Mitigation of Human-Caused Climate Change

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The issue in brief

- Disruption of global climate by human-produced greenhouse gases (GHG) in the atmosphere is the most dangerous and difficult of all the environmental problems caused by human activity.
- It's the most dangerous problem because climate is the "envelope" within which all other environmental conditions and processes operate.

  Distortions of this envelope of the magnitude that are underway are likely to so badly disrupt these conditions and processes as to impact adversely every dimension of human well-being that is tied to environment.

The issue in brief (continued)

- <u>It's the most difficult problem</u> because the dominant cause of the disruption – emission of carbon dioxide (CO_2) from fossil-fuel combustion – is a deeply embedded part of the process that currently supplies 80 percent of civilization's energy.
  - CO_2 is not a trace contaminant but a principal combustion product (~3 tonnes CO_2 per tonne of coal)
  - The world's energy system represents a huge capital investment (~$12 trillion worldwide) which turns over slowly (~30-50 years).
  - Thus there is no "quick fix". If the energy system of 2050 needs to be much different than today's, a major push to change it must start now.
  - So far, this isn't happening.

The issue in brief (continued)

Society has three options:

- Mitigation, which means measures to reduce the pace & magnitude of the changes in global climate being caused by human activities.

  Examples of mitigation include reducing emissions of GHG, enhancing “sinks” for these gases, and “geoengineering” to counteract the warming effects of GHG.

- Adaptation, which means measures to reduce the adverse impacts on human well-being resulting from the changes in climate that do occur.

  Examples of adaptation include changing agricultural practices, strengthening defenses against climate-related disease, and building more dams and dikes.

- Suffering the adverse impacts that are not avoided by either mitigation or adaptation.

The issue in brief (concluded)

Mitigation and adaptation are <u>both</u> essential.

- Human-caused climate change is already occurring.
- Adaptation efforts are already taking place and must be expanded.
- But adaptation becomes costlier and less effective as the magnitude of climate changes grows.
- The greater the amount of mitigation that can be achieved at affordable cost, the smaller the burdens placed on adaptation and the smaller the suffering.

The remainder of this tutorial focuses mainly on mitigation: the size of the need, the available approaches, and the policy levers and prospects.

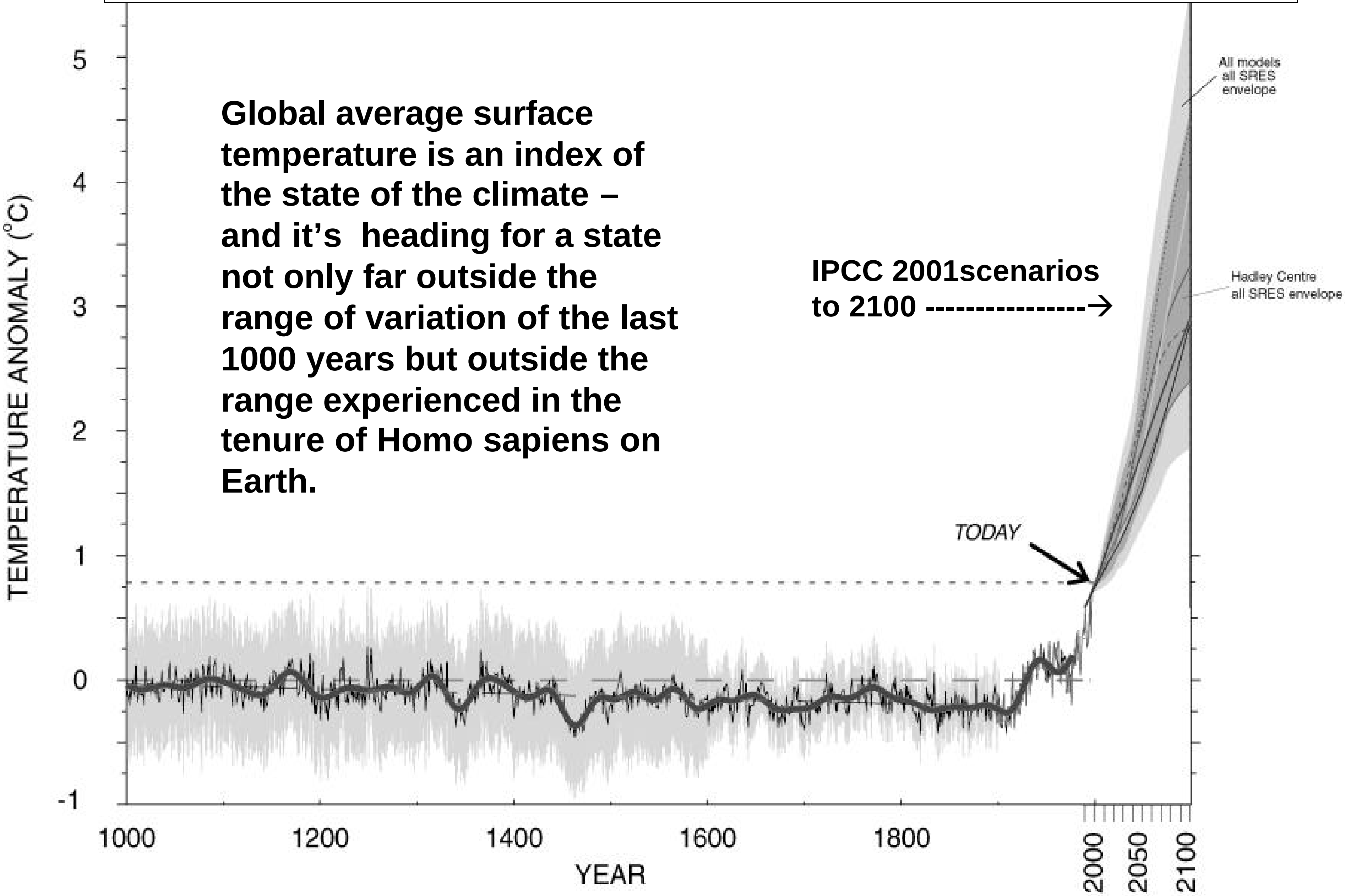
Mitigation: Where we're headed without it.

A "business as usual" scenario

	2000	2050	2100
	-------	-------	-------
Population, billions	6.1	9	10
Economy, trillion 2000$	45	150	480
Energy, exajoules	450	900	1800
Fossil C in CO_2, gigatons	6.4	14	21

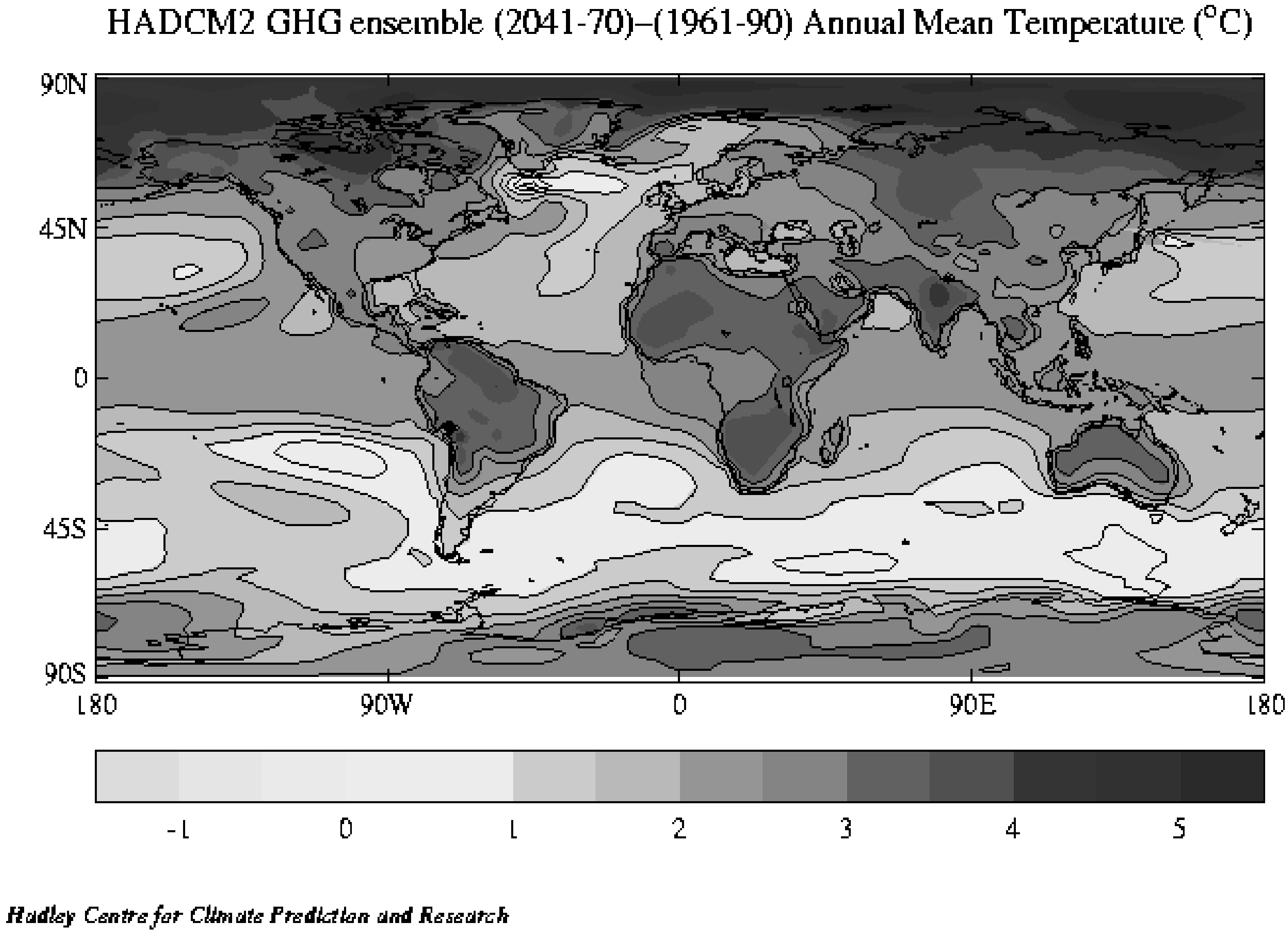
Corresponds to 2.4%/yr avg growth of real GDP, 1.0%/yr decline in energy intensity of GDP, 0.2%/yr decline in C intensity of energy supply.

1000 years of Earth temperature history…and 100 years of projection



Global average surface temperature is an index of the state of the climate – and it's heading for a state not only far outside the range of variation of the last 1000 years but outside the range experienced in the tenure of Homo sapiens on Earth.

Mitigation: Where we're headed without it.



Computer simulation of mid-21st-century warming under BAU: consequences come sooner because warming is non-uniform.

How much mitigation is needed?

- The UN Framework Convention on Climate Change of 1992 is “the law of the land” in 188 countries (including the United States).

- It calls for

  “*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*”.

- But there was no formal consensus in 1992 as to what constitutes “dangerous anthropogenic interference” or what level of GHG concentrations will produce it.

How much mitigation is needed? (continued)

There's still no consensus, but it's increasingly clear that the current level of anthropogenic interference is dangerous.

- Atmospheric CO_2 concentration is above 380 ppmv, compared to 278 ppmv in 1750 ("pre-industrial").
- Global average surface temperature (T_{avg}) is ~0.8°C above the pre-industrial value.
- The world is already experiencing rising incidence of floods, droughts, wildfires, heat waves, coral bleaching, summer melting of sea ice & permafrost, shrinkage of mountain glaciers, accelerating loss of Greenland and Antarctic ice, drying out of rainforests, and category 4 & 5 cyclones.
- T_{avg} would rise another 0.6°C even if GHG concentrations were stabilized today ("thermal lag" of oceans).

How much mitigation? (continued)

- Under continuation of “business as usual” (BAU) in growth of world GDP and use of fossil fuels, the increase in global average surface temperature above its pre-industrial value (?T_{avg}) is likely to reach almost 2°C by 2050, 3°C by 2100, and 4-5°C by 2150.
- The best current science indicates that…
  - ?T_{avg} ~ 1.5°C could mean the end of coral reefs & the extinction of polar bears;
  - ?T_{avg} ~ 2°C could mean catastrophic melting of Greenland & Antarctic ice, producing rates of sea-level rise that could reach 3-4 meters per century;
  - ?T_{avg} ~ 2.5°C is likely to sharply reduce crop yields worldwide.

How much mitigation is needed? (continued)

- Until a few years ago, many analysts and groups were suggesting a target of about 3°C.

  A 3°C target corresponds to a sum of human influences (changes in all greenhouse gases and absorbing & reflecting particles) equivalent to a doubling of pre-industrial CO_2 (to ~550 ppmv).

  This was a compromise: perhaps the highest value that might be tolerable (taking into account potential for adaptation) and at the same time the lowest value that might be achievable (taking into account the known mitigation options and their costs).

- Recent insights about impacts have led many analysts & groups, over the past few years, to argue for a tighter target, around 2°C.

  This would mean confining the sum of human influences to the equivalent of CO_2's reaching 400-450 ppmv.

  Many analysts doubt that so low a target can be achieved.

How much mitigation? (continued)

AN OUNCE OF PREVENTION…

- The costs of delay in initiating reductions are likely to be substantial. They depend strongly on the choice of climate-change goals.
- The lower the stabilization target deemed prudent, the higher the costs of delay in starting to move toward it.
- Any further delay in starting puts the ability to stabilize below 450 ppmv in doubt, irrespective of cost.
- For higher targets, moderate early action will cost far less than waiting until only drastic action can meet the target.
- Early action can be considered to be an insurance policy against costly catastrophe.

How much mitigation is needed? (concluded)

The conclusion is that we are going to need

as much mitigation as we can get,

as quickly as we can get it.

Approaches to mitigation

TYPES OF TECHNICAL MITIGATION MEASURES

- change the quantity or character of the human activities that lead to emissions of greenhouse gases, particulate matter, or precursors of these;
- alter the emissions of these substances from their natural sources;
- change the rates at which these substances are removed from the atmosphere;
- change other climate-relevant characteristics of the environment to offset undesired influences on climate resulting from human activities.

Approaches to mitigation (continued)

TYPES OF POLICY MEASURES FOR MITIGATION

- regulations (such as emission standards) and incentives (such as taxes or tax relief) to increase nongovernmental actors' use of the best technical options available in the marketplace;
- design & implementation of projects in which governments themselves exercise these technical options;
- government expenditures on research, development, & demonstration aimed at improving the technical options available in the marketplace;
- incentives for private investment in research, development, & demonstration to this end.

Selecting an appropriate mix of measures

- Identify the existing & prospective technical mitigation measures germane to all of the factors through which humans are influencing global climate. Analyze…
  - the realistic potential of each measure for reducing the relevant forcings over time,
  - the economic costs of using the measure at the desired scale
  - the likely significant environmental & social impacts of, as well as other obstacles to, its use.
- Identify the policy measures potentially available for promoting the most promising technical options (singly or in combination) and characterize these measures as to…
  - adequacy for achieving the desired aim,
  - efficiency,
  - equity,
  - "win-win" character (contribution to non-climate goals)
  - political feasibility.

Selecting an appropriate mix (continued)

- Select the subset of technical & policy measures to be pursued, based on the characteristics just listed and...
  - state of development of - and confidence about the characteristics of - the candidate options;
  - balance of the portfolio in relation to the range of forcings, short-term and long-term leverage, types of uncertainties & obstacles;
  - flexibility for adjustment as knowledge of the climate problem and the mitigation options improves over time;
  - adequacy of the portfolio against the scale of the challenge.

Principal human influences on climate, 1750-2000 & projected under BAU (forcings in watts/meter^2)

Influence	*Forcing to to 2000*	*Forcing to 2100*	*Mitigation opportunities*
carbon dioxide (CO_2)	1.5	5.1	fossil fuels, forests
CH_4, N_2O, halocarbons	1.0	1.6	fossil fuels, industry, agriculture
tropospheric ozone	0.4	0.9	fossil fuels
black soot	0.4	0.7	fossil fuels, fires
reflective particles	-0.9	-1.6	fossil fuels, fires
cloud-forming effects of particles	-0.7	-1.3	fossil fuels, fires
surface reflectivity	-0.2	-0.1?	land-cover change
TOTAL	1.5	5.4	

Values are central estimates with uncertainties ±10-50%.

Implications of the pattern of influences

- The warming effects of increased concentrations of GHG and black soot in the atmosphere are the dominant drivers of current global climate change.
- Among these, CO_2 is already the most important, and its importance relative to the other GHG and soot is expected to grow significantly during the 21st century.

  CO_2 accounted for 45% of the total positive anthropogenic forcing from 1750 as of 2000. Under the BAU scenarios, it would account for 60% in 2100.

- Fossil-fuel combustion is the dominant source of anthropogenic CO_2 emissions.

  Central estimates of anthropogenic CO_2 emissions in 2000 are 6.4 GtC from fossil fuels, 1.6 GtC from deforestation, 0.2 GtC from cement production. Under BAU, fossil & cement contributions increase ~3-fold by 2100, deforestation shrinks.

An aside: Why are scenarios of future climate change so often described only in terms of CO_2 emissions and concentrations, even though other gases and particles also have significant effects?

1. The warming effects of increases over the past 250 years in non-CO_2 GHG & absorbing particles have been approximately balanced by the cooling effects of increases in reflecting particles. Thus the net effect of all the human additions to the atmosphere over the past 250 years is (by coincidence) about equal to the CO_2 effect alone.
2. This may well remain approximately true in the future: growth or decline in emissions that add to reflective-particle concentrations might be matched by changes in emissions of black soot and non-CO_2 GHG, so that these positive & negative forcings continue to more or less balance each other in the 21st century.
3. To study scenarios in which this is not be the case, one can express the greenhouse-warming effects of non-CO_2 GHG in terms of "tonnes of CO_2 equivalent" (for emissions) and "parts per million of CO_2 equivalent" (for concentrations).

Technical options for reducing fossil CO_2 emissions

The emissions arise from a 4-fold product…

$$C = P \times GDP / P \times E / GDP \times C / E$$

where C = carbon content of emitted CO_2 (kilograms),

and the four contributing factors are

P = population, persons

GDP / P = economic activity per person, $/pers

E / GDP = energy intensity of economic activity, GJ/$

C / E = carbon intensity of energy supply, kg/GJ

For example, in the year 2000, the world figures were…

6.1×10^9 pers x $7400/pers x 0.01 GJ/$ x 14 kgC/GJ

= 6.4×10^{12} kgC = 6.4 billion tonnes C

Where's the leverage for reductions in these?

POPULATION

- Lower is better for lots of reasons: 8 billion people in 2100 is preferable by far to 10 billion.
  - Reduced growth can be achieved by measures that are attractive in their own right (e.g., education, opportunity, health care, reproductive rights for women).

GDP PER PERSON

- This is not a lever that most people want to use, because higher is generally accepted to be better.
  - But we're not getting rich as fast as we think if GDP growth comes at the expense of the environmental underpinnings of well-being.
  - Internalizing environmental costs of economic growth (including those of climate change) may slow that growth a bit...but not much.
  - Some lifestyle changes in industrialized countries might increase quality of life while reducing GDP.

Leverage against CO_2 emissions (continued)

ENERGY INTENSITY OF GDP

Getting more GDP out of less energy – i.e. increasing energy efficiency – has been a long-term trend.

It could be accelerated. It entails more efficient cars, trucks, planes, buildings, appliances, manufacturing processes. This opportunity offers the largest, cheapest, fastest leverage on carbon emissions.

CARBON INTENSITY OF ENERGY SUPPY

This ratio too has been falling, but more slowly than energy intensity of GDP. Reducing it entails changing…

- the mix of fossil & non-fossil energy sources (most importantly more renewables and/or nuclear)
- and/or the characteristics of fossil-fuel technologies (most importantly with carbon capture & sequestration).

Reducing E/GDP: Transportation

- Oil used as transport fuel ˜ 25% of global CO_2 from fossil-fuel combustion
- Growth in these uses can be reduced by…
  - increasing the efficiency of cars, trucks, buses, trains, aircraft
  - Increasing the load factors of these (e.g., passengers per vehicle per trip)
  - mode switching (e.g., cars → buses, trucks → trains)
  - urban & economic planning that affects living & production patterns so as to reduce commuting and freight transport

Reducing E/GDP: Buildings

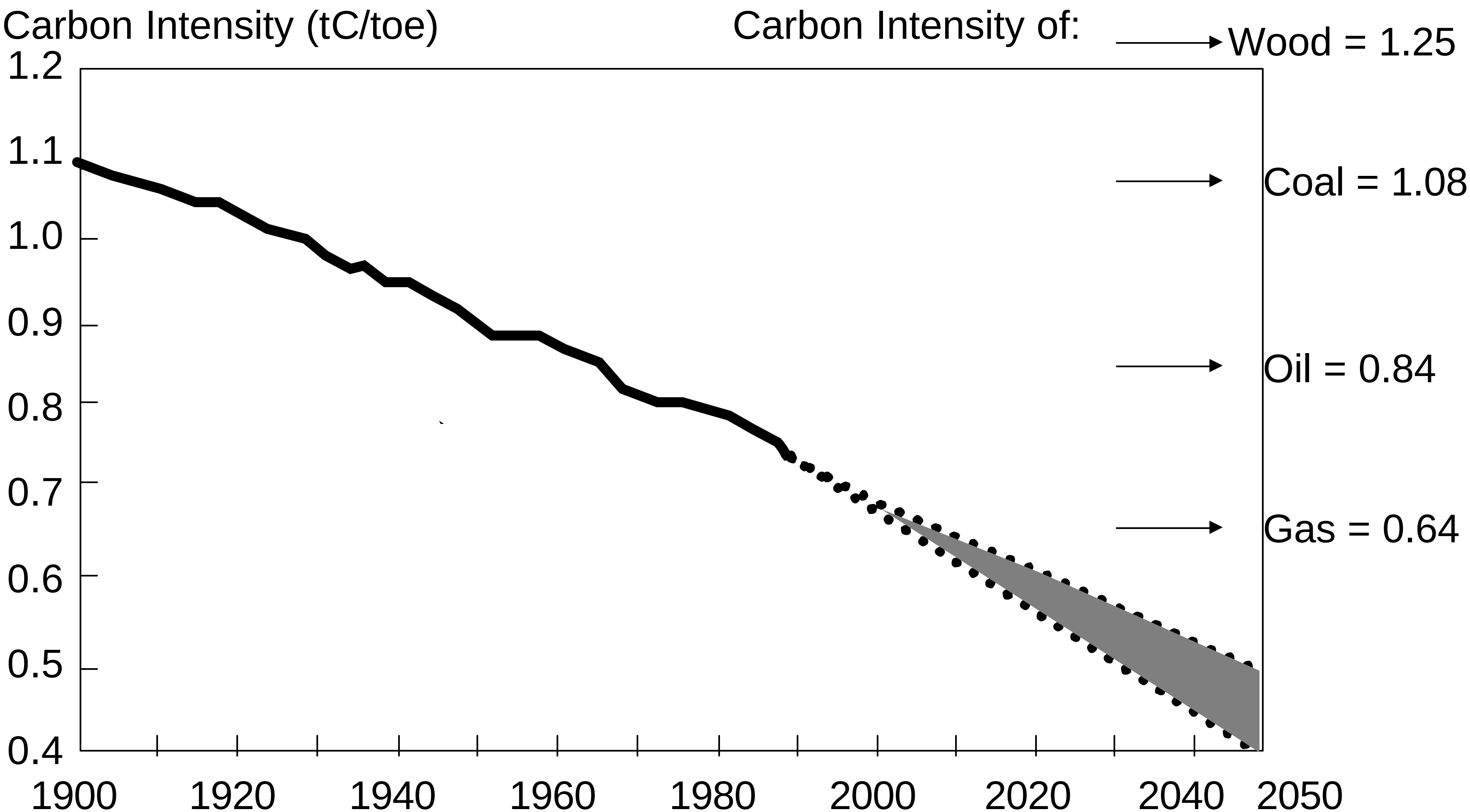
- Heating, cooling , refrigeration, lighting, office equipment ˜ 33% of global CO_2 from fossil-fuel combustion.
- Energy used for these purposes can be reduced by…
  - improvements in building envelopes (wall & roof insulation, high-performance windows)
  - improved building orientation, shading, passive energy storage;
  - increased efficiency of heating & cooling (improved furnaces, air conditioners, ground-water heat pumps)
  - increased efficiency of lighting, refrigerators, computers, other appliances

Reducing E/GDP: Industry

- Industrial energy use ~ 40% of global CO_2 from fossil-fuel combustion.
- Biggest users include oil refining, plastics, fertilizers, iron & steel, aluminum, cement, pulp & paper.
- Energy used for these purposes can be reduced by…
  - improved efficiency of electric motors & individual industrial processes
  - increased use of on-site combined heat & power (CHP)
  - increased recycling of energy-intensive materials
  - shift in composition of industrial activity from materials-intensive to knowledge- and information-intensive goods & services

C/E: History and BAU projections

Carbon Intensity of World Primary Energy, 1900-2050



Source: National Academy of Engineering, 1997

C/E: Will running out of fossil fuel take care of it?

- Combustion of conventional fossil fuels yields about

  15 million tonnes C in CO_2 per EJ of natural gas

  20 million tonnes C in CO_2 per EJ of petroleum

  25 million tonnes C in CO_2 per EJ of coal

  1 tonne of C makes 3.67 tonnes of CO_2

- Remaining ultimately recoverable resources would yield

  200+ billion tonnes of C in CO_2 from natural gas

  300+ billion tonnes of C in CO_2 from petroleum

  4,000 billion tonnes of C in CO_2 from coal

Current C content of the atmosphere (380 ppmv) = 800 billion tonnes C in CO_2, an increase of about 215 billion tonnes C since 1750. About half of added CO_2 now stays in atmosphere; if this remains so, adding 700 billion more tonnes of C in CO_2 will get us to 2X 1750 concentration.

There is more than enough conventional fossil fuel to double, even triple & quadruple, the pre-industrial atmospheric concentration of carbon dioxide.

Reducing C/E going forward

HERE THE POSSIBILITIES ARE…

- Increasing the efficiency of conversion of fossil-fuels to end-use energy forms (most importantly electricity)

  Potential is limited because conversion efficiencies are constrained by thermodynamics and already high.

- Switching from high C/E to low C/E fossil fuels (coal to oil & natural gas, oil to natural gas)

  Potential is limited because oil & gas are much less abundant than coal (unless unconventional gas resources become practical)

- CO_2 capture & sequestration (CCS) when fossil-fuels are converted or burned

- Switching from fossil to non-fossil primary energy sources (renewables & geothermal, nuclear)

The last two have the largest potential, so let's look at them more closely.

Carbon capture & storage: technology

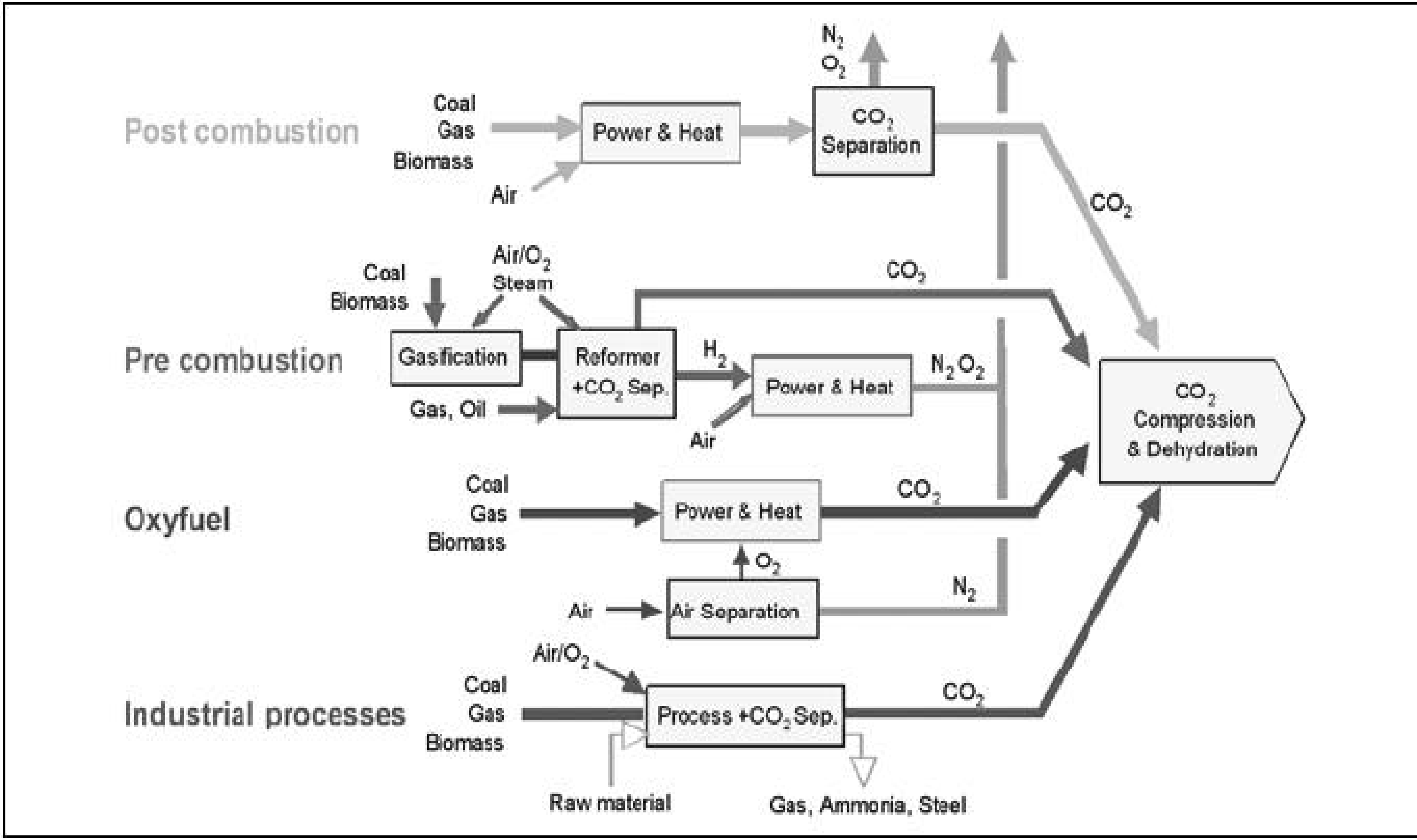


Figure TS.3. Overview of CO_2 capture processes and systems.

Courtesy Princeton Carbon Management Initiative

Carbon capture & storage: experience

Table TS.5. Sites where CO_2 storage has been done, is currently in progress or is planned, varying from small pilots to large-scale commercial applications.

Project name	Country	Injection start (year)	Approximate average daily injection rate ($tCO_2\ day^{-1}$)	Total (planned) storage (tCO_2)	Storage reservoir type
Weyburn	Canada	2000	3,000-5,000	20,000,000	EOR
In Salah	Algeria	2004	3,000-4,000	17,000,000	Gas field
Sleipner	Norway	1996	3,000	20,000,000	Saline formation
K12B	Netherlands	2004	100 (1,000 planned for 2006+)	8,000,000	Enhanced gas recovery
Frio	U.S.A	2004	177	1600	Saline formation
Fenn Big Valley	Canada	1998	50	200	ECBM
Qinshui Basin	China	2003	30	150	ECBM
Yubari	Japan	2004	10	200	ECBM
Recopol	Poland	2003	1	10	ECBM
Gorgon (planned)	Australia	~2009	10,000	unknown	Saline formation
Snøhvit (planned)	Norway	2006	2,000	unknown	Saline formation

Courtesy Princeton Carbon Management Initiative

Carbon capture & storage: economics

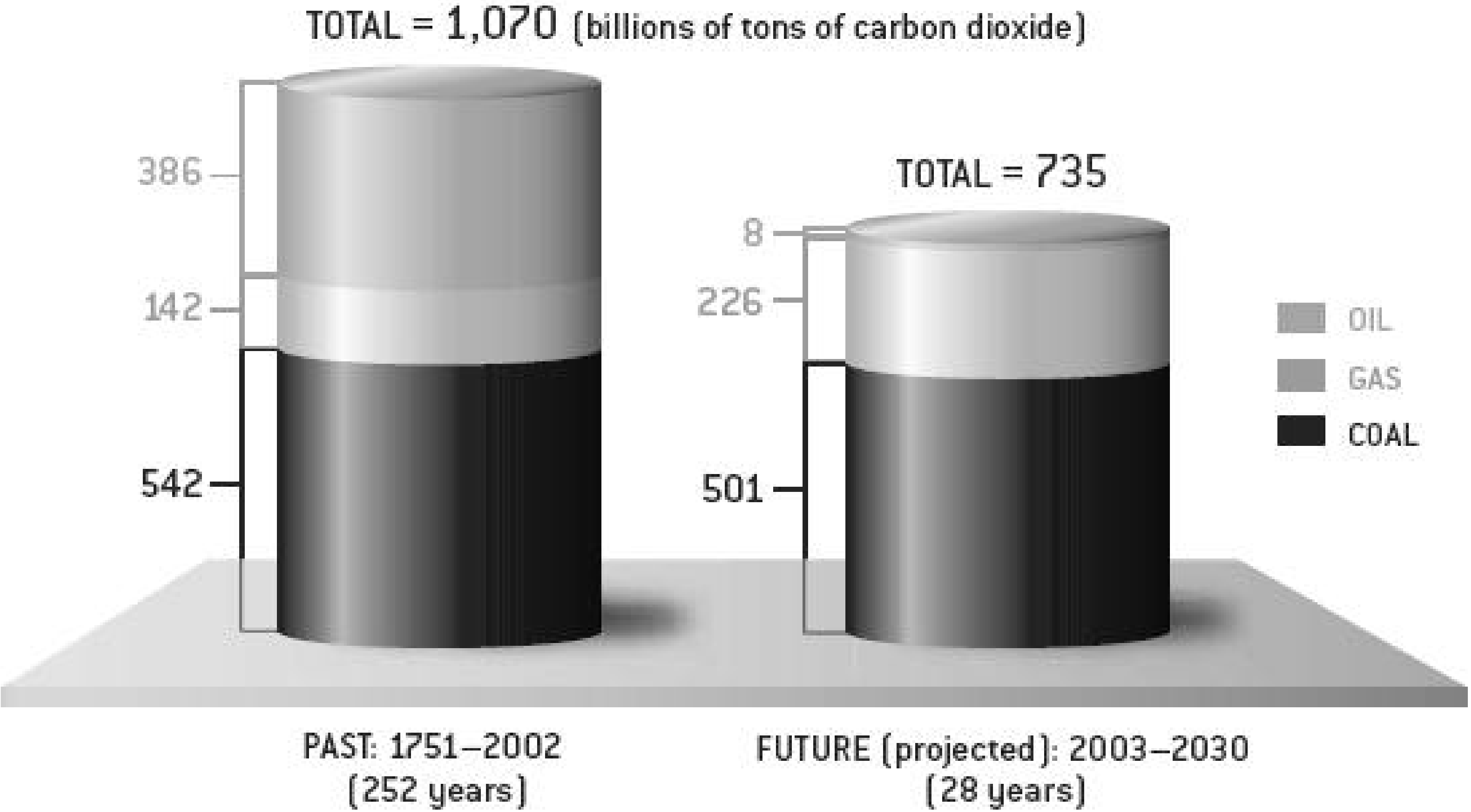
Table TS.9. 2002 Cost ranges for the components of a CCS system as applied to a given type of power plant or industrial source. The costs of the separate components cannot simply be summed to calculate the costs of the whole CCS system in US$/$CO_2$ avoided. All numbers are representative of the costs for large-scale, new installations, with natural gas prices assumed to be 2.8-4.4 US$ GJ^{-1} and coal prices 1-1.5 US$ GJ^{-1}.

CCS system components	Cost range	Remarks
Capture from a coal- or gas-fired power plant	15-75 US$/t$CO_2$ net captured	Net costs of captured CO_2, compared to the same plant without capture.
Capture from hydrogen and ammonia production or gas processing	5-55 US$/t$CO_2$ net captured	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	25-115 US$/t$CO_2$ net captured	Range reflects use of a number of different technologies and fuels.
Transportation	1-8 US$/t$CO_2$ transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO_2 yr^{-1}.
Geological storage[a]	0.5-8 US$/t$CO_2$ net injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.1-0.3 US$/t$CO_2$ injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Ocean storage	5-30 US$/t$CO_2$ net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification.
Mineral carbonation	50-100 US$/t$CO_2$ net mineralized	Range for the best case studied. Includes additional energy use for carbonation.

[a] Over the long term, there may be additional costs for remediation and liabilities.

Courtesy Princeton Carbon Management Initiative

What if we don't implement CCS? CO_2 emissions from power plants to be built in the next 25 years



LIFETIME FOSSIL-FUEL EMISSIONS from power plants projected to be built during the next quarter of a century will be comparable to all the emissions during the past 250 years. The left column

Courtesy David Hawkins, Rob Socolow, & Scientific American

The renewable option: Is it real?

SUNLIGHT: 100,000 TW reaches Earth's surface (100,000 TWy/year = 3.15 million EJ/yr), 30% on land.

Thus 1% of the land area receives 300 TWy/yr, so converting this to usable forms at 10% efficiency would yield 30 TWy/yr, about twice civilization's rate of energy use in 2004.

WIND: Solar energy flowing into the wind is ~2,000 TW.

Wind power estimated to be harvestable from windy sites covering 2% of Earth's land surface is about twice world electricity generation in 2004.

BIOMASS: Solar energy is stored by photosynthesis on land at a rate of about 60 TW.

Energy crops at twice the average terrestrial photosynthetic yield would give 12 TW from 10% of land area (equal to what's now used for agriculture). Converted to liquid biofuels at 50% efficiency, this would be 6 TWy/yr, more than world oil use in 2004.

Renewable energy potential is immense. Questions are what it will cost & how much society wants to pay for environmental & security advantages.

The nuclear option: size of the challenges

- If world electricity demand grows 2%/year until 2050 and nuclear share of electricity supply is to rise from 1/6 to 1/3…
  - nuclear capacity would have to grow from 350 GWe in 2000 to 1700 GWe in 2050;
  - this means 1,700 reactors of 1,000 MWe each.
- If these were light-water reactors on the once-through fuel cycle…
  - enrichment of their fuel will require ~250 million Separative Work Units (SWU);
  - diversion of 0.1% of this enrichment to production of HEU from natural uranium would make ~20 gun-type or ~80 implosion-type bombs.

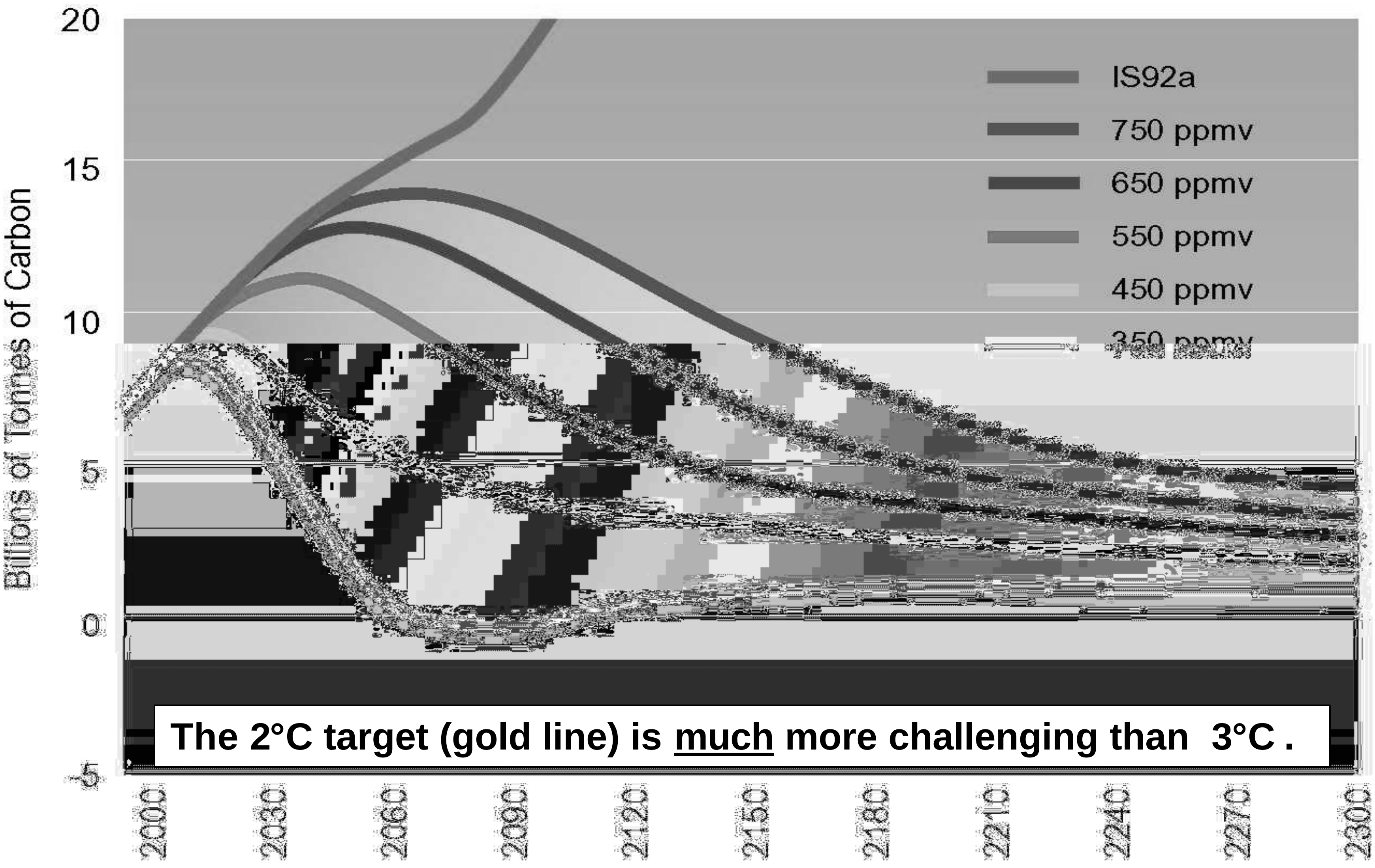
Nuclear-energy challenges (continued)

- If half the reactors were recycling their plutonium…
  - the associated flow of separated, directly weapon-usable plutonium would be 170,000 kg per year;
  - diversion of 0.1% of this quantity would make ~30 implosion-type bombs.
- Spent-fuel production in the once-through case would be…
  - 34,000 tonnes/yr, a Yucca Mountain every two years.

Conclusion: Expanding nuclear enough to take a modest bite out of the climate problem is conceivable, but doing so will depend on greatly increased seriousness in addressing the waste-management & proliferation challenges.

The CO_2 emissions challenge in summary

Emissions trajectories consistent with stabilizing atmospheric CO_2 at various levels (2005 = 380 ppmv)



The 2°C target (gold line) is <u>much</u> more challenging than 3°C .

Thought experiment: How much carbon-free energy needed to stabilize CO_2 at 550 ppm_v?

Carbon-free energy in 2000 (from renewables and nuclear energy) ~ 100 exajoules/year. (Fossil fuels ~ 350 EJ/yr)

With BAU economic growth, the future need for C-free energy (renewables, nuclear, & advanced fossil with CO_2 sequestration) depends on rate of improvement of energy efficiency as follows:

C-free energy (exajoules) in	2050	2100
	------	-------
E/GDP falls 1%/yr (BAU)	600	1500
E/GDP falls 1.5%/yr	350	800
E/GCP falls 2.0%/yr	180	350

Options besides reducing CO_2 emissions

Reducing emissions of methane & soot

- Anthropogenic methane (CH_4) comes 30% from energy systems, 30% from livestock, 25% from agriculture, 15% from landfills & waste treatment.
  - Technical means exist for reducing all of these.
  - Methane's relatively short atmospheric lifetime means emissions reductions translate quickly into reduced concentrations, thus reduced forcing.
- Soot comes from 2-stroke & diesel engines as well as from trad'l uses of biomass fuels, agricultural burning, and forest fires.
  - The engine and biomass fuels emissions are amenable to sharp reduction by technical means.
  - The very short atmospheric lifetime of soot (days to weeks) means emissions reductions translate quickly into reduced forcing.

Removal of GHG from the atmosphere

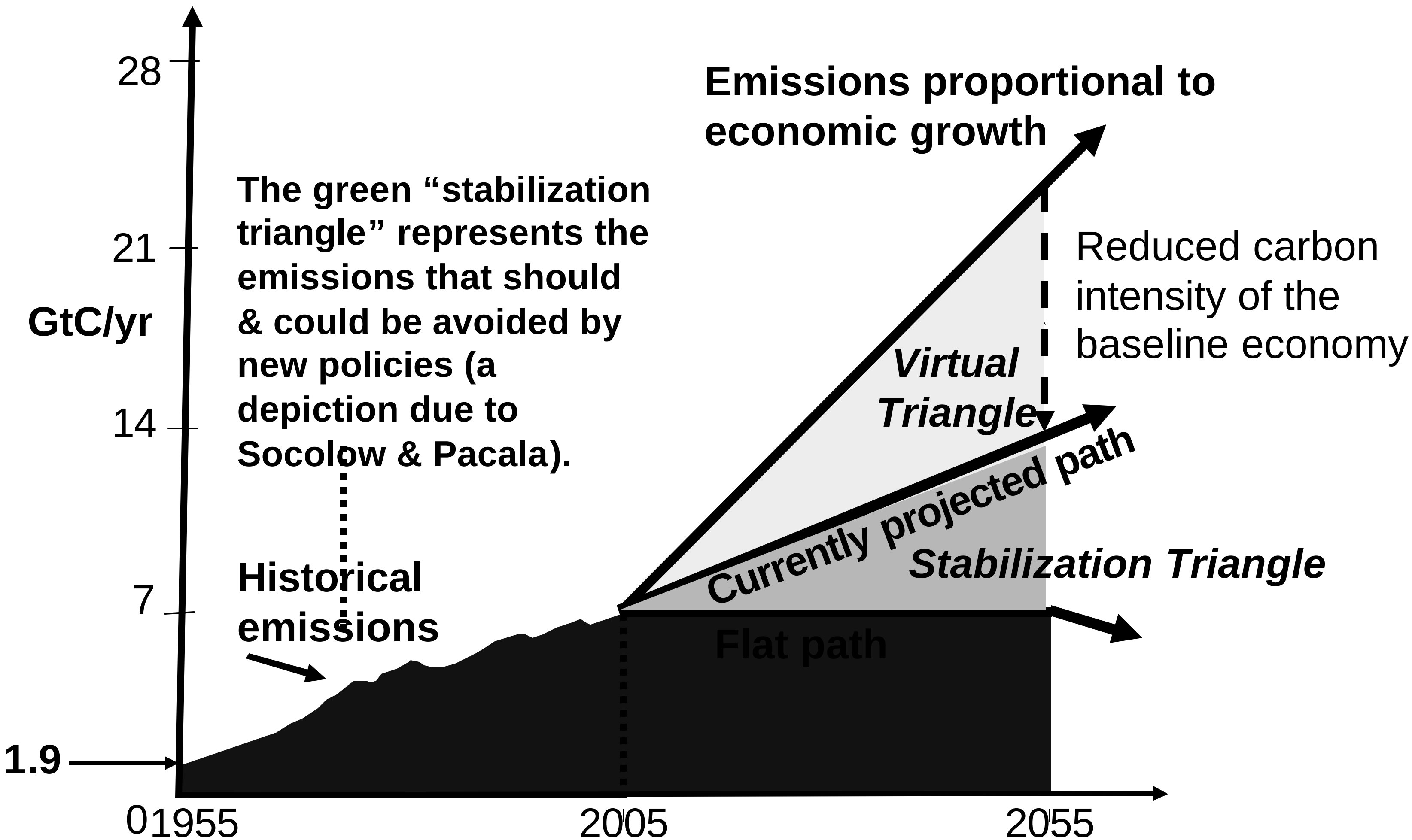
- Increasing carbon storage in terrestrial plants & soils is the biggest possibility in this category.
  - Techniques are afforestation, reforestation, avoided deforestation, improved management of agricultural soils.
  - IPCC 3rd Assessment optimistically estimated total potential of 100 billion tonnes C uptake by 2050 (~20% of BAU emissions)
- Ocean fertilization to increase carbon uptake by phyto-plankton currently looks questionable both in terms of efficacy and in terms of undesired side effects.
- "Scrubbing" CO2 out of the atmosphere technologically appears to be 5-10 times more costly than capturing it before emission at power plants.

Geo-engineering to counter GHG forcing

- Increasing surface reflectivity to cool the Earth
  - Humans have done this inadvertently by deforestation, desertification, but more is undesirable.
  - Reflectivity of man-made surfaces (buildings, roads) can be increased, but global impact is limited by small fraction of land surface used for these purposes (~2%).
  - Large-scale alteration of reflectivity of oceans would be expected to have undesired climatological & ecological side effects.
- Increasing the atmosphere's reflectivity by injecting reflecting particles into the stratosphere might be reversible & affordable, but would be likely to deplete stratospheric ozone.
- Placing reflecting materials or mirrors in Earth orbit (or at the Lagrangian equilibration point between the Sun and the Earth) would be staggeringly expensive.

Thinking about a portfolio of measures

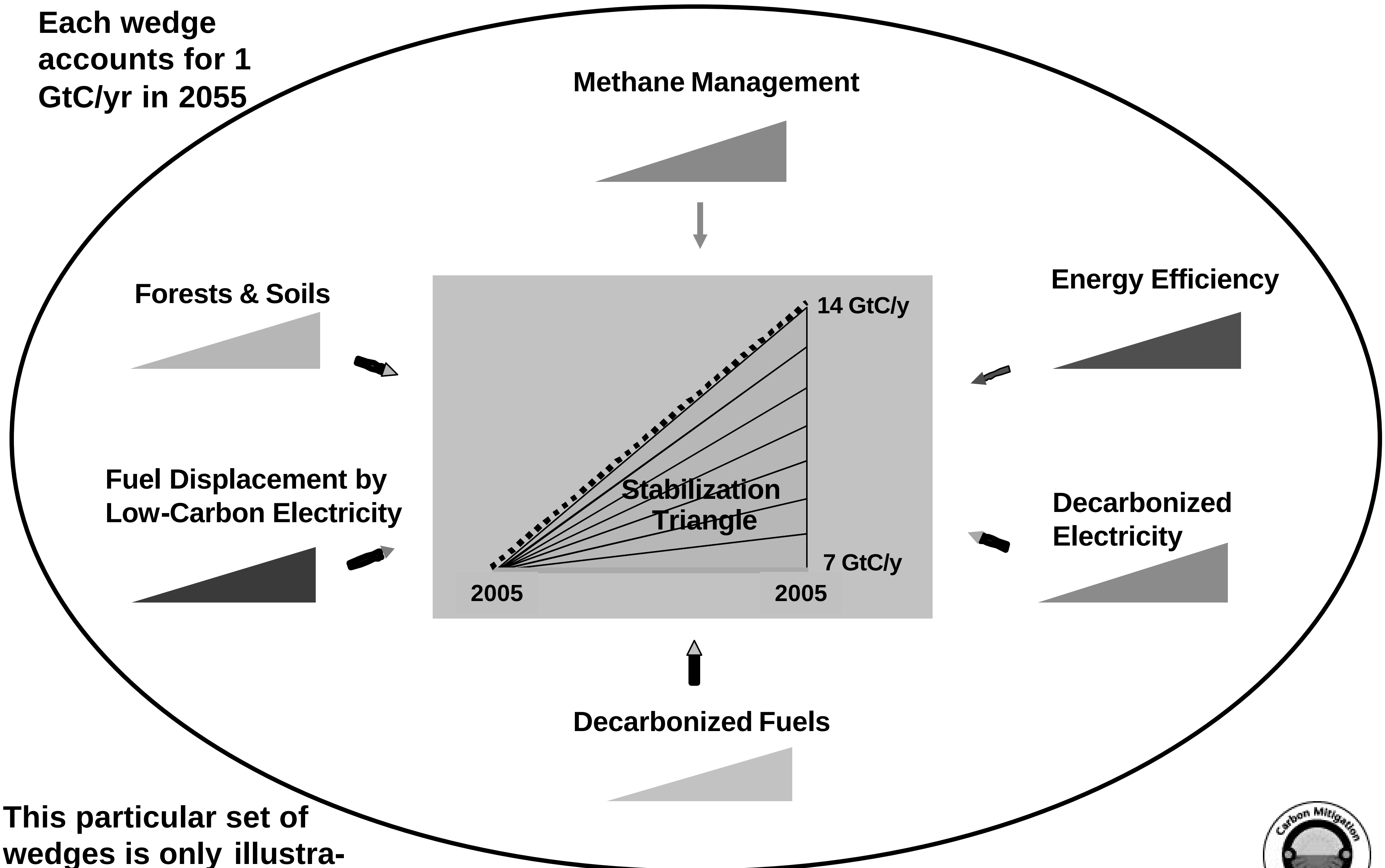
Stabilizing at 450-500 ppmv would be possible if emissions were flat for ~50 years, then declined.



The virtual triangle results more from structural shifts in the economy (toward services) and less from the carbon-saving activity required to fill the stabilization triangle.

The triangle can be filled by a portfolio of 7 wedges

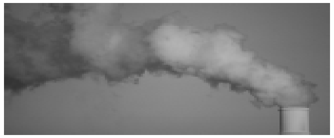
Each wedge accounts for 1 GtC/yr in 2055



This particular set of wedges is only illustrative, not prescriptive.

Fifteen example wedges

CO_2 Capture & Storage (CCS)



CO_2 capture:

1. Introduce CCS at 800 GW coal or 1600 GW natural gas plants (1100 GW coal today)
2. Introduce CCS at plants producing 250 MtH_2/yr from coal or 500 MtH_2/yr from natural gas (40 MtH_2/yr today)
3. Introduce CCS at synfuels plants producing 30 mbd from coal (200x Sasol)

H_2 safety, infrastructure

Geologic storage:
Create 3500 Sleipners

Durable storage

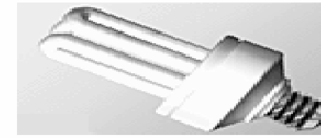
Wind and Solar

4. Add 2 million 1-MW-peak windmills (50 times current level) on 30 Mha, displacing coal electricity
5. Add 2000 GW-peak PV plants (700 times current level) on 2 Mha, displacing coal electricity

6. Add 4 million windmills or 4000 GW-peak PV plants generating 200 MtH_2/yr, displacing gasoline hybrid cars

Energy storage, H_2 safety, infrastructure
PV production cost

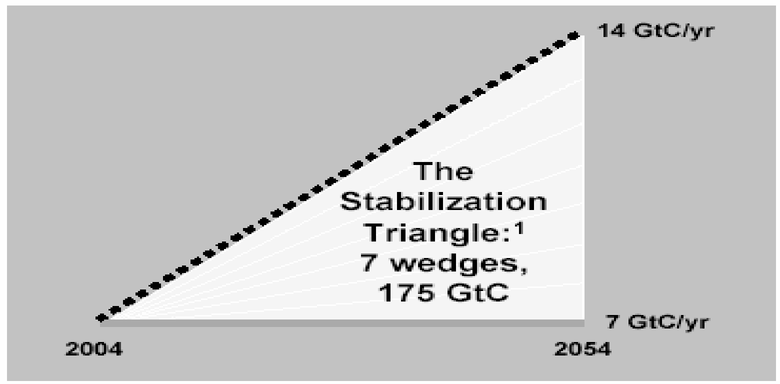
Energy Efficiency & Conservation



Increase economy-wide emissions/GDP reduction by additional 0.15%/yr (e.g. increase US goal of 1.96%/yr to 2.11%/yr):

8. Increase fuel economy for 2 billion cars from 30 to 60 mpg
9. Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5,000 miles/yr
10. Cut carbon emissions in buildings/appliances by 1/4 over 2054 projection
11. Produce twice today's coal output at 60% efficiency instead of 40% (compare with 32% today)

Weak incentives, urban design, lifestyle changes

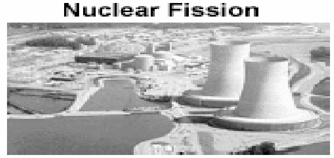


Forests & Soils

14. Decrease tropical deforestation to zero instead of 0.5 GtC/yr, and establish 300 Mha of new tree plantations (twice current level)
15. Implement conservation tillage on all cropland (10 times current level)

Competing land use, verification, reversibility

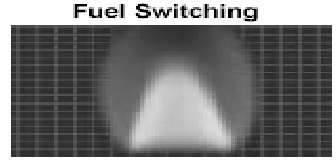
Nuclear Fission



13. Add 700 GW nuclear plants (compare with 350 GW today) replacing coal

Nuclear proliferation, terrorism, waste

Fuel Switching



12. Replace 1400 GW coal plants with natural gas plants (compare with 350 GW natural gas today)

Competing demands for natural gas

Biomass Fuel

7. Add 50 times current US and Brazil ethanol production on 250 Mha (1/6 world cropland)

Biodiversity, competing land use

Beyond 2054

More wedges will be needed to maintain the trajectory established by the stabilization triangle, and scaling up the above technologies are unlikely to be enough to satisfy growing energy demand. Therefore, it is imperative that advanced technologies, including **artificial photosynthesis, satellite solar power, nuclear fusion,** and **geoengineering strategies** be developed now,[3] so that the second and subsequent "runners" have the necessary tools to do their jobs.

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Policy Options

Policy options for promoting mitigation

Measures to affect choices among available technologies

- analysis of and education about the options
- correction of perverse incentives
- lowering bureaucratic barriers
- financing for targeted options
- performance & portfolio standards
- subsidies for targeted options
- emission cap & trade programs
- taxes on carbon or energy

These are listed in order of increasing intrusiveness & political difficulty. But combinations that don't include one of the last two will not be sufficient.

Measures to improve mix of available technologies

- improving capabilities for RD&D
- encouraging RD&D with tax policy & other policies
- funding the conduct of RD&D
- promoting niche & pre-commercial deployment
- international transfer of resulting technologies

Policy options embraced to date

- The Kyoto Protocol
  - a landmark as a negotiated global commitment to move forward to address the problem
  - but limited in time frame, magnitude of required reductions, and participation
- The EU carbon trading system
  - implemented starting in January 2005, embracing 12,000 installations accounting for almost half of EU carbon emissions
  - C trading price reached $100/tC, but has recently fallen amid loss of confidence about monitoring, cheating
- Non-federal jurisdictions in the United States
  - USA has not ratified Kyoto; federal climate policy consists only of research, incentives, and modest “voluntary” targets.
  - But 28 states have climate-action plans, 21 have renewable portfolio standards, and many corporations are acting.
  - US Senate endorsed mandatory, national GHG restraints in 6/05.

Sense of the Senate Resolution, 6-22-05

It is the sense of the Senate that Congress should enact a comprehensive and effective national program of mandatory, market-based limits and incentives on emissions of green-house gases that slow, stop, and reverse the growth of such emissions at a rate and in a manner that--

(1) will not significantly harm the United States economy; and

(2) will encourage comparable action by other nations that are major trading partners and key contributors to global emissions.

Corporate Commitments and Results

BP: 10% reduction, $650 million saved

DuPont: 69% reduction, $2 billion saved

Lafarge: 10% reduction, "It's made us more competitive"

Cinergy: 5% reduction

Entergy: Absolute cap

Alcan: 10% reduction

3M: 35% reduction, $200 million saved

Toyota: 19% reduction

Suncor Energy: 6% reduction

IBM: 65% reduction, $791 million saved

GM: 72% reduction

Alcoa: 25% reduction, $100 million saved

Shell: 9% reduction

United Technologies: 37% reduction

Nike: 13% reduction

Kodak: 17% reduction

GE: 1% reduction, $1.5 billion clean tech R&D

Polaroid: 25% reduction

Policy recommendations (my own)

- Pursue a new global framework for mitigation and adaptation in the post-Kyoto period

    It must include mandatory, economy-wide reductions in GHG emissions below BAU everywhere, and it needs to be equitable, achievable, and adequate to the magnitude of the challenge.

- Pursue "win-win" technical and policy measures

    Pursue most vigorously those measures that address economic, social, and non-climate environmental goals as well as climate.

- Increase investments in energy-technology innovation

    A tripling to quadrupling of government investments is warranted worldwide, along with increased incentives for innovation in the private sector.

- Expand international cooperation on energy-technology innovation

    Cooperation is needed to reduce costs & spread benefits in implementing climate-friendly technologies in the interest of the whole world.

Can we get it done? The role of public opinion

Public opinion on climate change (2003-4)

TABLE 1. Responses To "Many Scientists Believe that Human Activities, Such as Burning Fossil Fuels to Drive Cars and Generate Electricity, Are Causing the Earth's Atmosphere to Warm Somewhat. There are Many Ways that [My Country] May Respond to this Situation. Which of the Following Statements Comes Closest to Your Opinion?"

Answer	United States	United Kingdom	Sweden	Japan
I believe that firms and government researchers will develop new technologies to solve the problem.	21	26	37	22
I believe we will have to change our lifestyles to reduce energy consumption.	32	27	22	66
I believe we will learn to live with and adapt to a warmer climate.	17	13	19	4
I believe global warming is a problem but [my country] won't do anything about it.	24	21	14	6
I believe we will do nothing since global warming is not a problem.	7	3	2	NA
Not sure	NA	10	6	2

D. M. Reiner et al., ES&T, February 2006

Only 7% of Americans think climate change is not a problem. We can get this done!

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