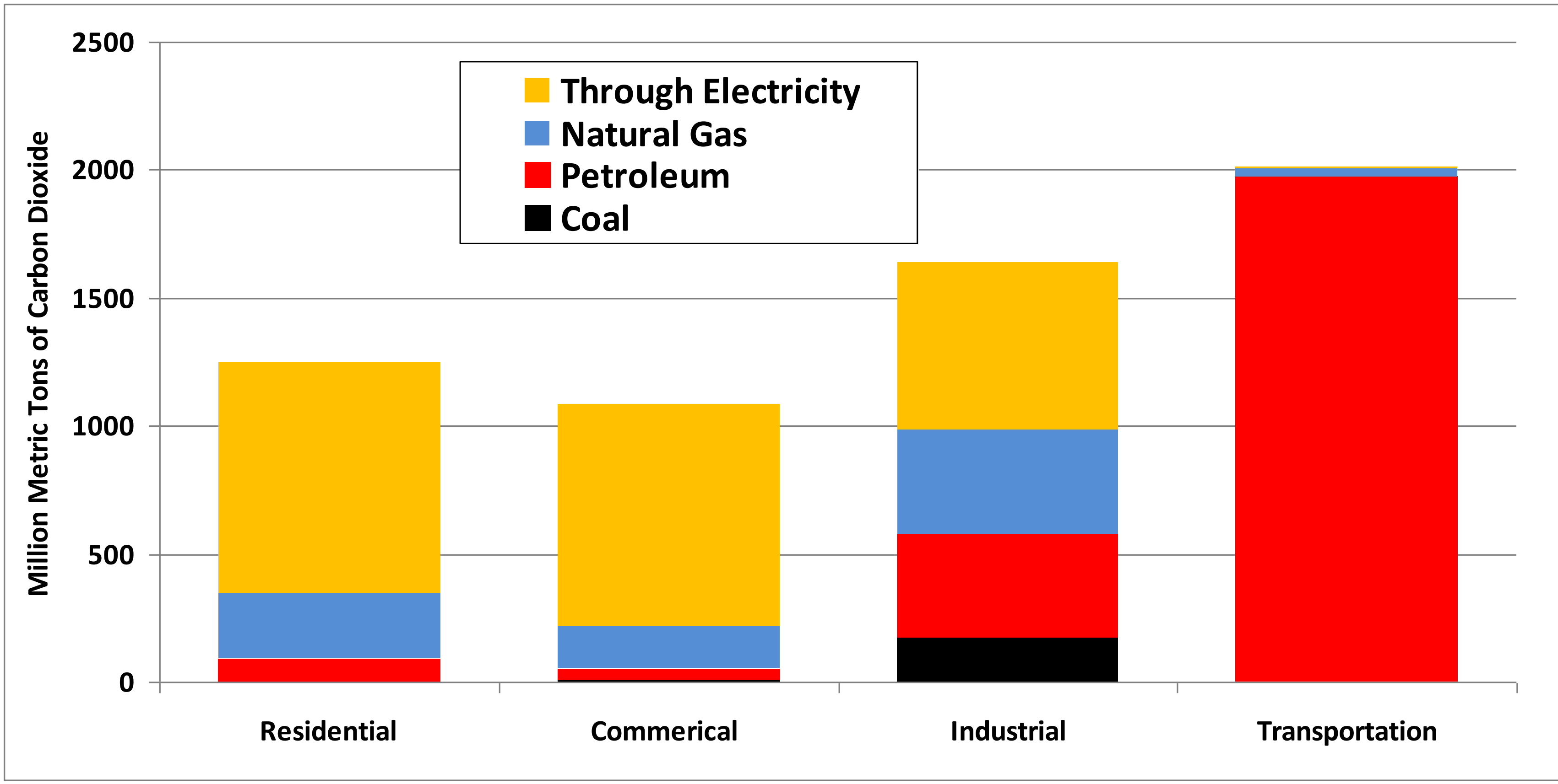
Power electronics for variable-speed-drive motors.

Integration of electricity and thermal energy ("cogeneration").

Can also integrate electricity and fuels/chemicals.

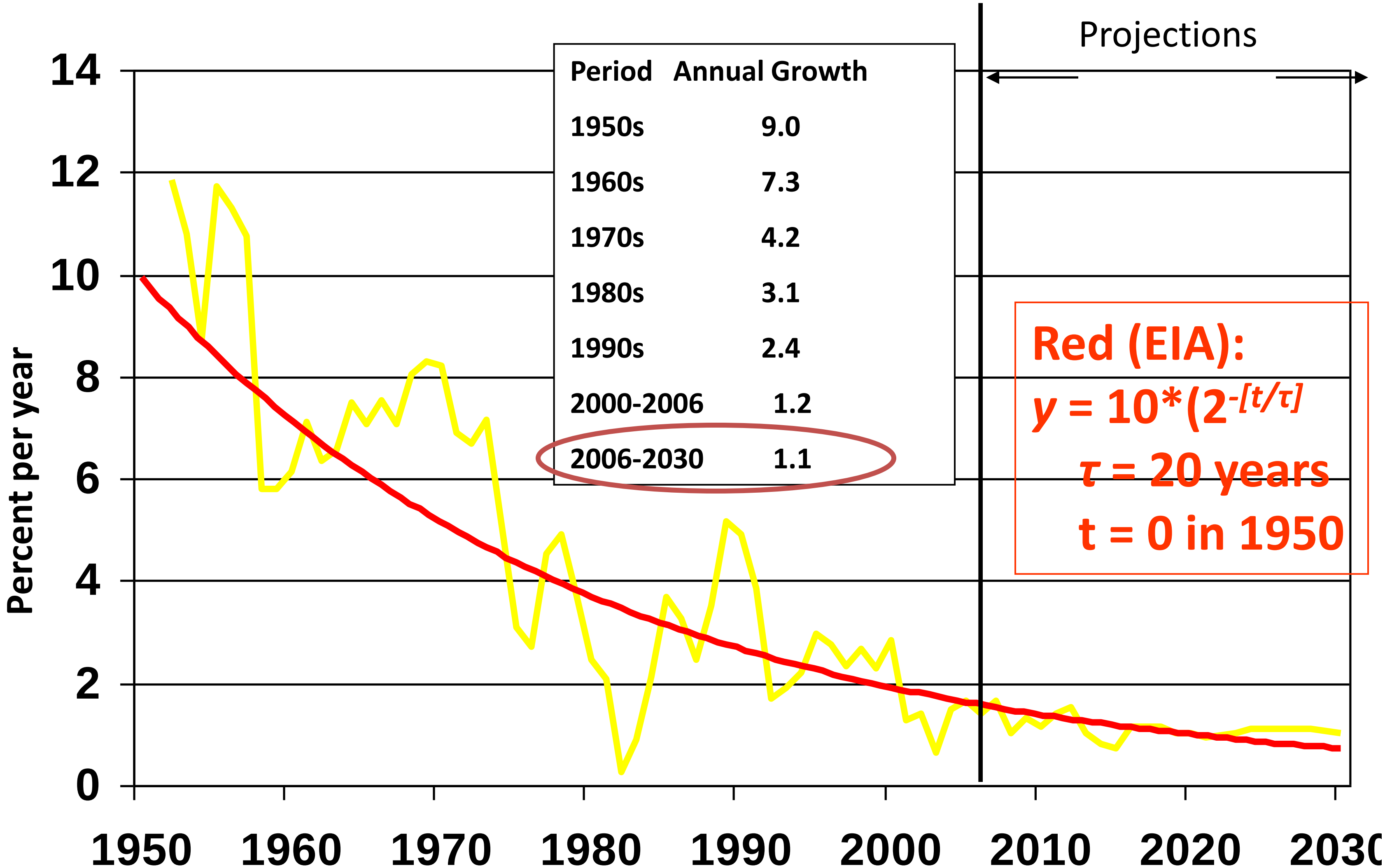
Efficient lighting.

At the power plant, CO_2 heads for the sky, most electrons head for buildings!



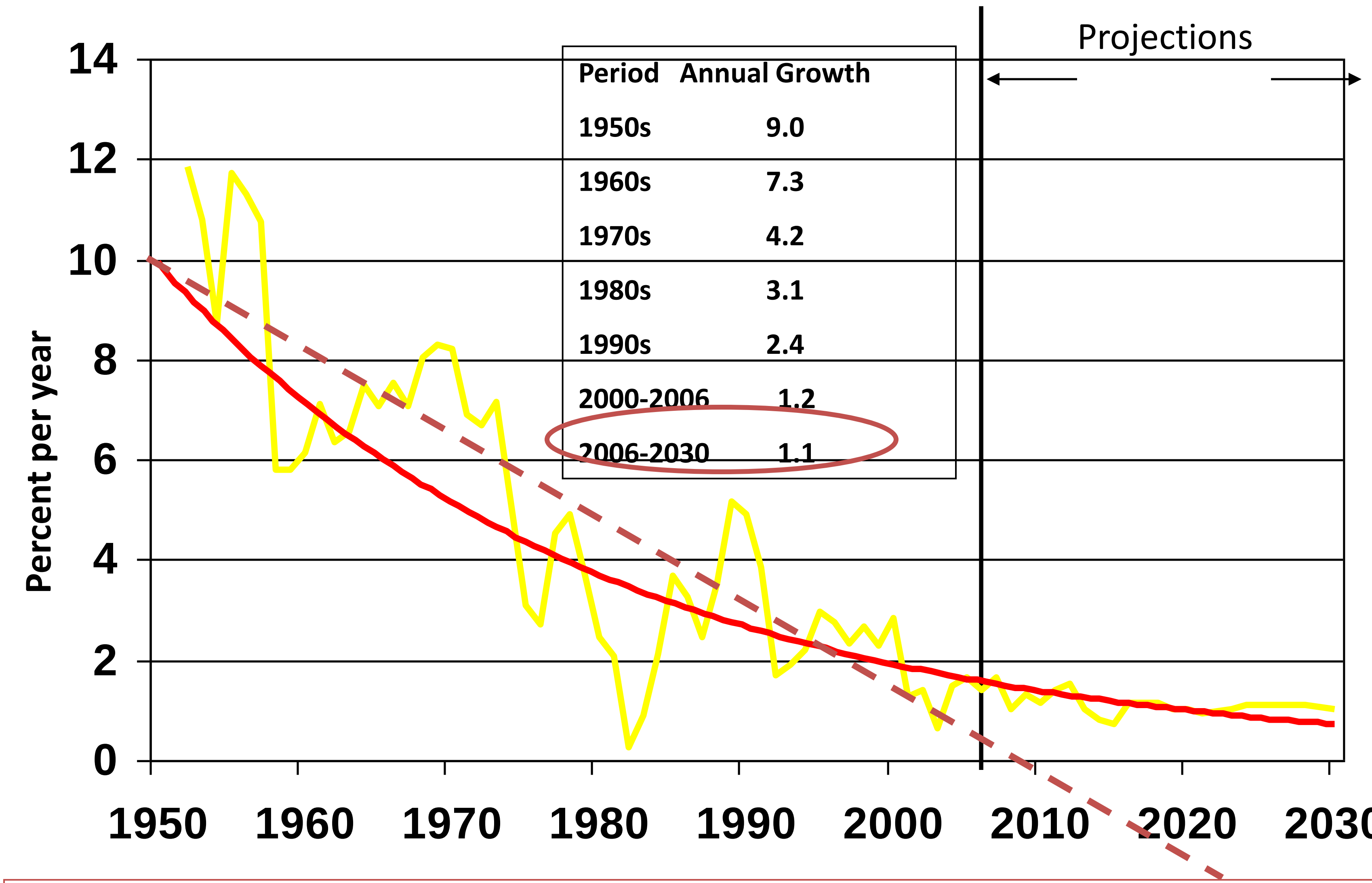
U.S. CO2 emissions, 2007, electricity allocated. *Source*: J. Sweeney, 2009.

Conceive of the far side of a peak



U.S. electricity growth rate (3-year rolling average, percent)

Conceive of the far side of a peak



Physics and economics allow negative values! Dashed line: RHS.

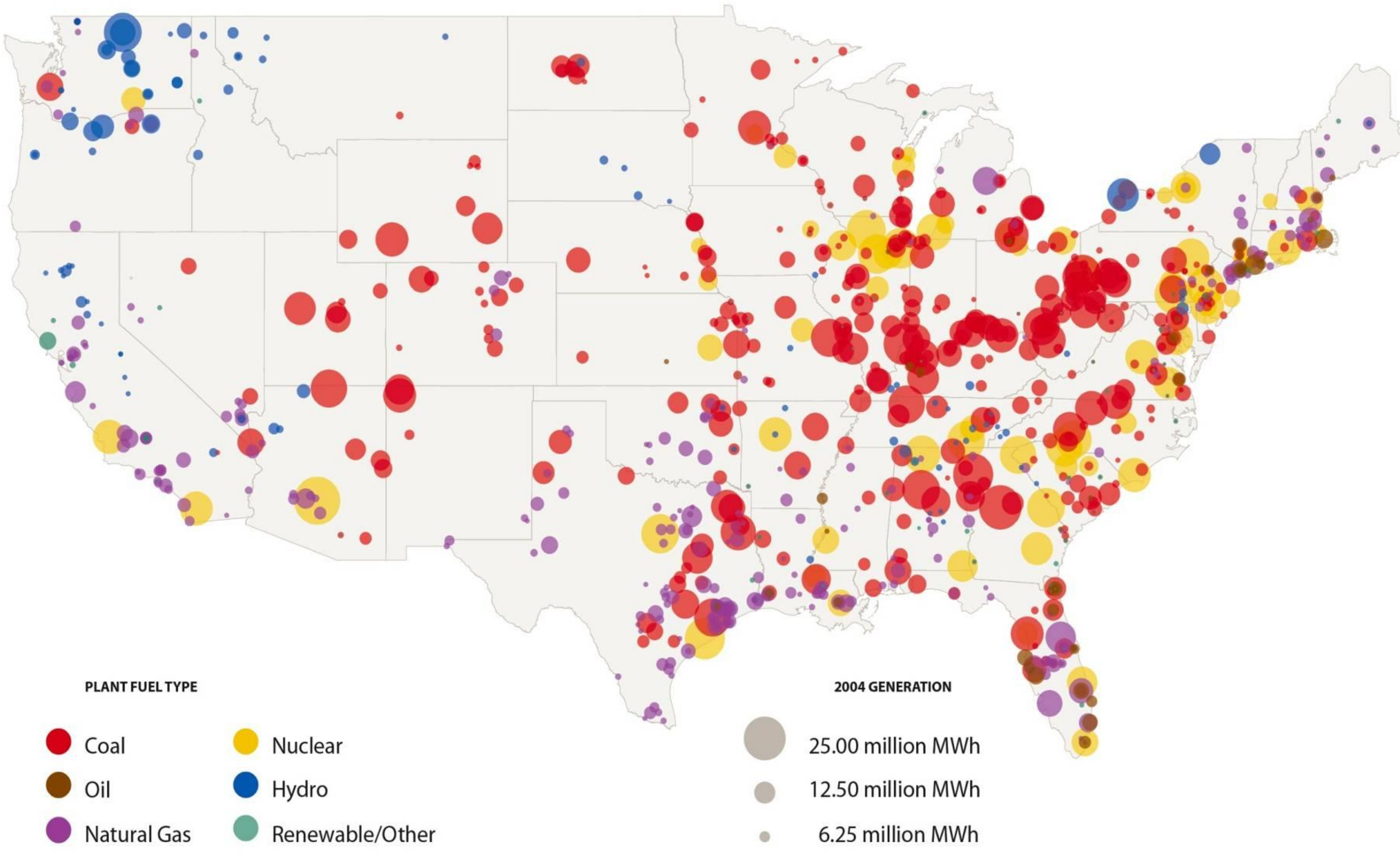
Has energy demand peaked in industrialized countries?

If any industrialized country makes energy efficiency a priority, at least two of its peaks can be in its past:

- oil consumption
- electric power consumption

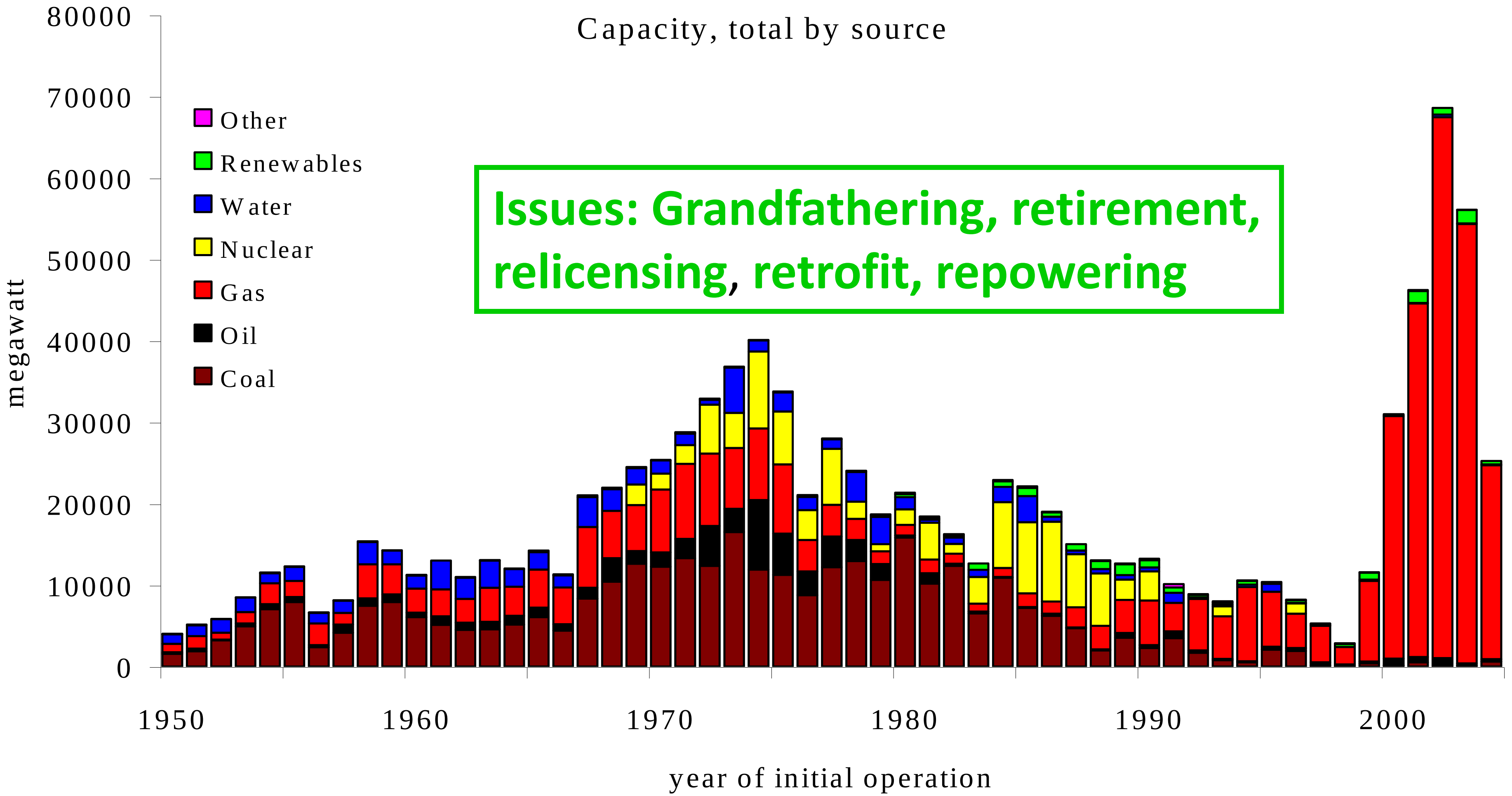
CENTRALIZED ENERGY CONVERSION

Legacy: U.S. Power Plants



Source: *Benchmarking Air Emissions*, April 2006. The report was co-sponsored by CERES, NRDC and PSEG.

Will U.S. power plants retire?



Source: EIA. Joseph.Beamon@eia.doe.gov

Coal-electricity Wedges

700 modern (90% capacity factor, 50% efficient) 1-GW coal plants, with CO_2 vented, will emit 1 GtC each year, if by "modern" we mean that the carbon intensity is:

0.18 kgC/kWh, or 0.66 kgCO_2/kWh.

Electricity-supply wedges result from not building such plants.

Fuel Switching: Coal to gas

Photo by J.C. Willett (U.S. Geological Survey).

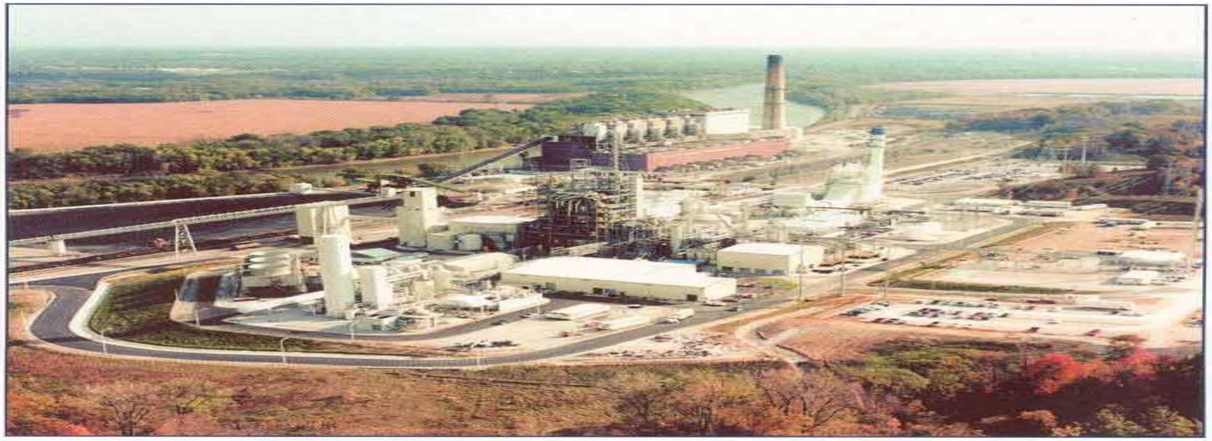
Effort needed by 2062 for one wedge:

Replace the output of 1400 GW of coal-fired electric plants with natural-gas-fired plants.

A wedge requires an amount of natural gas equal to that used for all purposes today.

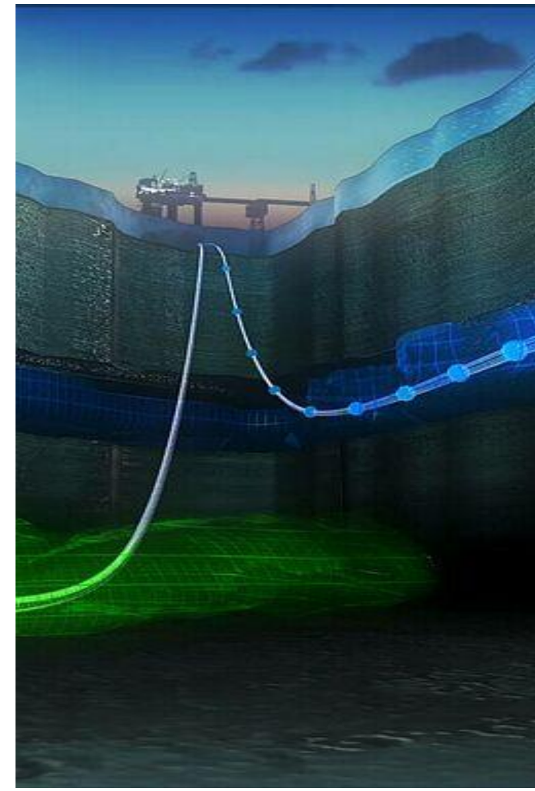
A wedge requires 50 LNG tanker deliveries every day, or the equivalent of 50 Alaska pipelines

Coal with Carbon Capture and Storage



The Wabash coal gasification reprocessing project

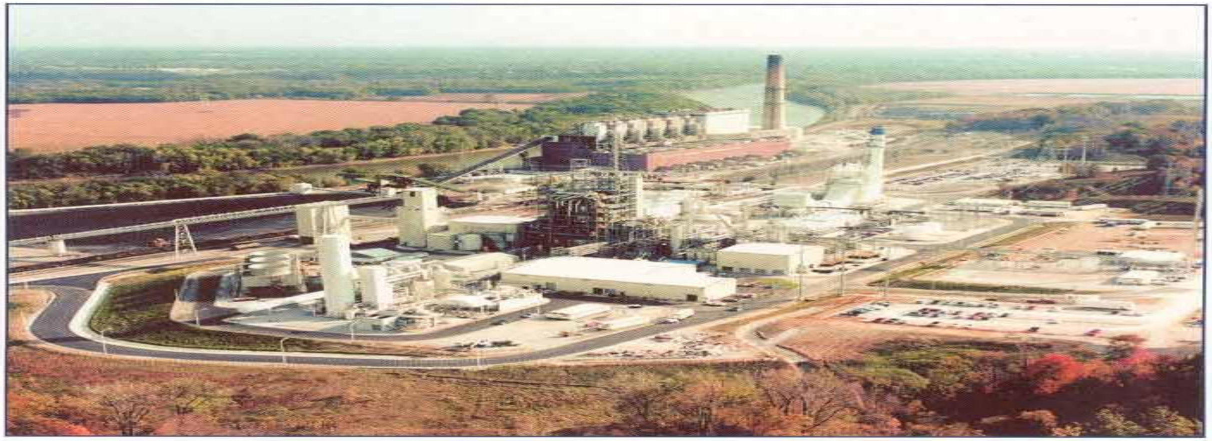
1 wedge: By 2062, 800 GW, 90% capture.



Sleipner field, Norway

Graphics courtesy of DOE Office of Fossil Energy and *Statoil ASA*

Coal with Carbon Capture and Storage



The Wabash coal gasification reprocessing project

1 wedge: By 2062, 800 GW, 90% capture.

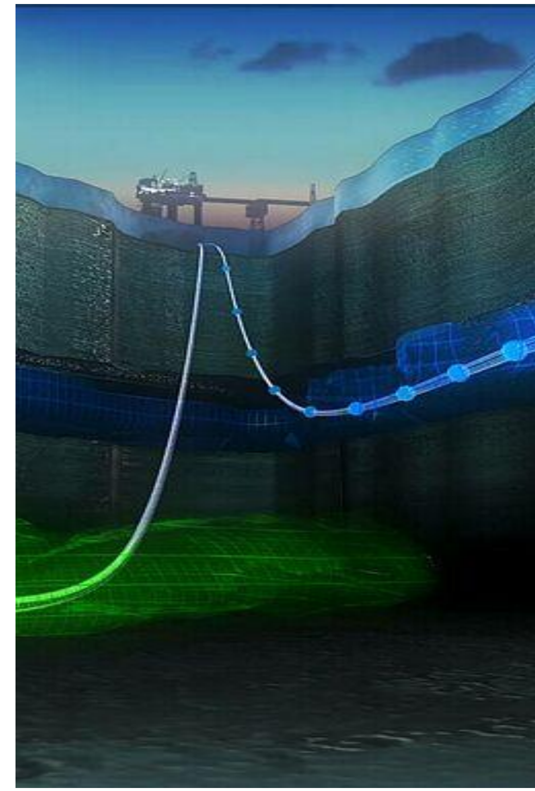
Pre-combustion capture (after gasification)

or

post-combustion capture from flue gas

or

capture from flue gas after burning in O_2.

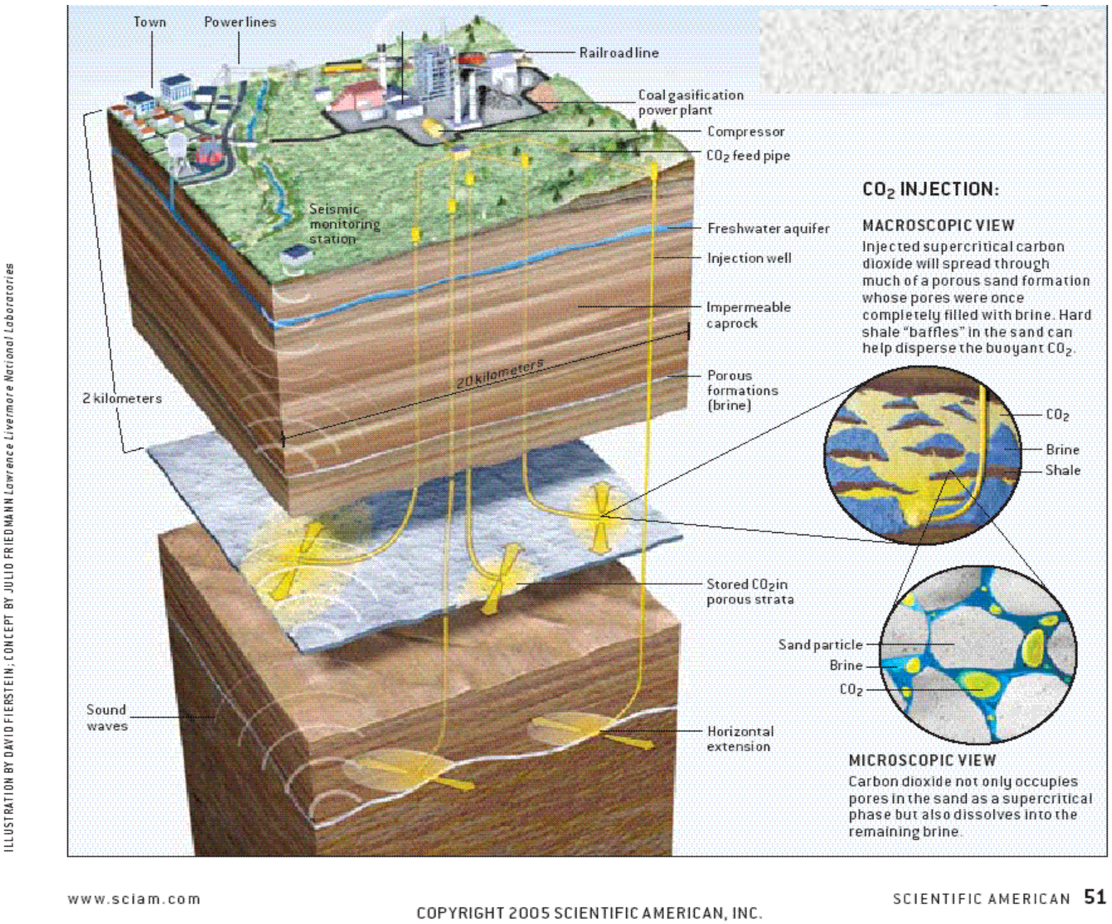


Sleipner field, Norway

Critical CO_2 pressure: 7.38 MPa (740 m hydrostatic pressure)

Graphics courtesy of DOE Office of Fossil Energy and *Statoil ASA*

The Future Coal or Natural Gas Power Plant



Shown here: After 10 years of operation of a 1000 MW coal plant, 60 Mt (90 Mm^3) of CO_2 have been injected, filling a horizontal area of 40 km^2 in each of two formations.

Assumptions:

- 10% porosity
- **1/3 of pore space accessed**
- 60 m total vertical height for the two formations.

- *Note:* Plant is still young.

Injection rate is 150,000 bbl(CO_2)/day, or 300 million standard cubic feet/day (scfd). That's 3 billion barrels, or 6 trillion standard cubic feet, over 60 years.

Renewable Power

***Installed already, world-wide*:**		
Wind:	**240 GW_{peak}**	**(through 2011)**
Photovoltaic:	**40 GW_{peak}**	**(through 2010)**
Concentrators:	**Very little**	

Photovoltaic Power

Effort needed by 2062 for one wedge:

2000 GW_{peak} displacing coal (x3 for intermittency)

2010: 40 GW_{peak} (2%),16 GW/yr

If 200 kWh/m^2-yr and coal at 1 $kgCO_2/kWh$, then 2 Mha:

400 million 50-m^2 rooftop units,

200 km x 100 km desert collectors

Graphics courtesy of DOE Photovoltaics Program

Concentrating Solar Power (CSP)

Source: Noah Kaye, SEIA, April 2007

Effort needed by 2062 for one wedge:

2000 GW_{peak} displacing coal

2 million hectares, if same land use efficiency as PV

Wind Electricity

Effort needed by 2062 for 1 wedge:

One million 2-MW_{peak} windmills displacing coal power.

2011: 240,000 MW_{peak} (12%)

Are they ugly or beautiful?

Source: Hal Harvey, TPG talk, Aspen, CO, July 2007

Nuclear power and dry-cask storage

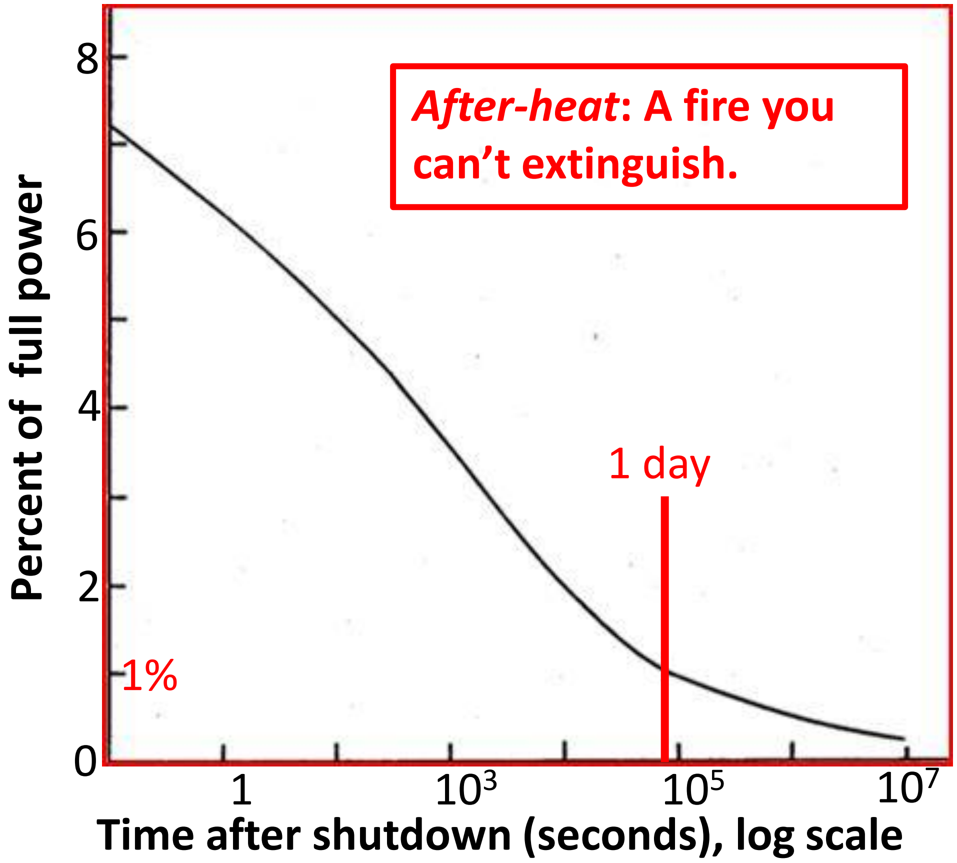
Effort needed by 2062 for 1 wedge:

700 GW (twice current capacity) displacing coal power.

Phasing out nuclear power in favor of coal creates the need for another half wedge.

Nuclear power and "after-heat"

Fukushima Daiichi, before the accident



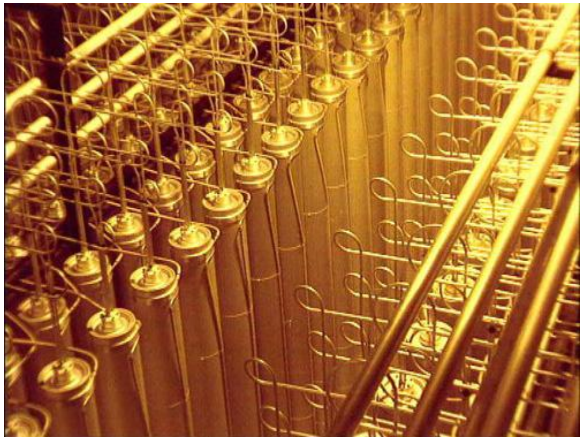
Source: Nautilus Institute for Security and Sustainability, 2011. *After the Deluge: Short and Medium-term Impacts of the Reactor Damage Caused by the Japan Earthquake and Tsunami.*

Source: A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 54

Nuclear-power fuel cycle and nuclear war

Both uranium isotope enrichment (the “front end” of the fuel cycle) and spent-fuel reprocessing to recover plutonium (the “back end” of the fuel cycle) are routes to nuclear weapons.

Nuclear power cannot become a safe global energy source until much stronger international institutions are developed to govern the nuclear power fuel cycle in all countries.



Gas-centrifuges for enrichment

France’s reprocessing plant at La Hague

“Solutions” can bring serious problems of their own.

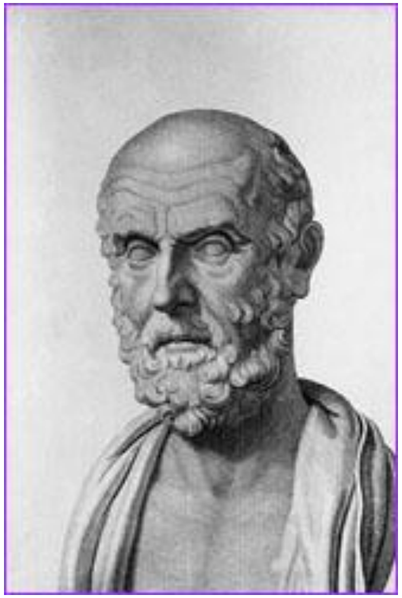
Every “solution” has a dark side.

Conservation	Regimentation
Renewables	Competing uses of land
“Clean coal”	Mining: worker and land impacts
Nuclear power	Nuclear war
Geoengineering	Technological hegemony

Risk management: In choosing targets, we must take into account both the risks of disruption from climate change and the risks of disruption from mitigation.

Can a target be too strict?

“I will apply, for the benefit of the sick, all measures that are required, avoiding those twin traps of overtreatment and therapeutic nihilism.”



Hippocrates

* Modern version of the Hippocratic oath, Louis Lasagna, 1964. http://www.pbs.org/wgbh/nova/doctors/oath_modern.html

"The Wedge Model is the iPod of climate change: You fill it with your favorite things."

David Hawkins, NRDC, 2007.

“The Wedge Model is the iPod of climate change: You fill it with your favorite things.”

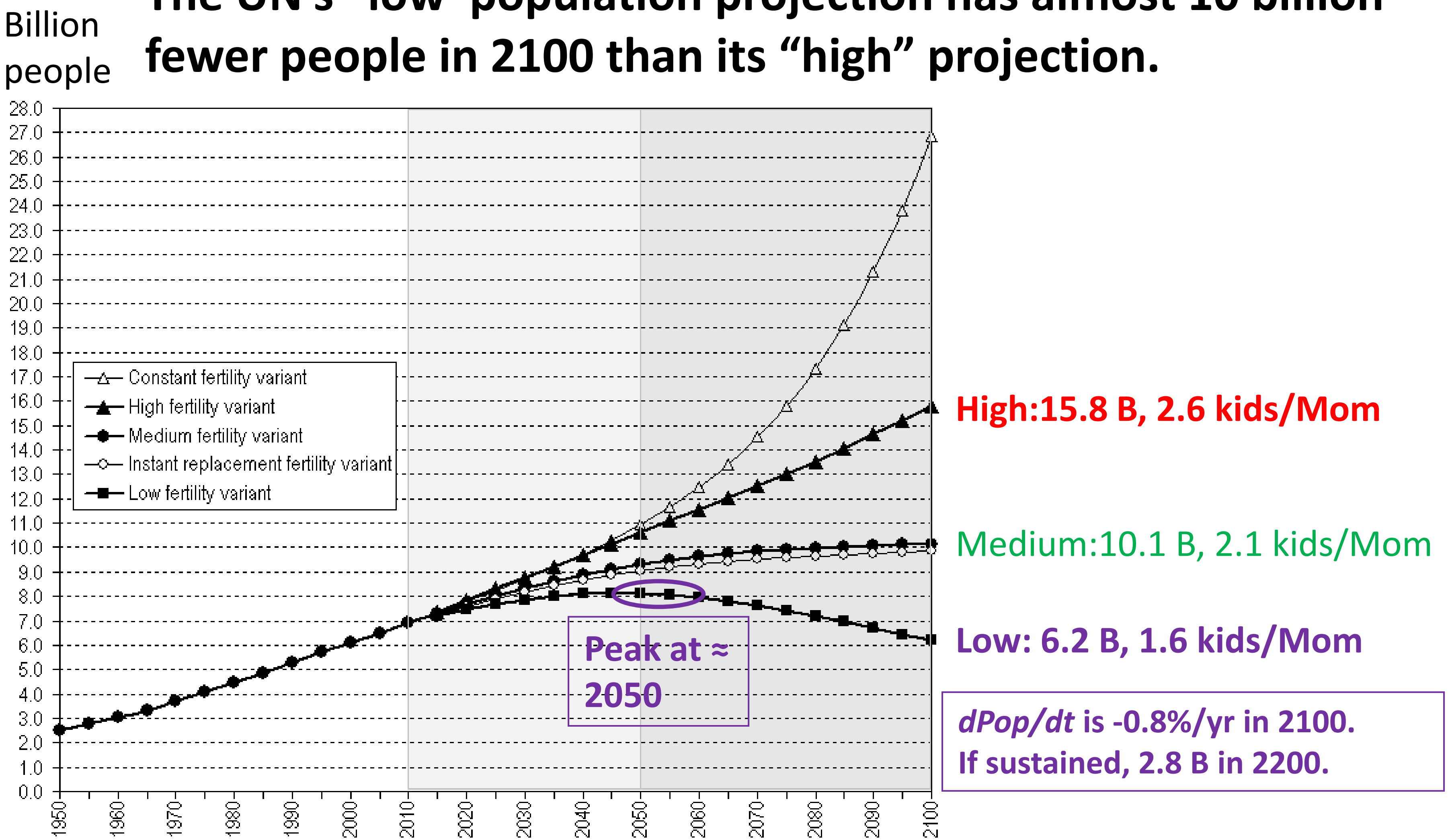
David Hawkins, NRDC, 2007.

Therefore, prepare to negotiate with others, who have different favorite things.

Concluding Thoughts

The future global population

The UN's "low"population projection has almost 10 billion fewer people in 2100 than its "high" projection.



Source: United Nations. http://esa.un.org/unpd/wpp/unpp/panel_population.htm

How many children will you have?

Imagining our collective future: "Prospicience"

Prospicience: "The art [and science] of looking ahead."

In the past 50 years we have become aware of the history of our Universe, our Earth, and life.

Can we achieve a comparable understanding of human civilization at various future times: 50 years ahead – *vs.* 500 years and *vs.* 5000 years? Prospicience is needed to address planning horizons, infrastructure, waste management….

Imagine spending as much effort on our collective destiny on Earth as we spend on our personal destiny in the afterlife!

We have scarcely begun to ask: What are we on Earth to do?

In order to know the truth,
it is necessary to imagine
a thousand falsehoods.

Sidney Coleman, ca. 1964, perhaps a quote from H.G. Wells

Grounds for optimism

1. The world today has a terribly inefficient energy system.
2. Carbon emissions have just begun to be priced.
3. Most of the 2062 physical plant is not yet built.
4. Many smart and committed young people now find energy problems exciting.

Fitting on the Earth

Our planet, Earth, is the only one we have.

Fortunately:

Our science has discovered threats fairly early;

We can identify a myriad of helpful technologies;

We have a moral compass that tells us to care about everyone alive today and about the collective future of our species.

What has seemed too hard becomes what simply must be done.

Co-authors, some recent papers

Wedges

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Jeff Greenblatt (LBNL)
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Nuclear power

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One-billion high emitters

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