

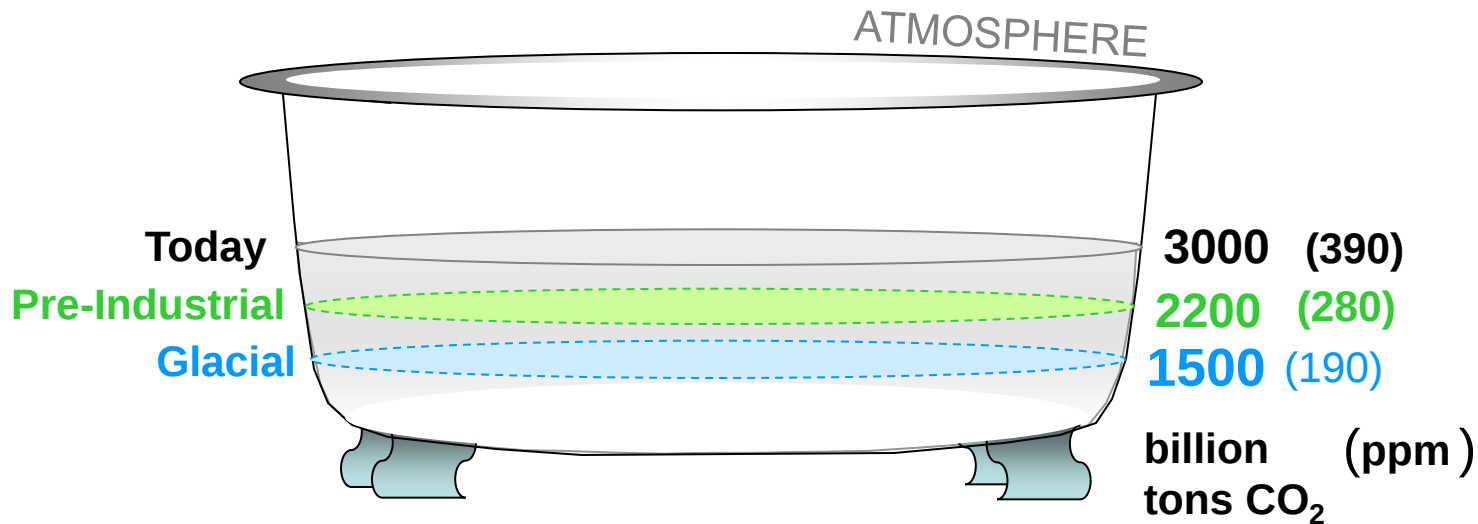
Stabilization Wedges and the Polygame

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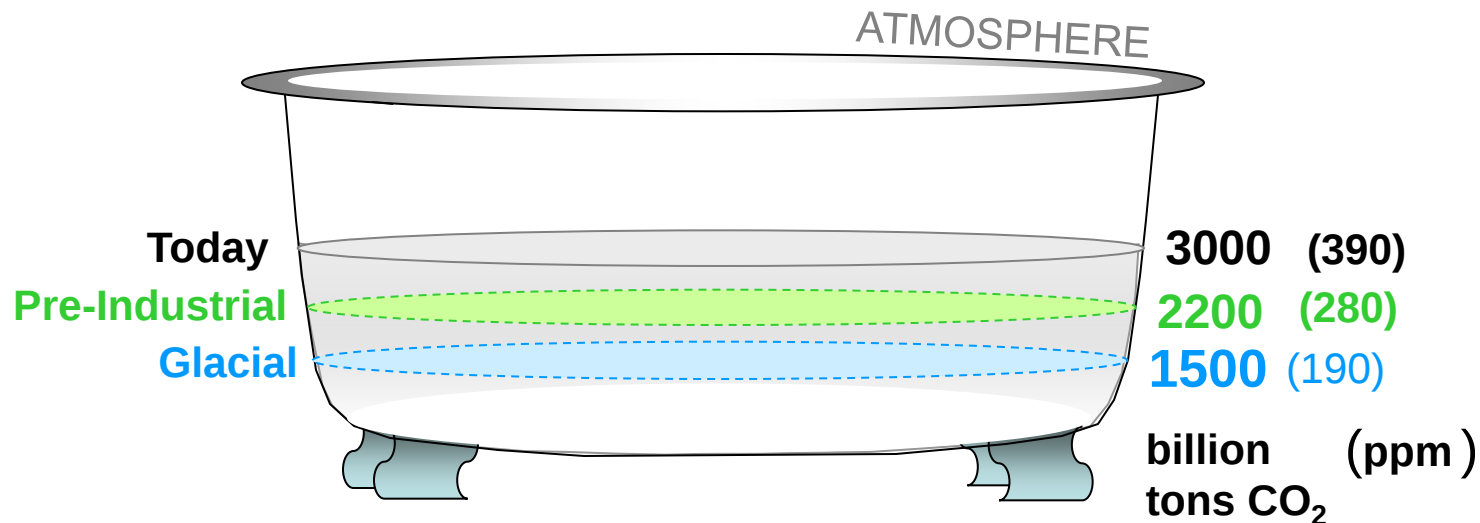
Guest lecture
ASP (Alta Scuola Politecnica)
Politecnico di Milano and Politecnico di Torino
Belgirate, Italy

May 24, 2013

Past and present levels of CO₂ in the atmosphere



Past and present levels of CO₂ in the atmosphere

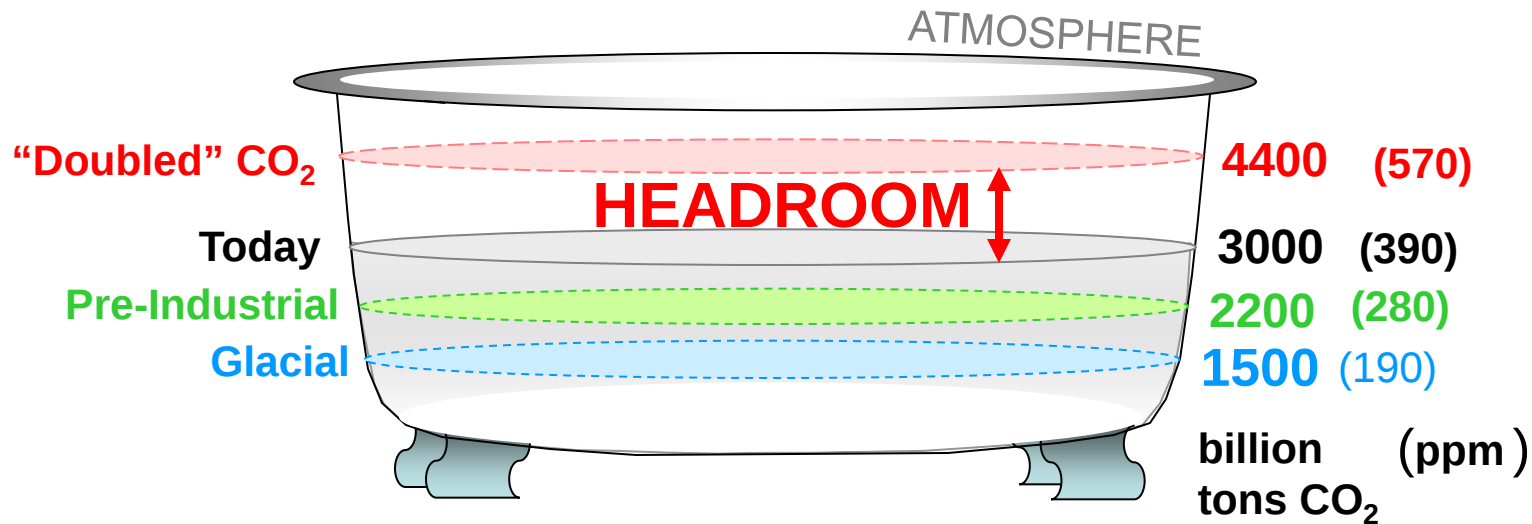


Rosetta Stone: To raise the concentration of CO₂ in the atmosphere by **one part per million**:

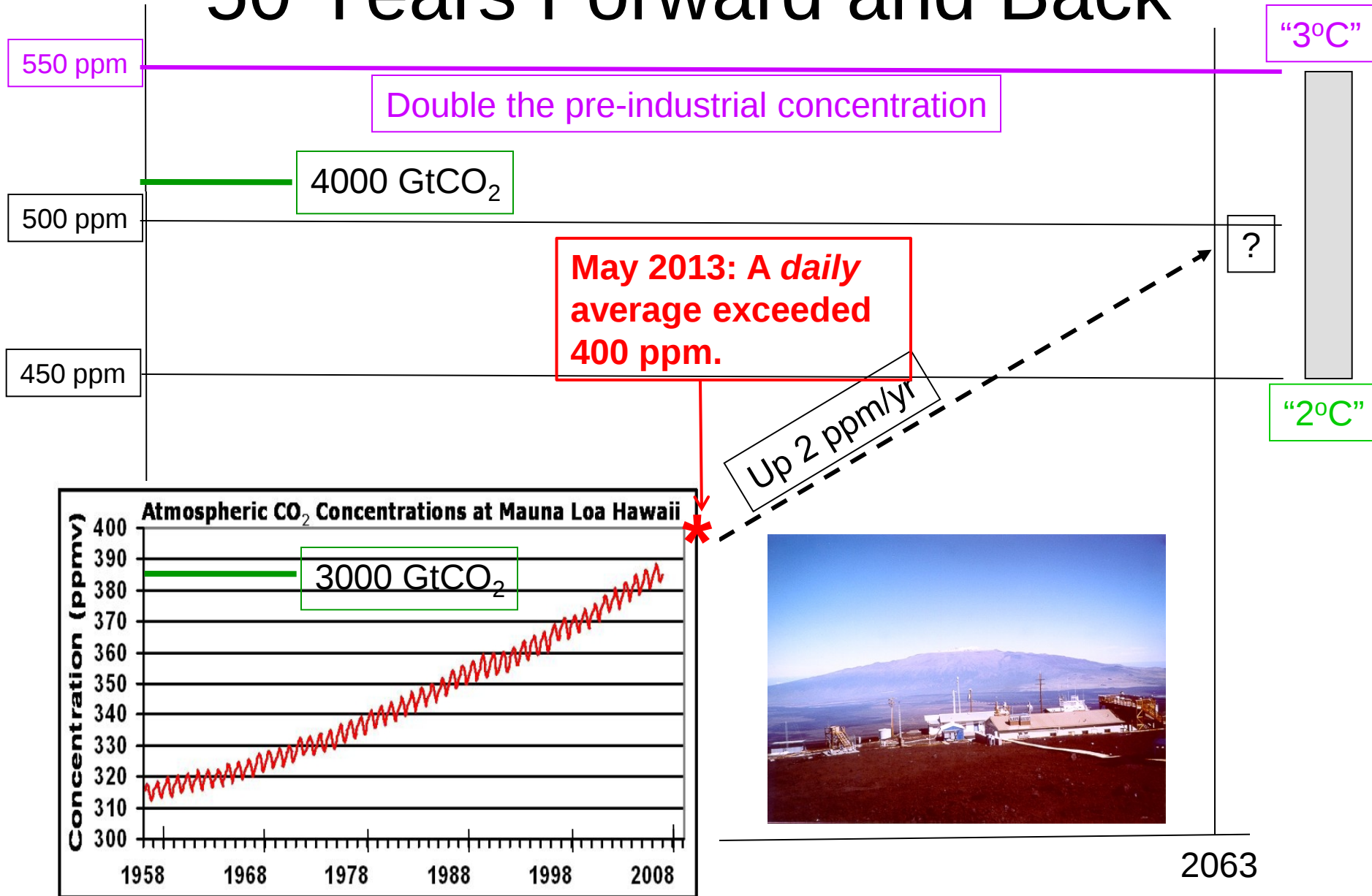
add **7.8 billion tons of CO₂**,

in which are **2.1 billion tons of carbon**.

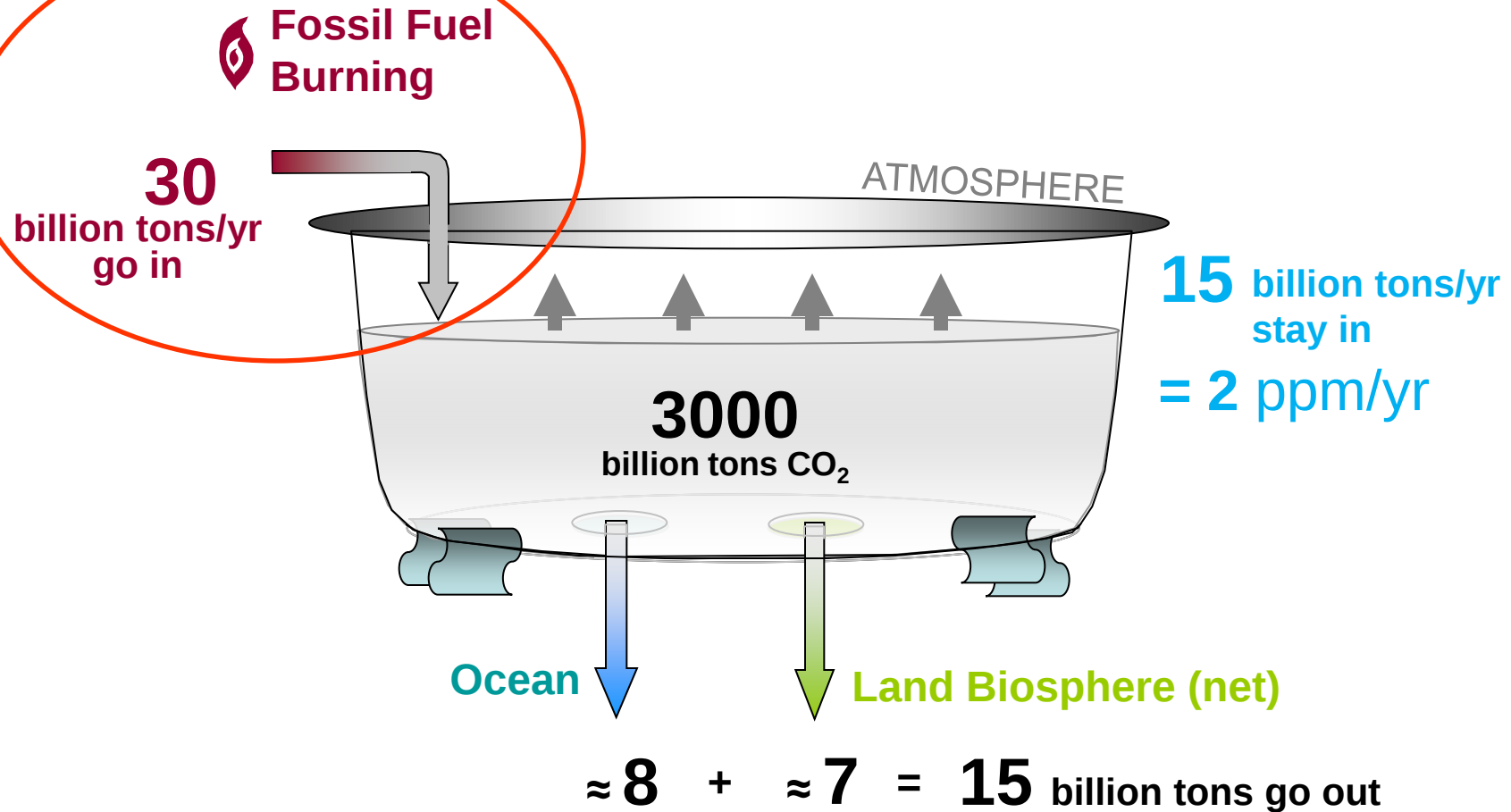
Past, present, and potential future levels of CO₂ in the atmosphere



50 Years Forward and Back



Sources and sinks of CO₂



Today, global per-capita emissions are $\approx 4 \text{ tCO}_2/\text{yr}$.

Four ways to emit 4 tonCO₂/yr (today's global per capita average)

Activity	Amount producing 4 ton CO ₂ /yr emissions
a) Drive	24,000 km/yr, 5 liters/100km
b) Fly	24,000 km/yr
c) Heat home	Natural gas, average house, average climate
d) Lights	300 kWh/month when all coal-power (600 kWh/month, natural-gas-power)

Princeton University CO₂ in 2007

University emissions*	112,000 tCO ₂
12,500 participants**	
Per-capita emissions	9 tCO ₂

*On-site cogeneration plant, purchased electricity, fuel for University fleet.

**7,100 students and 5,400 employees

What about Politecnico di Milano? Politecnico di Torino?

To play Polygame, we adapt The Wedge Model

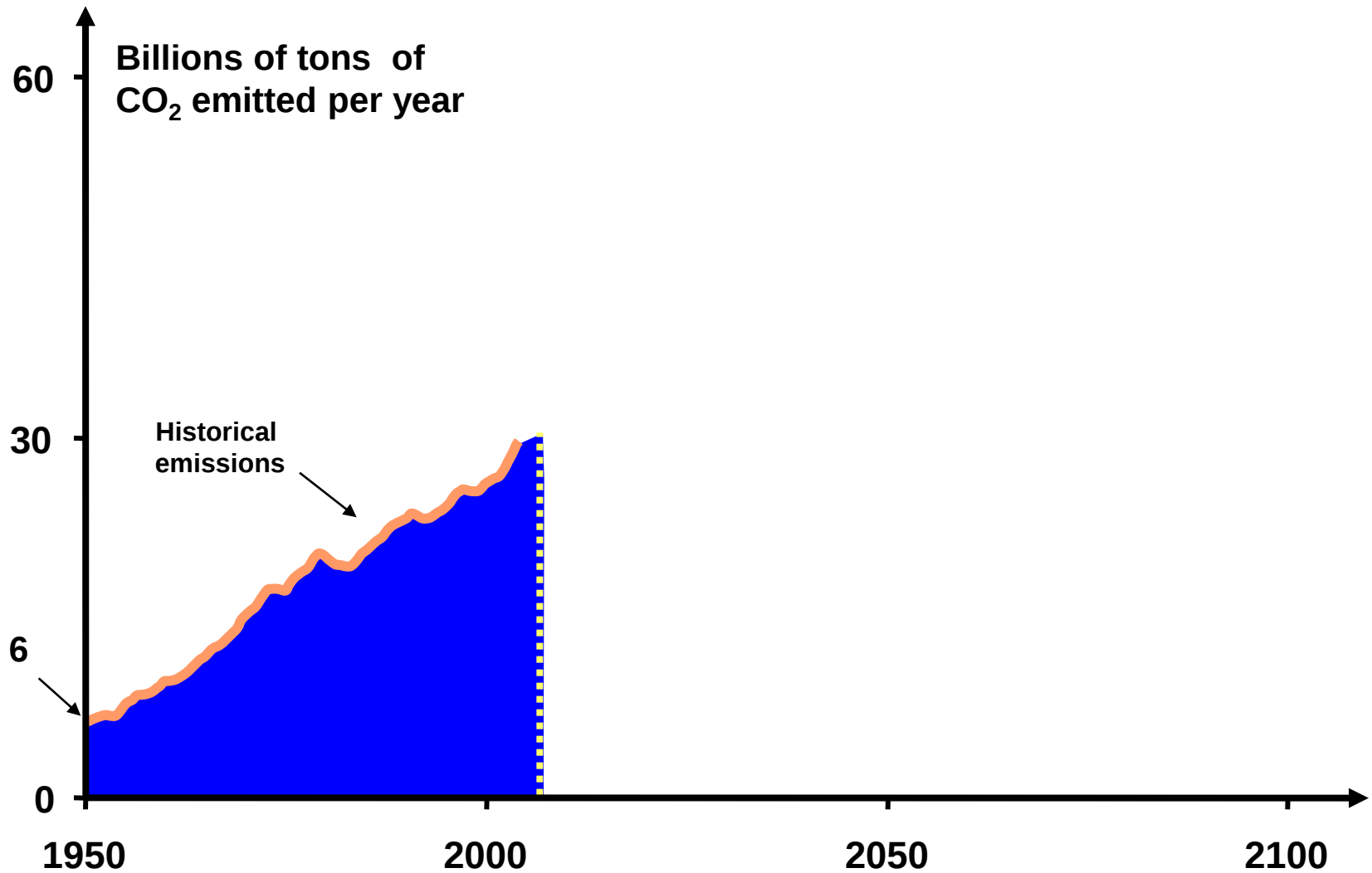
Co-author: Steve Pacala

Articles:

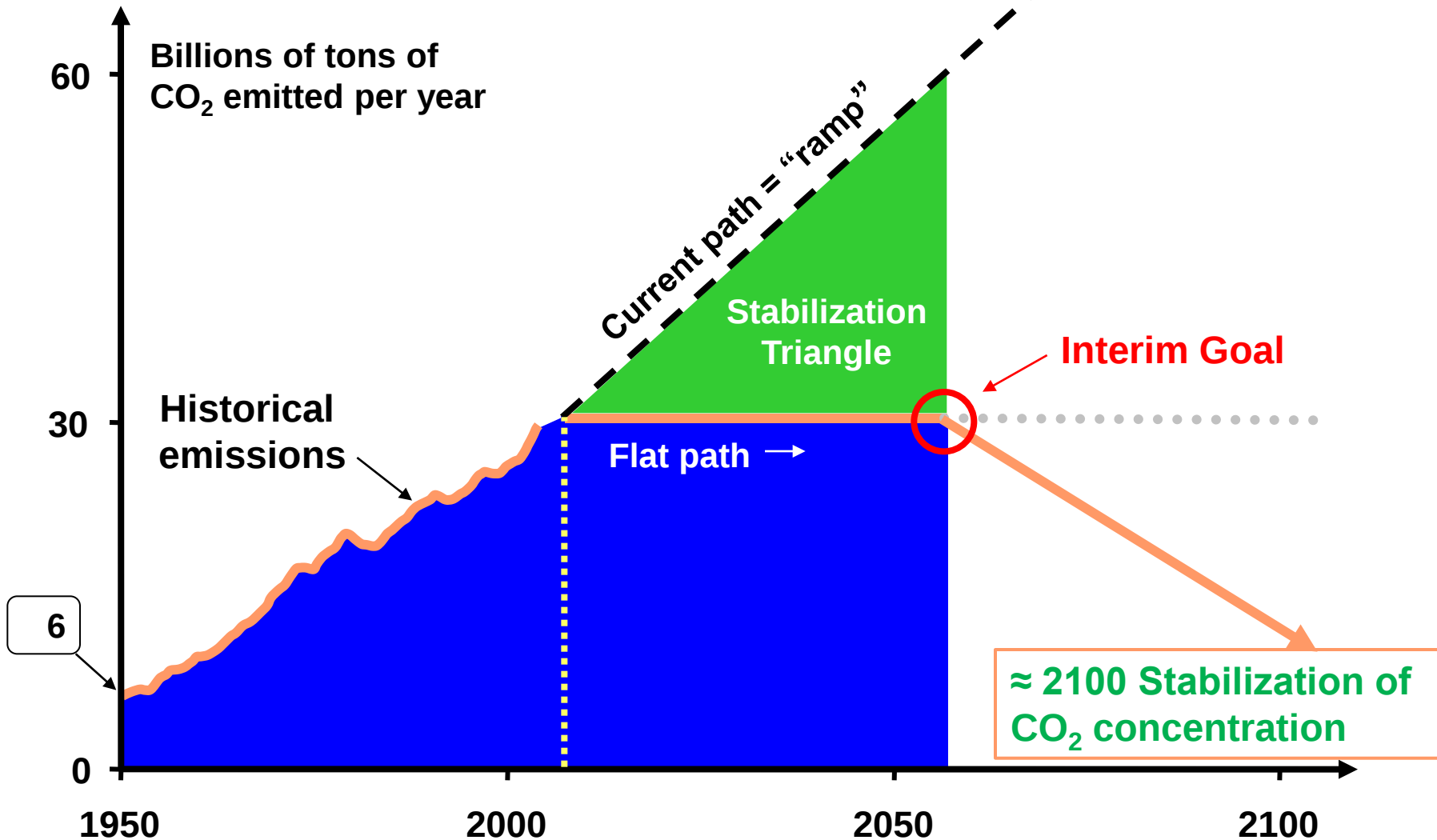
Science (2004)

Scientific American (2006)

Historical Emissions

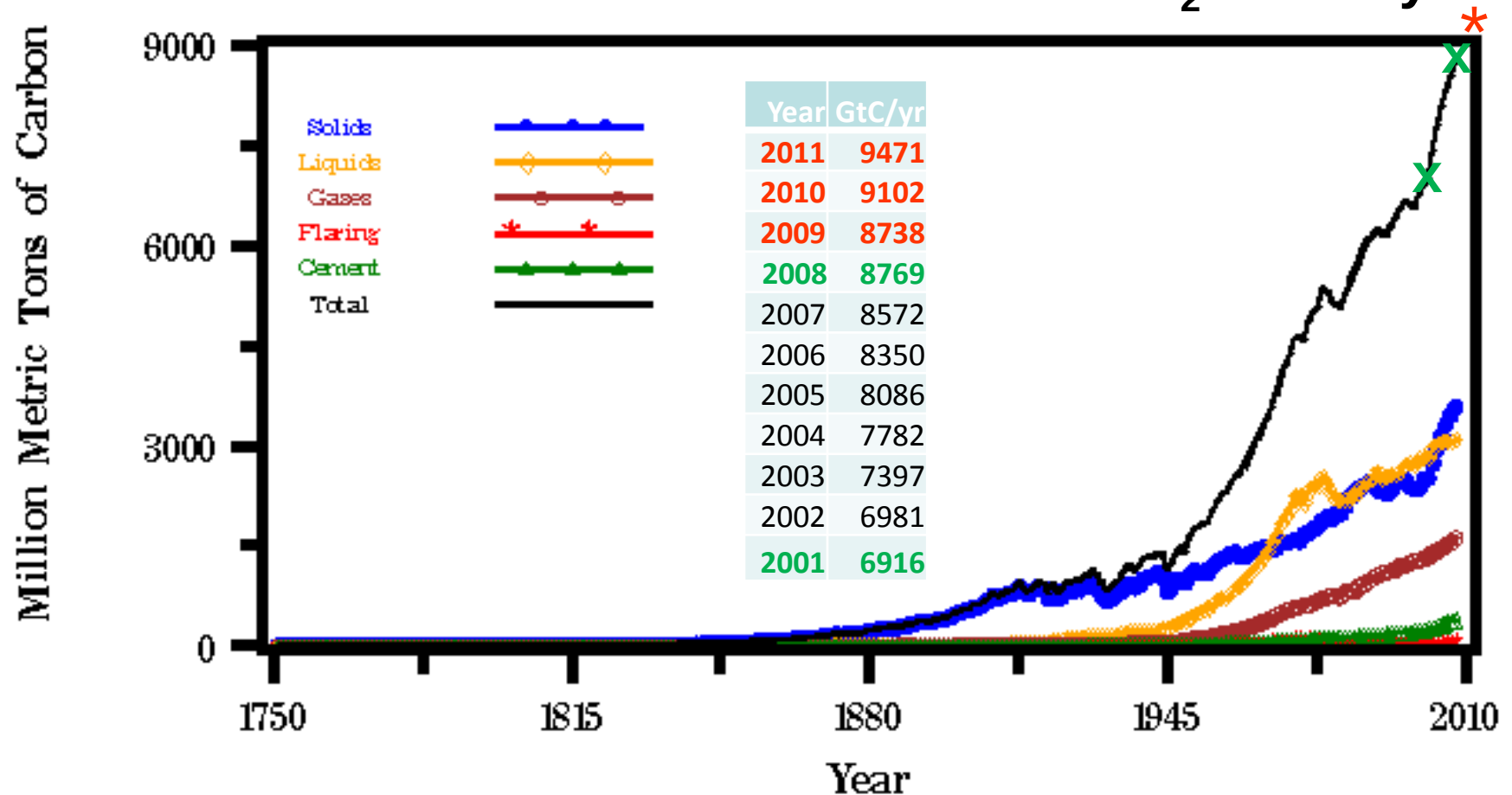


The Stabilization Triangle



We have lost precious time.

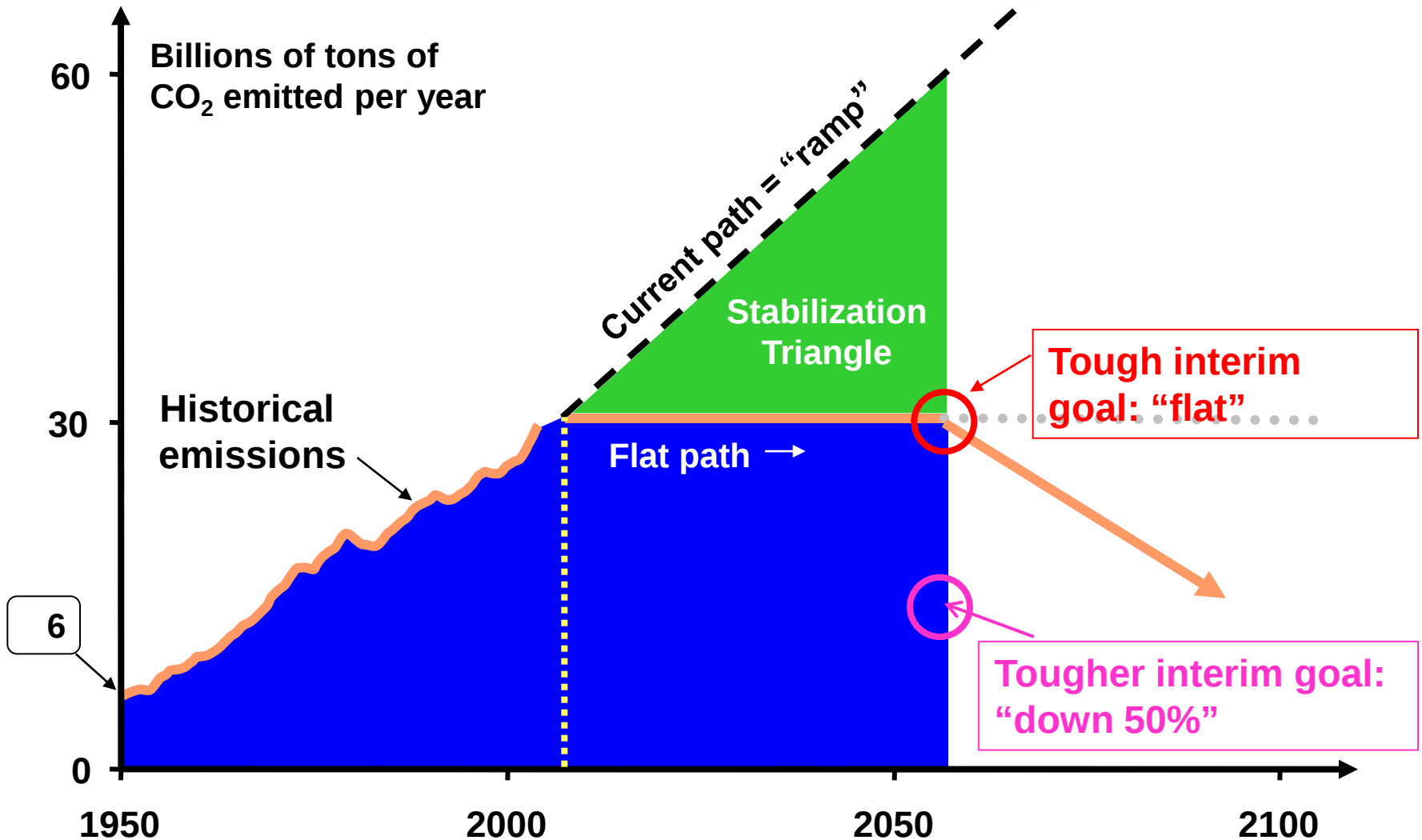
Annual Rate of Emissions of CO₂ Globally



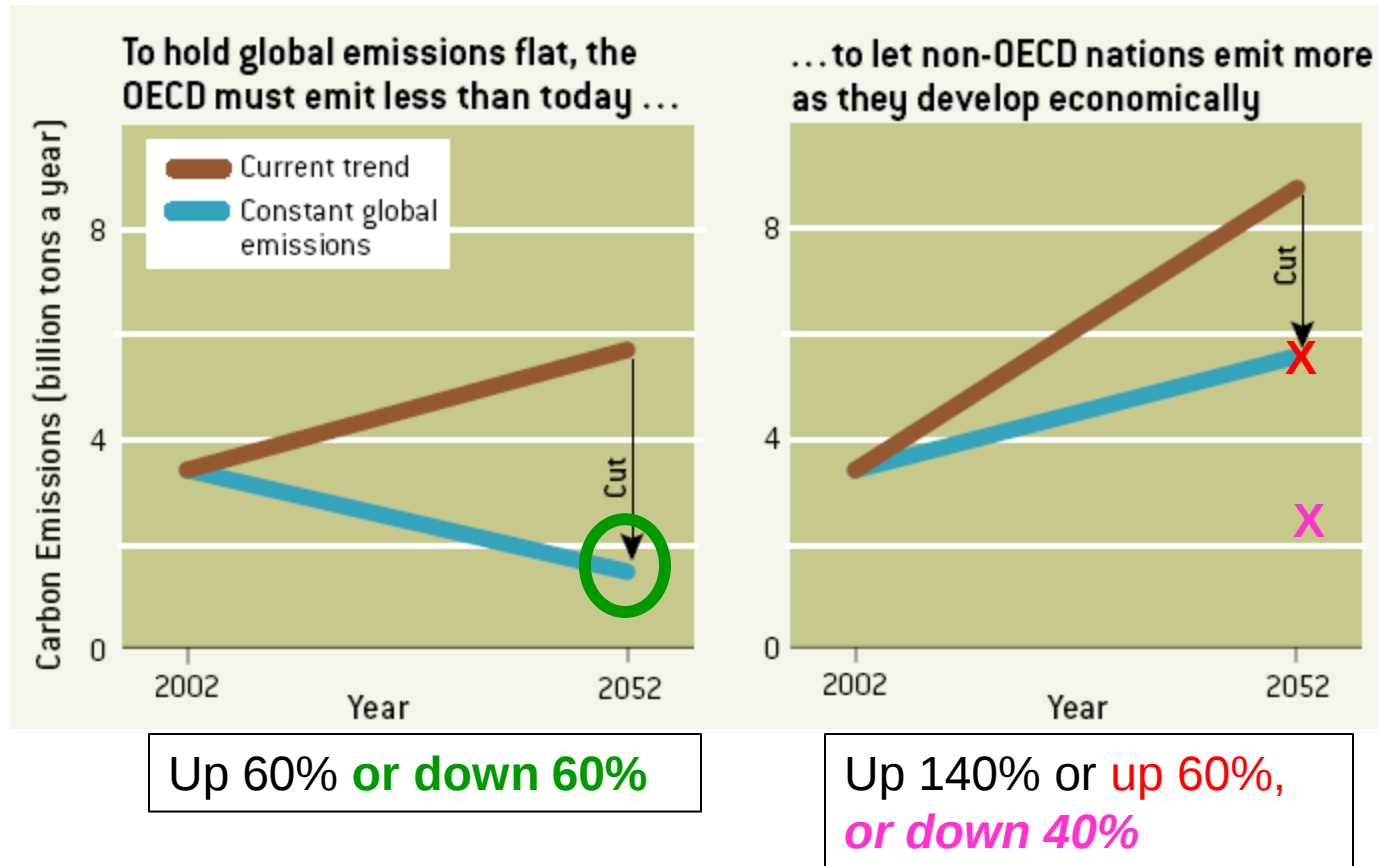
Source (accessed 10/1/11): <http://cdiac.ornl.gov/trends/emis/glo.html>.

Updated 1/5/13

The Stabilization Triangle



“Flat” vs. “down 50%” is mostly about the developing world’s emissions



Polygame in China must explore low-carbon industrialization.

GHGs emissions in Italy 1990-2010

1990: ~520MtCO₂/y

2011: ~490MtCO₂/y

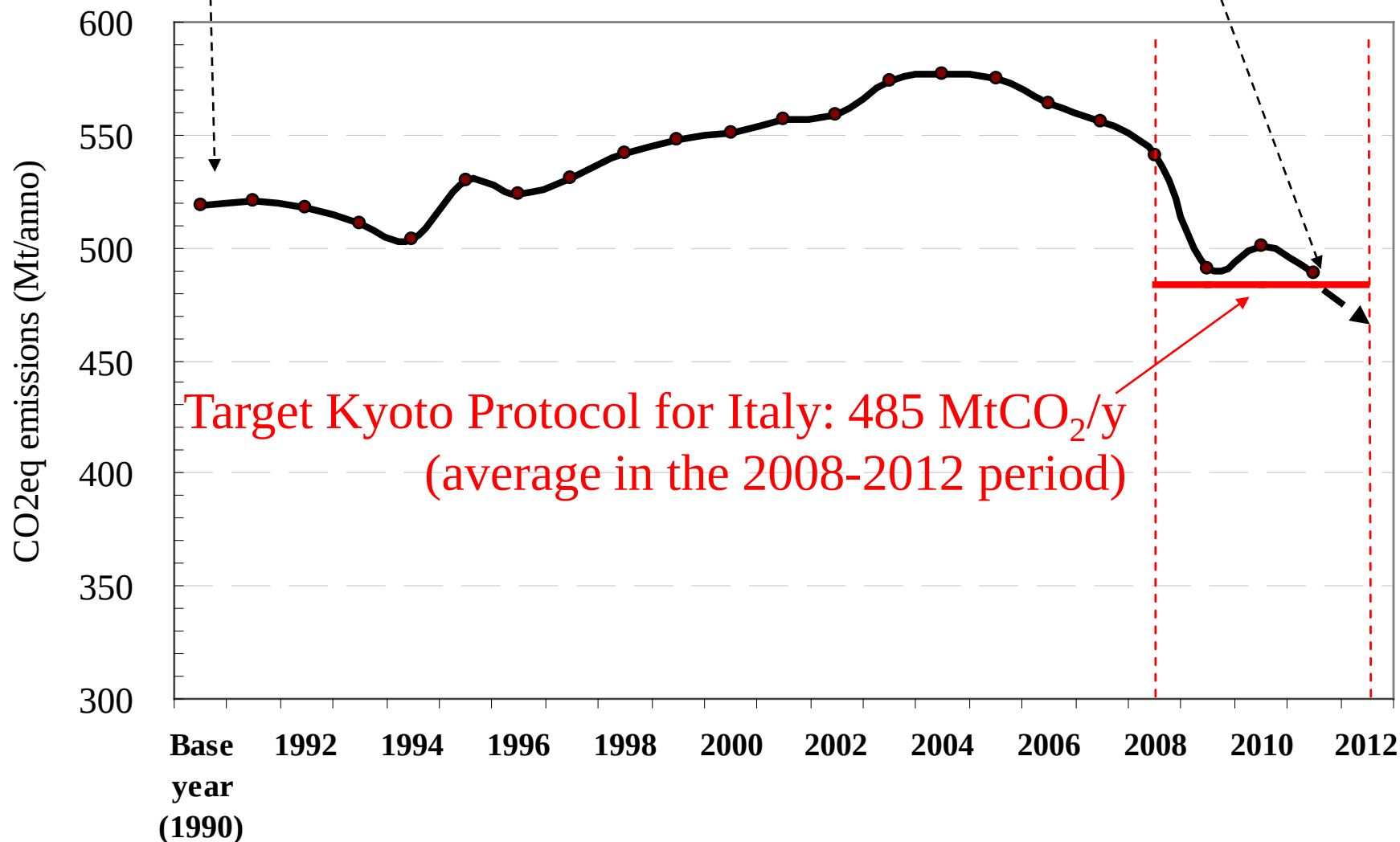
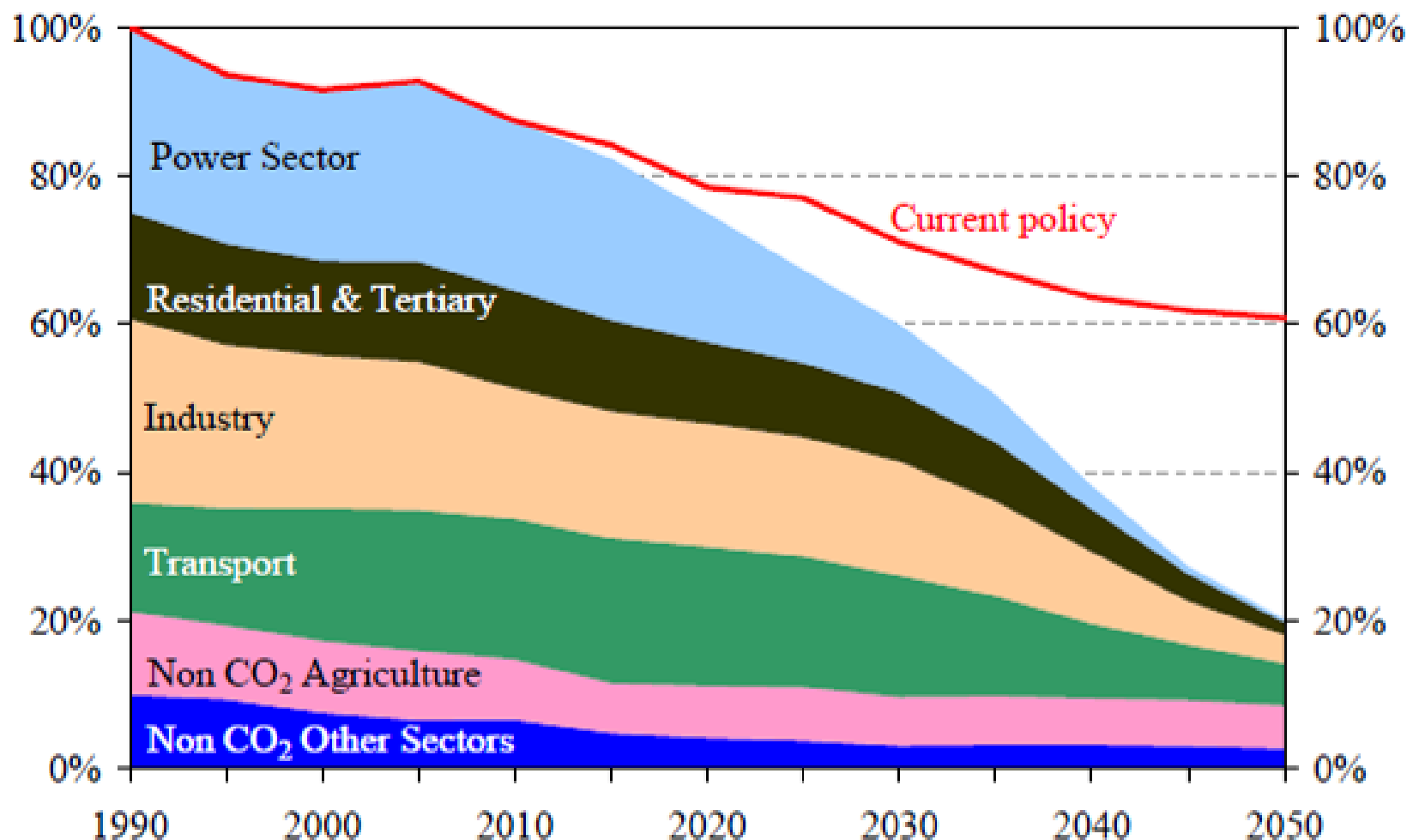


Figure 1: EU GHG emissions towards an 80% domestic reduction (100% =1990)



Fonte: Roadmap for moving to a low-carbon economy in 2050

http://ec.europa.eu/clima/policies/roadmap/index_en.htm

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°C.
	YES	Environmentalists, nuclear advocates are often here. 2°C.	OUR WORKING ASSUMPTIONS. 3°C, tough job.

How do we bend the curve?

Three ways:

Be very smart, so no policy is needed.

“ $S < C$ ” (solar is cheaper than coal).

Regulatory policy and referenda: Forbid and require.

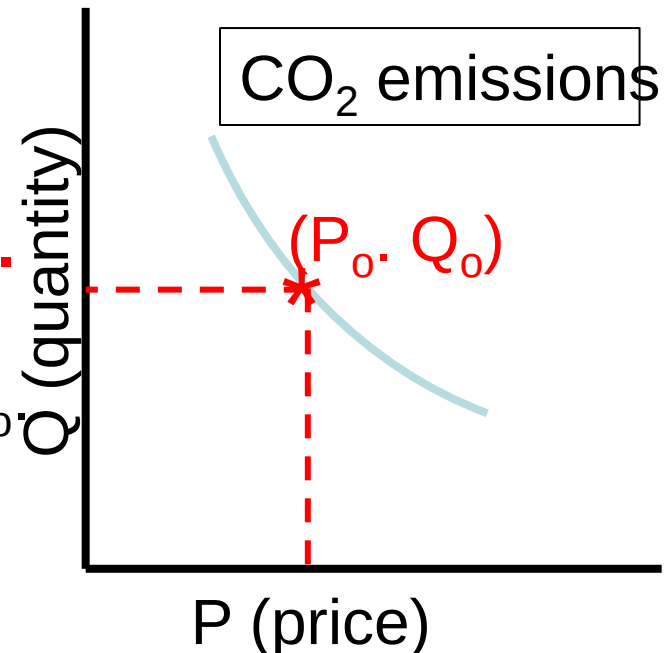
Market-based policies: Change relative prices.

**“Cap-and-trade” and “tax”
in their pure forms are identical.**

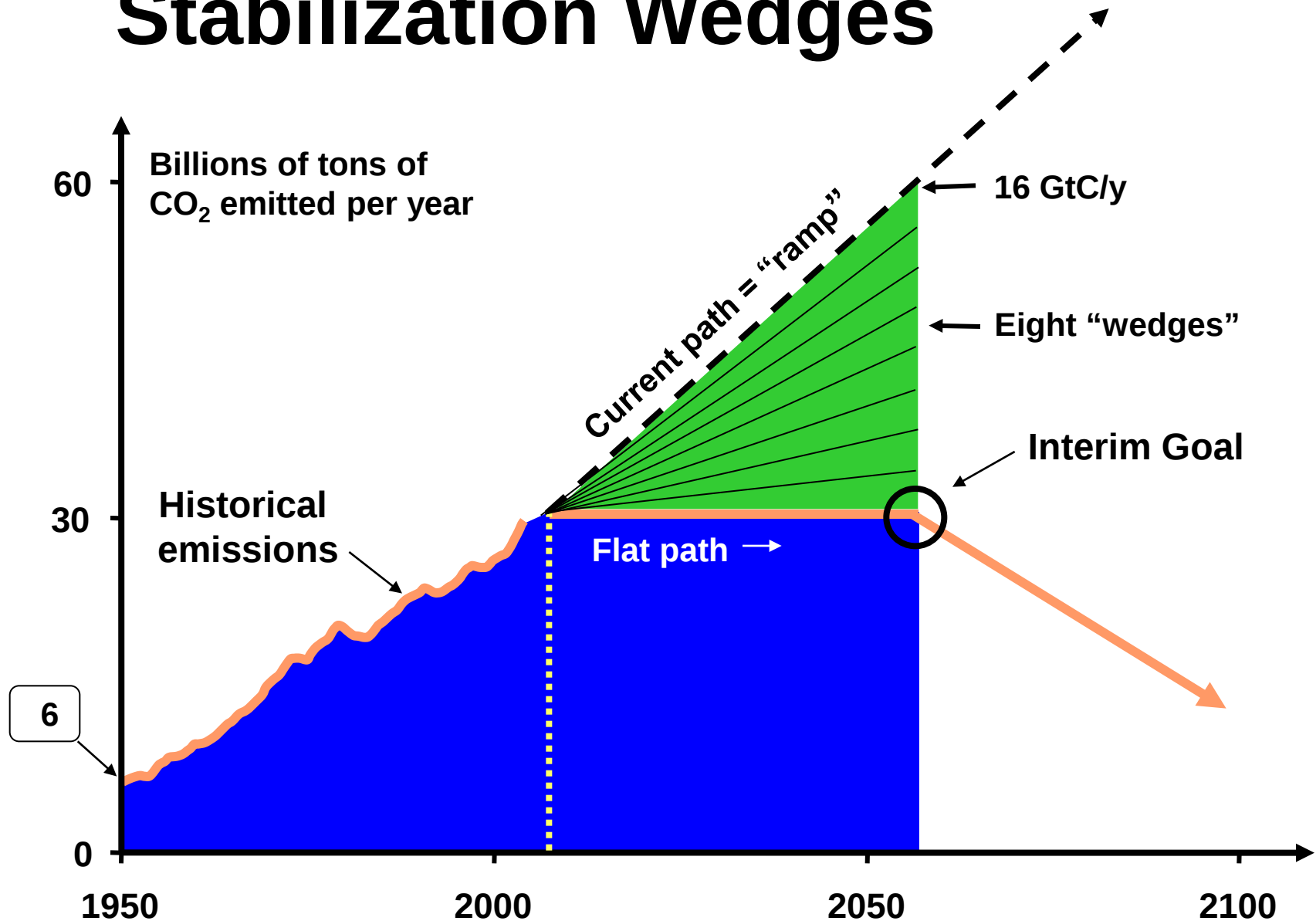
Assume $Q(P)$ exists:

Cap-and-trade: Fix Q_0 , then find P_0 .

Tax: Fix P_0 , then find Q_0 .

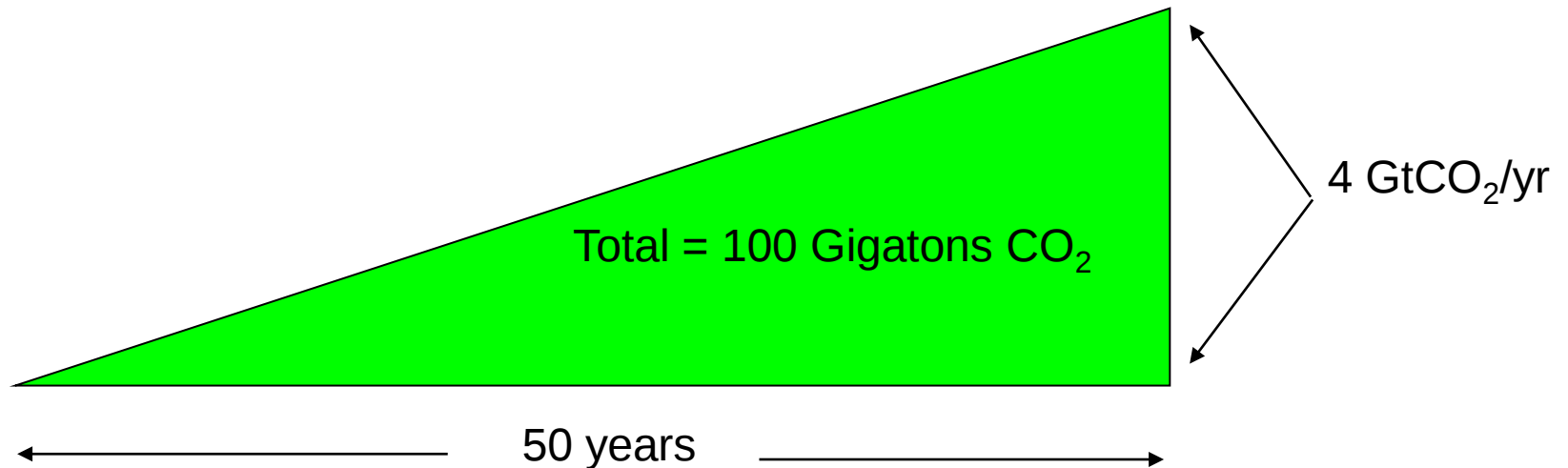


Stabilization Wedges

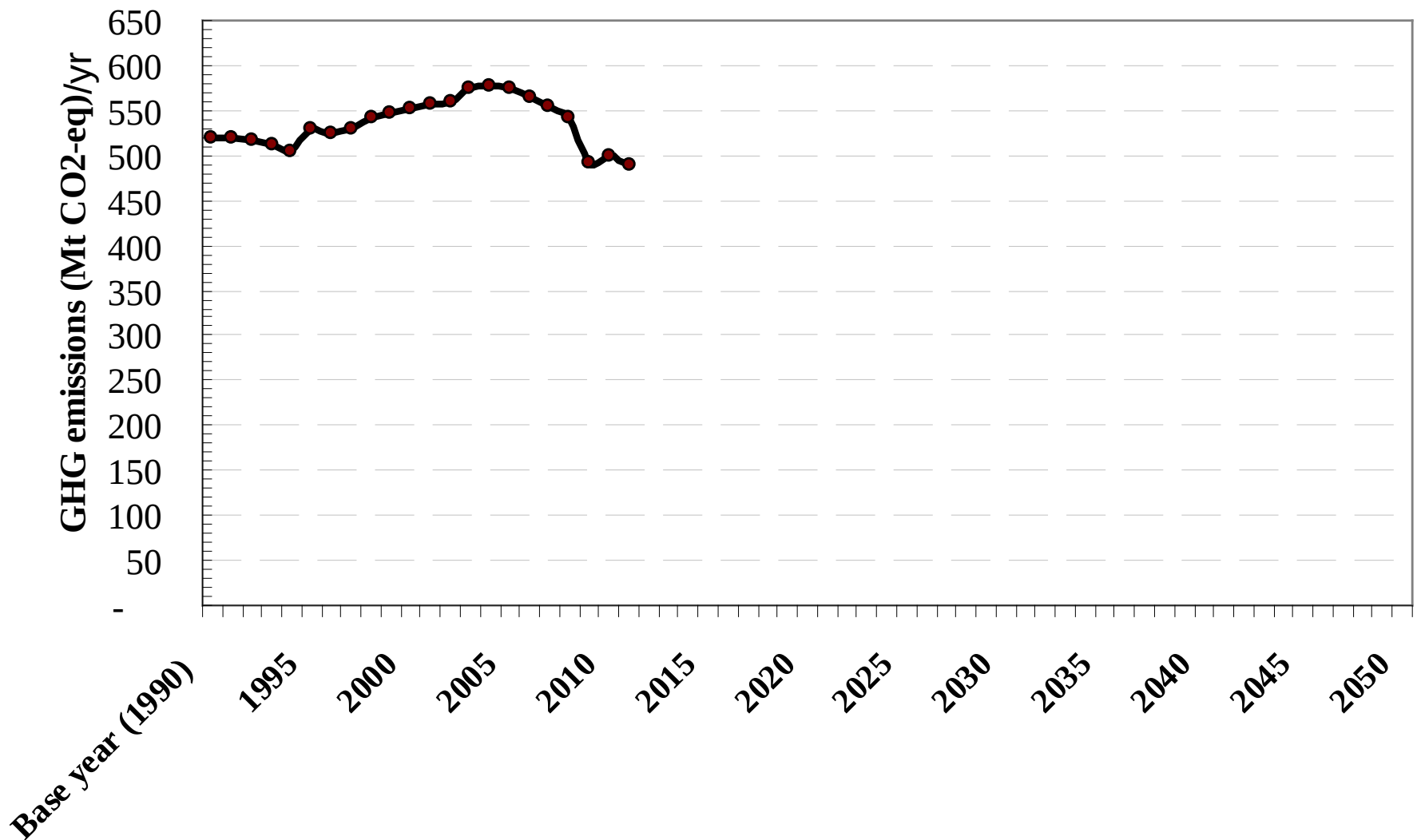


What is a Global “Wedge”?

A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 4 GtCO₂/yr. The strategy has the potential to be commercialized at very large scale.



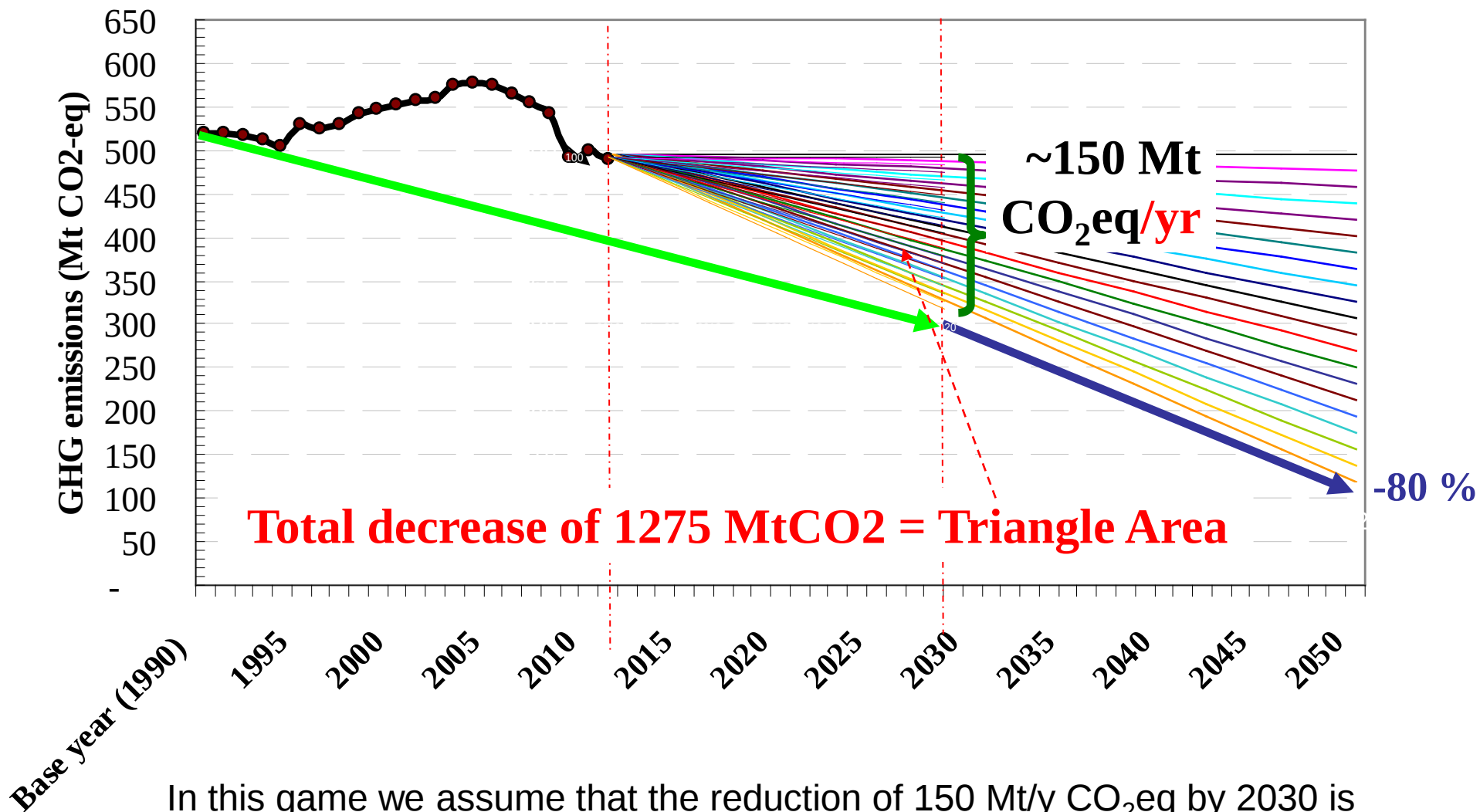
A wedge avoids the emissions of 100 GtCO₂.
This is six trillion dollars at \$60/tCO₂.



Emission in 2011: 490Mt/y.

We need an additional reduction of 180 Mt/y

We assume that 30Mt/y will be reduced with flexible mechanism (i.e. CDM) and 150Mt/y will be reduced by domestic measures

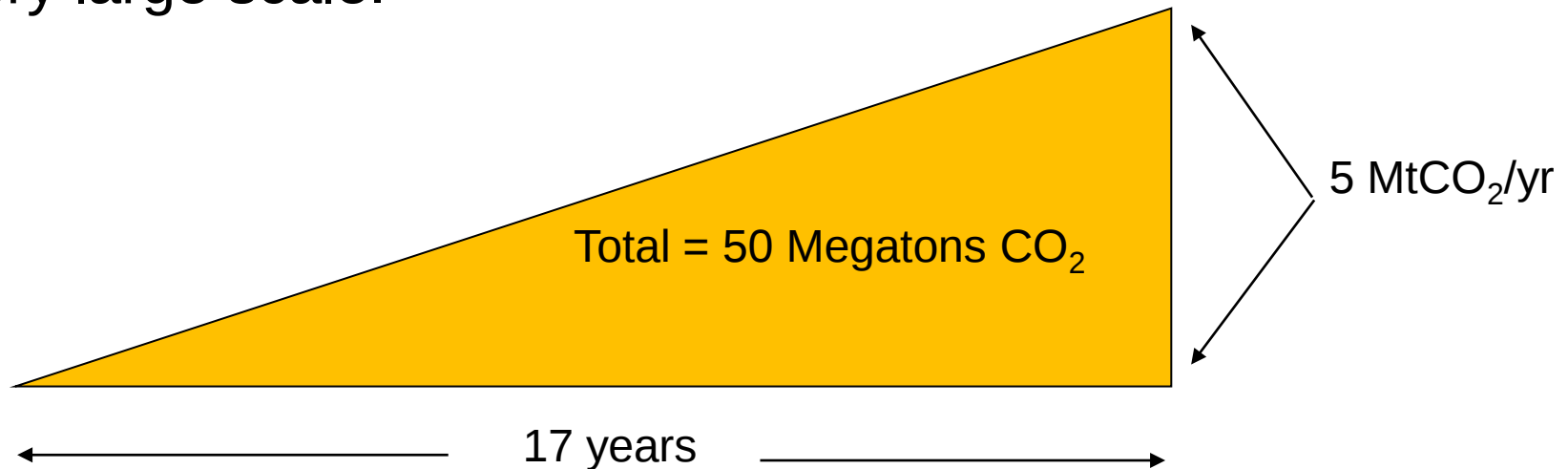


In this game we assume that the reduction of 150 Mt/y CO₂eq by 2030 is accomplished by combining 30 "strategies" (i.e. wedges) each of which gives a reduction (by the year 2030) of 5 Mt/y.

It is also assumed that the reduction grows linearly, so that the cumulative reduction in the period 2013-2030 is 1275Mt/y
(triangle area=150x17/2)

What is a “Polygame Wedge”?

A “polygame wedge” is a strategy to reduce carbon emissions that grows in 17 years from zero to 5 MtCO₂/yr. The strategy has the potential to be commercialized at very large scale.



A wedge avoids the emissions of 42.5 MtCO₂ (1/2400 of a global wedge). This is 1.7 billion euros at 40€/tCO₂.

Needed: 30 wedges

The 30 wedges could be selected between 20 “options” that consider mitigation technologies and practices currently commercially available and in use in Italy

Each single “options” in the PolyGame should have the potential to provide at least one wedge of 5 Mt CO₂eq at the end of the period (by 2030).

A “solution” can be used for more than one wedge
(a total of 30 wedges are needed!)

There could be other options but the 20 selected are the reference for this Polygame

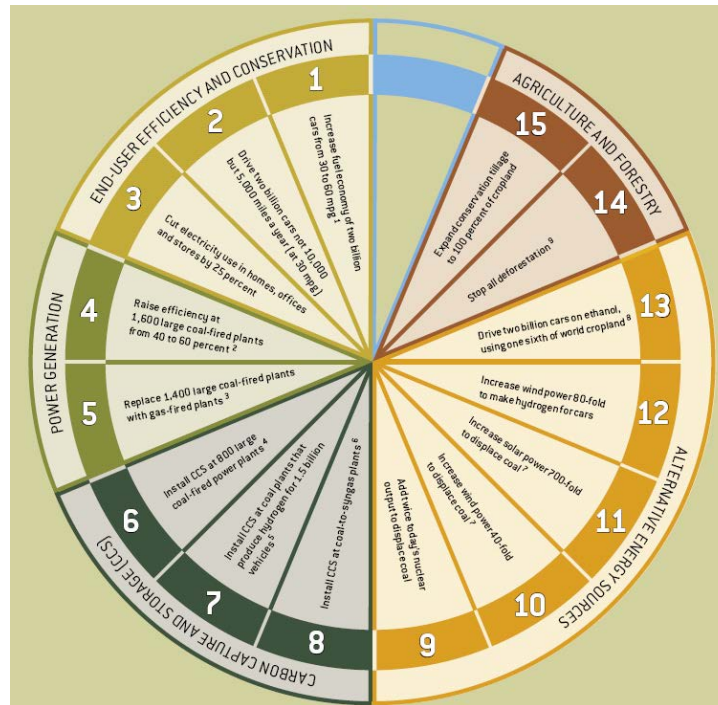
Available: 20 wedge strategies (1 of 2)

1. Car efficiency
2. Ethanol in the fuel
3. Reduction of car use
4. Cycling
5. Freight moved from truck to rail and ship
6. Energy efficient apartments
7. Efficiency in lighting
8. Efficiency in household electric appliances
9. Efficiency in industrial electric motors

Available: 20 wedge strategies (2 of 2)

- 10. Nuclear energy
- 11. Efficiency in thermoelectric production
- 12. Wind turbines
- 13. Photovoltaic energy
- 14. Carbon-fuelled power plants with CCS
- 15. Pellets use in domestic appliances
- 16. Biomass-fueled power plants
- 17. Forest sinks
- 18. Conservative (e.g. no-tillage) agriculture
- 19. Waste managed in an integrated system
- 20. Reduction of beef consumption in diet

How many different wedges?



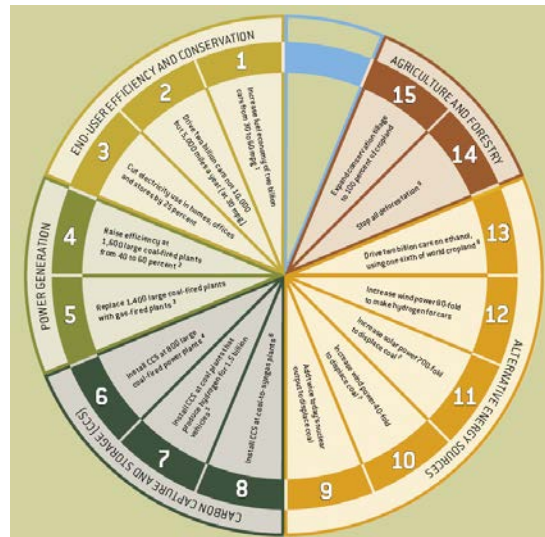
Source; Socolow and Pacala, *Scientific American*, September 2006, p.54

15 different wedges in Pacala-Socolow

20 different wedges in Polygame, lots of overlap.

You are allowed to create new ones!

How many different wedges?



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

Generic questions about each wedge that you consider:

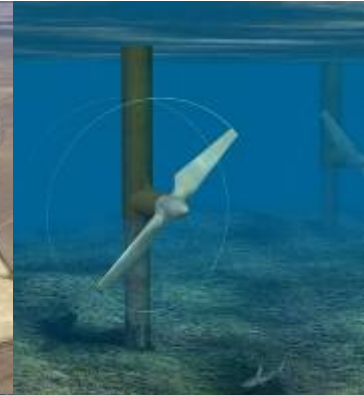
Is the overall cost to Italy for the second use of a wedge larger or smaller than the cost of its first use? (Is the second “wind” wedge less costly than the first?)

How many times can Italy use the same wedge before creating insurmountable problems?

Other wedges?

1. Modernise old hydro stations
2. Small hydro-electric
3. Energy savings
4. Electricity from salt water
5. Wave power
6. Geothermal energy
7. Raw muscle power
8. Tidal power
9. Heat pumps
10. Concentrated solar energy
11. Electric vehicles
12. Fuel cells for shipping
13. Cleaner fertiliser production
14. Use surplus heat
15. Biochar
16. Carbon dioxide removal (CDR) from the atmosphere

There are a lot of other things to do: you can try to build a new wedges



The Polygame assumes that the cost of a climate policy is not the main problem

- Some measures are already convenient
- Other measures are likely to be adopted by relying on market force alone
- Others measures are more cost-effective to society when their co-benefits are considered along with their energy and climate benefits
- There are many co-benefits of GHG mitigation: e.g., healthier lives from reduced air pollution, energy security, balance of trade improvement, provision of modern energy services to rural areas, and employment
- Benefits may offset a substantial fraction of mitigation costs
- **The costs are not a major barrier**

For simplicity, we don't consider in the Polygame the overlap between the reductions of different wedges

Demand Wedges

Efficient Use of Electricity



Effort needed by 2063 for 1 wedge:

25% reduction in expected 2063 electricity use in commercial and residential buildings

Efficient Use of Fuel



Effort needed by 2063 for 1 wedge:

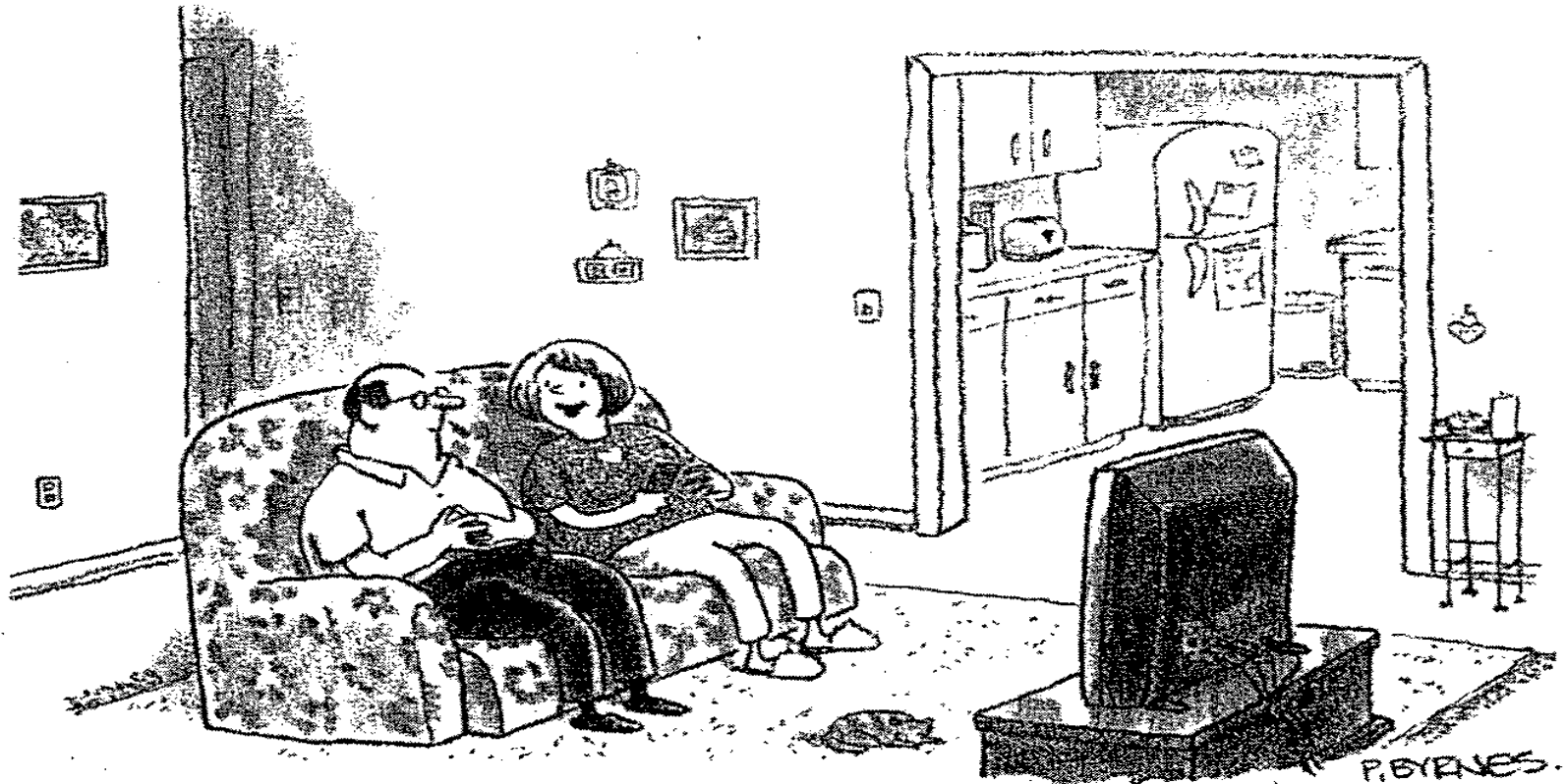
Note: Drive 16,000 km at 8 liters/100km: emit 1 tC ($\approx 4 \text{ tCO}_2$)

2 billion cars driven 16,000 km/yr at not 8 but **4** l/100km.

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.

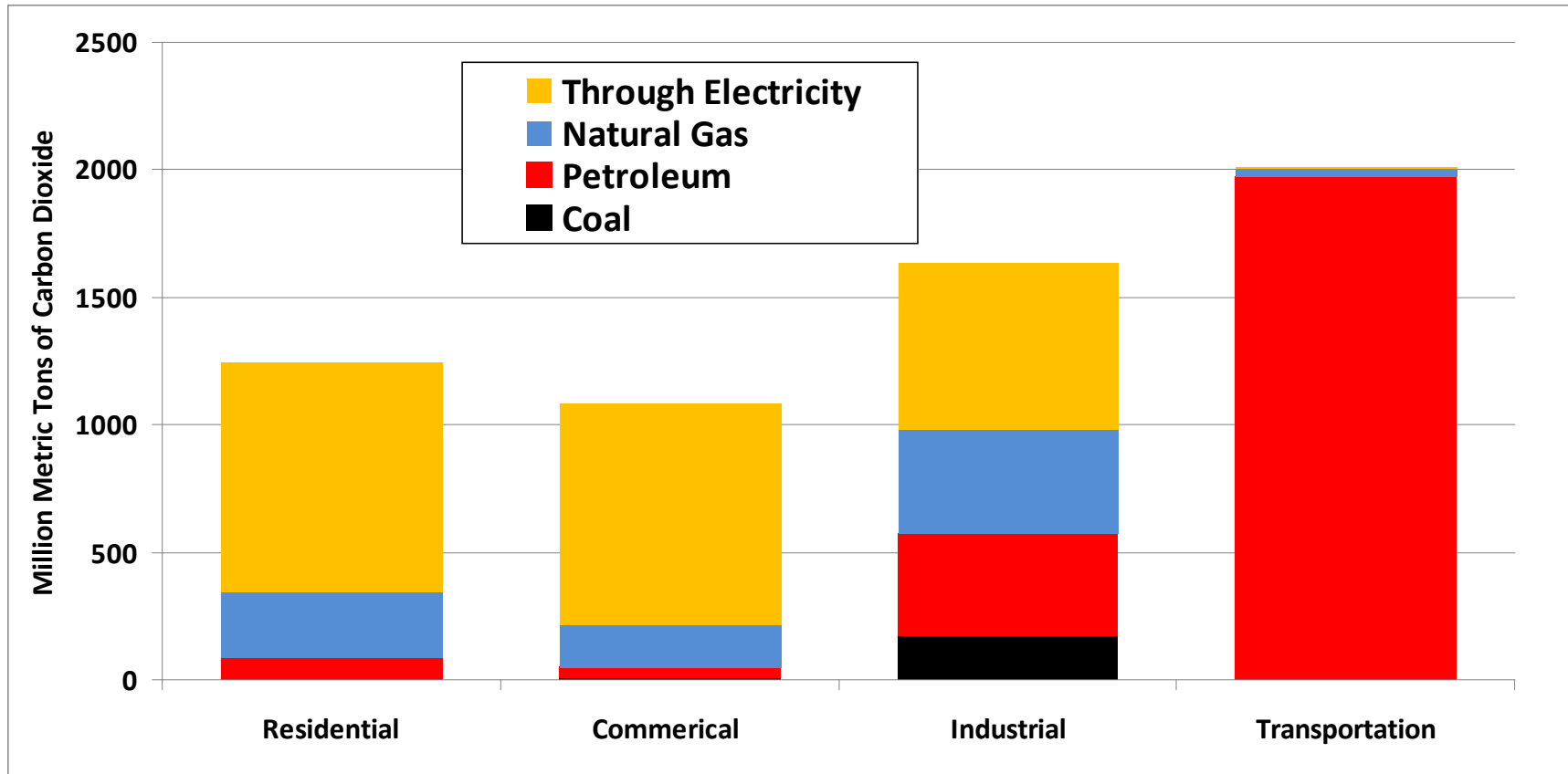
Can virtual experiences substitute for travel?



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

From *The New Yorker*, April 21, 2008

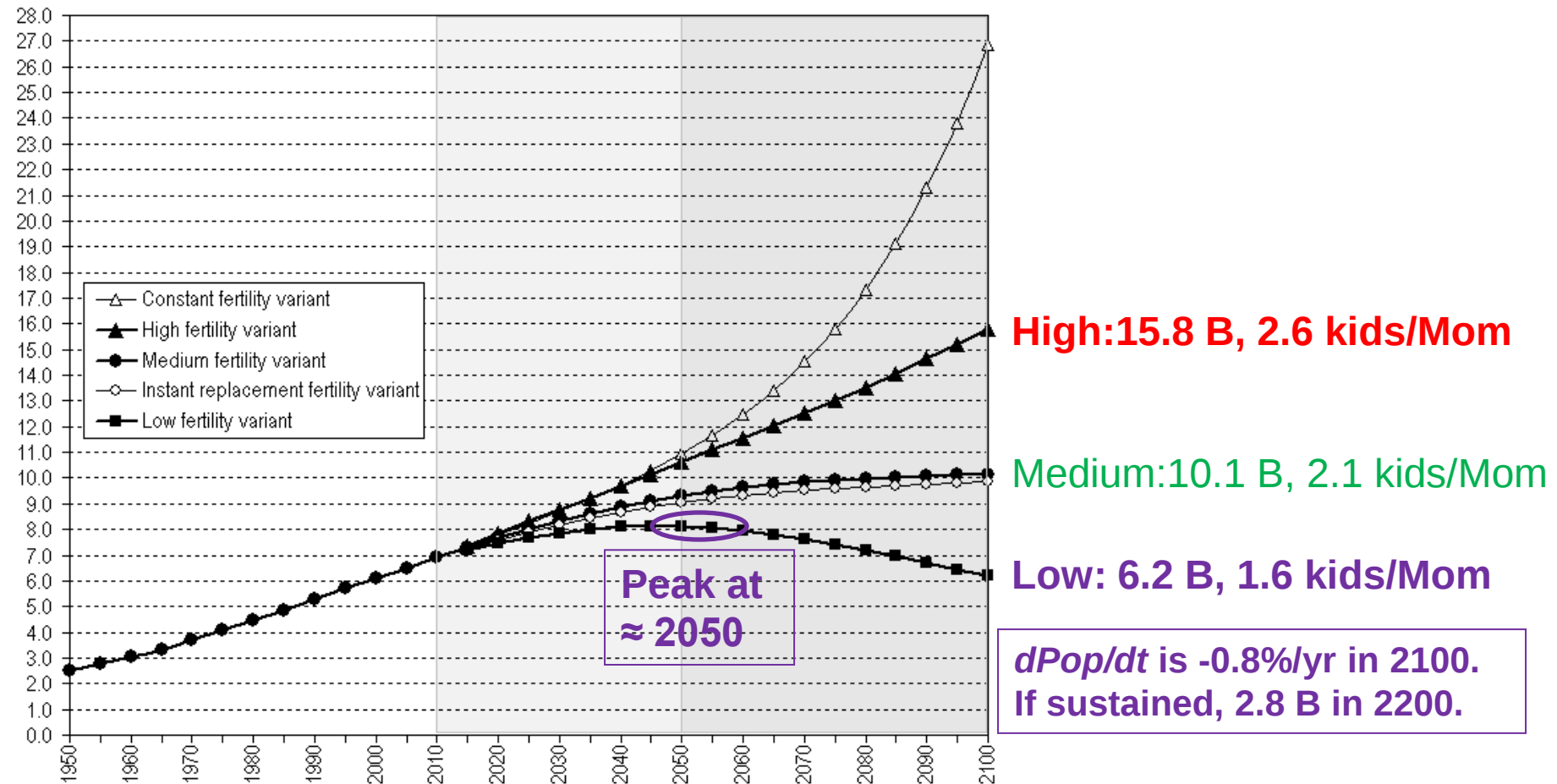
At the power plant, CO₂ heads for the sky, most electrons head for buildings!



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

The population wedge

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?

Climate change is a consequence of prosperity

The CO₂ problem is a problem of modernity, a byproduct of choices about what to consume, how to spend time.

Today, it is nearly universally believed, a good life is one lived with exuberance.

We seek independence, privacy, safety, comfort, beauty, variety of experience – goals that can thwart low-consumption living.

Supply Wedges

Coal-electricity Wedges

Assume 700 modern (90% capacity factor, 50% efficient) 1-GW coal plants, with CO₂ vented, will emit 1 GtC each year.

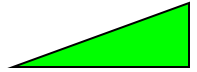
This carbon intensity is:

0.18 kgC/kWh

0.66 kgCO₂/kWh

Electricity-supply wedges result from not building such plants.

Photovoltaic Power



Effort needed by 2063 for one wedge:

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

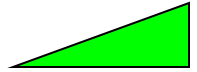
2010: 40 GW_{peak} (2%), 16 GW/yr

If 200 kWh/m²-yr and coal at 1 kgCO₂/kWh, then 2 Mha:

400 million 50-m² rooftop units,

200 km x 100 km desert collectors

Concentrating Solar Power (CSP)

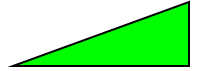


Effort needed by 2063 for one wedge:

2000 GW_{peak} displacing coal

2 million hectares, if same land use efficiency as PV

Wind Power



**Effort needed by
2063 for 1 wedge:**

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

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

Are they ugly or beautiful?

Intermittency needs attention

Huge uncharted research frontier. As renewables achieve >20% penetration on grids, intermittency (non-constant, unpredictable) must be addressed.

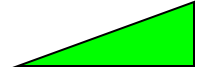
Strategies:

- Diversity of supply (wind flux is often larger at night)

- Complementary energy source (e.g., natural gas)

- Storage for various durations, from seconds to days

Nuclear Power



**Effort needed by
2063 for 1 wedge:**

700 GW (twice
current capacity)
displacing coal
power.

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

Fukushima: How significant?



Source: “After the Deluge: Short and Medium-term Impacts of the Reactor Damage Caused by the Japan Earthquake and Tsunami.” Nautilus Institute for Security and Sustainability, March 17, 2011. **Figure 4 :** Fukushima Number 1 Nuclear Power Plant

Nuclear power and nuclear war

Before I would welcome a nuclear wedge, I would want to see much stronger international institutions to prevent the diversion into nuclear weapons of the uranium and plutonium associated with nuclear power.

It would be terrible to exchange climate change for nuclear war anywhere on the planet.

Fuel Switching: Coal to gas

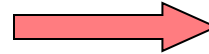
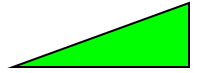


Photo by J.C. Willett (U.S. Geological Survey).

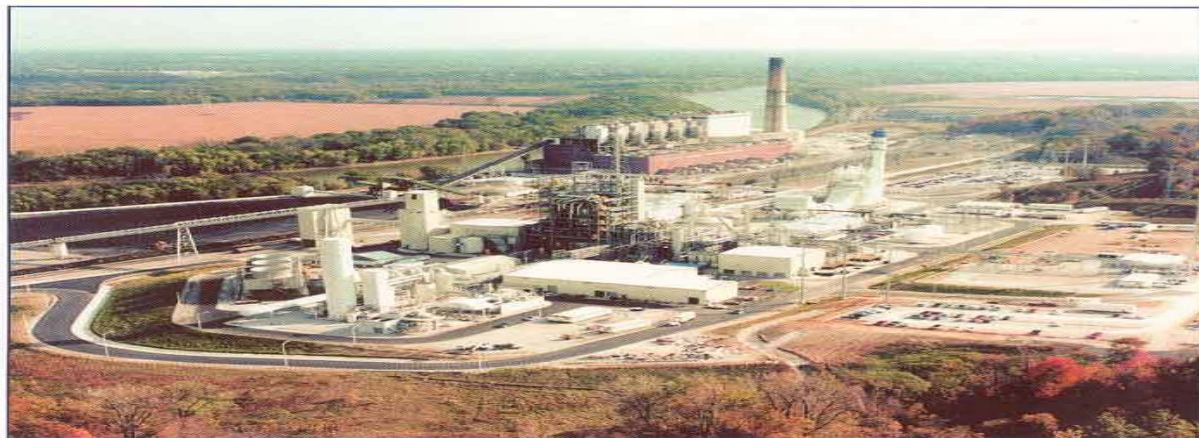
**Effort needed by 2063
for one wedge:**

**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**

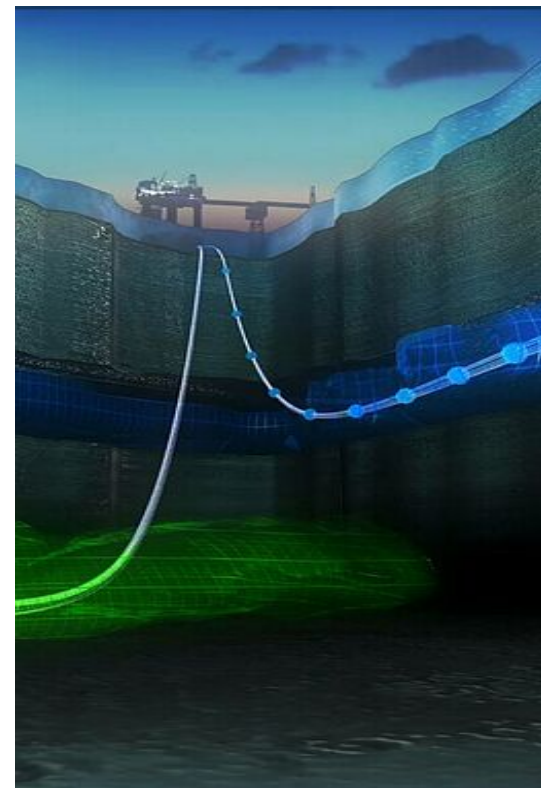
Coal with Carbon Capture and Storage



The Wabash coal gasification reprocessing project

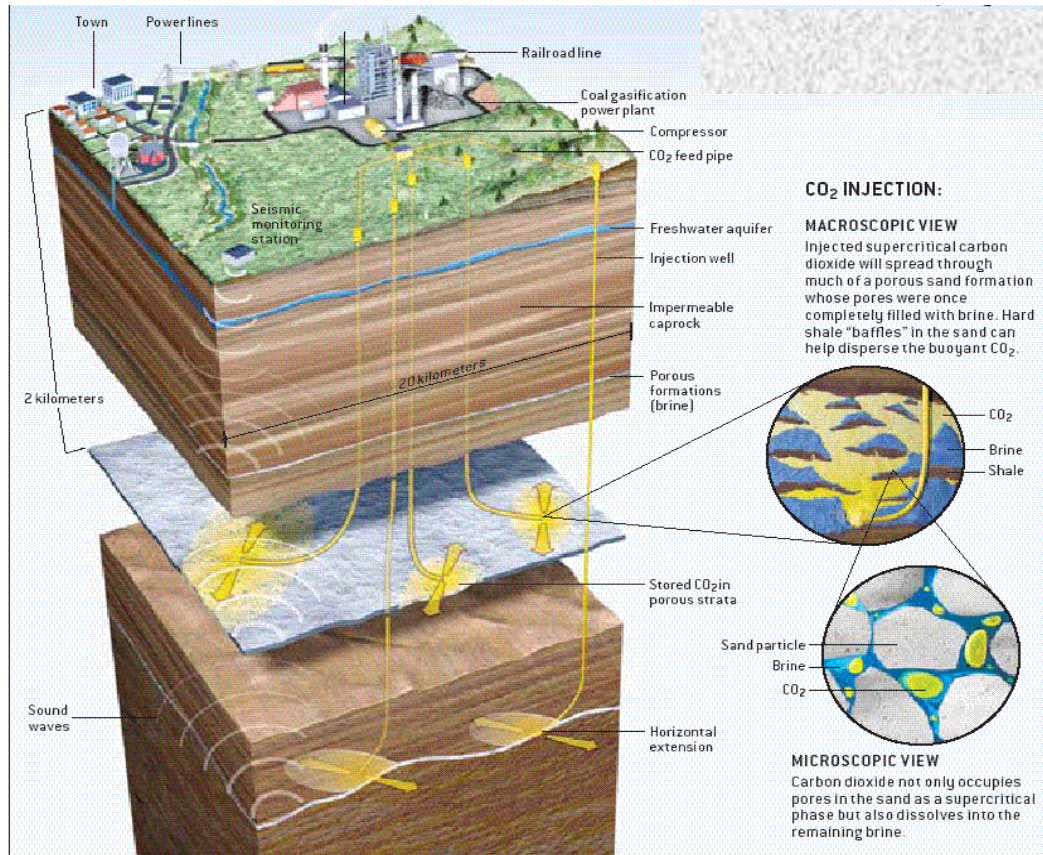
Effort needed by 2063 for 1 wedge:

Carbon capture and storage at 800 GW coal power plants.



Sleipner field, Norway

The Future Coal or Natural Gas Power Plant



Shown here: After 10 years of operation of a 1000 MW coal plant, 60 Mt (90 Mm³) of CO₂ have been injected, filling a horizontal area of 40 km² 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(CO₂)/day, or 300 million standard cubic feet/day (scfd). That's 3 billion barrels, or 6 trillion standard cubic feet, over 60 years.

“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

“Solutions” can bring serious problems of their own.

Every “solution” has a dark side.

Conservation

Renewables

“Clean coal”

Nuclear power

Geoengineering

Regimentation

Competing uses of land

Mining: worker and land impacts

Nuclear war

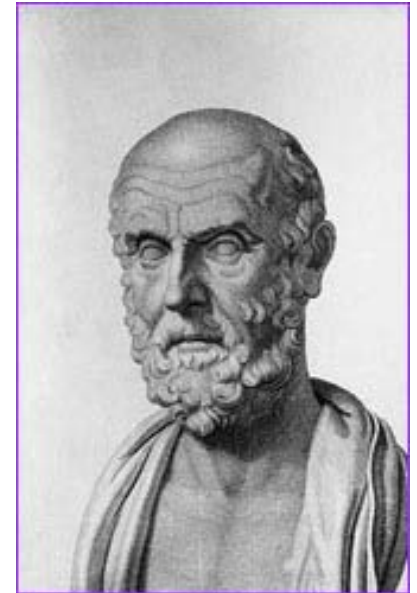
Technological hegemony

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

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 2063 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 not only about those alive today but also about the collective future of our species.

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

[illegible]

Now, go play Polygame!