The Challenge of Climate Change

A Town Hall at BP, Houston

Steve Pacala and Robert Socolow
Princeton University

December 15, 2016

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Carbon Mitigation Initiative

CMI Structure

Research Groups:
Science
Technology
Integration

Co-Directors:
S. Pacala
R. Socolow

BP:
C. Feilding
G. Hill

Collaborators (partial list):
GFDL, Princeton NJ
Tsinghua University
Politecnico di Milano
University of Bergen
Climate Central, Princeton NJ

Advisory Council:
S. Benson, Stanford
D. Burtraw, Resources for the Future
D. Hawkins, Natural Resources Defense Council
M. Levi, Council on Foreign Relations
D. Schrag, Harvard

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CMI has now been extended through 2020.

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History

CMI began in 2000, at a time when John Browne sensed that the world might pass through a discontinuity and begin to take climate change seriously. He wanted BP to develop a comfortable relationship with a research center that would advance climate science and analyze low-carbon technology.

The following few years were indeed characterized by greatly increased interest and concern: serious initiatives in carbon trading and subsidies for low-carbon energy – including CO_2 capture and storage (CCS). Princeton and BP were leaders in this effort in our respective domains.

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Much has changed and is changing

Low-carbon energy is arriving unevenly: wind, solar, and vehicle fuel efficiency are being realized at a one-wedge pace, while hydrogen power, CCS, and nuclear power are faltering. Innovation in the energy sector has been dramatically affected by the arrival of shale gas and oil and low energy prices. In climate science new modeling capability is enabling forceful, credible statements about extreme events.

An international regime has emerged in the past year, based on "nationally determined contributions," which engages all sectors and creates strong pressure on the oil and gas industry to become proactive.

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Risks of climate change for BP

The climate problem has the potential to disrupt BP's core business in at least three ways:

1. Effective climate policies can emerge that discourage fossil fuel consumption, that impose environmental performance standards on production processes, and that subsidize or otherwise promote efficiency and low carbon energy.
2. Climate-motivated research can create disruptive new energy technology.
3. The consequences of climate change can directly disrupt BP's investments in energy production infrastructure and supply chains.

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BP supports CMI to help manage risks

1. CMI sharpens BP's corporate perspective on climate change. It provides BP with strategic understanding of the potential physical, biological and human systems impacts.

2. BP benefits when CMI disseminates sound information that supports effective public policy discussions.

3. BP leverages the much larger research programs of the CMI investigators.

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An update on climate science

Basic Science of Greenhouse Warming

Three independent lines of evidence:

1. Records from the geologic past.
2. Records from the historic period.
3. Physical understanding and models.

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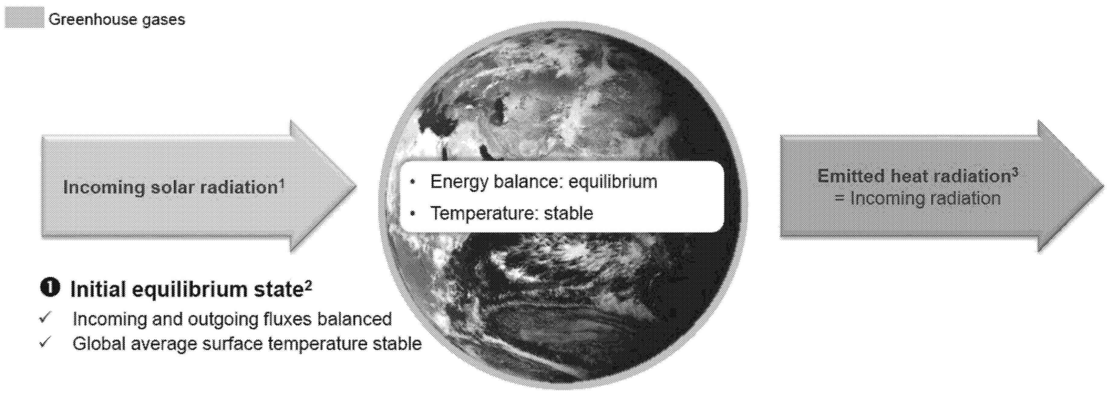
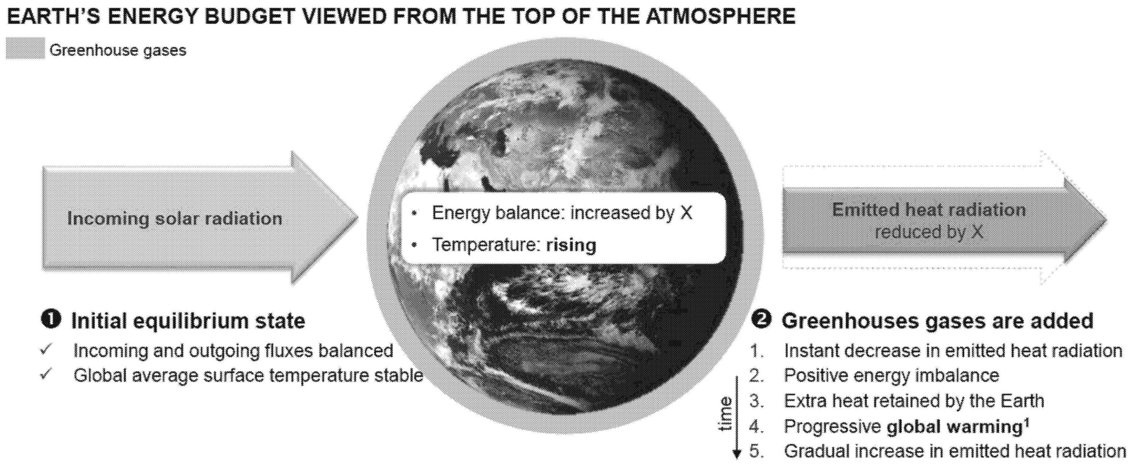
EARTH'S ENERGY BUDGET VIEWED FROM THE TOP OF THE ATMOSPHERE



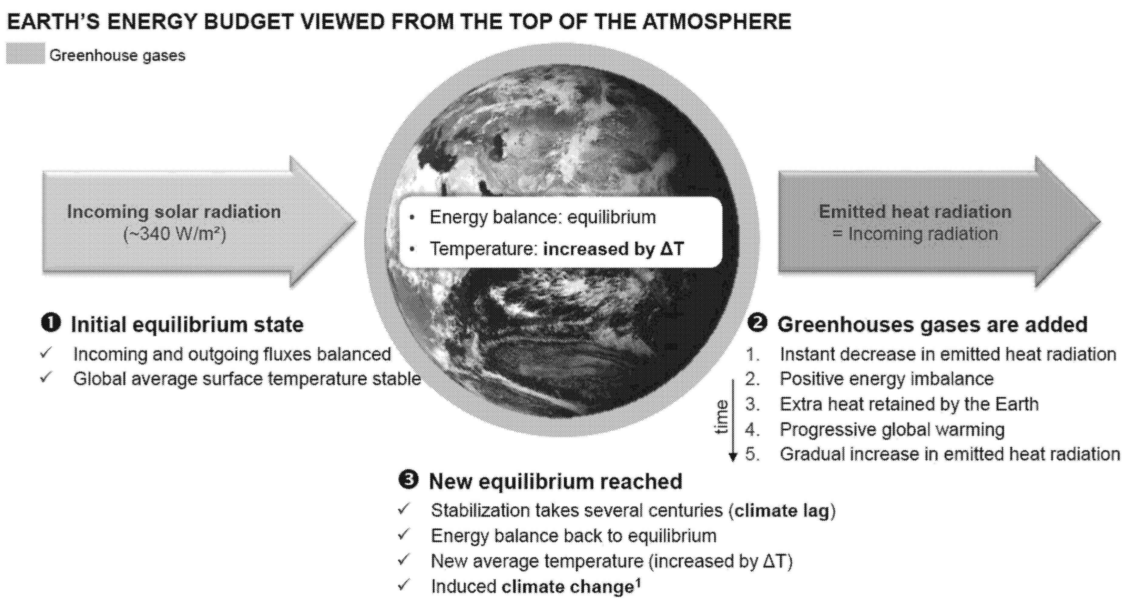
One person per minute walks into a department store. Each stays 2 hours and then leaves.

There are 120 people in the store. One leaves and one arrives every minute.

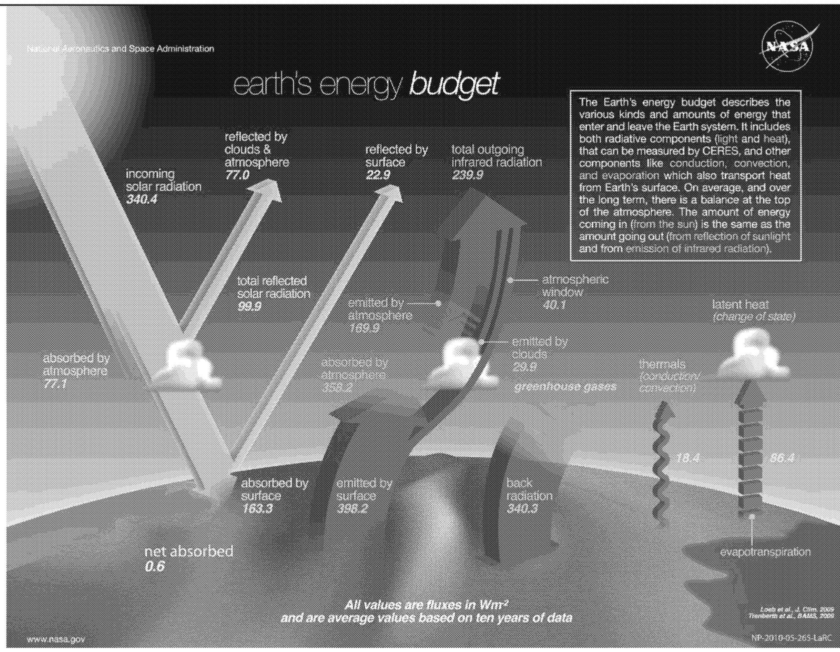


All of a sudden, somebody unveils the new Iphone, which you can try out in the store, and it causes each person to spend 3 hours in the store.

For the next hour, nobody leaves, and the number of people in the store increases by 1 per minute until it reaches 180 one hour after the Iphone first appears.

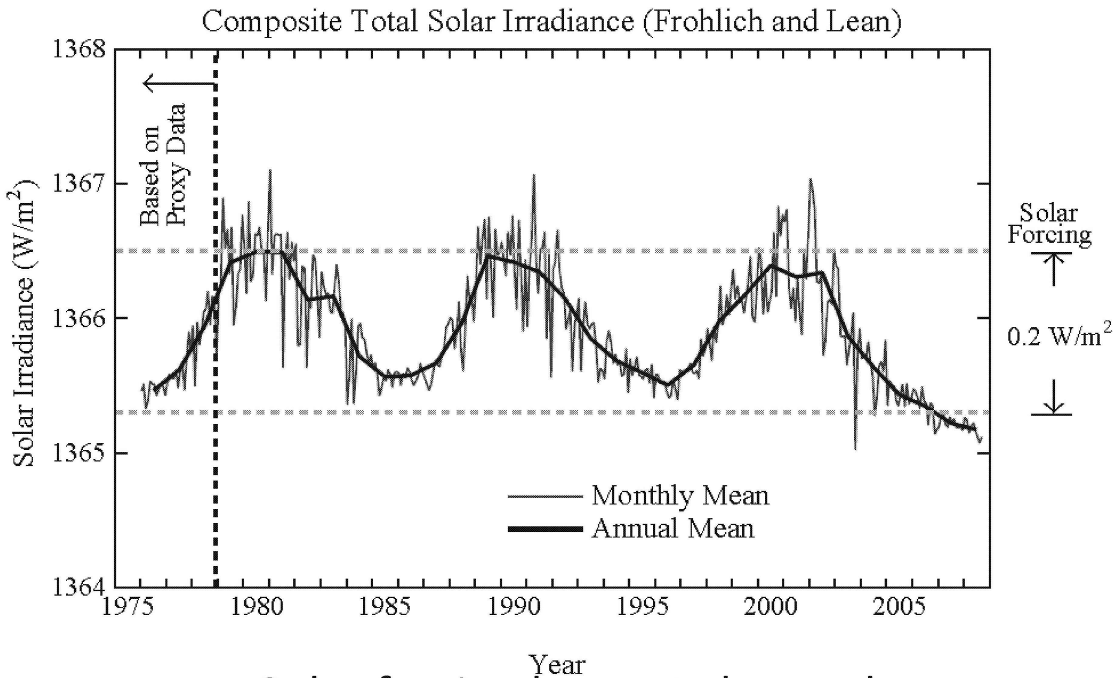


In the subsequent hour, one person per minute finds that they have been in the store for 3 hours and leaves, which reestablishes the balance between arrivals and departures. But now there are 180 people in the store.



Satellites measure the current energy imbalance. NASA's Ceres: 340.4-77.0-22.9-239.9= 0.6 W/m^2 .

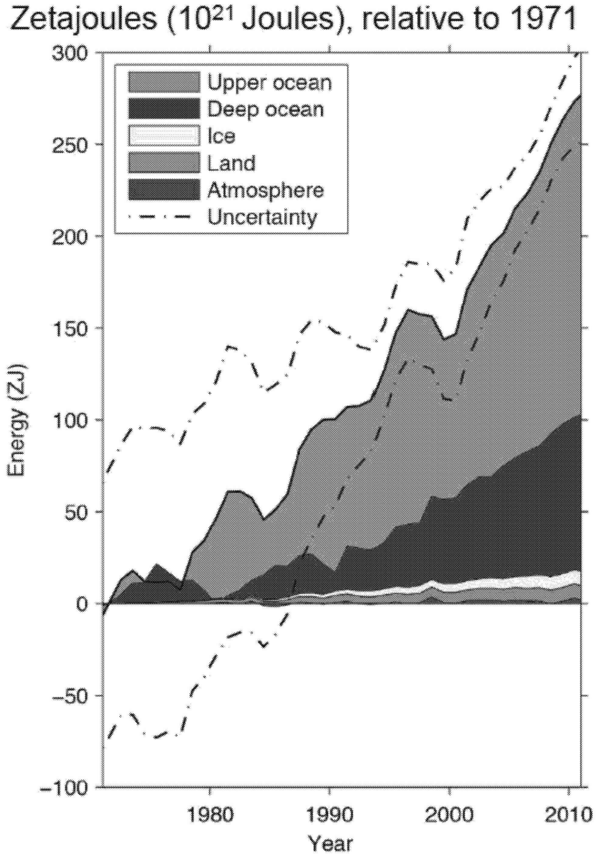
Energy in > energy out by 300 terrawatts.



Solar forcing has not changed
Sun spots don't cause global warming.

Let me make note of the assertion that the world could be headed into colder times because of changes on the sun, because that misconception has been spread widely.

Solar irradiance has been measured since the late 1970s, and the solar irradiance remains at or near a prolonged solar minimum, which is deeper than the prior measured minima. This is data of Frohlich and Lean through the end of September. These solar irradiance variations do not have any known relation with the shorter period oscillations of Pacific Ocean temperature. In a few moments I show quantitatively that the effect of the sun is not negligible on longer time scales (the time scale of the 10-12 year solar cycle and longer time scales), but it is much smaller than the climate forcing due to human-made greenhouse gases.



Extra heat energy stored in the Earth since 1971. Most is in the oceans.

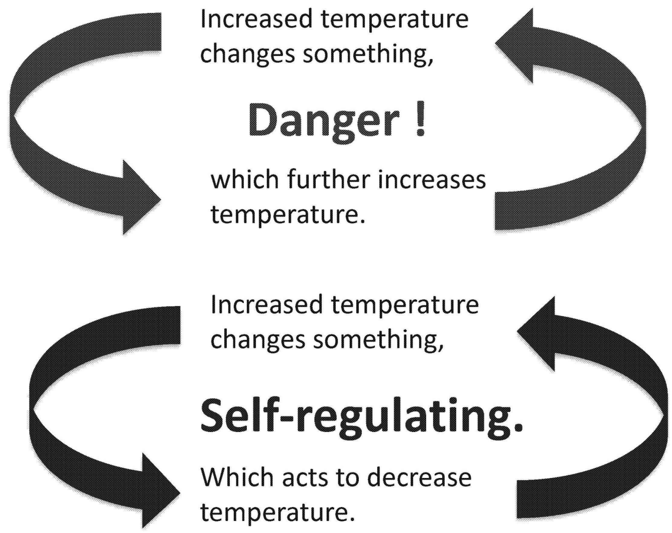
1 Watt = 1 Joule per second

IPCC AR5. ©2015 SBC Energy Institute.

Positive and Negative Climate Feedbacks

Positive:

Negative:



Climate Feedbacks

DIRECT EFFECT - 0.3 °C of warming per 1 W/m^2 of radiative forcing.

IPCC AR5.

Climate Feedbacks

DIRECT EFFECT - 0.3 °C of warming per 1 W/m^2 of radiative forcing.

INDIRECT EFFECTS - another 0.3°C (±0.06) from the WATER VAPOR FEEDBACK

Global warming increases the concentration of water vapor in the atmosphere and water vapor is a potent greenhouse gas.

Positive Feedback.

Climate Feedbacks

DIRECT EFFECT - 0.3 °C of warming per 1 W/m^2 of radiative forcing.

INDIRECT EFFECTS - another 0.3°C (±0.06) from the WATER VAPOR FEEDBACK
+
0.1°C (±0.03) from the ICE-ALBEDO FEEDBACK

Warming melts the polar ice caps which causes the poles to absorb more sunlight, which further warms the planet.

Positive Feedback.

Climate Feedbacks

DIRECT EFFECT - 0.3 °C of warming per 1 W/m^2 of radiative forcing.

INDIRECT EFFECTS - another 0.3°C ($\pm$0.06) from the WATER VAPOR FEEDBACK
+
0.1°C ($\pm$0.03)(from the ICE-ALBEDO FEEDBACK
+
0.1°C ($\pm$0.23) from the CLOUD-ALBEDO FEEDBACK

Warming changes the abundances of different types of clouds. The net effect is probably to favor less reflective clouds, which further warms the plants. But this is uncertain.

Positive Feedback.

IPCC AR5.

Climate Feedbacks

DIRECT EFFECT - 0.3 °C of warming per 1 W/m^2 of radiative forcing.

INDIRECT EFFECTS - another 0.3°C (±0.06) from the WATER VAPOR FEEDBACK

\+

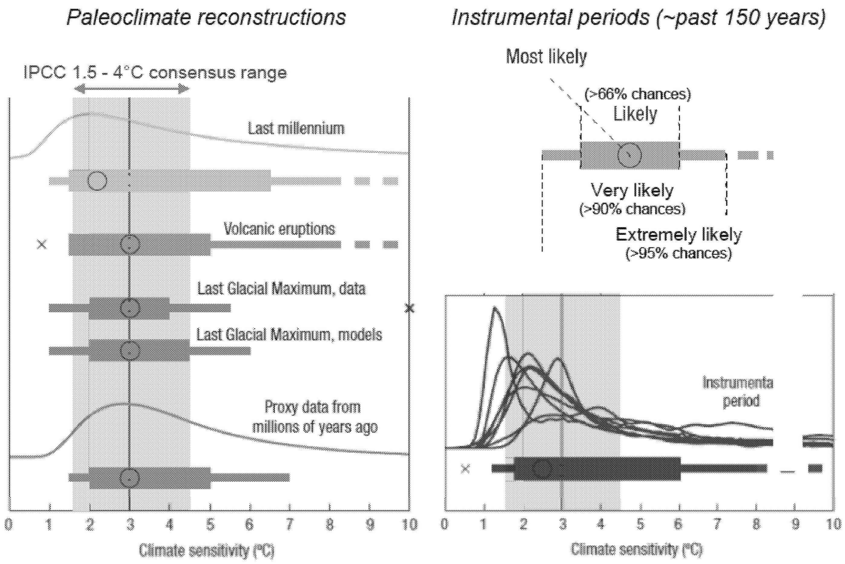
0.1°C (±0.03)(from the ICE-ALBEDO FEEDBACK

\+

0.1°C (±0.23) from the CLOUD-ALBEDO FEEDBACK

Thus, a doubling of preindustrial CO_2 (3.7 W/m^2 of forcing) means roughly 3°C of warming (plus or minus 50% meaning about one chance in six of either 2°C or 4°C).

Climate Sensitivity: Warming from a doubling of the preindustrial CO2 from 280 ppm to 560 ppm.

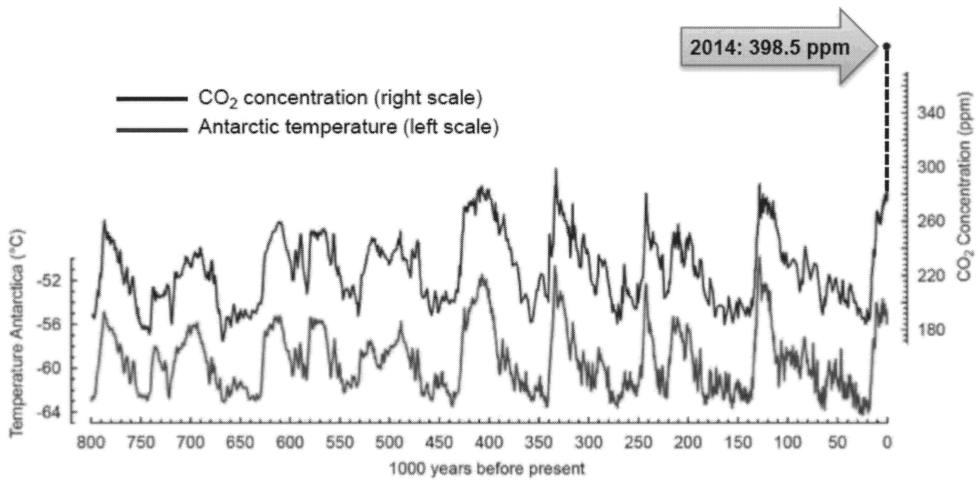


Note: [1] The colored lines show distribution probabilities of various empirical estimates of sensitivity based on analogs from the past. The horizontal bars summarize uncertainty ranges, and the vertical grey area indicate the IPCC's consensus sensitivity range, of 1.5-4.5°C. [2] Because different climate forcers operate in different ways and the climatic state can affect the climate sensitivity, there is no single best value that can be applied and it is best to consider the value as being within the range indicated (see slide 45).

IPCC AR5. ©2015 SBC Energy Institute.

Three Independent Lines of Evidence

1. Records from the geologic past. Whenever atmospheric CO2 increased, temperature also increased and vice versa.



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Source: Climate Change Evidence, Impacts and Choices. National Academy of Sciences. 2014. ©2015 SBC Energy Institute.

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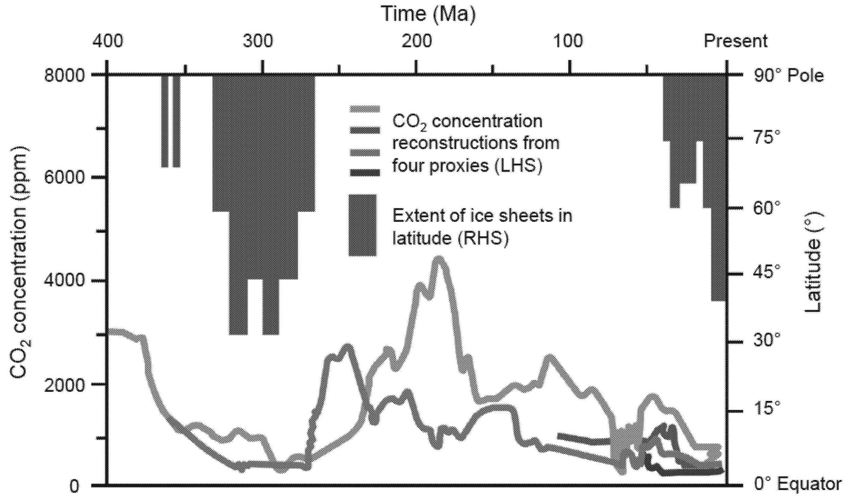
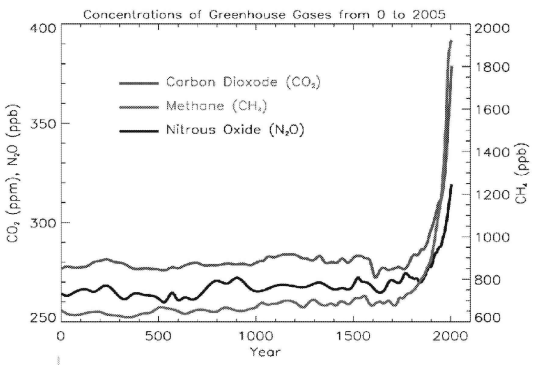
Glaciation and CO2 over the last 400 million years.



IPCC AR4 (2007), section 6.1.

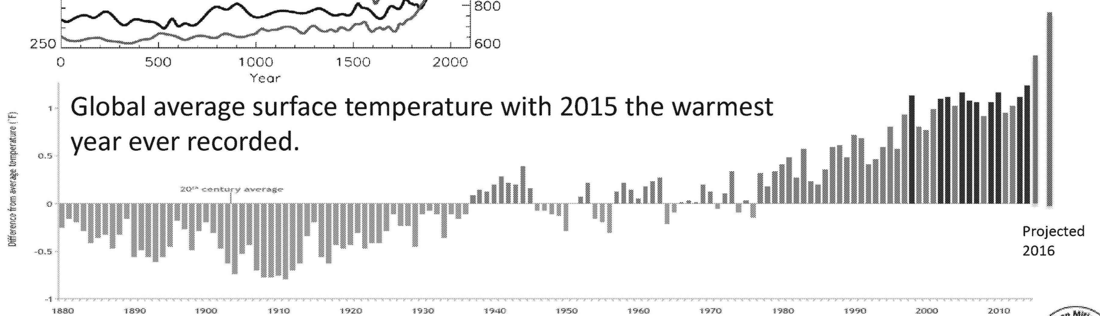
Three Independent Lines of Evidence

2. Records from the historic period. Anthropogenic greenhouse gases and temperature increased rapidly after the industrial revolution



The two most important anthropogenic greenhouse gases are CO2 and CH4. We know from isotopic measurements that the increase in CO2 is primarily due to fossil emissions (~90%). Fossil emissions also contribute to the increase in CH4, but biogenic emissions are the dominant cause.

Global average surface temperature with 2015 the warmest year ever recorded.



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Source: Climate Change Evidence, Impacts and Choices. National Academy of Sciences. 2014; NOAA

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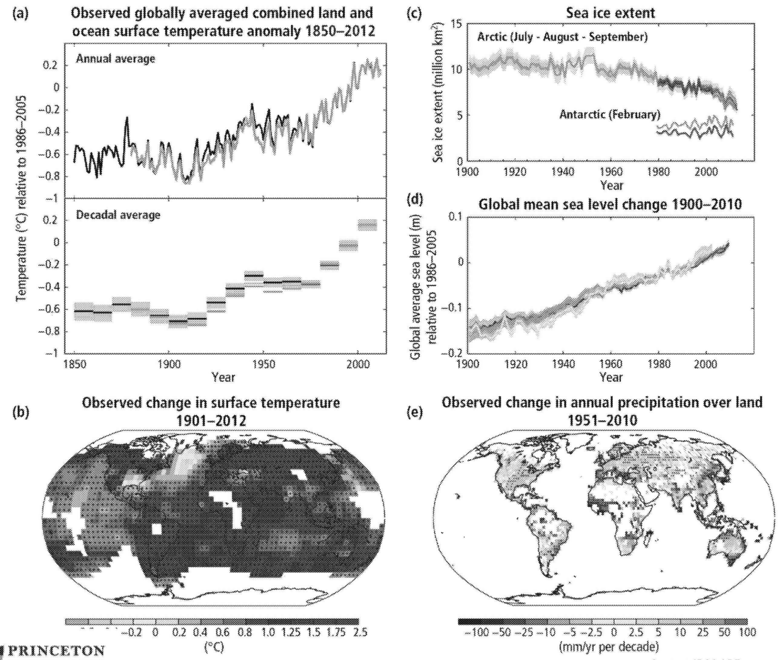
Three Independent Lines of Evidence

2. Records from the historic period. A large number of other climate changes have accompanied the warming.



Source: IPCC AR5.

Reduced arctic sea ice, sea level rise and altered patterns of precipitation (at left), as well as stratospheric cooling (expected under greenhouse surface warming), ocean acidification, and decreased continental ice volume in the arctic and Antarctic.

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BPA_HCOR_00043078

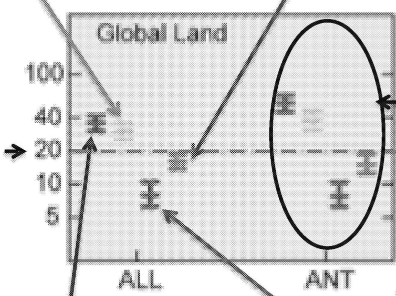
2. Records from the historical period

The frequency of extreme heat and precipitation has increased dramatically, with the largest changes in the most extreme events.

Coldest **daytime high**

Hottest daytime high

Return time in the 1990's for an extreme with a 20-year return time in the 1960's



Model-estimates of changes due solely to anthropogenic GHG's and aerosols.

1960's coldest nighttime low in 20-years occurs every 38 years in the 1990's

1960's hottest nighttime low in 20-years occurs every 8 years in the 1990's

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Source: IPCC SREX on Extremes and AR5

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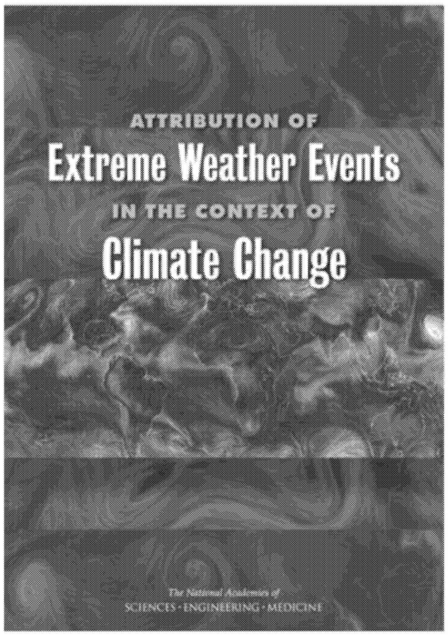
The climate problem has the potential to disrupt BP's core business in at least four ways

A new NAS report on “attribution”



“It is now often possible to make and defend quantitative statements about the extent to which human-induced climate change …has influenced either the magnitude or the probability of occurrence of specific types of events or event classes.

NAS: National Academy of Sciences (U.S.)

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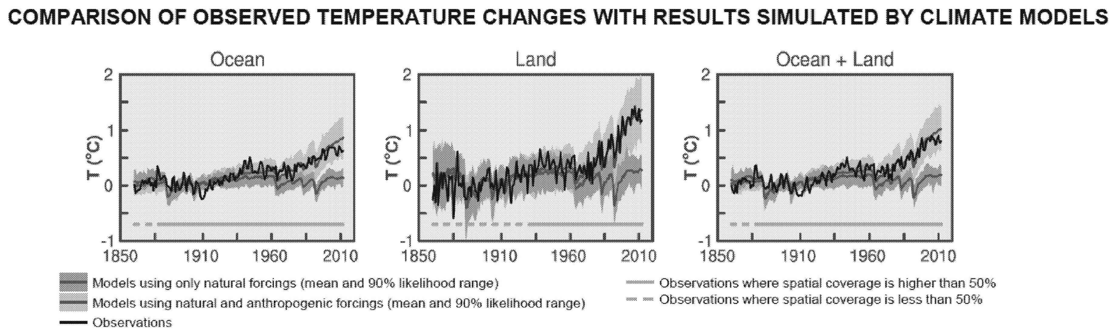
Source: http://www.nap.edu/catalog/21852/attribution-of-extreme-weather-events-in-the-context-of-climate-change.

Three Independent Lines of Evidence

3. Physical understanding and models. Climate models predict observed climate change and imply that it is caused primarily by anthropogenic greenhouse gases and aerosols



Models with only natural forcing such as volcanic eruptions do not predict observed temperature changes (blue and purple), whereas models with anthropogenic forcing (pink and purple) agree with the data (black lines). The height of a colored band shows the within- and between-model uncertainty Source: IPCC AR5.

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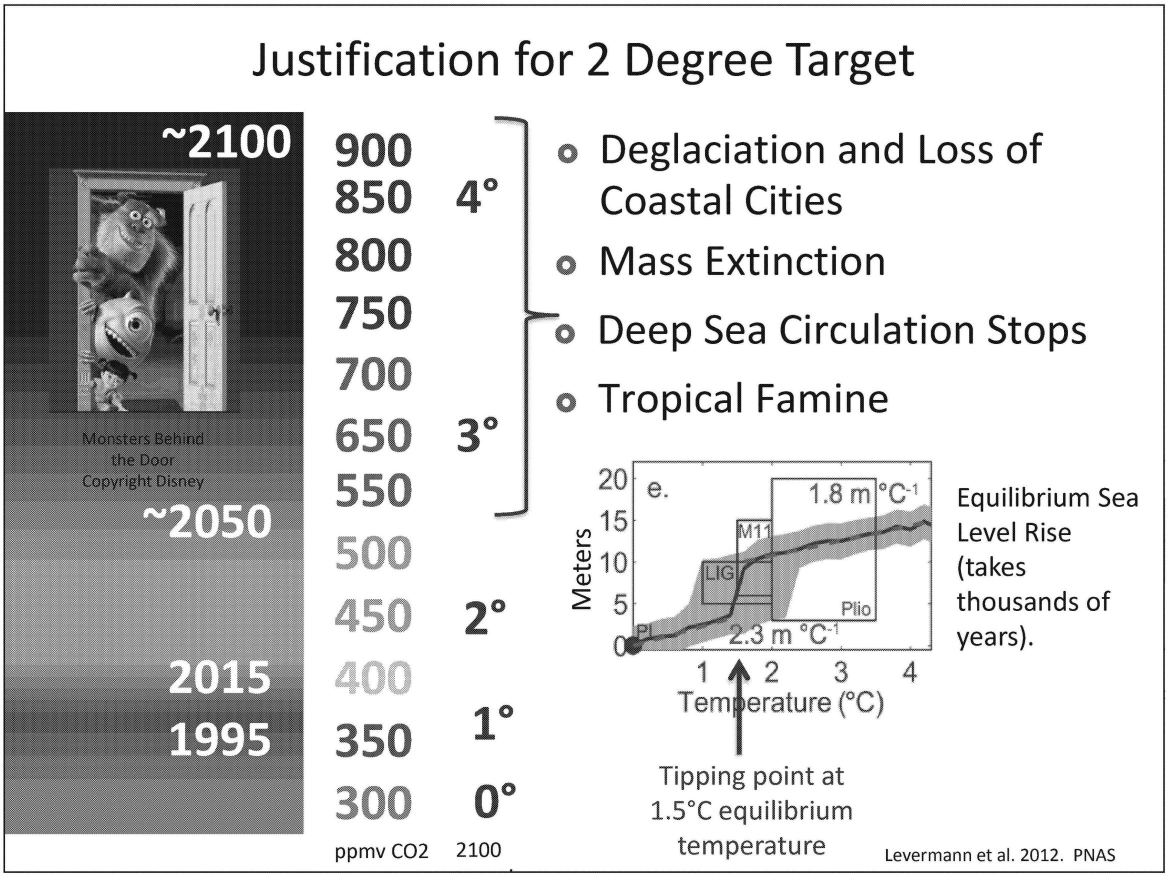
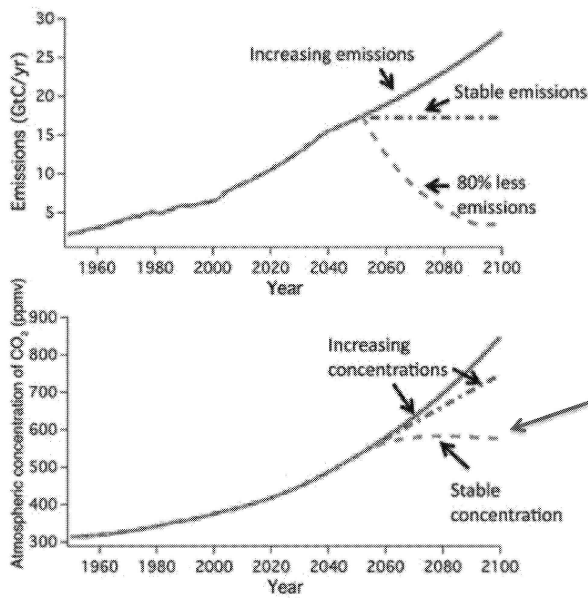


What does 10 years of delay mean? The atmosphere started with ~300 parts per million of carbon dioxide (the primary greenhouse gas) before the industrial revolution. It past 350 , at the end of the 20th century, the level at which we should have stopped according to Bill McHibben and 350.org. It is just under 400 today. 450 was the targeted maximum behind the Waxman-Markey bill. Most scientists think that the most dangerous consequences begin above 450. 500 is now the closest feasible target, but we are very likely to slip to 550, even if we start a crash program at the end of the decade. And 550 is where the climate monsters begin to come into the room. My lab's model predicts that we couldn't even stop at 550, because carbon dioxide from a a trillion tons of newly decomposed peat would enter the atmosphere and push the concentration to 750-850. At these levels, we expect a rogue's gallery, from the loss of all of our costal cities because of >10 m of seal level rise, to cessation of the ocean's circulation, mass extinctions and unprecedented famine.

Because CO_2 lasts for centuries, stabilizing its atmospheric concentration requires greatly reduced emissions.



Emissions do not need to stop altogether because of natural CO2 sinks.

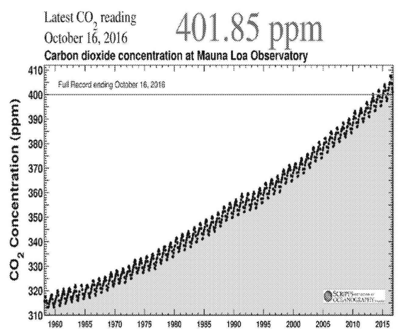
Source: Climate Change Evidence, Impacts and Choices. NRC

Stabilization CO_2-equivalent concentration (ppmv): range and best estimate			Equilibrium global average warming (°C)
320	← **340** →	380	1
370	← **430** →	540	2
440	← **540** →	760	3
530	← **670** →	1060	4
620	← **840** →	1490	5

Note: Green and red numbers represent low and high ends of ranges, respectively; **black bolded** numbers represent best estimates.

This means CO_2 plus other greenhouse gases and aerosols, converted into the CO_2 concentration giving equivalent radiative forcing.

Source: Warming World: Impacts by Degree. NRC 2011



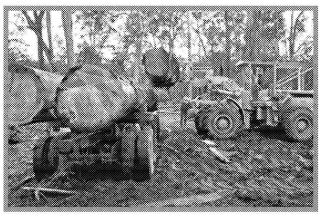
We are currently at ~402 ppm and would reach 430 ppm in a couple of decades

GLOBAL CARBON PROJECT

Fate of anthropogenic CO_2 emissions (2006-2015)

34.1 $GtCO_2$/yr

91%



9%

3.5 $GtCO_2$/yr

Sources = Sinks

16.4 $GtCO_2$/yr

44%

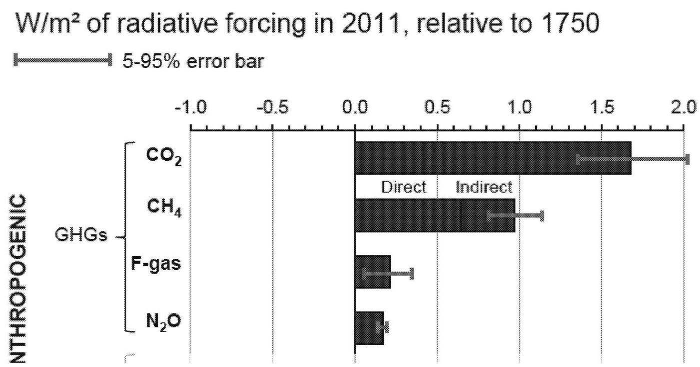
31%

11.6 $GtCO_2$/yr

26%

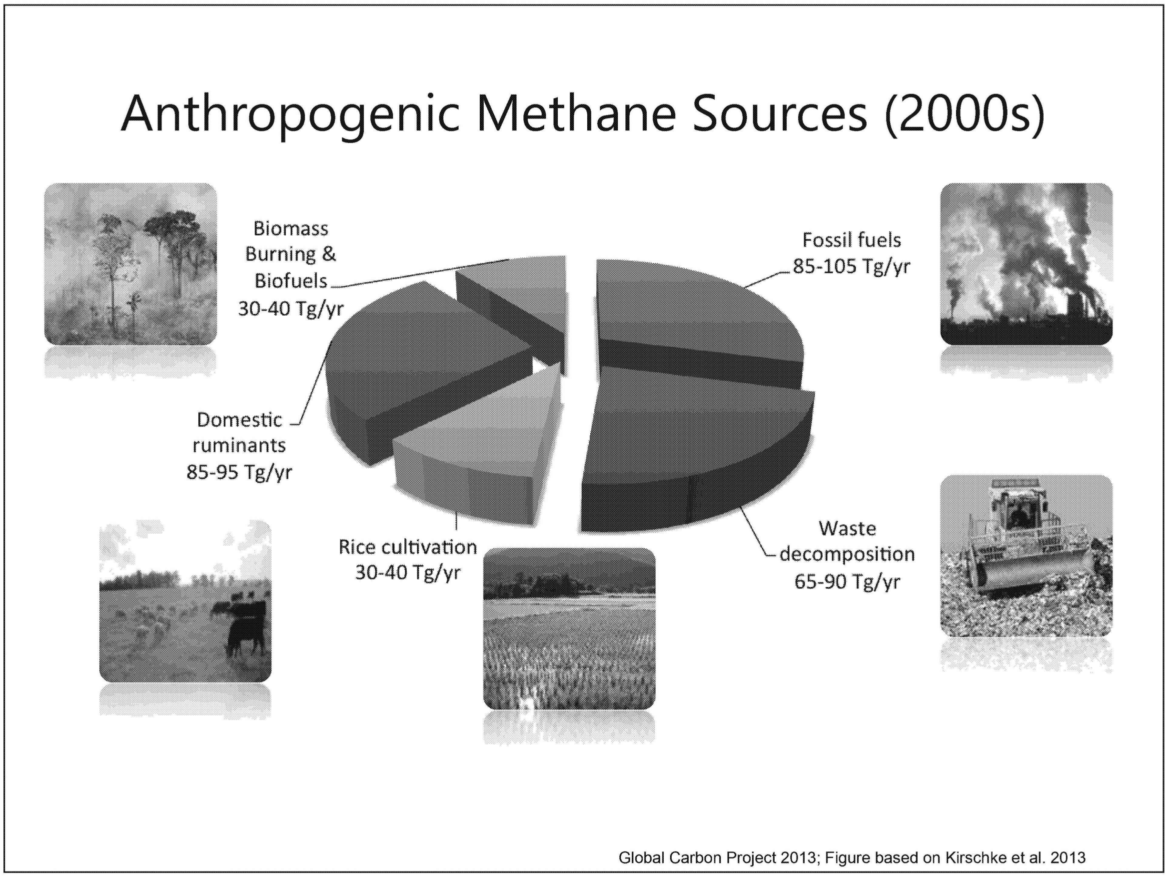
9.7 $GtCO_2$/yr

Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2016; Global Carbon Budget 2016

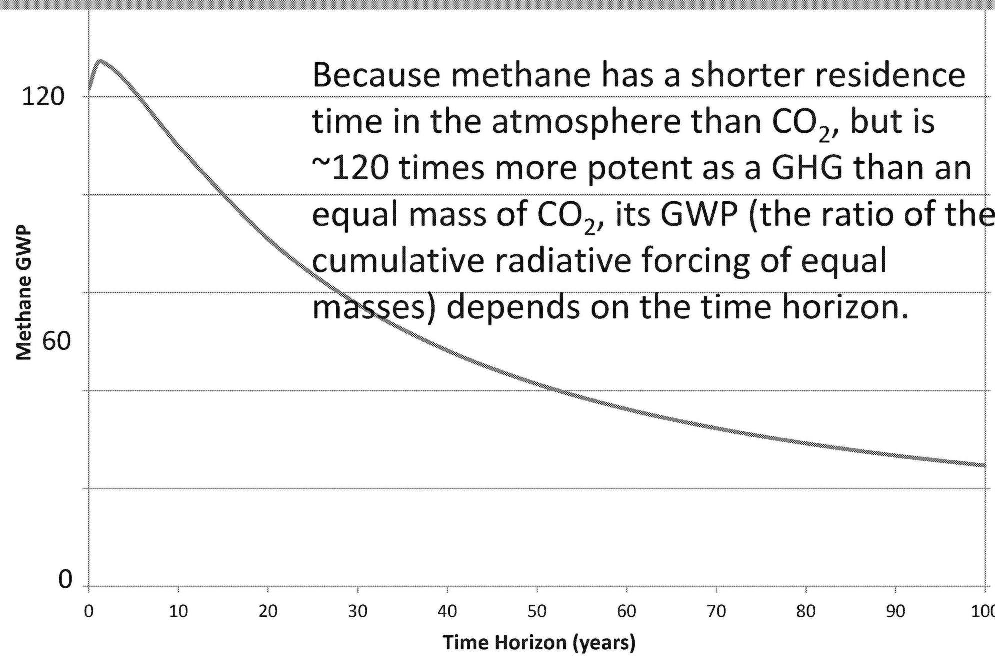


Reductions in methane allow room for additional CO_2 emissions under the Paris target.

IPCC AR5. ©2015 SBC Energy Institute.


Anthropogenic Methane Sources (2000s)
Biomass Burning & Biofuels 30-40 Tg/yr
Fossil fuels 85-105 Tg/yr
Domestic ruminants 85-95 Tg/yr
Rice cultivation 30-40 Tg/yr
Waste decomposition 65-90 Tg/yr
Global Carbon Project 2013; Figure based on Kirschke et al. 2013

Methane Global Warming Potential



Because methane has a shorter residence time in the atmosphere than CO_2, but is ~120 times more potent as a GHG than an equal mass of CO_2, its GWP (the ratio of the cumulative radiative forcing of equal masses) depends on the time horizon.

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Hand-off to Rob

Four world views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO		
	YES		

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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.
	YES	Environmentalists, nuclear advocates are often here.	WHY WE ARE HERE.

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A single big idea

We are confronting one overarching, counterintuitive, new idea:
Human beings are able to change the planet at global scale.

Only recently have a significant fraction of the world's forests been cleared and its fisheries depleted. Only recently have the surface oceans become noticeably more acidic. Only recently has the concentration of carbon dioxide in the atmosphere climbed far outside its range of the past million years.

The *anthropocene* – the geological period when human actions dominate global change – has already started.

This new idea is unwelcome. We wish we lived on a larger planet.

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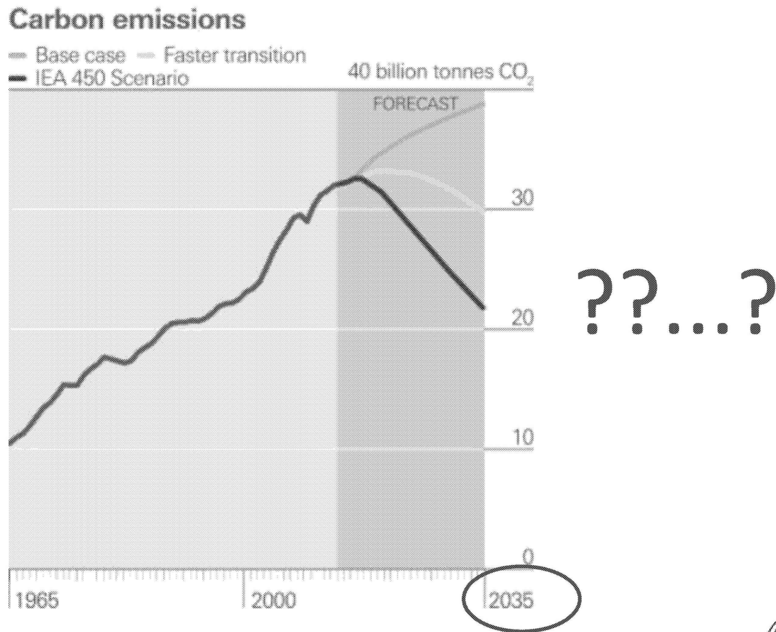
CO_2 pathways to 2035 in BP's *Energy Outlook*



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Source: BP Energy Outlook 2035

The "two degrees" goal

To attain the "two-degree" goal, the average temperature of the surface of the Earth should never exceed its pre-industrial temperature by more than 2^{o}C.

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Cumulative emissions and temperature

0 $GtCO_2$ — 1600 — 3200 — 4800

More than a century | A few decades | Another few decades

1°C, already — 2°C — 3°C

1°C will result from anthropogenic CO_2 emissions to date.

2°C results from future emissions equaling historic emissions.

3°C will result from roughly a tripling the historical total.

The probability is about 1/6 for both:

getting 3°C while aiming for 2°C (being unlucky)
getting 2°C while aiming for 3°C (being lucky).

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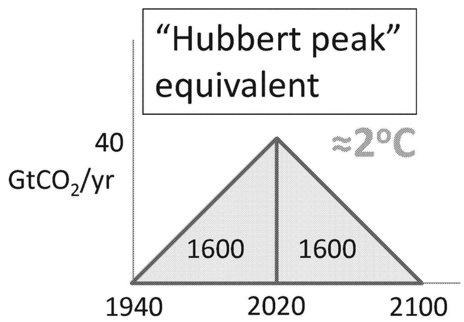
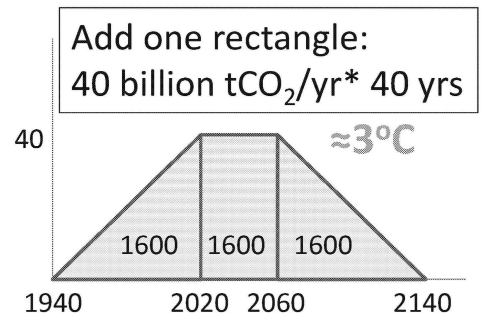
Carbon emission trajectories for 2°C and 3°C





Fossil fuels are so abundant that, for even a weak climate target, *attractive* fossil fuel will be left in the ground.

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“Carbon budgets”: drivers of climate policies

Tough choices:

- When?
- Whose?
- Used where?
- For what purpose?
- Which fossil fuels ($CH_{0.8}$ *vs.* CH_4)?

Which fossil fuels will we judge to be “unburnable” and leave in the ground? Who decides?

Such decision-making is unprecedented.

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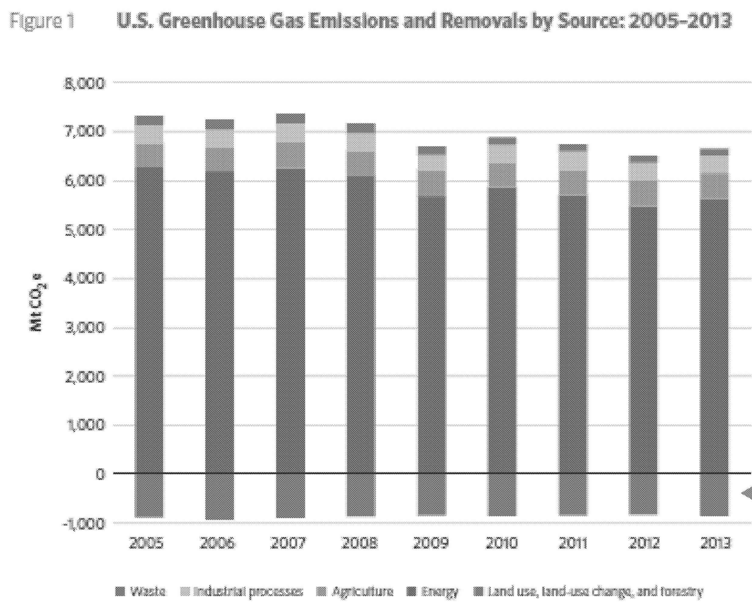
U.S. official greenhouse gas accounting



Emissions are heading downward

Biocarbon accounting will improve everywhere.

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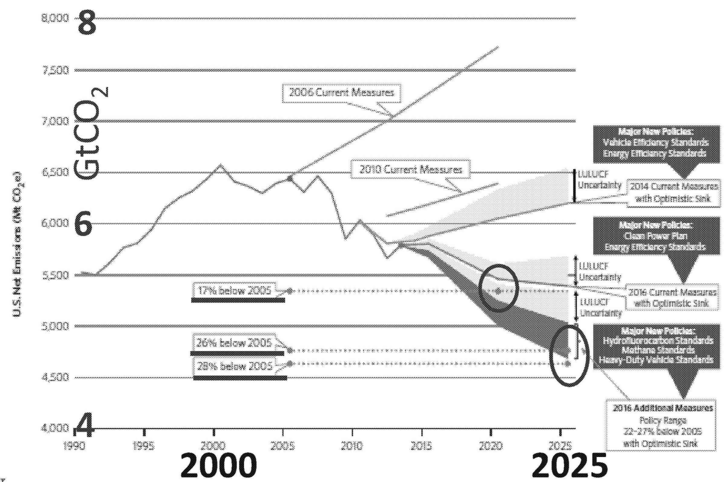
U.S. emissions targets

Figure 6 **U.S. Emissions Projections—2016 *Current Measures* Compared with Potential Reductions from *Additional Measures* Consistent with the *Climate Action Plan***

Also shown are previous projections from the 2006, 2010, and 2014 U.S. Climate Action Reports, which demonstrate the dramatic ratcheting down of projected U.S. emissions over the past decade.



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Source: 2016 SECOND BIENNIAL REPORT of the USA under the UNFCCC. U.S. Department of State. http://unfccc.int/national_reports/biennial_reports_and_iar/submitted_biennial_reports/items/7550.php.

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U.S. CO_2 Policies (2030 framework)

Electric Power: Clean Power Plan*; renewables subsidies

*CO_2 emissions from electricity sector: 32% below 2005 in 2030

Transportation: efficiency standards; alternative fuels

Buildings: efficiency standards

Other greenhouse gases: HFCs, methane

Agriculture and forestry

Research and development

Regional emissions trading (states)

Source: 2016 SECOND BIENNIAL REPORT of the USA under the UN Framework Convention on Climate Change. U.S. Department of State. http://unfccc.int/national_reports/biennial_reports_and_iar/submitted_biennial_reports/items/7550.php.

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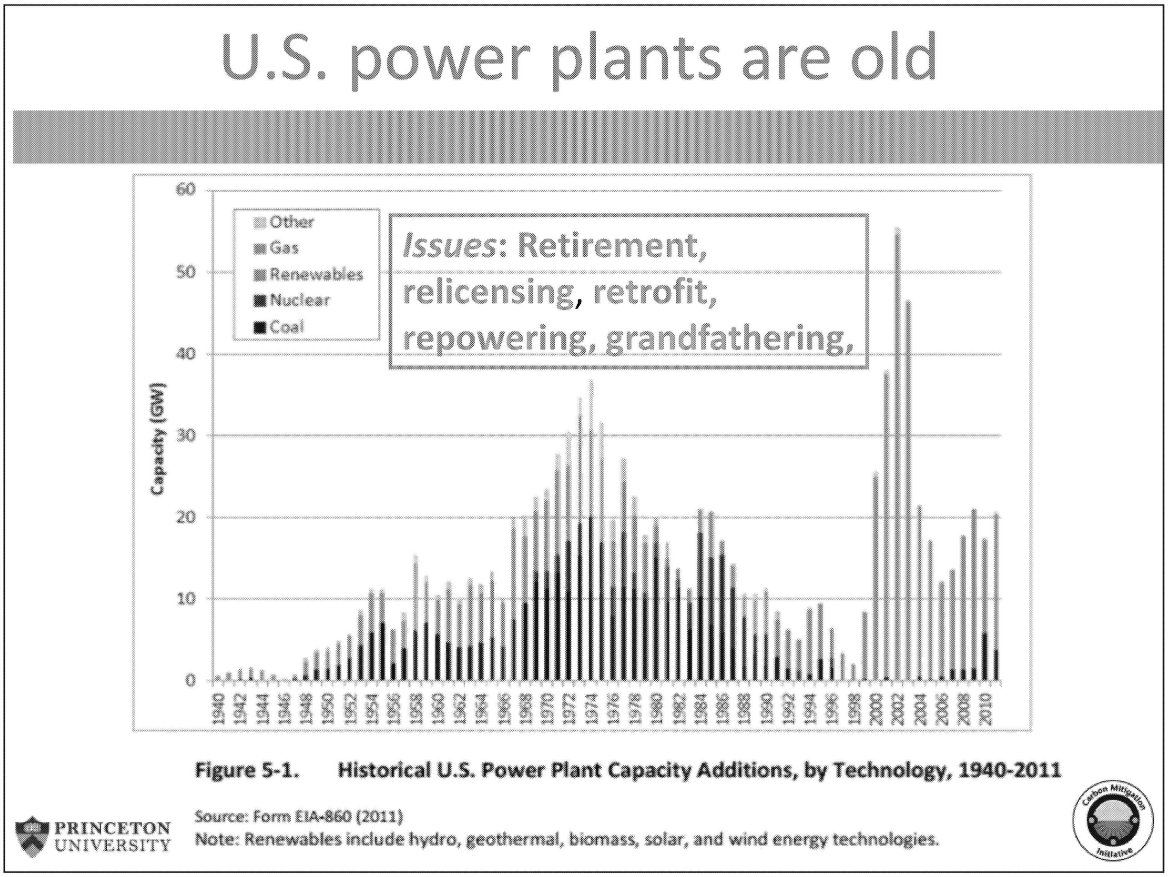
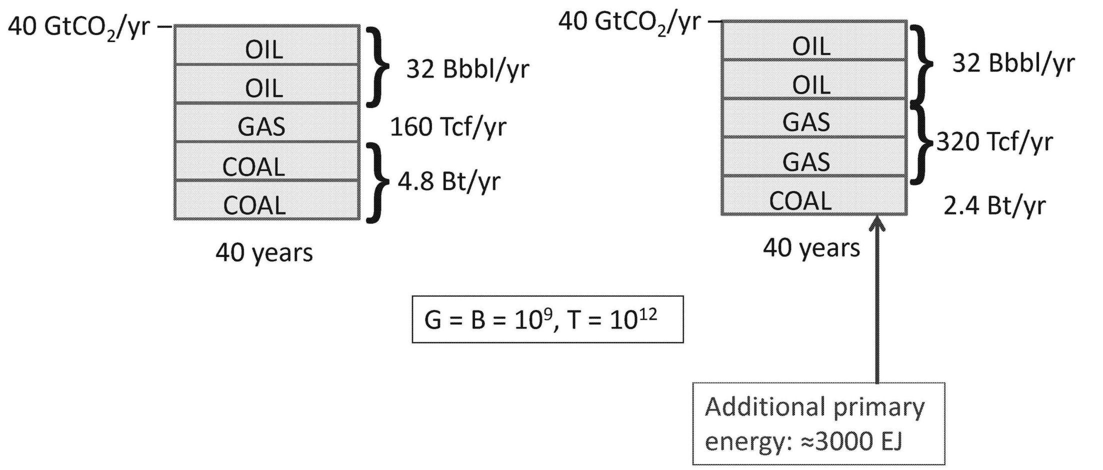


Joseph Beamon, Joseph.Beamon@eia.doe.gov, is a person at EIA who knows about this slide. He sent Greg Eyring another version of this slide, 8-21-08, with EIA forecast attached.
I don't know what 5-1 refers to.
My previous download, whose end bar was 2004 and which I showed many times, had the 2002 natural gas peak at over 70 GW.

Gas v. coal: two 1600 $GtCO_2$ rectangles



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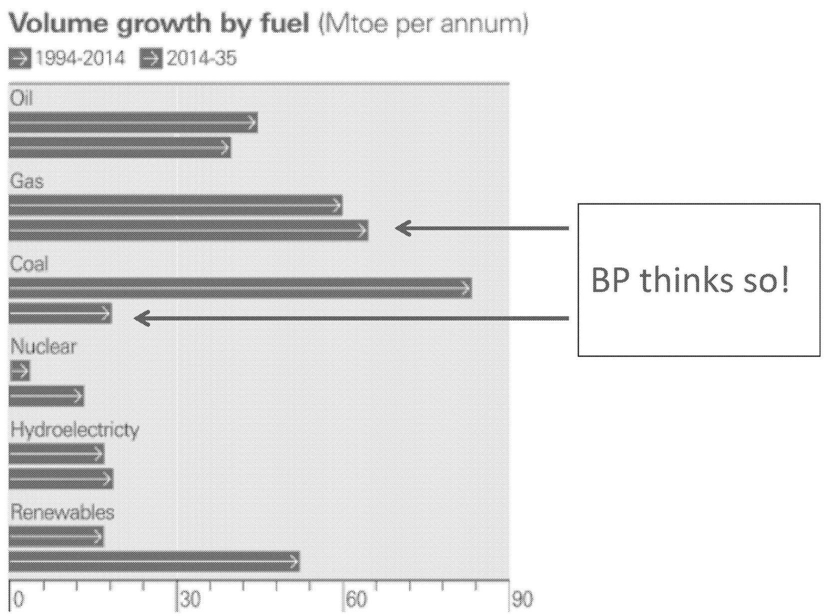
Will natural gas really displace coal?



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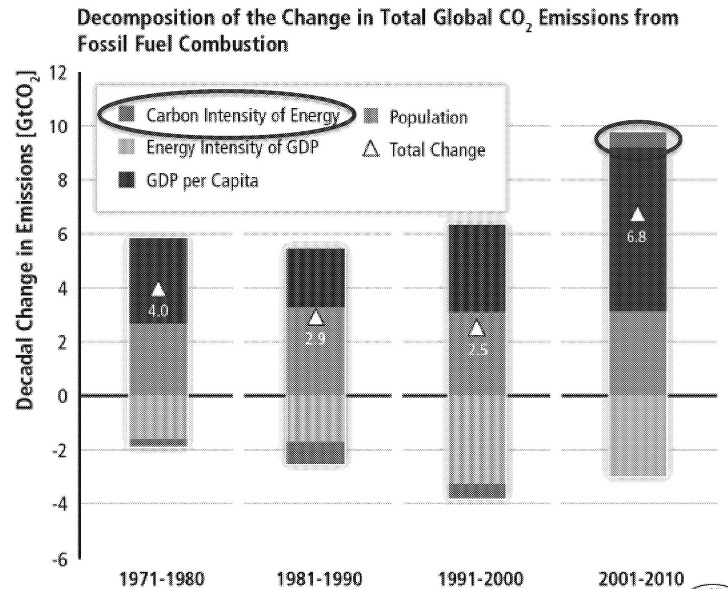
Source: BP Energy Outlook 2035

The carbon intensity of global energy: growing!

Kaya Identity

$$F = P\left(\frac{G}{P}\right)\left(\frac{E}{G}\right)\left(\frac{F}{E}\right)$$

F: World carbon emissions
P: World population
G: Economic output (World GDP)
E: World primary energy



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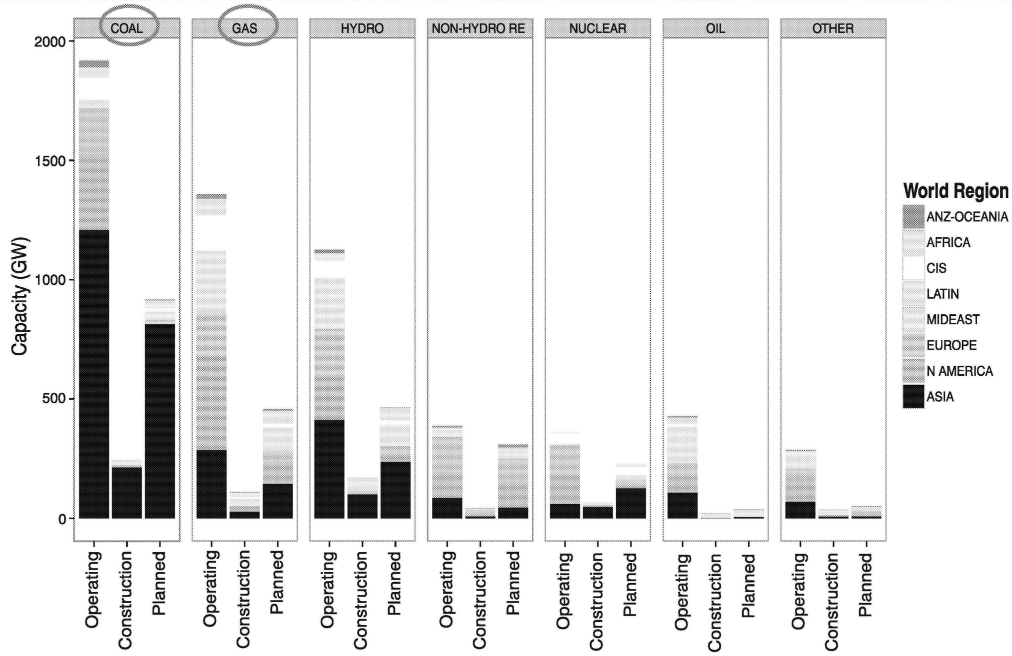
Source: IPCC AR5 WG3 SPM 2014, Fig SPM.3

New coal dominates new gas in power sector



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Source: Phil Hannam, from *Platts data,* Dec. 2015

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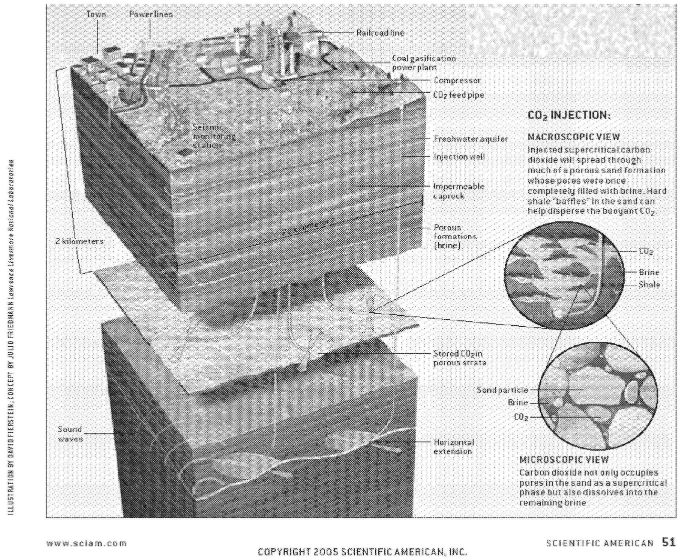
Future coal plant, CO_2 captured and stored



Assume:
1000 MW coal plant
10 years of operation
60 m usable, vertically
10% porosity
1/3 of pore space is CO_2

Result:
Horizontal area: 40 km^2.

For biomass too (BECCS)?

How long does the CO_2 need to stay down?
Excessively strict early rules could thwart CCS.

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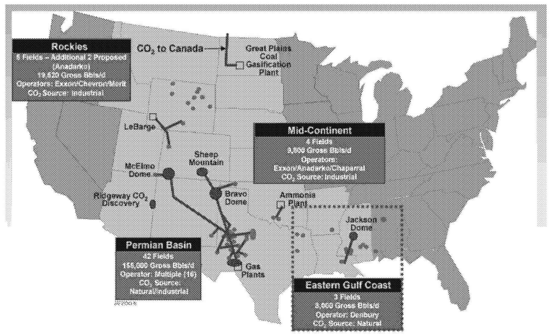
A new world for EOR at \$100/tCO_2



Enhanced oil recovery (EOR): EOR at 2 to 3 barrel produced per ton of CO_2 stored (typical) stores roughly one carbon atom for each carbon atom produced*. At \$30 to \$50 per barrel and \$100/tCO2, the two revenue streams are equal.

How will EOR be changed by a \$100/tCO_2 price?

* 1 bbl oil: ~120 kgC; 1 tCO_2: 272 kgC.

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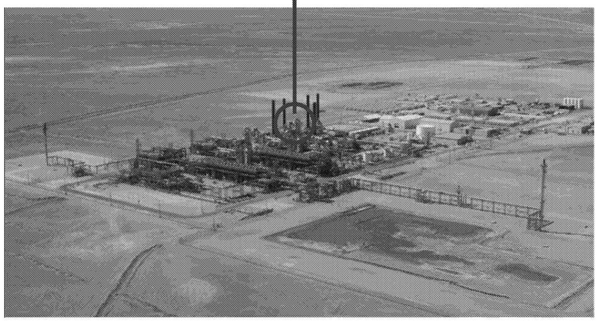
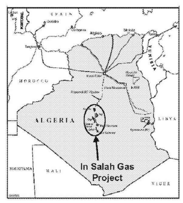
1 bbl oil:~120 kgC; 1 tCO2: 272 kgC.

Source: A slide of Bob Williams from his talk in China, summer 2008

A CCS Project in In Salah, Algeria



Natural gas purification by CO_2 removal, then CO_2 pressurization for nearby injection



The In Salah Gas Joint Venture CCS project is led by BP.

Separation at amine contactor towers

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Technology to reduce energy demand

Four ways to emit 5 ton CO_2/yr (today's global per capita average)

Activity	Amount producing 5 ton CO_2/yr emissions
a) Drive	20,000 miles per year, 45 mpg
b) Fly	20,000 miles/year
c) Heat home	Natural gas, average house, average climate
d) Use electricity	400 kWh/month if all coal-power (1000 gCO_2/kWh) 800 kWh/month, natural-gas-power (500 gCO_2/kWh)

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Source for flying value: Airbus, Flying by Nature: Global Market Forecast 2007-2026.Airbus S.A.S. Blagnac, Cedex, France: 2007. From Bradley Werntz, term paper, MAE 328, 2009.

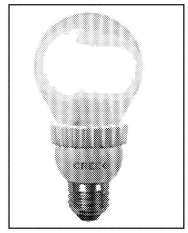
Calculation: 2006 at 4.5 liters/100 revenue-passenger-kilometers is how many miles per gallon? 1.189 gallons/62.2 passenger miles, or 52.3 miles per gallon. Round off to 50 mpg. Note: 30 mpg corresponds to 7.5 liters/RPK, valid in the late 1980s. 50 mpg and 15,000 miles/yr means 300 gals/yr, as with the car above.

Florida 2008: 219.6 TWh generated, 551 gCO2/kWh (120.9 MtCO2 from elec)

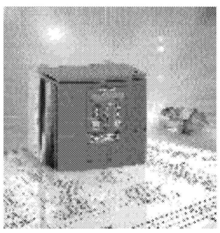
Efficiency and Conservation

transport

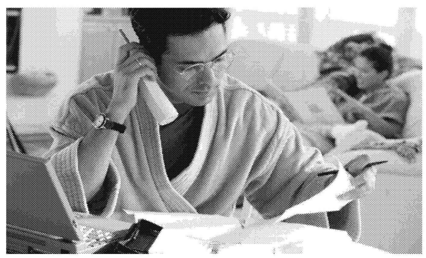
buildings



industry



information



power

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The carbon price in a climate-focused world: ≈\$100/tCO_2

Upstream, the impacts are particularly dramatic. **\$100/tCO_2** is:

\$40/barrel of oil
\$5/million Btu of natural gas
\$200/ton of high-quality coal.

Downstream, percent increases in prices are smaller. **\$100/tCO_2** is:

\$0.80/U.S. gallon of gasoline
\$0.08/kWh electricity from coal
\$0.04/kWh electricity from natural gas.

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“Solutions” 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: We must take into account both the risks of disruption from climate change and the risks of disruption from mitigation.

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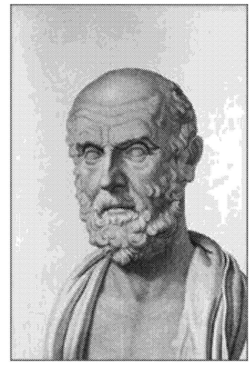
Patient Earth

"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**

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CMI high-level messages: Climate science

Steady progress: The land-ocean-atmosphere system, past and present, continues to be clarified by careful science. Princeton's own significant contributions can be partially credited to BP support.

Global methane: Natural gas is responsible for about one quarter of anthropogenic methane emissions, and tightening the natural gas system is the low-hanging fruit of the global methane cycle. Satellite-based and ground-based citizen surveillance is feasible.

Attribution: A new National Academy of Sciences report is portentous: "It is now often possible to make and defend quantitative statements about the extent to which human-induced climate change…has influenced either the magnitude or the probability of occurrence of specific types of events or event classes."

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These are our views of several controversial subjects. We are not speaking for BP.

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High-level messages: Paris Agreement

Square One: The Agreement's call for universal voluntary commitments will pressure every sector to act constructively.

Aspirational goals: "Two degrees" and "zero net carbon by 2050" require a carbon price above \$100/tCO_2, the halving of global CO_2 emissions, and less natural gas use than projected. CCS would help. Meanwhile, coal dominates industrialization in Asia.

Biocarbon: Common pricing of fossil carbon and biocarbon may result in hundreds of millions of hectares dedicated to fossil fuel replacement and atmospheric CO_2 removal. Governments can prevent dangerous mitigation by imposing forceful "conditionality."

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These are our views of several controversial subjects. We are not speaking for BP.

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Recommendation #1 for BP
Address your core activities.

1. *Upstream CO_2*: Lead in curtailing flaring, promote CCS where gas is processed, redesign EOR for when CO_2 storage becomes a revenue stream.
2. *Upstream fugitive CH_4:* Demonstrate best practices – minimal release, fast response to carelessness. Beyond safety.
3. *Gas for coal:* Work out the limits on how much and how fast, e.g., to restrain the juggernaut in Asia.
4. *Gas for "firming":* Provide dispatchable power via partnerships where gas backs up intermittent renewables.

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Recommendation #2 for BP
Engage policymaking proactively.

1. *Be real and helpful about carbon pricing*. What should we expect to see happen at $5/tCO_2$? What about $100/tCO_2$, reached by a ramp that is credible?
2. *Identify yourselves with carbon efficiency*. *Examples*:
   A. When bringing gas to new cities, assure efficient buildings/appliances.
   B. Help your industrial and power-plant customer to use your fuel efficiently (the customer's side of the meter).

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Grounds for optimism

1. The world today has a terribly inefficient systems for using carbon.

2. Carbon emissions have just begun to be priced.

3. Most of the 2066 global infrastructure is not yet built.

4. **Very smart scientists and engineers – and talented people in many other fields – now find the climate challenge exciting.**

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EXTRA SLIDES

The Paris Agreement's 2050 objective

Article 2: Significantly less than 2 °C of warming.

Article 4, Section 1: **Sources balance sinks in the second half of the century.**
Result: Constant atmospheric CO_2.

In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty.

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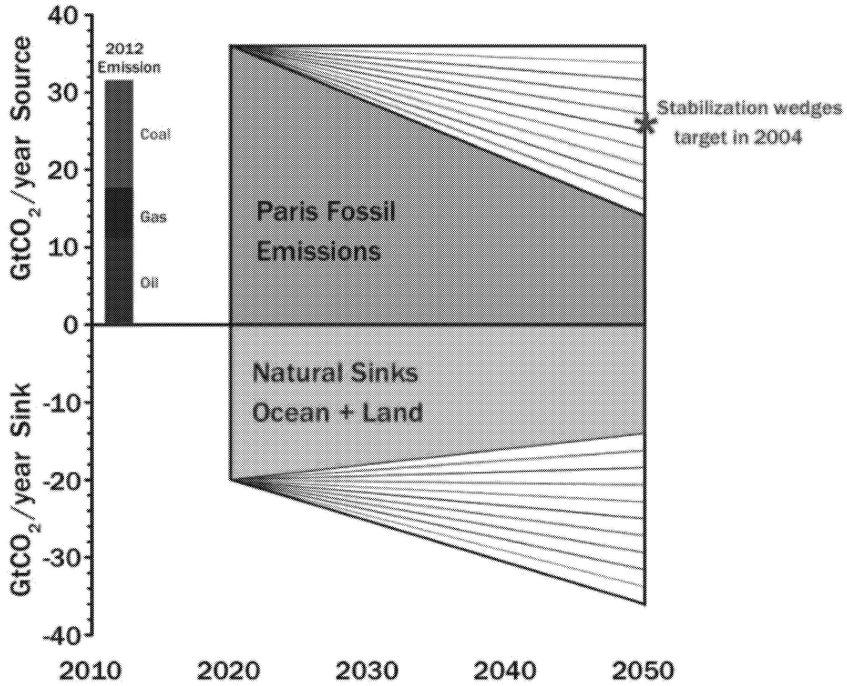
Fossil Emissions Under Paris Agreement



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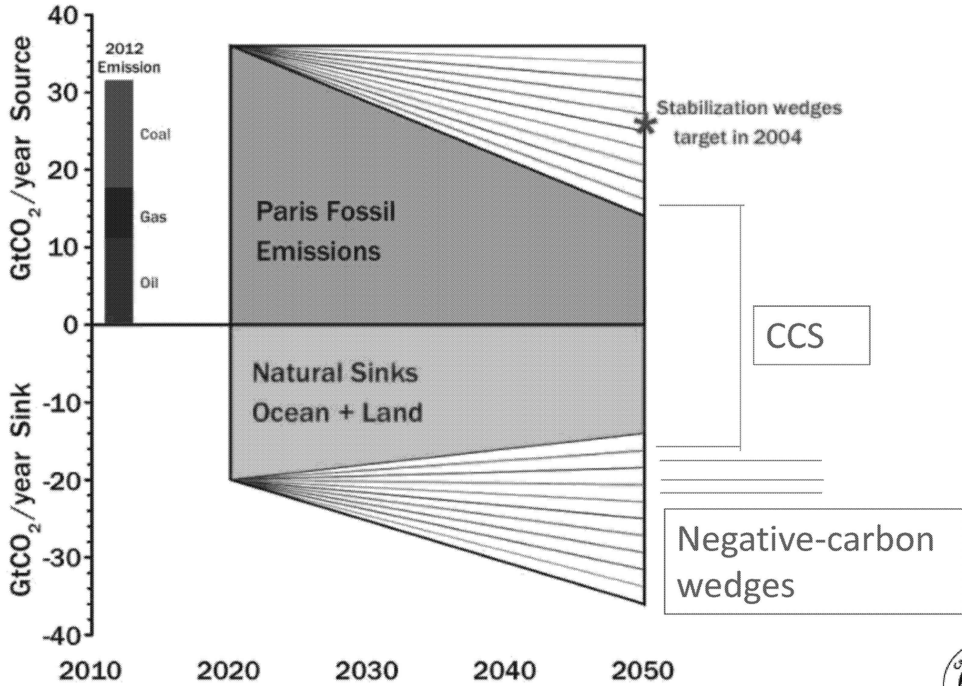
Paris negative-carbon wedges



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The scale of sinks wedges at mid-century

A sink wedge: Remove 0.6 GtC/yr (2.2 $GtCO_2$/yr) in 2050. (Neglect ocean and land feedback returning CO_2 to the atmosphere.)

- CCS from 500 GW coal or 1000 GW gas
- BECCS: Cellulosic ethanol to CCS power, with 100% carbon captured, on 100 Mha (roughly half of US cropland today).
- Temperate afforestation on 200 Mha or tropical afforestation on 100 Mha.
- DAC (direct air capture): Structures 10 m high capturing 75% of the CO_2 in 4 m/s air, with 4000 km total length.
- Restore lost soil carbon on 20% of global cropland or half the lost carbon on 40% of the cropland
- Manage pastures for soil carbon storage (i.e. breed for grasses with lignified roots, reduce overgrazing)

BECCS cellulosic ethanol: 1 liter/m^2 rule of thumb. Also 6tC/ha-yr tropical [check] perennials. C in ethanol is 4/7 of total mass.

Afforestation: 4t/ha-yr in tropical, 2t/ha-yr in temperate – as trees grow.

Soil carbon: See LM3 and Global Carbon Project: 69 GtC lost through agriculture, can be restored. Pasture can probably be restored too.

Add gas for coal.

Do these freshly.

CO_2 Utilization Task Force Report, now online

LETTER REPORT FOR: Secretary of Energy Ernest J. Moniz
FROM: Secretary of Energy Advisory Board (SEAB) CO_2 Utilization Task Force

SUBJECT: Task Force on RD&D strategy for CO_2 Utilization and/or Negative Emissions at the Gigatonne Scale

DATE: November 28, 2016

The scope can be conveyed by the titles of the five recommendations for R&D:

Recommendation 1 – Systems Modeling
Recommendation 2 – Harnessing the Natural Biological Carbon Cycle
Recommendation 3 – Synthetic Transformations of CO_2
Recommendation 4 - Carbon Dioxide Sequestration in Geologic Formations
Recommendation 5 – Carbon Dioxide Capture and other Separation Technologies

Task Force Members

Sally Benson, Stanford
Emily Carter, Princeton
Arun Majumdar, Stanford **, chair
Michael Ramage, formerly Exxon-Mobil
Eric Toone, Duke
Mark Wrighton, Washington University
Rafael Bras, Georgia Tech**
John Deutch, MIT**
Don Ort, University of Illinois,
Robert Socolow, Princeton
George Whitesides, Harvard
*** SEAB member*

A schematic view of low-carbon technology

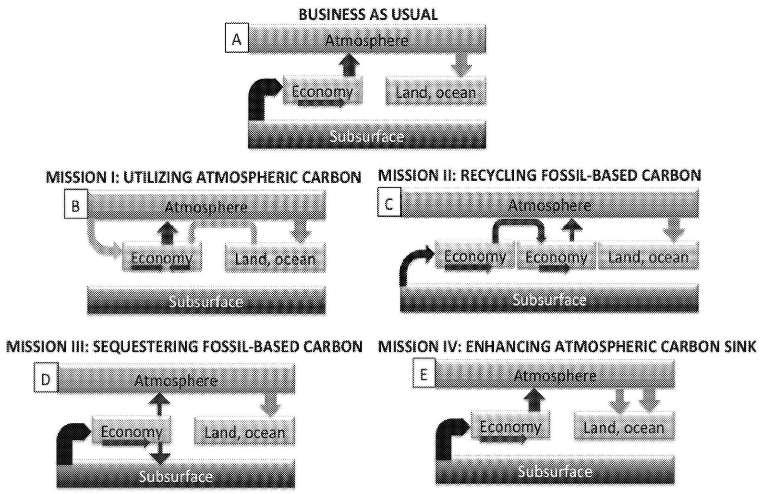

Figure A4.2: Schematic representation of the current fossil fuel economy (Business as Usual, Panel A) and four missions (Panels B, C, D, and E) that could reduce CO_2 emissions to the atmosphere. Panel B (Mission I): Use carbon from the land or atmosphere; Panel C (Mission II), recycle combustion-generated CO_2; Panel D (Mission III), prevent combustion-generated CO_2 from reaching the atmosphere; Panel E (Mission IV), enhance the land and ocean CO_2 sinks.

IMPLICATIONS FOR CHINA

Two children playing "Leapfrog."

To leapfrog: to do something for the first time when initially in second place, thereby gaining first place.

China is leapfrogging over the rest of the world with high-voltage transmission, for example.

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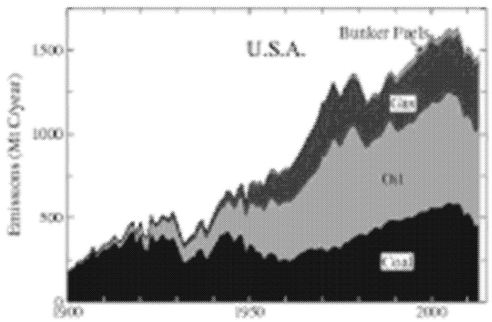
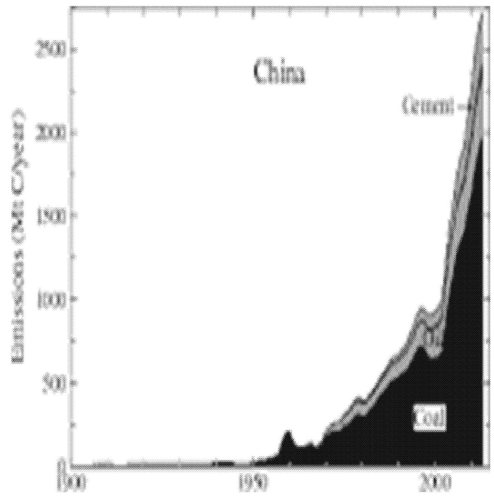
It's mostly about coal





1900 2000 1900 2000

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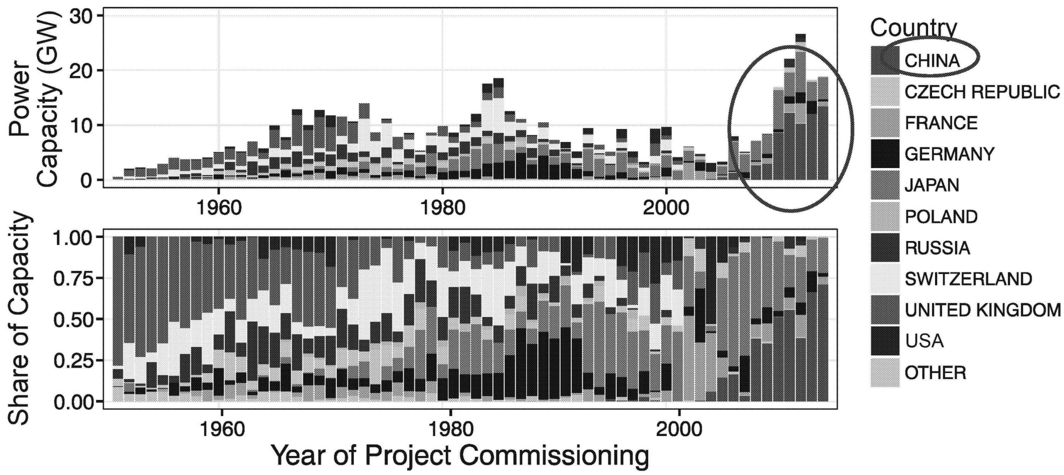
Exports matter: China now dominates the export of coal power and its financing.



Shown: All coal plants that use a foreign-produced turbine

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Source: Phil Hannam, 2016. Ph.D. Thesis, Princeton University.

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Enthusiasm for Carbon Policy in China

Low-carbon path will be followed, independent of U.S. actions.

Carbon management fits with China's top-down planning:

- Addresses endemic overcapacity (in coal, solar, wind, etc.), creates an urgency to impose rules and gain control.
- Justifies central government sway over provinces.
- Provides a rationale for nuclear power investment, widely supported by elites.
- Will accelerate cap and trade, now in pilot stage.

Not yet a priority: energy efficiency (e.g., in buildings) that addresses immense pent-up consumer demand.

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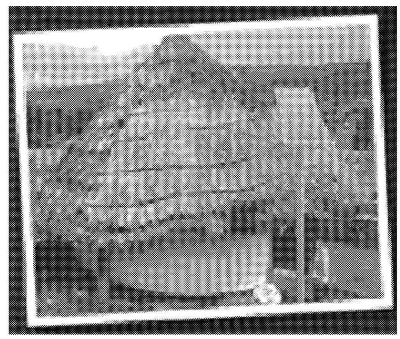
Solar power

Centralized, Xitieshan,

Photo: Vinaykumar8687, https://commons.wikimedia.org/w/index.php?curid=35401850.

Distributed



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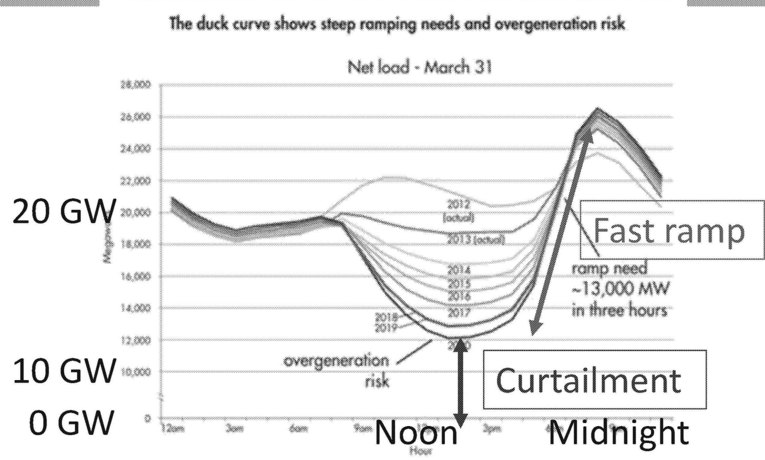
Intermittency and the "Duck Curve"



Intermittency Strategies:

- Storage
- Dispersed sources
- Load shifting
- Gas turbines

The hourly net load in California on March 31 of successive years. Actual data for 2012 and 2013, modeled data for later years.

Plotted is total electricity consumption *minus* electricity produced from utility wind and solar sources, for the grid managed by the California Independent System Operator.

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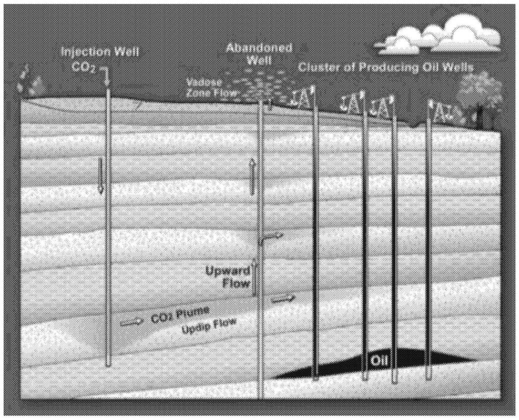
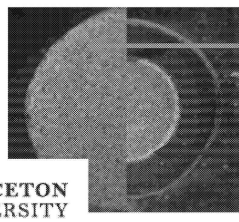
Will CO_2 escape up old wells?



Source of figure above: Michael Celia

"The best data we have on the state of old wells indicate that leakage of CO_2 should not be excessive and that CO_2 injection should be able to proceed without leakage along old wells being a show stopper."

Michael Celia, Princeton University



Unreacted H-type cement

Cement after 3 weeks in flow-through reactor at 50°C and pH 2.4. Color variation is due to changes in oxidation in iron impurities.

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