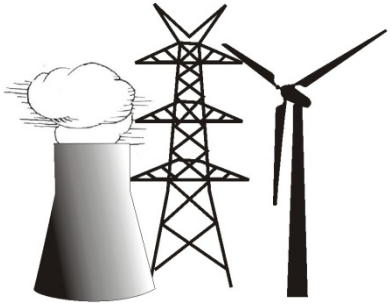

Carnegie Mellon Electricity Industry Center

Carbon and Climate Issues

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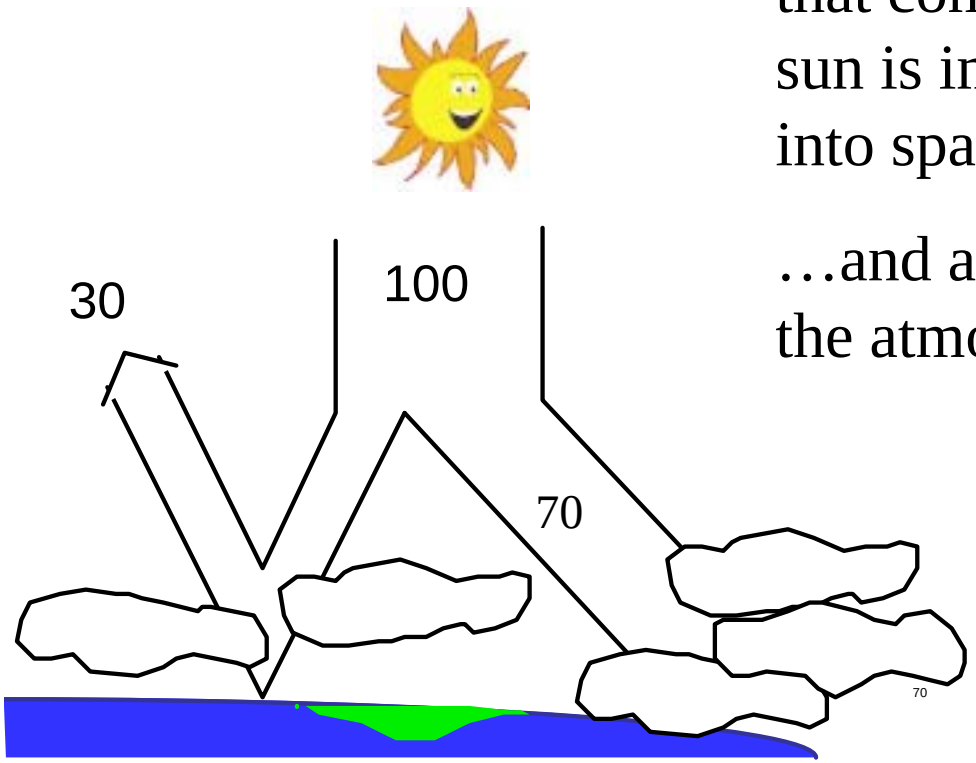
This evening I will briefly address five questions:

1. What is the basic science behind the issue of climate change?
2. Isn't there enormous uncertainty about climate change?
3. What impacts can we expect to see from climate change?
4. What can we do to reduce climate change and minimize its adverse impacts?
5. Can we afford to do anything?

1. What is the basic science behind the issue of climate change?

Sun-earth system

A quick review



About 30% of the light energy that comes to the earth from the sun is immediately reflected back into space…

…and about 70% is absorbed by the atmosphere and the ground.

BUT…while the atmosphere is transparent to visual light, it is opaque to heat (infrared).

So heat energy gets trapped.

This is termed the "greenhouse effect."

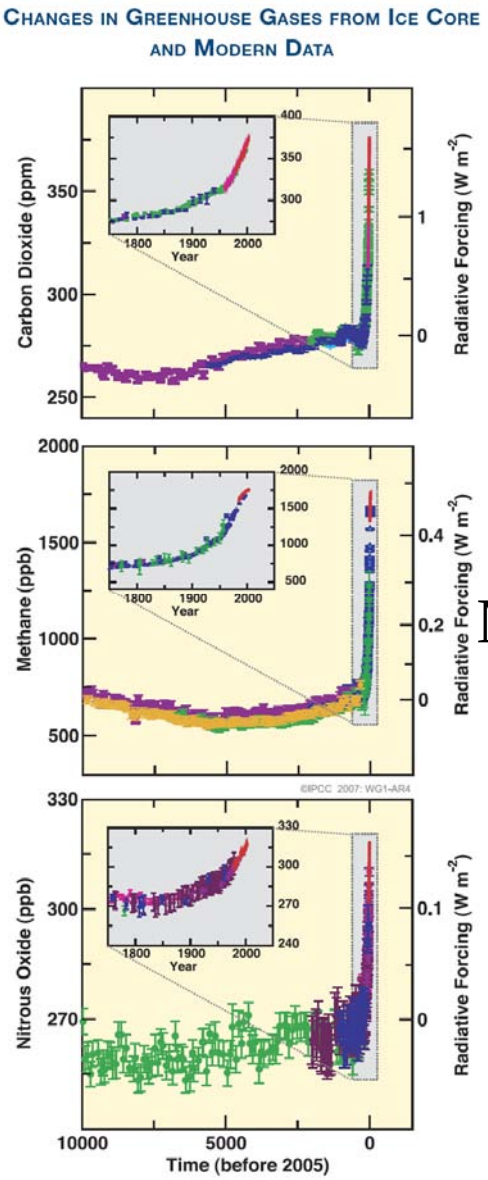
Carbon dioxide is a natural trace constituent of the atmosphere. It, together with water vapor, traps infrared radiation, keeping Earth roughly 65 °F warmer than it would otherwise be.

If we increase the amount of carbon dioxide a lot, the planet will get hot. Venus, with an atmosphere that has roughly one hundred times as much CO_2 as the earth's, has an average surface temperature of 855 °F. Without an atmosphere, it would be ~ 0 °F.

As a former planetary astronomer, I can tell you that the greenhouse effect is more than “just a theory”!

Consequences of burning fossil fuel

When people burn coal, oil and gas the carbon in those fuels combines with oxygen in the air, energy is released, and carbon dioxide (CO_2) is created. Much of it remains in the atmosphere for $\geq$100 yrs. Since the beginning of the industrial revolution, atmospheric concentration has risen by about 30%. The same is true for other "greenhouse" gases such as methane and nitrous oxide.



CO_2

Methane

NO_x

Source: IPCC FAR WG1, 2007

But, this is all rather abstract…let me try to make it more specific

Consider...

…the Bruce Mansfield power plant (2360 MW) located on the Ohio River, just west of Pittsburgh.

A plant this size burns the equivalent of about 230 hopper cars (100 tons each) of coal every day.

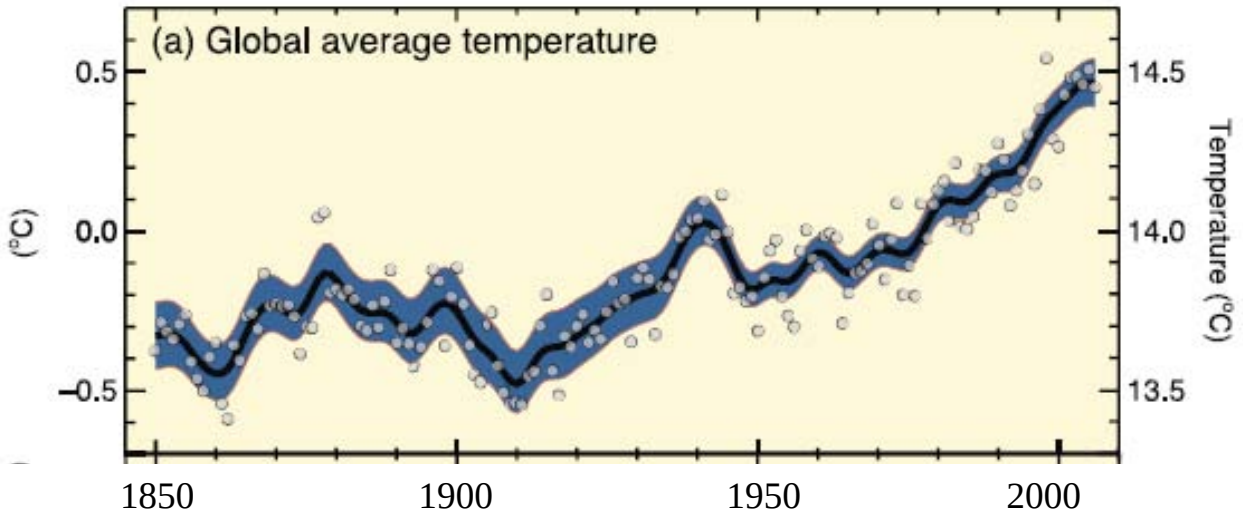
If coal were pure carbon, that would be the same as taking 130 such cars, converting them into invisible CO_2 gas, and releasing them into the atmosphere every day.

Many such plants are operating all over the U.S. and the world.

Sources: www.industcards.com/ st-coal-usa-pa.htm and www.battelle.org. Calculations by Jay Apt.

The steady build-up…

…of greenhouse gases (GHGs) in the atmosphere from hundreds of years of industrial activity has produced a corresponding increase in the average temperature of the earth.

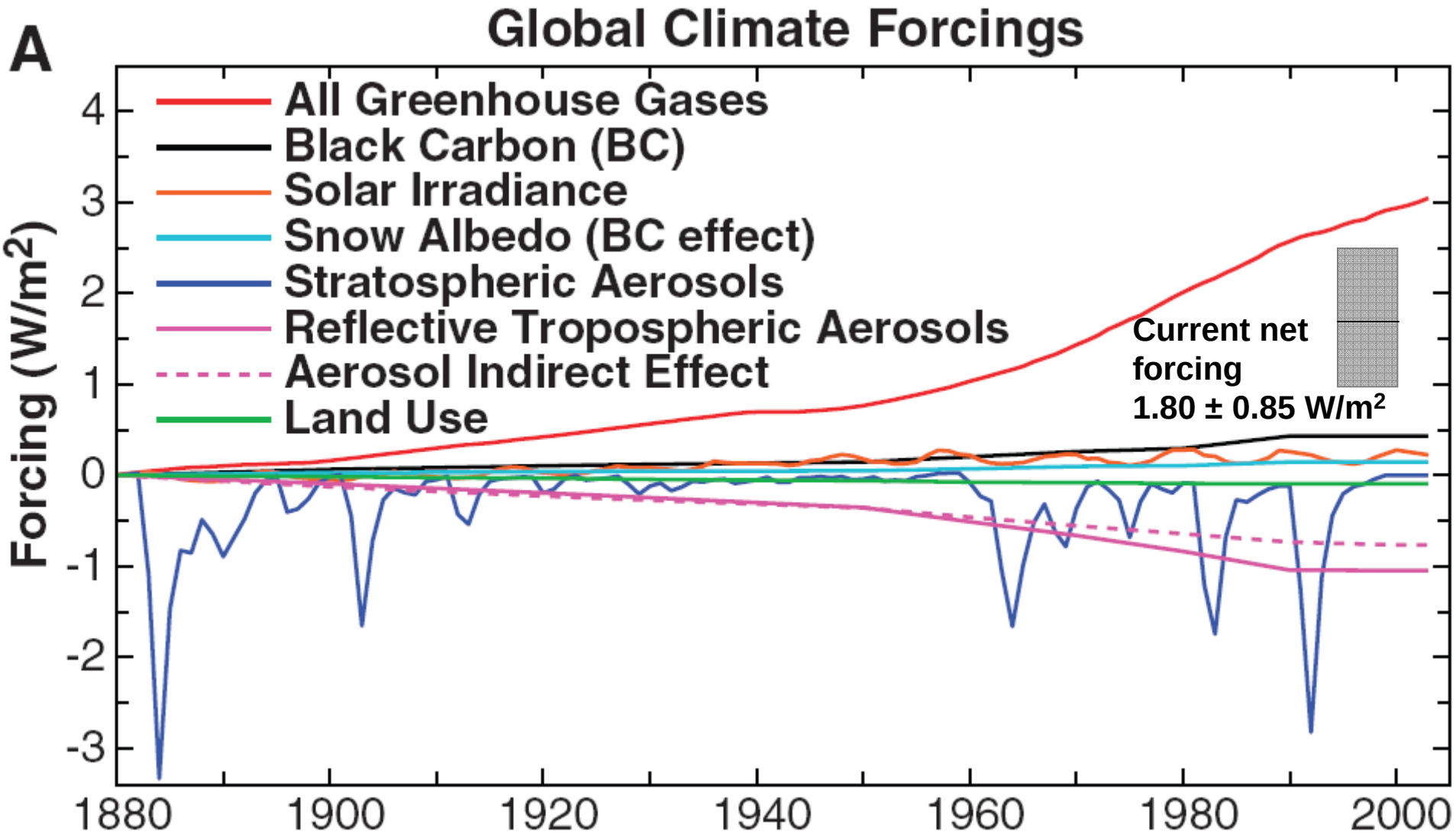


Warming over the past 100 years ~1.3°F

Source: IPCC FAR WG1, 2007

Aren’t the temperature changes just caused by the sun, or soot, rather than humans?

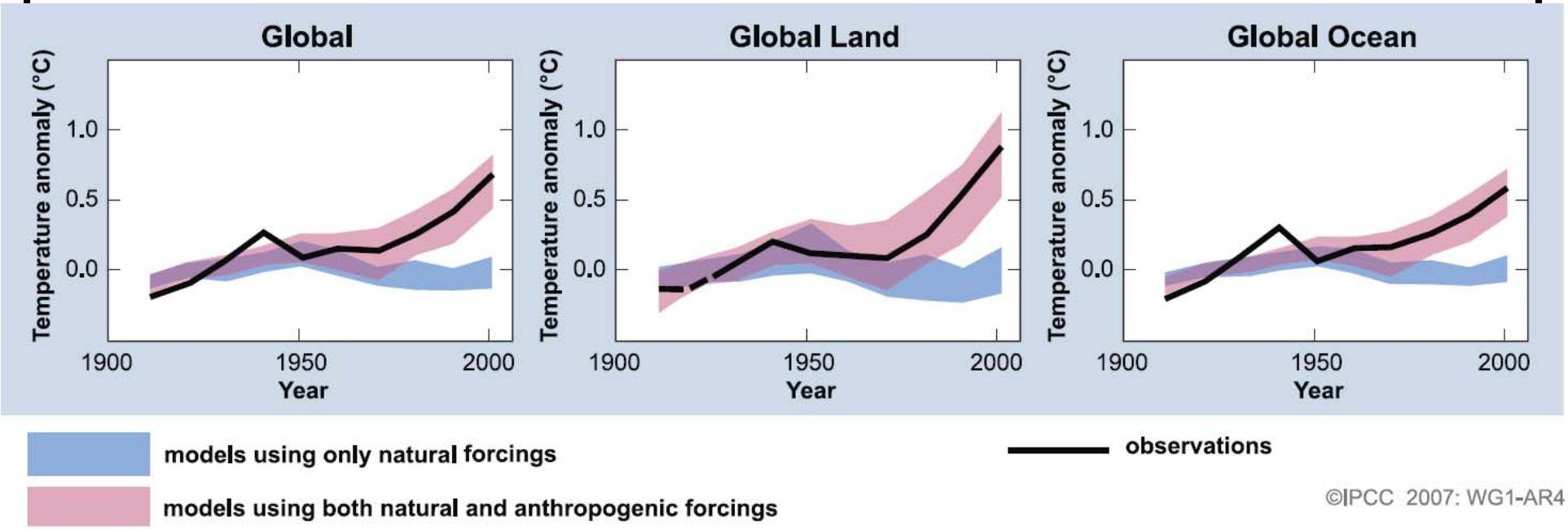
Sunlight hitting the Earth's surface deposits 343 Watts per square meter.



Source: Hansen et al. *Science* 308 (5727): 1431-1435 (2005)

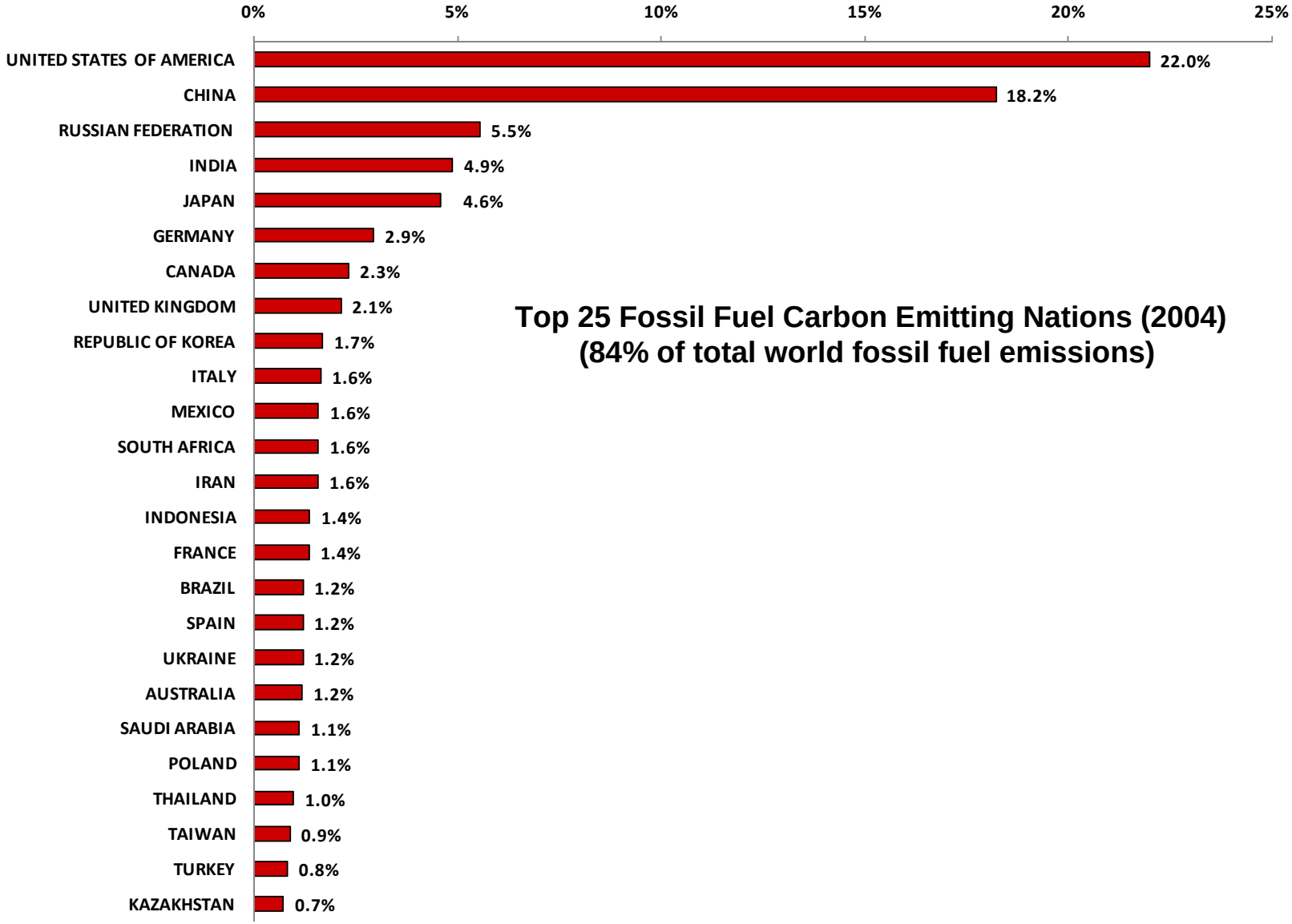
Are Humans the Cause?

Most probably, yes



A climate model projection that includes
both natural processes and human activities closely matches
actual measurements of 20th-century temperature changes.

2004 Carbon Emissions from Fossil Fuels

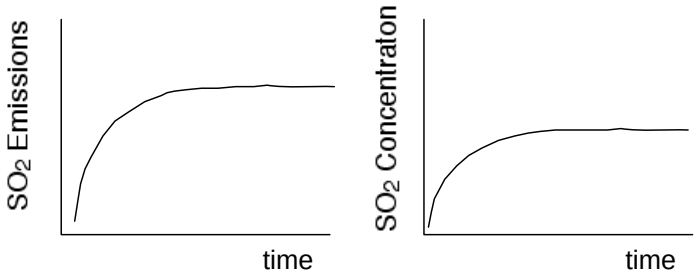


Top 25 Fossil Fuel Carbon Emitting Nations (2004)
(84% of total world fossil fuel emissions)

Source: Oak Ridge National Laboratory, http://cdiac.ornl.gov/trends/emis/top2004.tot

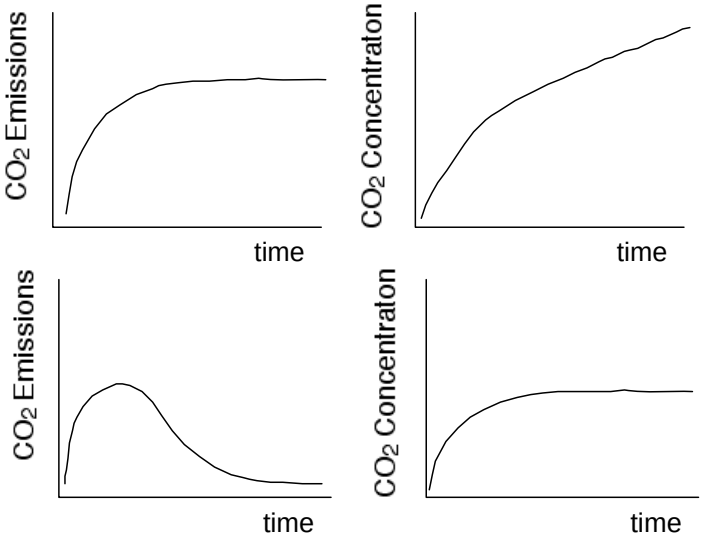
CO_2 is not like conventional air pollutants

Conventional pollutants like SO_2 or NO_x have a residence time in the atmosphere of just a few hours or days. Thus, stabilizing emissions of such pollutants results in stabilizing their concentration.



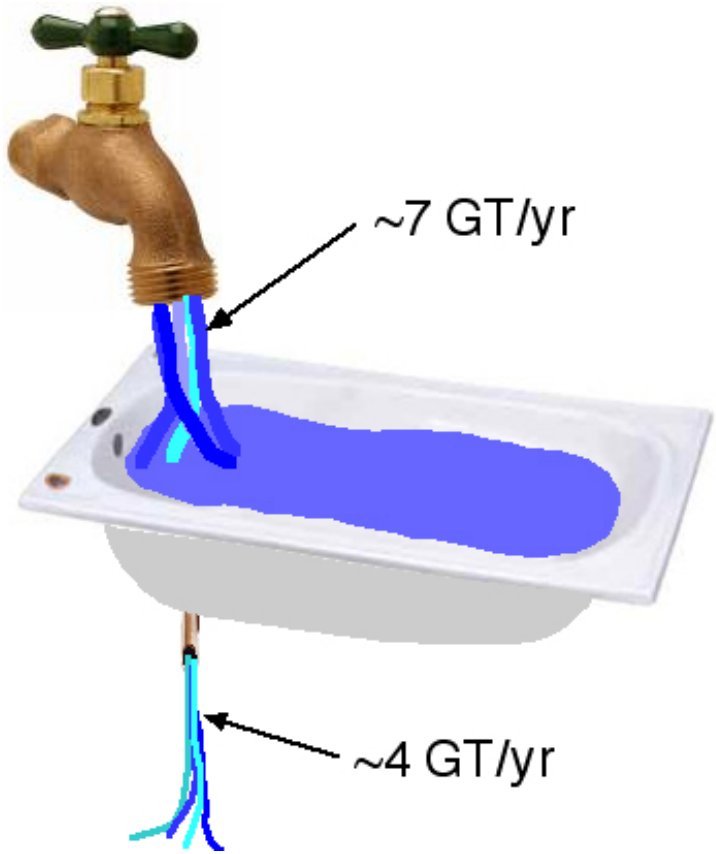
*This is **not** true of carbon dioxide.*

When CO_2 is emitted much of it lasts in the atmosphere for ~100 years. Thus, stabilizing atmospheric *concentrations* of CO_2 will require the world to reduce emissions *by at least 80%*.

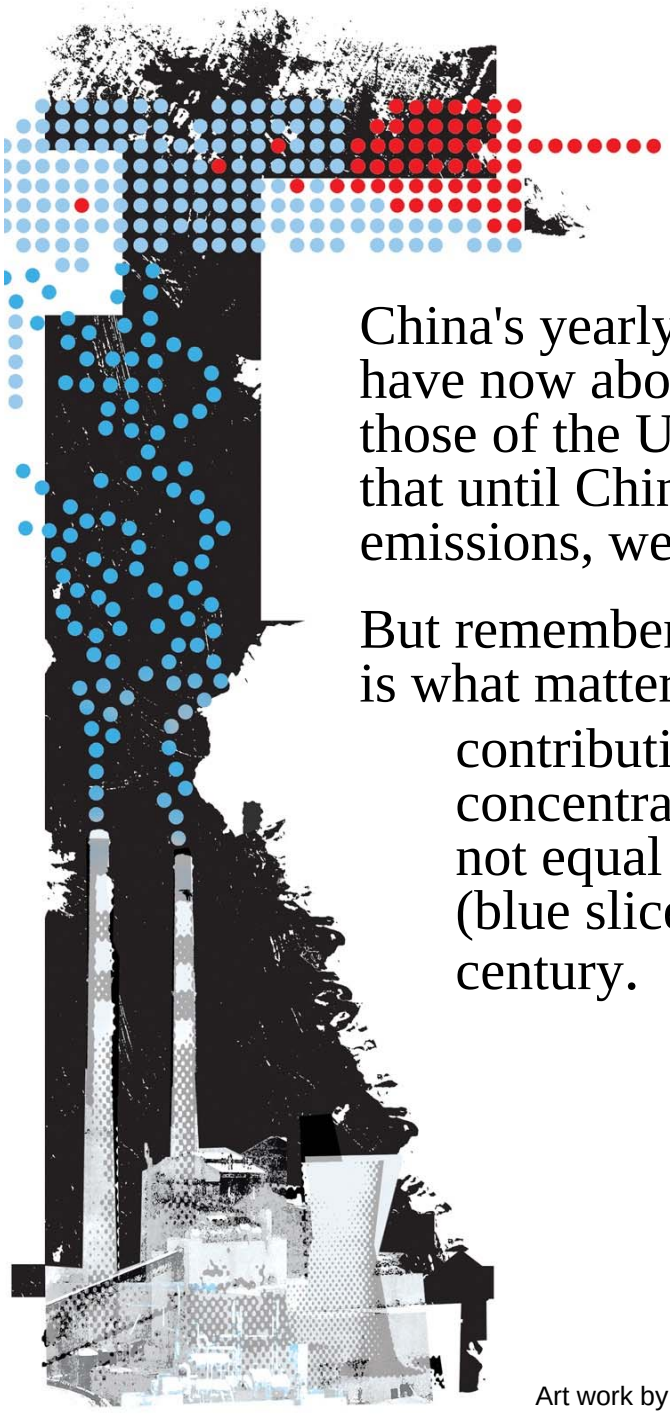


A useful analogy is…

…a bath tub with a very large faucet and a much smaller drain:



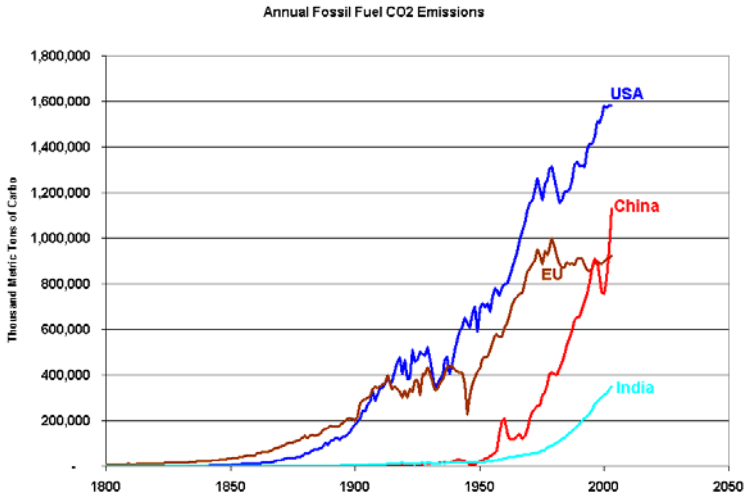
A key corollary:



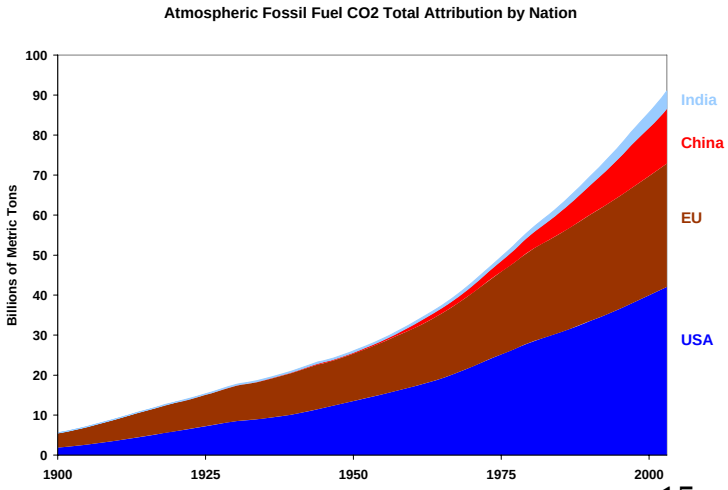
China's yearly emissions have now about matched those of the U.S. Some argue that until China controls emissions, we should not.

But remember, *concentration* is what matters, and China's contributions to concentration (red slice) will not equal those of the U.S. (blue slice) until mid-century.

Emissions over time



Concentration over time



Art work by Daniel Marsula, *Pittsburgh Post-Gazette*

2. Isn't there enormous uncertainty about climate change?

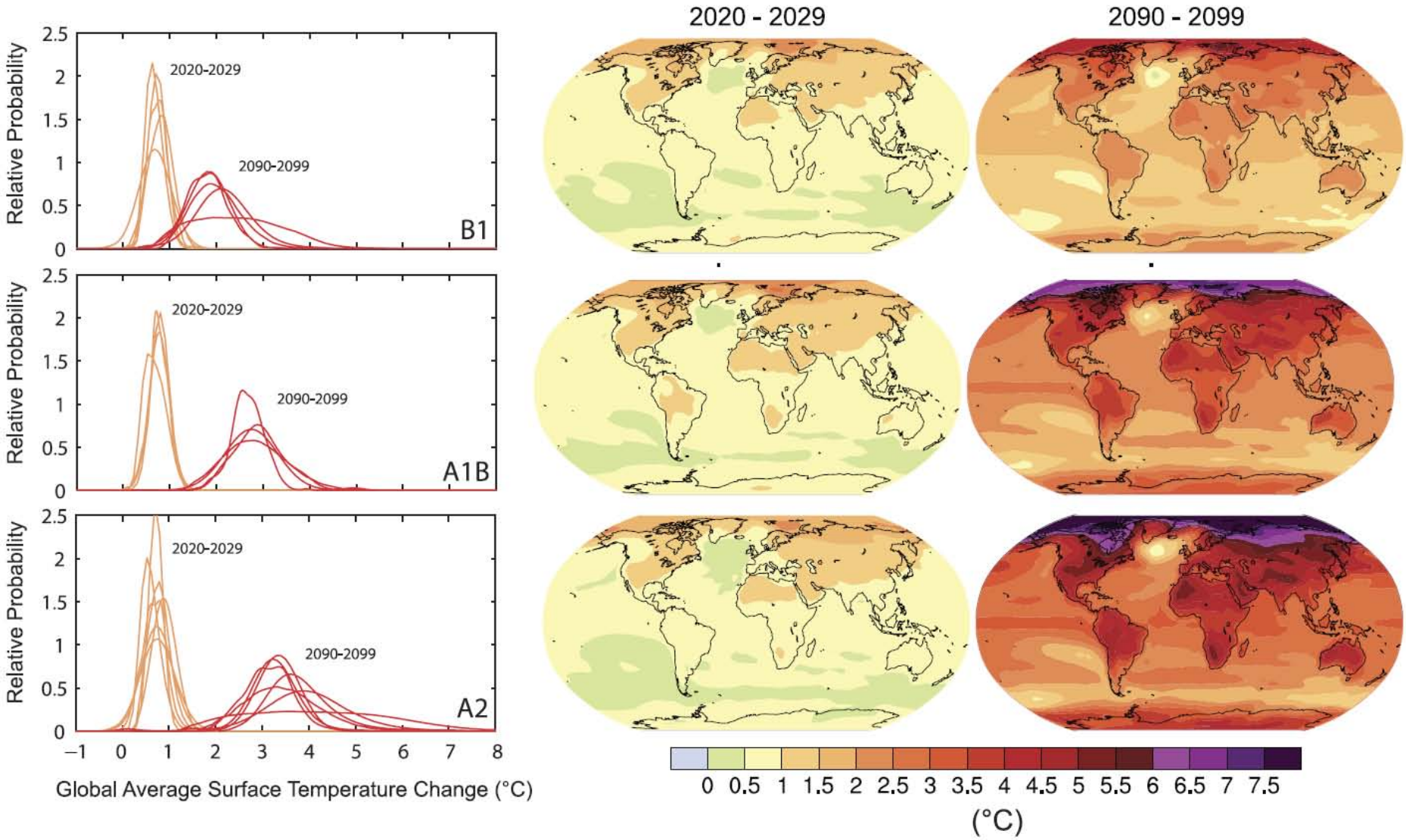
There is ***no*** uncertainty…

…about whether CO_2 and other greenhouse gases (GHGs) are warming the planet and changing the climate. Talk about uncertainty about these issues is largely the result of intentional obfuscation by those with short-term economic interests.

There ***is*** uncertainty about:

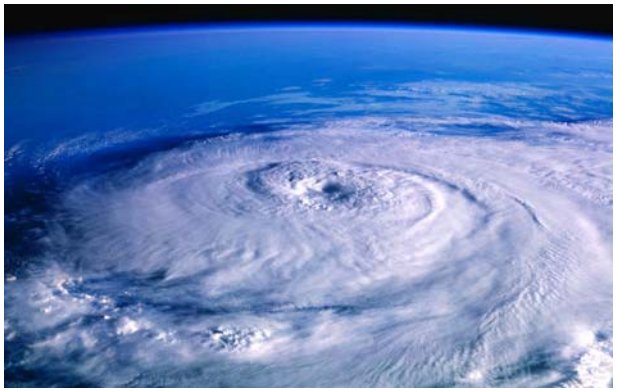
- How much more GHG humans will add to the atmosphere over the next century;
- How much additional warming those additions will produce; and
- The details of many of the changes that will result:
  - In climate, weather and the oceans
  - In natural ecosystems
  - In human activities (agriculture, water, etc.).

Projections of Surface Temperatures



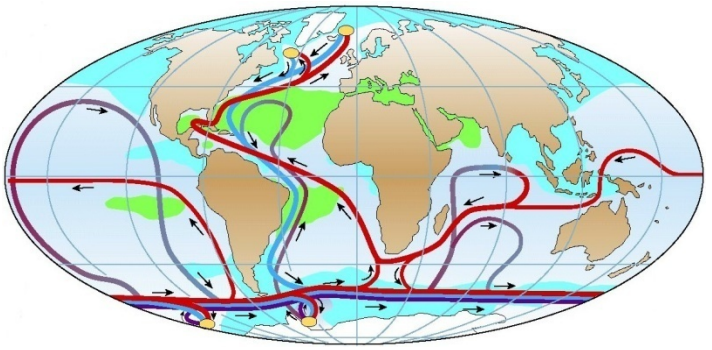
Source: IPCC WG1 2007

Two examples of uncertainty about climate change detail



1. It is still unclear whether and how climate change may affect the frequency, intensity and track of hurricanes.

2. It is unclear whether and how much climate change will affect the AMOC or "ocean conveyor belt."



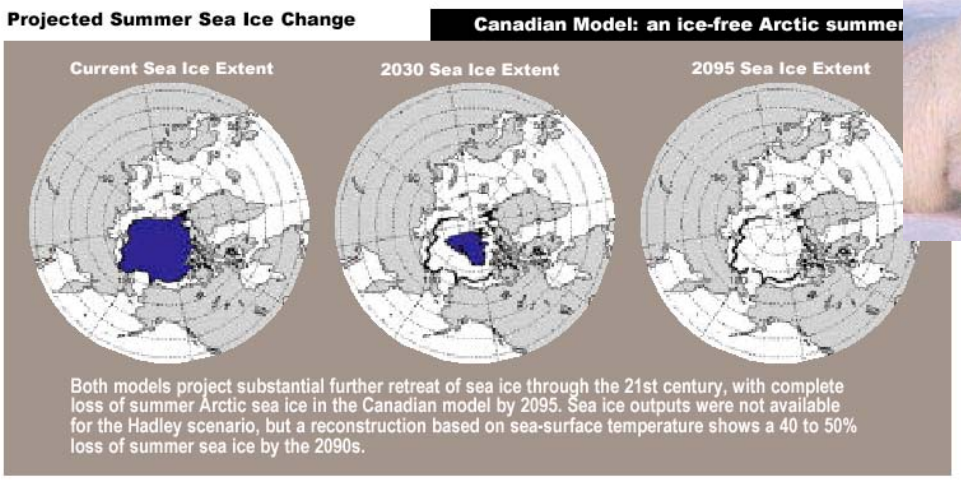
Source: Kuhlbrodt et al, 2004.

3. What impacts can we expect to see from climate change?

Warming will be…

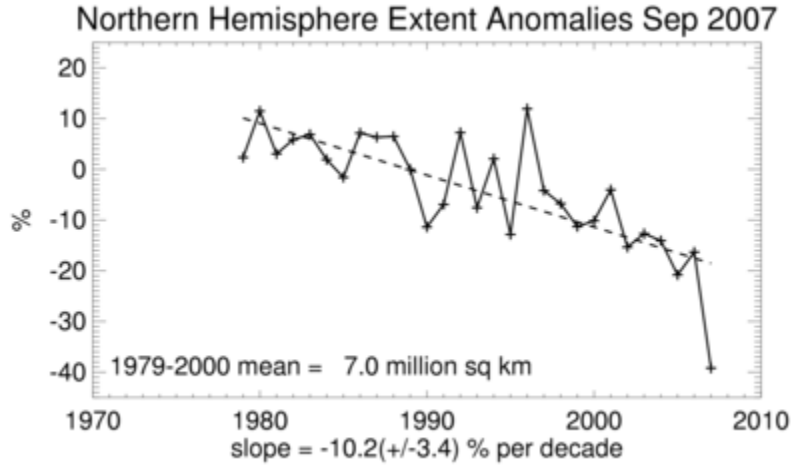
…greatest at the poles. The extent of summer polar sea ice is already decreasing.

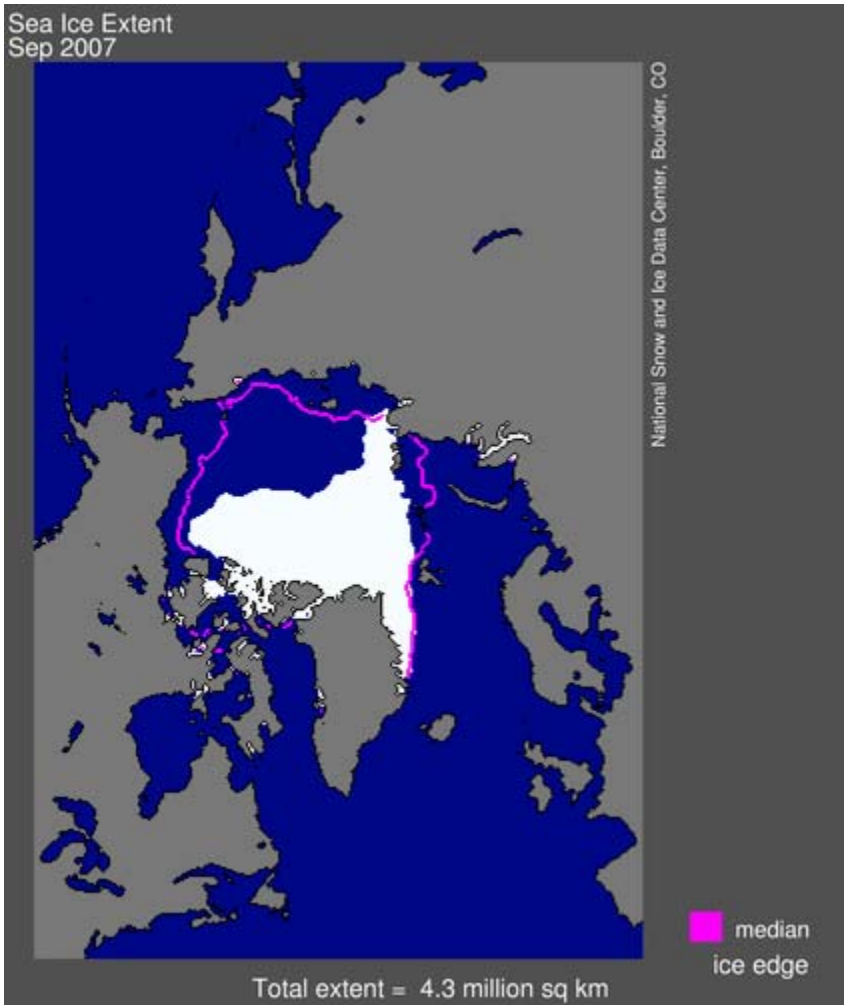
Some models suggest the summertime Arctic Ocean will be ice free by 2100.



Sources: U.S. National Assessment, Polar Bear International and NOAA

The Northwest Passage was ice free in September 2007.





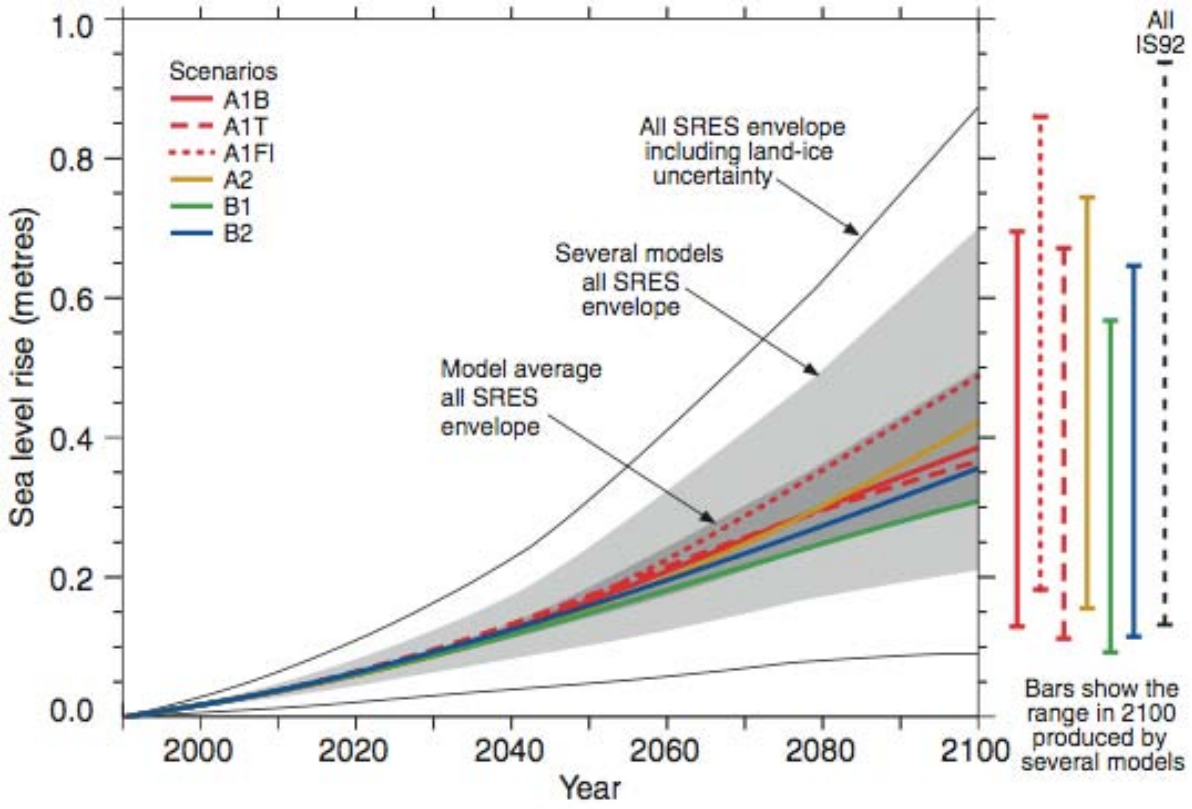
Source: http://nsidc.org/data/seaice_index/

Ocean changes

- Decrease in surface water pH of 0.1 (from 7.8)
  - Detectable worldwide
  - Measurable change has penetrated to >1000m depth
- Changes in pH may have a strong effect on the toxicity of metals, ammonia, and nitrite.
- Predicted deep ocean pH change of 0.3 and surface pH change of 0.5 by 2100
- Higher temperatures are correlated with coral reef "bleaching" at the 95% level
  - 100 million people depend on coral reefs

As water warms it expands…

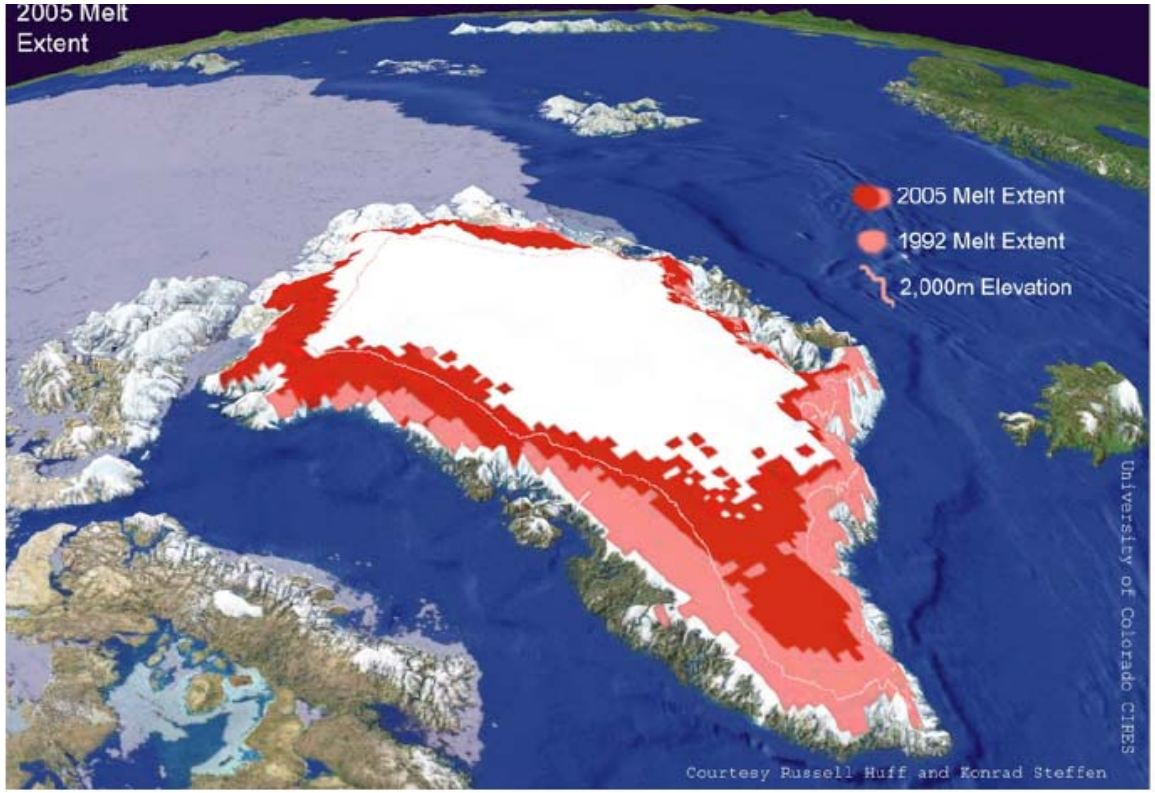
…so global warming will also produce sea level rise.



Source: IPCC WG1 2001.

The IPCC estimates may be too small…

…because new studies of Greenland suggest that it is melting more quickly than anyone thought.



4. What can we do to reduce climate change and minimize its adverse impact?

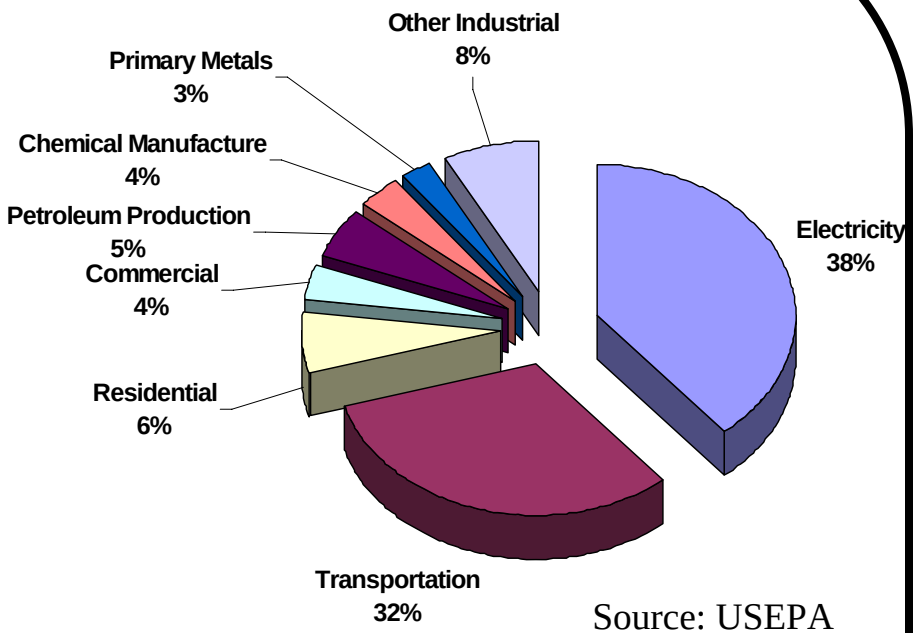
The simple answer is:

1. Reduce future emissions of greenhouse gases - especially CO_2 from burning coal, oil and natural gas.

2. Plan to adapt to the change to which the earth is already committed because of the greenhouse gases that we have already added to the atmosphere.

CO_2 emissions…

…from electric power make up over a third of U.S. emissions from fossil fuel…the largest single source.



Source: USEPA

A variety of strategies are available to reduce these emissions in a cost-effective way:

Today

- Conservation/efficiency
- Fuel switching
- DG w/CHP
- Nuclear
- Wind
- Biomass

In 5 - 15years

- Coal w/carbon capture and deep geological sequestration
- Solar thermal

>15 years

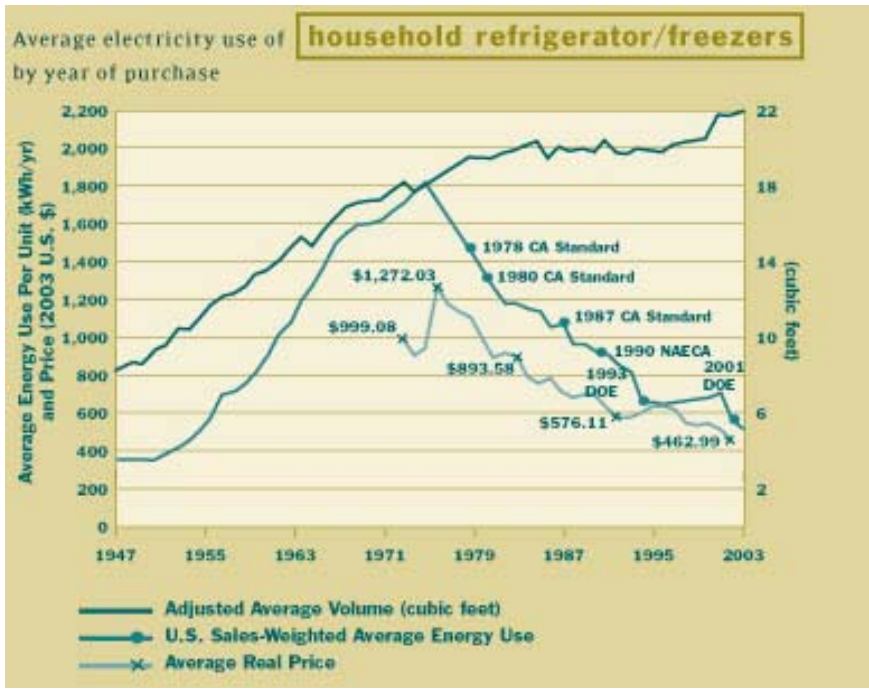
- Solar photovoltaics?
- Others?

Conservation

There is an enormous potential to reduce CO_2 emissions through more efficient use of electricity. Many, but by no means all, firms adopt energy efficient technologies as they become cost-effective.

However, regulation and standards are essential, especially in the consumer market.

Consider the case of refrigerators:

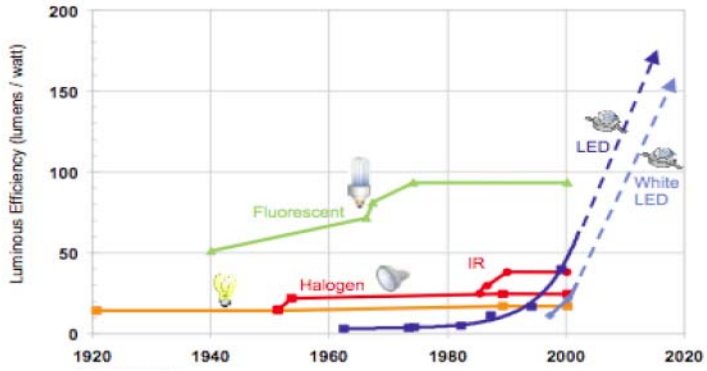


Source: Marilyn Brown, Frank Southworth, and Theresa Stovall, *Towards a Climate Friendly Built Environment*, a Report of the Pew Center on Global Climate Change, 2005.

Conservation/efficiency…(Cont.)

Lighting is 20% of all electricity.

Incandescent bulbs are horribly inefficient. Solid state lighting has great potential.



Other examples are power supplies and plasma TVs.

There are a number of State programs promoting end-use efficiency. Vermont and California are two of the best examples.

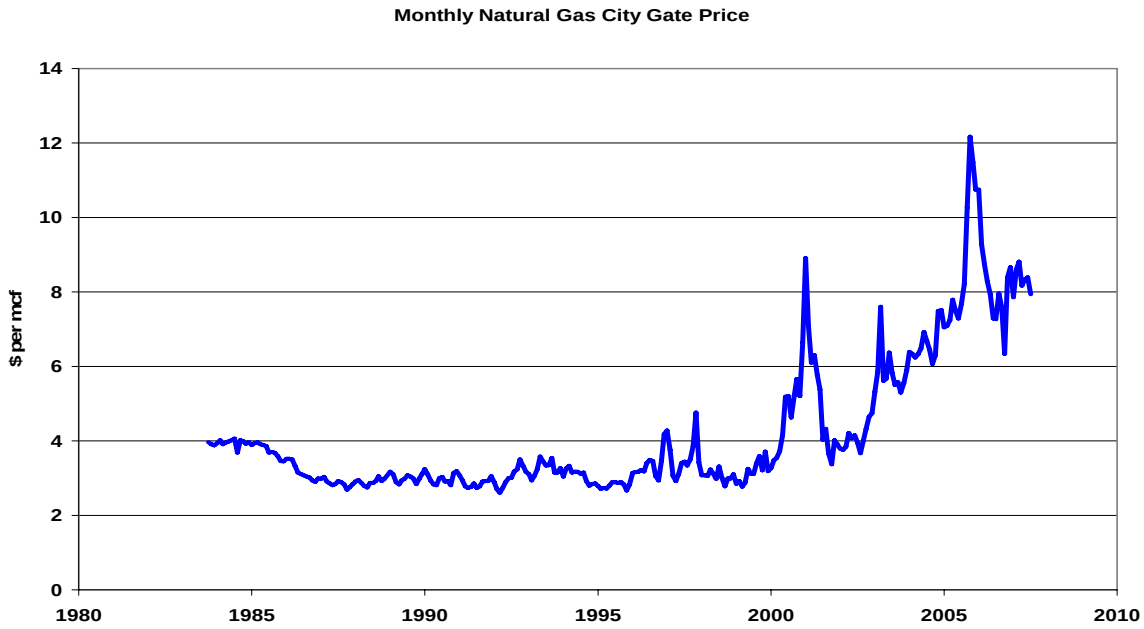
Sources: lumiled, mobilephoneaccessories, cpamerica & plasmas-direct

Fuel Switching

Today the U.S. makes over half its electricity from coal. Natural gas produces only about half as much CO_2 per kWh of generated electric power as coal.

Thus, switching generation to gas can rapidly reduce emissions. BUT, gas prices have been highly volatile and…

Source: shipphoto



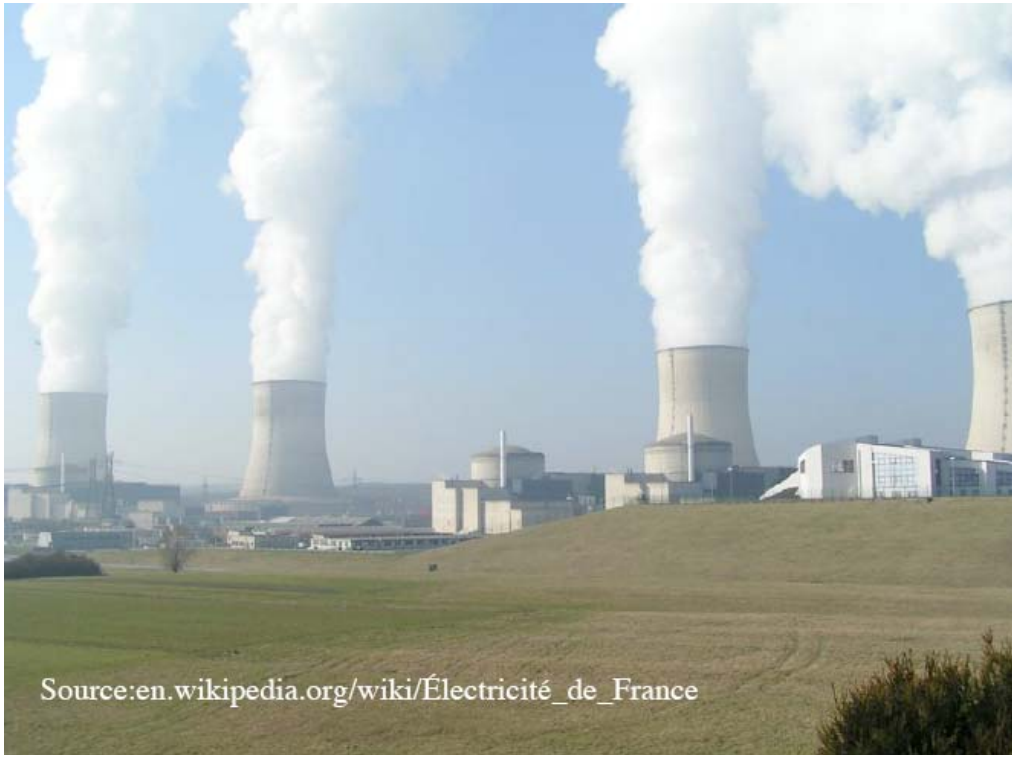
…US supplies are limited.

Combined Heat and Power

Because these systems use the "waste heat" rather than throwing it away, overall energy efficiency can be ≥80% as opposed to ~40% or less for central station power plants.

Nuclear

As the French have clearly shown, despite its various issues, nuclear power is capable of serving a nation's electricity needs without CO_2 emissions. About 88% of EdF's electricity is generated in 58 nuclear power plants at 19 different sites.



Source: www.edf.fr/12025m/txt/Homefr/EDFEnergies/Nuclearpower.html

But, before it can play…

…an expanded role in the U.S. I believe that the following issues must be better resolved:

- Disposition of spent fuel
- Cost
- Liability/safety

And internationally:

- Internationalization of the back end of the fuel cycle (so as to minimize the risk of weapons proliferation).

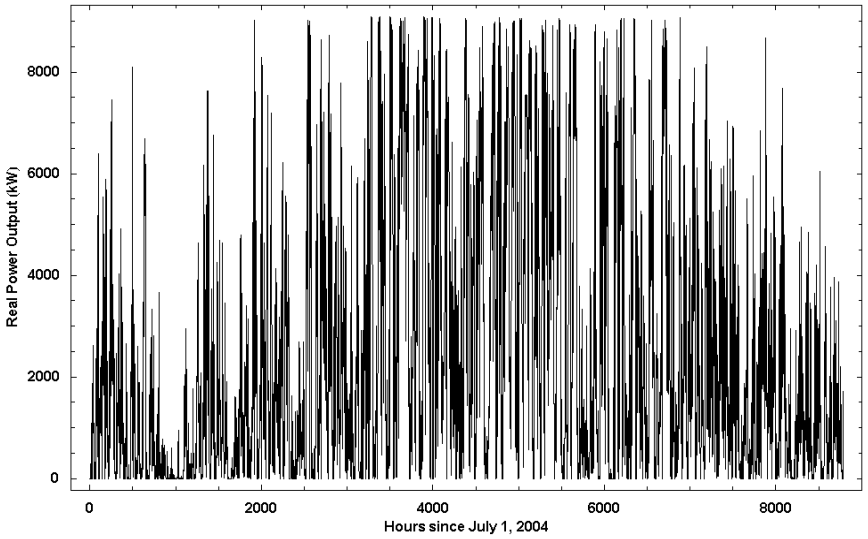
Wind

Costs are becoming quite competitive.

About 0.6% of U.S. electricity now comes from wind.

The big problem is intermittency.

Land use is controversial.



Source: www.uvi.edu

Bottom line on wind

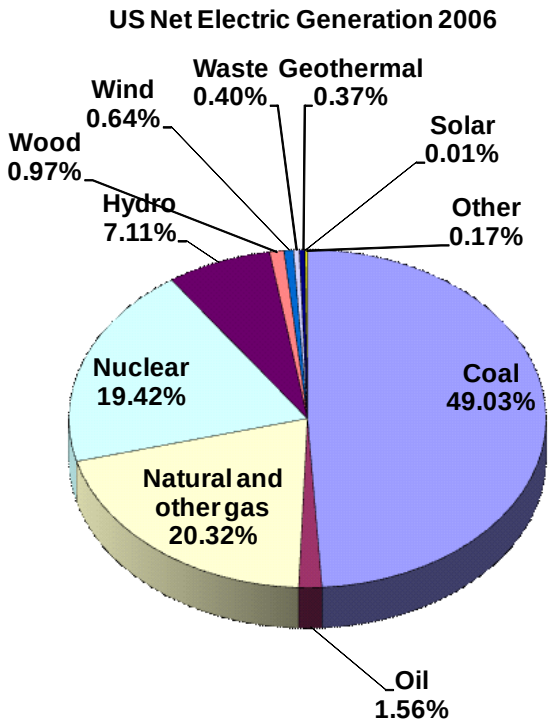
Wind can be a serious contributor to producing low carbon electricity. However, for it to play a major role we will need:

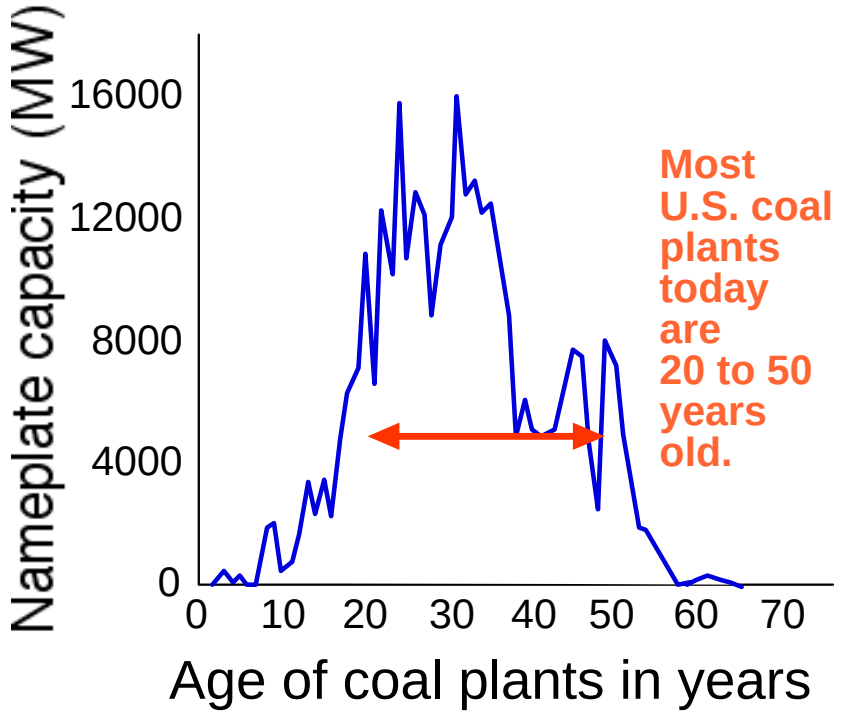
- Fast response hydro (available only in a few places in the U.S.) or pumped hydro (problems with siting). Or, more natural gas.
- Fly wheel storage, battery storage or ultra capacitors.
- Fast response load control.

The Raccoon Mountain project is TVA's largest hydro facility. Water is pumped to this mountaintop reservoir and then released to generate electricity when added power is needed by the TVA system.

All are possible but will take time and will likely limit rate and amount of deployment.

The U.S. makes just under half of its electricity from coal



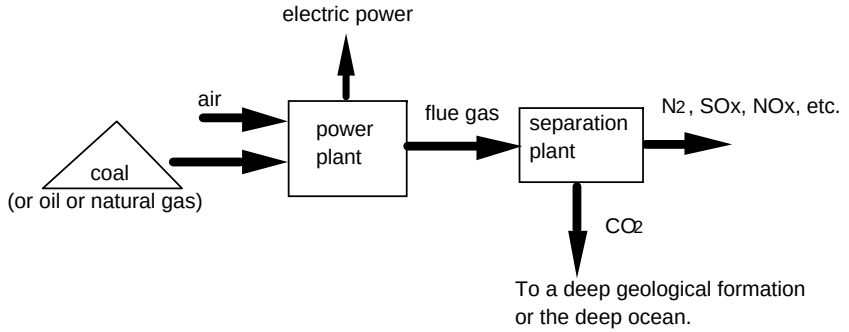


Many coal plants are old and will soon need to be replaced.

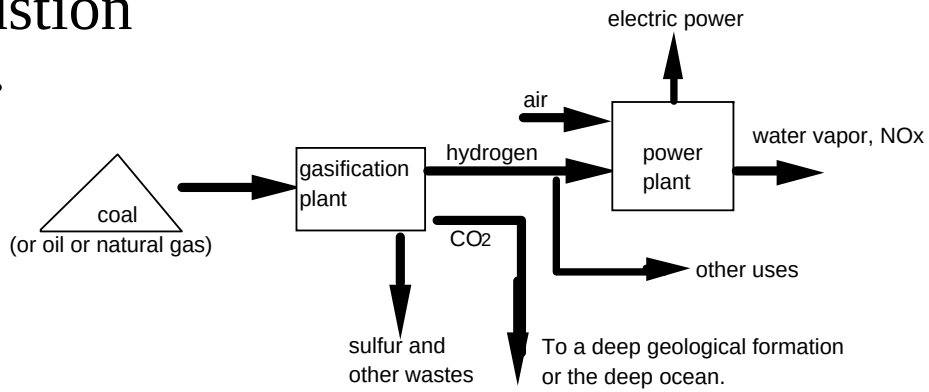
CO_2 Capture and Sequestration (CCS)

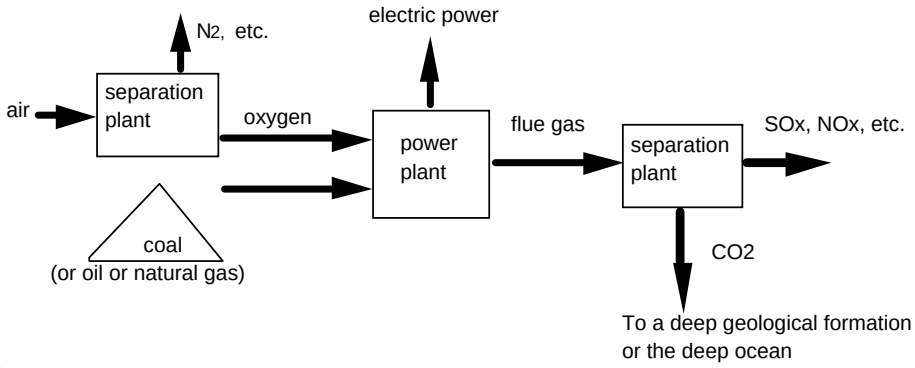
There are several strategies.

1. Post-combustion separation after combustion in air.



2. Pre-combustion separation.





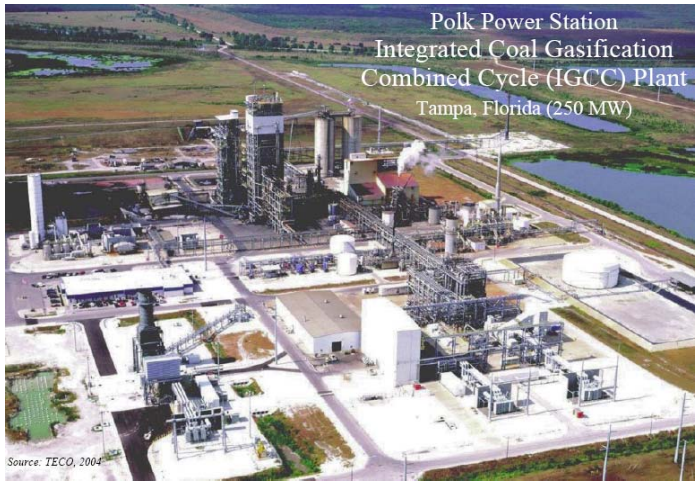
3. Combustion in oxygen

This is not just pie in the sky

All the pieces exist today at commercial scale

Sources: www.free-pictures-photos.com and movementbuilding.org

There are two IGCC plants now operating in the U.S.

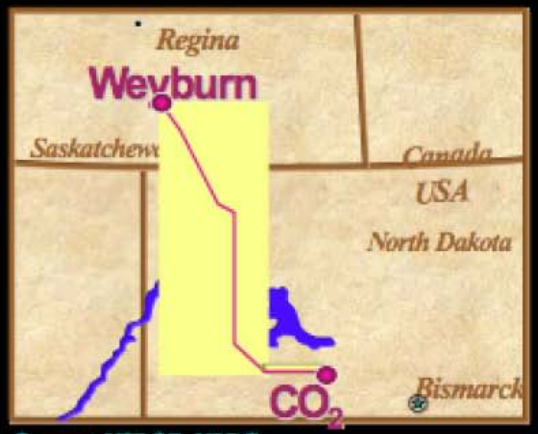


The Wabash Valley Plant in Indiana, 262 MW_e. Repowered an existing old coal unit.

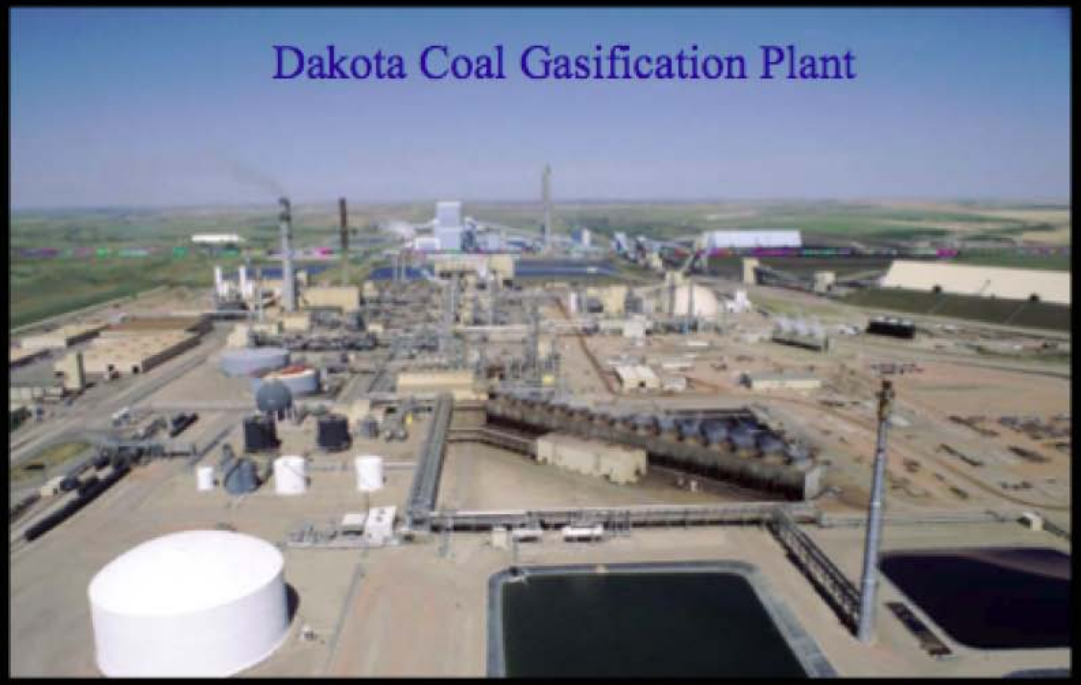
The Tampa Electric Polk Station, 250 MW_e. A new plant.

For details on both plants see: http://www.fe.doe.gov/programs/powersystems/gasification/gasificationpioneer.html

Geological Storage of Captured CO_2 with Enhanced Oil Recovery (EOR)



Sources: USDOE; NRDC

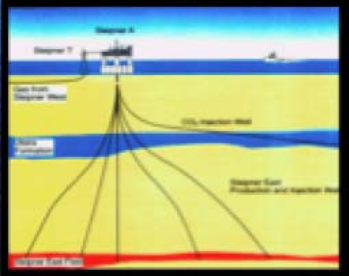


E.S. Rubin, Carnegie Mellon

CO_2 Capture from Natural Gas Treatment with Deep Saline Aquifer Storage

Source: Statoil

Sleipner *(Norway)*



In Salah /Krechba *(Algeria)*

Source: BP

E.S. Rubin, Carnegie Mellon

Solar thermal

Unlike wind, there is *much* more solar energy than humans need. While there are several solar thermal power plants now operating, and more in development, it is not yet clear how economical they will prove to be.

Source:sunflower-solar

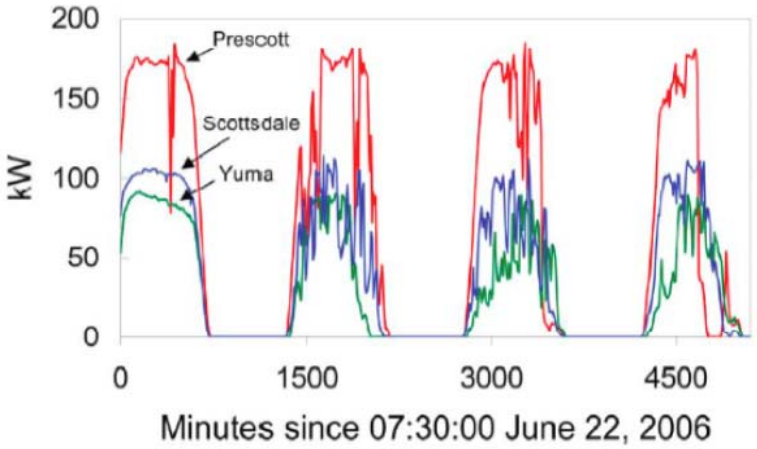
Solar has long been used for domestic water heating in many part of the world.

Solar Photovoltaic

The problem is cost - both the cost of the cells, and also the cost of the "balance of system" (which today is half the total cost). Solar is even more intermittent than wind (e.g. 19% capacity factor in Arizona).

All developed world installations today are *heavily* subsidized.

Perhaps research will get prices down to competitive levels, but that will take decades and major innovation.



A cautionary tale

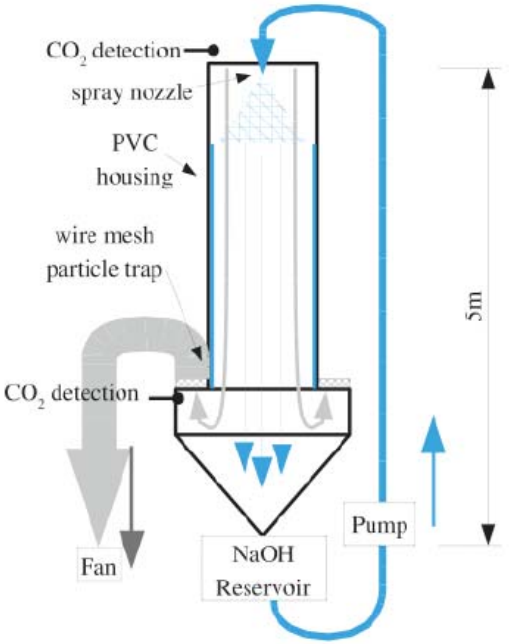
Pennsylvania's politicians have implemented a requirement for 800 MW of solar PV.

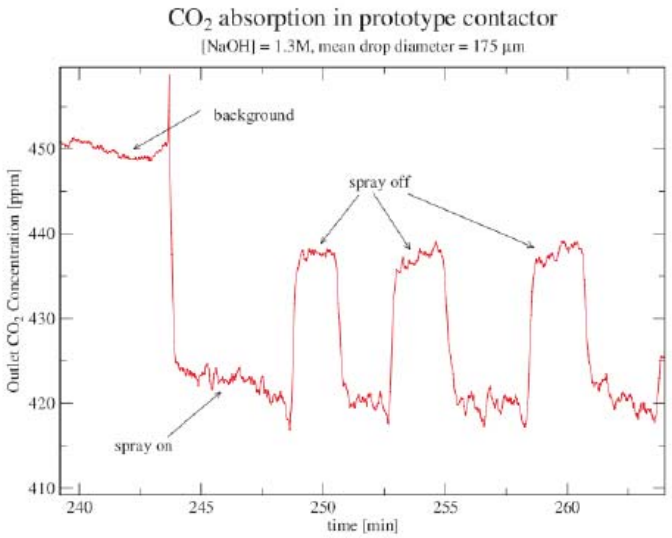
I have estimated that between now and 2020 this will cost Pennsylvania's ratepayers $1.8 billion more than the same amount of wind (and $400-million per year thereafter)!

Direct air scrubbing

Josh Stolaroff has just completed a Ph.D. with us looking at the feasibility of directly scrubbing CO_2 from the atmosphere.

Costs estimates are ~140 $/ton CO_2.





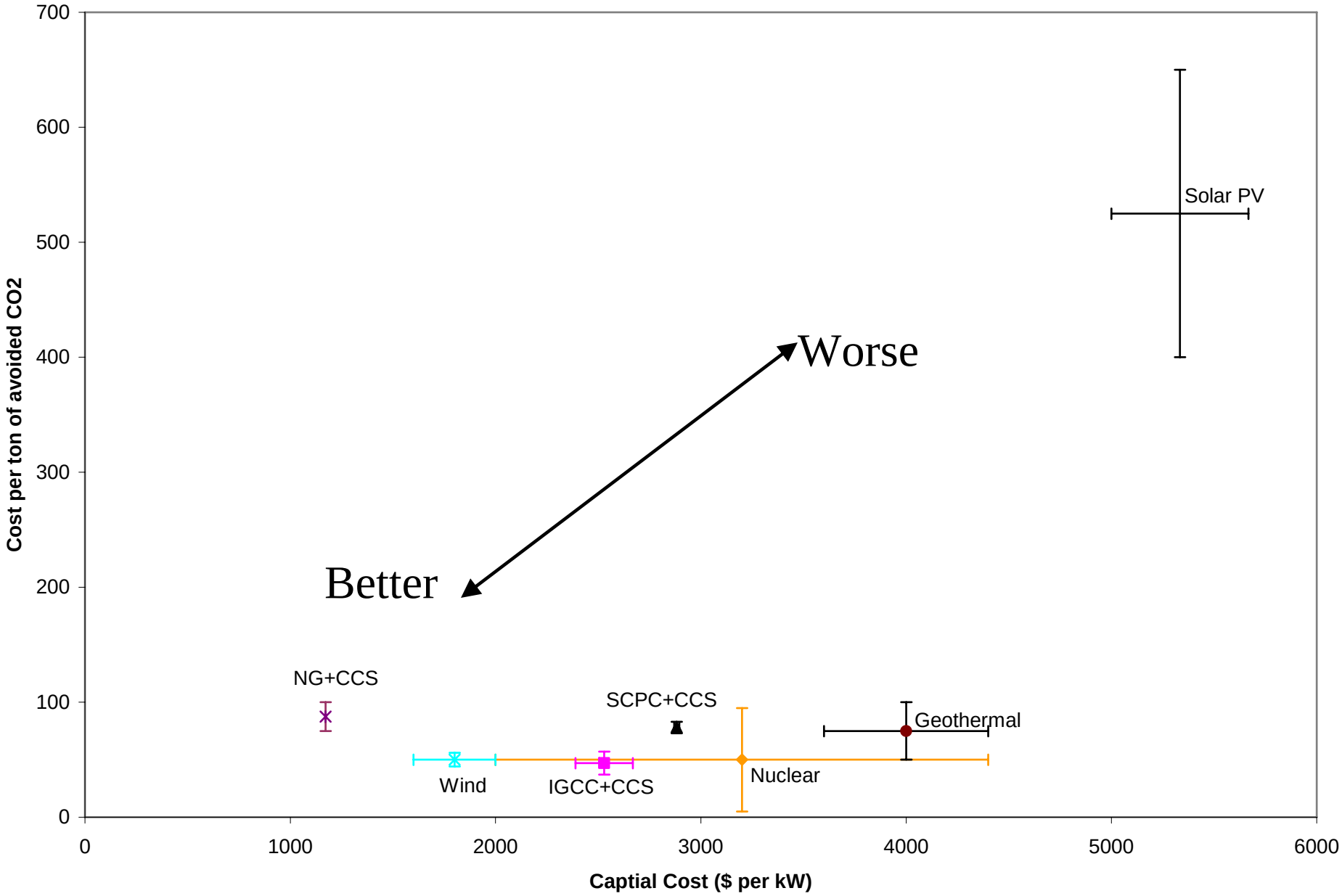
Source: J. Stolaroff

5. Can we afford it?

Metric: Carbon Mitigation Cost

Technology	Cost per metric ton of CO_2 emission avoided
State conservation programs (up to 4% of load)	$5 – $20
New coal gasification with capture and sequestration	$37 – $57
Nuclear (with decommissioning cost)	$5 – $95
Wind power in Texas (with intermittency costs, but without storage)	$44 – $56
New subcritical or supercritical pulverized coal with post-combustion capture and sequestration	$73 – $83
Geothermal power	$50 – $100
New natural gas with capture and sequestration	$75 – $100
Direct capture from the air	$80 – $250
Solar photovoltaic power in Arizona (without storage or intermittency costs)	$400 – $650

NETL 2007 study (older costs)



The US spent 1.5 – 2 % of GDP
on air cleanup
in the 1970's and 1980's.
Best estimates for US electric sector
carbon control are 0.2 – 0.6% of GDP.

The IPCC global average GDP reduction
in the year 2050 to stabilize at
twice pre-industrial levels of CO_2
is in the range of 0.1 to 1.8 % of GDP,
with most models 0.4 – 0.9% of GDP.

Bottom line

Increasing levels of greenhouse gases - and the climate change they are causing - are real *and they are a major problem*.

Over the coming decades, there will be pressure for *enormous changes in the nature and operation of the global energy systems*.

To stabilize concentrations, the world is going to have to reduce its emissions of CO_2 and other GHGs by *at least 90%*. It is affordable, at a cost about the same as those of the Clean Air Act.