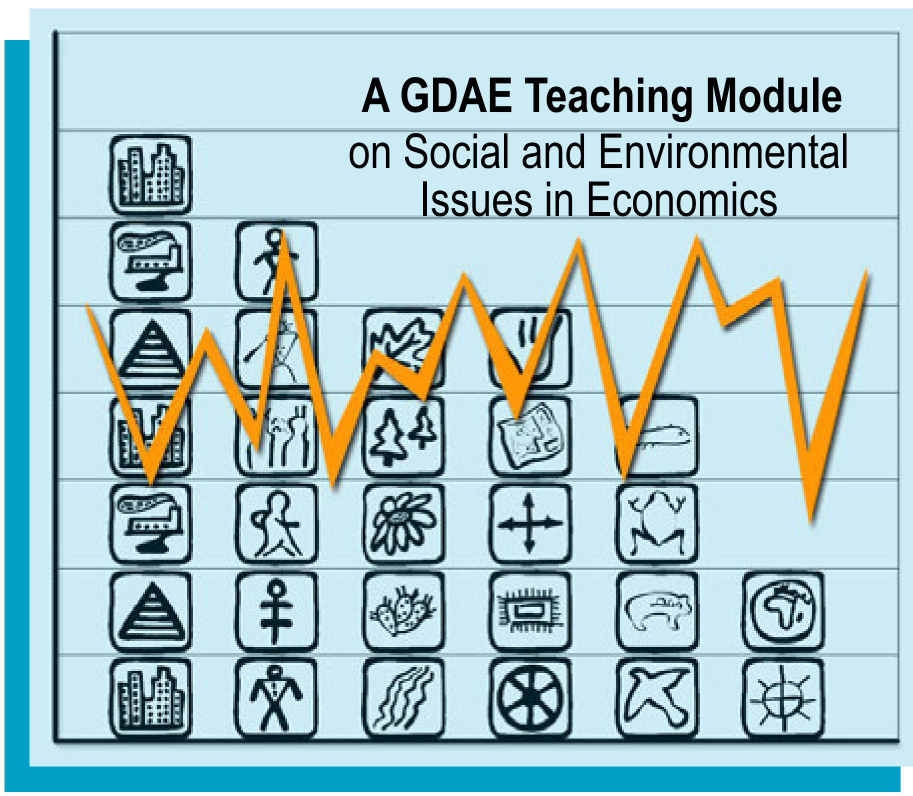
The Economics of Global Climate Change

by Jonathan M. Harris,
Brian Roach and Anne-Marie Codur



Global Development And Environment Institute
Tufts University
Medford, MA 02155
http://ase.tufts.edu/gdae

Students may also download the module directly from
http://www.ase.tufts.edu/gdae/education_materials/modules.html

Comments and feedback from course use are welcomed:
Global Development And Environment Institute
Tufts University
Medford, MA 02155
http://ase.tufts.edu/gdae

E-mail: gdae@tufts.edu

NOTE – terms denoted in **bold face** are defined in the **KEY TERMS AND CONCEPTS** section at the end of the module.

This module is based is based on Chapters 18 and 19 of Harris and Roach, *Environmental and Natural Resource Economics: A Contemporary Approach (2014).*

Table of Contents

1. CAUSES AND CONSEQUENCES OF CLIMATE CHANGE 3

Trends and Projections for Global Carbon Emissions 6

Trends and Projections for Global Climate 10

2. ECONOMIC ANALYSIS OF CLIMATE CHANGE 16

Cost-Benefit Studies of Global Climate Change 19

3. ANALYZING LONG-TERM EFFECTS OF CLIMATE CHANGE 25

Climate Change and Inequality 28

4. POLICY RESPONSES TO CLIMATE CHANGE 29

Economic Policy Options: Carbon Taxes 31

Economic Policy Options: Tradable Permits 35

Other Policy Tools: Subsidies, Standards, R&D, and Technology Transfer 38

The Technical Challenge 40

Climate Change Policy in Practice 43

The Future of Climate Change Policy 48

5. SUMMARY 50

KEY TERMS AND CONCEPTS 51

REFERENCES 53

DISCUSSION QUESTIONS 56

EXERCISES 57

WEB LINKS 58

THE ECONOMICS OF GLOBAL CLIMATE CHANGE

1. CAUSES AND CONSEQUENCES OF CLIMATE CHANGE

Global climate change[1] is a major issue confronting policymakers worldwide. In terms of economic analysis, **greenhouse gas** emissions, which cause planetary climate changes, represent both an environmental **externality** and the overuse of a **common property resource.**

Recent statements by the U.S. Global Research Program and the American Geophysical Union indicate the widespread scientific acceptance of the reality of climate change:

> Evidence for climate change abounds, from the top of the atmosphere to the depth of the oceans. Scientists and engineers from around the world have meticulously collected this evidence, using satellites and networks of weather balloons, observing and measuring changes in location and behaviors of species and functioning of ecosystems. Taken together, this evidence tells an unambiguous story: the planet is warming, and over the half century, this warming has been driven primarily by human activity.
>
> - U.S. Global Change Research Program, Third National Climate Assessment, May 2014 – Overview and Report Findings, p.7.

> Humanity is the major influence on the global climate change observed over the past 50 years. Rapid societal responses can significantly lessen negative outcomes.
>
> - American Geophysical Union, 2013.

The atmosphere is a **global commons** into which individuals and firms can release pollution. Global pollution creates a "public bad" born by all -- a negative externality with a wide impact. In many countries environmental protection laws limit the release of local and regional air pollutants. In these situations, in economic terminology, the negative externalities associated with local and regional pollutants have to some degree been internalized. But, until recently, few controls existed for carbon dioxide (CO_2), the major greenhouse gas. This global air pollutant has no short-term damaging effects at ground level, but atmospheric accumulations of carbon dioxide and other greenhouse gases will have significant effects on global temperature and weather, although there is uncertainty about the probable scale and timing of these effects (See Box 1).

In a 2013 report, the Intergovernmental Panel on Climate Change (IPCC) emphasized that "Warming of the climate system is unequivocal, and since the1950s, many observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished,

[1] The issue, often called global warming, is more accurately referred to as global climate change. The phenomenon will produce complex effects – with warming in some areas, cooling in others, and generally increased variability in weather patterns.

sea level has risen, and the concentrations of greenhouse effects have increased". The report clearly attributes this phenomenon to human-made causes by asserting that "the largest contribution is caused by the increase in the atmospheric concentration of CO_2". They project a temperature change by 2100 of between 1.5°C (2.7F) and 4.8°C (8.6F).

If indeed the effects of climate change are likely to be severe, it is in everyone's interest to lower their emissions for the common good. If no agreement or rules on emissions exist, actions by individual firms, cities or nations will be inadequate. Climate change can thus be viewed as a **public good** issue, requiring collaborative action. Since the problem is global, only a strong international agreement binding nations to act for the common good can prevent serious environmental consequences.

Because CO_2 and other greenhouse gases continuously accumulate in the atmosphere, stabilizing or "freezing" emissions will not solve the problem. Greenhouse gases persist in the atmosphere for decades or even centuries, continuing to affect the climate of the entire planet long after they are emitted. Greenhouse gases are **stock pollutants**: only major reductions in emissions, to a level consistent with the planet's absorptive capacity will prevent ever-increasing atmospheric accumulations. Current estimates of the planet's absorptive capacity are about 20-50% of current human-caused emissions of carbon, implying that a reduction of at least 50-80% is needed.[2] The development of national and international policies to combat global climate change is a huge challenge, involving many scientific, economic, and social issues.

[2] According to the 2010 World Development Report, human-caused carbon emissions in 2007 totaled about 9 Gt (Billion Tons) of carbon. Of this amount, oceans and terrestrial systems can take up about 3.4 Gt of carbon a year. (World Bank, 2010). Since oceanic stocks of carbon have already increased significantly, leading to ocean acidification, absorption capacity for the future may be lower.

BOX 1: WHAT IS THE GREENHOUSE EFFECT?

The sun's rays travel through a greenhouse's glass to warm the air inside, but the glass acts as a barrier to the escape of heat. Thus plants that require warm weather can be grown in cold climates. The global greenhouse effect, through which the earth's atmosphere acts like the glass in a greenhouse, was first described by French scientist Jean Baptiste Fourier in 1824.

Clouds, water vapor, and the natural greenhouse gases carbon dioxide (CO_2), methane, nitrous oxide, and ozone allow inbound solar radiation to pass through, but serve as a barrier to outgoing infrared heat. This creates the natural **greenhouse effect**, which makes the planet suitable for life. Without it, the average surface temperature on the planet would average around -18° C (0ºF), instead of approximately 15°C (60º F).

The possibility of an *enhanced* or *human-induced* greenhouse effect was introduced one hundred years ago by the Swedish scientist Svante Arrhenius. He hypothesized that the increased burning of coal would lead to an increased concentration of carbon dioxide in the atmosphere, and would warm the earth. Since Arrhenius' time greenhouse gas emissions have grown dramatically. Carbon dioxide concentrations in the atmosphere have increased by over 40% above pre-industrial levels.[1] In addition to increased burning of fossil fuels such as coal, oil and natural gas, synthetic chemical substances such as chlorofluorocarbons (CFCs) as well as methane and nitrous oxide emissions from agriculture and industry contribute to the greenhouse effect. When the contribution of other greenhouse gases is included, the overall effect is equivalent to a concentration of almost 450 ppm of CO_2, referred to as CO_2e.[1]

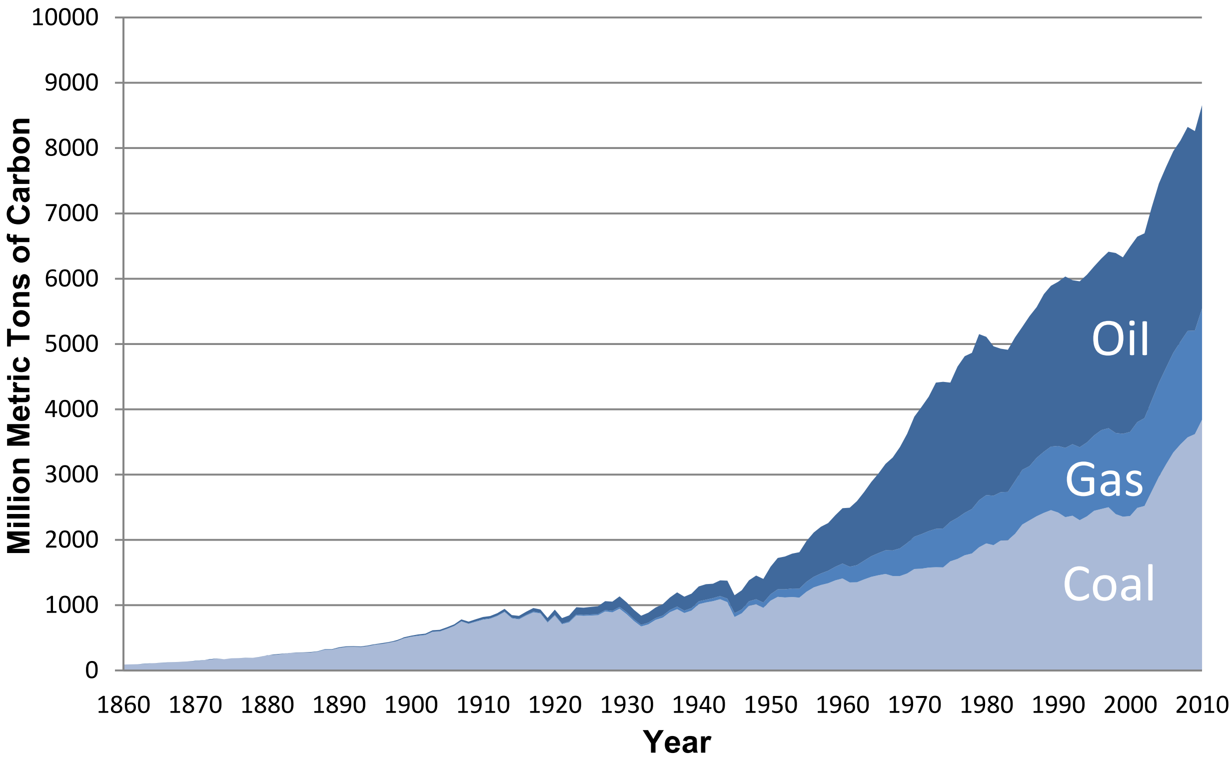
Scientists have developed complex computer models that estimate the effect of current and future greenhouse gas emissions on the global climate. While considerable uncertainty remains in these models, virtually all scientists agree that the human-induced greenhouse effect poses a significant threat to the global ecosystem. The Intergovernmental Panel on Climate Change (IPCC) projects continued temperature increases, ice sheet melting, and sea-level rise, and states that "most aspects of climate change will persist for many centuries even if emissions of CO_2 are stopped. This represents a substantial multi-century climate change commitment created by past, present and future emissions of CO_2."

Sources: Cline, 1992; Fankhauser, 1995; IPCC 2013.

Trends and Projections for Global Carbon Emissions

Global emissions of carbon dioxide from the combustion of fossil fuels rose dramatically during the 20th century, as illustrated in Figure 1. The use of liquid fuel (primarily oil) is currently responsible for about 35% of global carbon emissions from fossil fuels, while solid fuel (coal) is the source of another 40% and combustion of natural gas accounts for 18%. China surpassed the US in 2006 as the largest carbon emitter in the world. In 2012, China released about 27% of global carbon emissions, followed by the US with about 14.5% and by the 28 countries of the European Union with 10%.[3]

Figure 1. Carbon Emissions from Fossil Fuel Consumption, 1860-2010

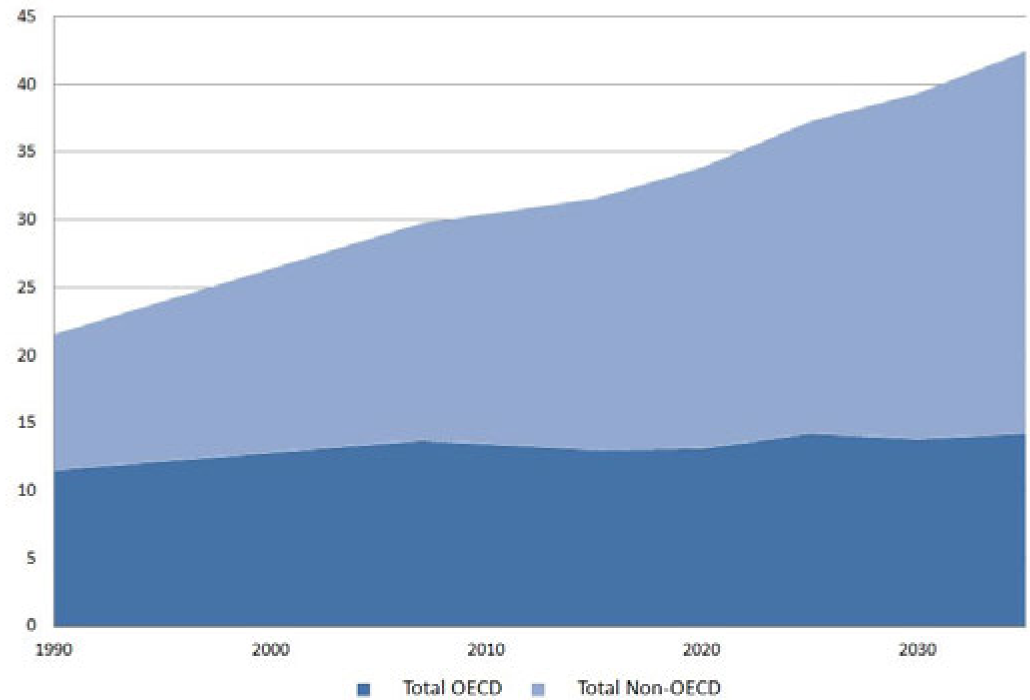


Source: Carbon Dioxide Information Analysis Center (CDIAC), http://cdiac.ornl.gov/trends/trends.html , accessed April 2013

Progress on combating global climate change has been slow, despite many global conferences dealing with the issue—including the 1992 United Nations Conference on Environment and Development (UNCED) at Rio de Janeiro; a 1997 meeting in Kyoto, Japan that produced the agreement known as the Kyoto Protocol; the World Summit on Sustainable Development in 2002; the Copenhagen Conference in 2009; and conferences in Cancun, Durban, Doha, Warsaw, and Lima in 2010-2014.(For a detailed list of climate conferences, accomplishments and failures see Box 2). Current projections show carbon emissions continuing to increase in the future. (see Figure 2).

3 Data from Global Carbon Atlas http://www.globalcarbonatlas.org/?q=emissions

Figure 2. Projected Carbon Dioxide Emissions through 2030, by Region (Million Metric Tons of CO2)



Source: U.S. Department of Energy, 2011. The vertical axis in Figure 2 measures million metric tons of carbon dioxide whereas the vertical axis in Figure 1 showed million metric tons of carbon; the weight of a given amount of emissions measured in tons of carbon dioxide is about 3.67 times the total weight in carbon.
Note: The Organization for Economic Co-operation and Development (OECD) is an organization of mostly developed countries committed to democracy and the market economy. Members of the OECD include many of the world's most advanced countries but also some emerging countries like Mexico, Chile and Turkey. See list of 34 countries members of OECD here: http://www.oecd.org/about/membersandpartners/list-oecd-member-countries.htm

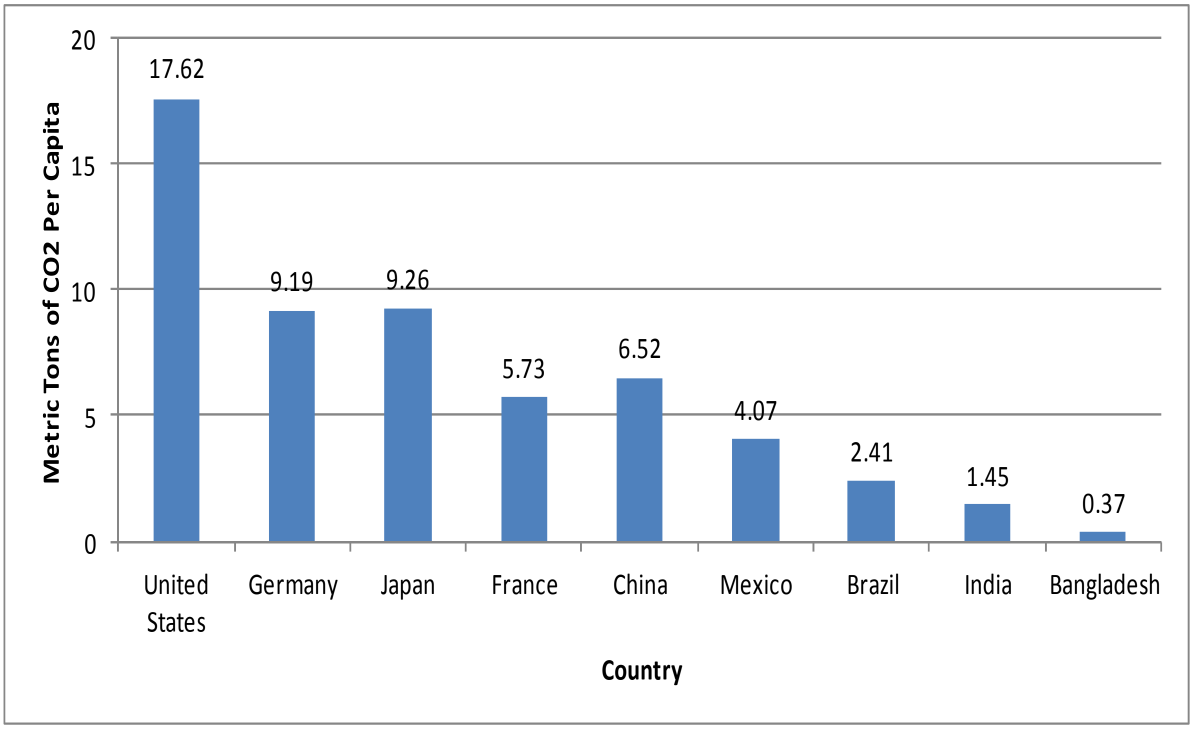
As Figure 2 shows, the growth in carbon emissions is expected to continue in the coming decades. According to the U.S. Energy Information Administration, global CO_2 emissions are projected to increase by approximately 71% between 2005 and 2035.[4] These projections are for the U.S.E.I.A.'s "reference case", which assumes business as usual (BAU), with no major efforts to reduce carbon emissions. As we will see, strong polices to shift away from carbon-based fuels could alter these projections.

As of 2012, the industrialized countries (members of OECD) were responsible for 35% of global carbon emissions[5]. As seen in Figure 2 most of the growth in future carbon emissions is expected to come from rapidly expanding developing economies such as China and India. For example, CO_2 emissions in China are projected to grow by 143% between 2005 and 2035.[6]

[4] Adapted from US Energy Information Administration, 2011, available at http://www.eia.gov/analysis/projection-data.cfm#intlproj
[5] Data: http://www.globalcarbonatlas.org/?q=emissions
[6] Data from US Energy Information Administration, 2011, available at http://www.eia.gov/analysis/projection-data.cfm#intlproj

Although carbon emissions are projected to grow fastest in developing nations, per-capita emissions in 2035 will still be much higher in the industrialized countries - they are about six times higher in 2013, as shown in Figure 3. The developing nations argue that they should not be required to limit their emissions while the industrial nations continue to emit so much more on a per-capita basis. The global imbalance in per-capita emissions is a critical issue that has yet to be adequately addressed in the policy debate on global climate change, and disagreement on this issue of relative responsibilities has accounted for much of the deadlock at global climate talks (see Box 2).

Figure 3. Per-Capita Emissions of Carbon Dioxide by Country



Source: U.S. Energy Information Administration, Accessed April 2013.

BOX 2: BRIEF HISTORY OF INTERNATIONAL CLIMATE NEGOTIATIONS

Year, Location	Outcome
1992, Rio de Janeiro	Negotiations start with completion of U.N. Framework Convention on Climate Change (UNFCCC). Countries agree to voluntarily reduce emissions with "common but differentiated responsibilities."
1995, Berlin	The first annual Conference of the Parties to the framework, known as a "COP." U.S. agrees to exempt developing countries from binding obligations.
1997, Kyoto	COP-3 diplomats approve the Kyoto Protocol. Mandates developed countries to cut greenhouse gas emissions relative to baseline emissions by 2008-2012 period.
2000, The Hague	Outgoing Clinton administration and Europeans differ on some COP-6 terms, mainly over credit for carbon sinks such as agriculture and forests. Talks collapse.
2001, Bonn	A second session of the COP-6 talks works out terms for compliance and financing. The Bush administration had rejected the Kyoto Protocol and the U.S. was only an observer to the talks.
2004, Buenos Aires	U.S. blocks formal negotiations on post-Kyoto treaty. COP-10 diplomats try informal talks.
2007, Bali	COP-13 diplomats approve schedule for post-Kyoto negotiations to end in 2009.
2009, Copenhagen	COP-15 fails to produce a binding post-Kyoto agreement. Instead, the Copenhagen Accord declares the importance of limiting warming to under 2°C, yet without any binding targets. Developed countries pledge to provide financing to developing countries of $30 billion annually, rising to $100 billion by 2020.
2010, Cancun	Nations meet to work out details of the “Green Climate Fund” agreed to in Copenhagen.
2011, Durban	COP-17 participating countries agreed to adopt a universal legal agreement on climate change as soon as possible, and no later than 2015, to take effect by 2020.
2012, Doha; 2013, Warsaw; 2014, Lima; December 2015, Paris	COP-18 through COP-20 agree to extend the life of the Kyoto protocol, and in principle to commit all countries to emissions cuts, but without any binding agreement. COP-21 in Paris in 2015 is considered to be the “Summit of the last chance” for a binding agreement[7]

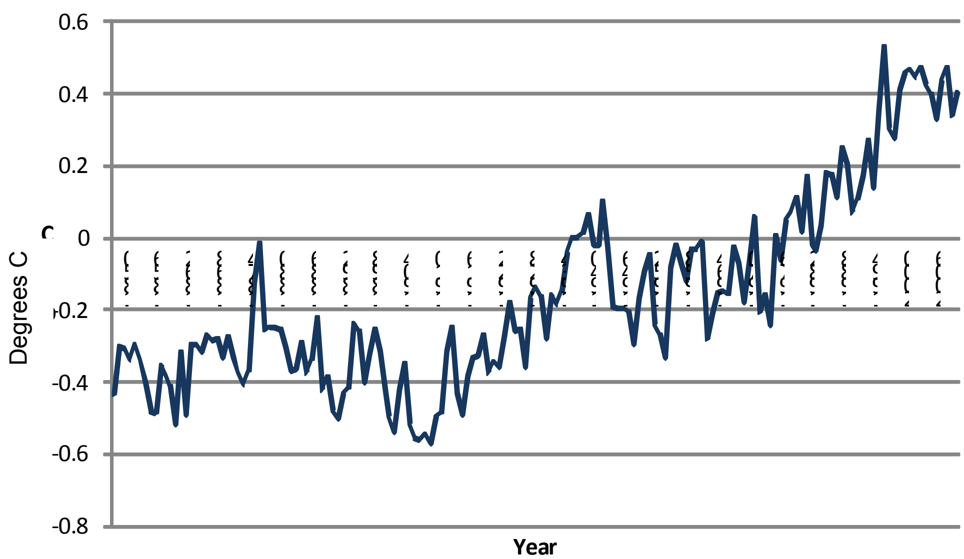
Sources: Adapted from ClimateWire, Environment & Energy Publishing (E&E), http://www.eenews.net/ , retrieved in 2011; United Nations Framework on Climate Change (UNFCC) http://unfccc.int/2860.php

[7] See Jeffrey Sachs, “Our last chance for a safe planet” at http://www.project-syndicate.org/commentary/jeffrey-d-sachs-warns-that-the-un-s-climate-change-conference-in-paris-in-2015-must-not-be-allowed-to-fail

Trends and Projections for Global Climate

The earth has warmed significantly since reliable weather records have been kept (Figure 4). Over the last 100 years the global average temperature has risen about 0.7°C, or about 1.3°F. Nine of the ten warmest years in the modern meteorological record have occurred since the year 2000.[8] Each of the last three decades (1980s, 1990s, 2000s) has been successively warmer at the Earth's surface than any preceding decade since 1850. In the Northern hemisphere, 1983-2012 was likely the warmest 30-year period of the last 1400 years. The year 2014 was recorded as the hottest year since record-keeping began in 1880, according to the National Oceanic and Atmospheric Administration (NOAA). Ocean and land temperatures rose over 1 degree Fahrenheit above the 20th century average.[9]

Figure 4: Global Annual Temperature Anomalies (degrees C), 1850-2012



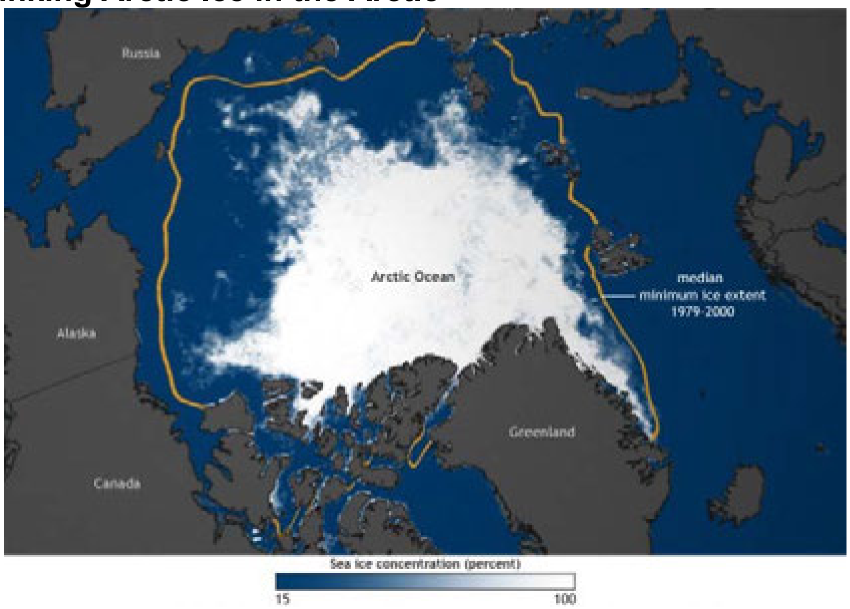
Source: Carbon Dioxide Information Analysis Center; CDIAC, accessed April 2013, http://cdiac.ornl.gov/ftp/trends/temp/jonescru/global.txt
Note: The zero baseline represents the average global temperature from 1961-1990.

There is also evidence that the rate of warming, currently about 0.13°C per decade, is increasing[10]. Not all areas are warming equally. The Arctic and Antarctic regions have been warming at about double the global rate.[11] The melting of the Artic has been accelerating at a rapid rate in the last decade. Melting ice in the Arctic is not only a result of global warming, but a cause of further warming, since open ocean

[8] NASA Goddard Institute for Space Studies, Jan 19, 2012. http://www.giss.nasa.gov/research/news/20120119/.
[9] Justin Gillis, "2014 Breaks Heat Record, Challenging Global Warming Skeptics," *New York Times*, Jan. 16, 2015.
[10] Adapted from US EPA, accessed 2011, available at http://www.epa.gov/climatechange/science/recenttc.html , also from IPCC 2013.
[11] IPCC, 2007, working group I: The Physical Science Basis.

reflects less sunlight than ice cover, absorbing more of the sun's energy rather than reflecting it back, a phenomenon known as reduced albedo (see Figure 5).[12]

Figure 5: Shrinking Arctic Ice in the Arctic



Source: http://thinkprogress.org/climate/2014/02/18/3302341/arctic-sea-ice-melt-ocean-absorbs-heat/.
Figure is based on data from the National Snow and Ice Data Center. Credit: Climate.gov.

> The Intergovernmental Panel on Climate Change (IPCC) in 2013 concluded that Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. This evidence for human influence has grown. It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century. (IPCC, 2013, Summary for policymakers, p. 15)

Warmer temperatures have produced noticeable effects on ecosystems. In most regions of the world, glaciers are retreating. For example, it has been estimated that there were approximately 150 glaciers when the Glacier National Park was established in Montana in 1910. In 2010, there were only 25 glaciers larger than 25 acres remaining and by 2030 it is estimated that the park will no longer have any of its namesake glaciers.[13]

Climate change is also leading to rising sea levels. Sea-level rise is attributed to the melting of glaciers and ice sheets, and to the fact that water expands when it is heated. The oceans warmed, on average, about 0.1°C between 1961 and 2003. The combination of warmer oceans and melting ice has led to sea levels rising at about two millimeters per year (See Box 3).

[12] Ari Phillips, "Melting Ice Makes the Arctic a Much Worse Heat Magnet than Scientists Feared," http://thinkprogress.org/climate/2014/02/18/3302341/arctic-sea-ice-melt-ocean-absorbs-heat/
[13] http://nrmsc.usgs.gov/research/glacier_retreat.htm

BOX 3: PACIFIC ISLANDS DISAPPEAR AS OCEANS RISE

Two islands in the Pacific Ocean nation of Kiribati—Tebua Tarawa and Abanuea—have disappeared as a result of rising sea level. Others, both in Kiribati and in the neighboring island nation of Tuvalu, are nearly gone. So far the seas have completely engulfed only uninhabited, relatively small islands, but the crisis is growing all around the shores of the world's atolls. Scientists estimate the current sea level rise in the Pacific at about 2 millimeters per year, and expect that rate to accelerate due to climate change.

Populated islands are already suffering. The main islands of Kiribati, Tuvalu, and the Marshall Islands (also in the Pacific) have suffered severe floods as high tides demolish sea walls, bridges and roads, and swamp homes and plantations. Almost the entire coastline of the 29 Marshall Islands atolls is eroding. World War II graves on its main Majuro atoll are washing away, roads and subsoils have been swept into the sea, and the airport has been flooded several times despite the supposed protection of a high sea wall.

The people of Tuvalu are finding it difficult to grow their crops because the rising seas are poisoning the soil with salt. In both Kiribati and the Marshall Islands families are desperately trying to keep the waves at bay by dumping trucks, cars and other old machinery in the sea and surrounding them with rocks. The situation is so bad that the leaders of Kiribati are considering a plan to move the entire nation of 103,000 people to Fiji. Some villages have already moved.

It is much the same story far away in the Maldives. The Indian Ocean is sweeping away the beaches of one-third of its 200 inhabited islands. "Sea-level rise is not a fashionable scientific hypothesis," says President Gayoom. "It is a fact."

The seas are rising partly because global warming is melting glaciers and nibbling away at the polar ice caps, but mainly because the oceans expand as their water warms. Scientists' best estimate is that these processes will raise sea levels by about 1.5 feet over the next century, quite enough to destroy several island nations.

The higher the seas rise, the more often storms will sweep the waves across the narrow atolls carrying away the land—and storms are expected to increase as the world warms up. Many islands will become uninhabitable long before they physically disappear, as salt from the sea contaminates the underground freshwater supplies on which they depend.

Adapted from: Lean, Geoffrey "They're Going Under; Two Islands Have Disappeared Beneath the Pacific Ocean—Sunk by Global Warming," *The Independent*, June 13, 1999, p. 15 (Used with permission of *The Independent*); "Kiribati Global Warming Fears: Entire Nation May Move to Fiji," Associated Press, March 12, 2012.

In addition to rising ocean temperatures, increased CO_2 in the atmosphere results in **ocean acidification**. According to the U.S. National Oceanic and Atmospheric Administration, "around half of all carbon dioxide produced by humans since the Industrial Revolution has dissolved into the world's oceans. This absorption slows down global warming, but it also lowers the oceans pH, making it more acidic. More acidic water can corrode minerals that many marine creatures rely on to build their protective shells and skeletons."[14]

A recent report in *Science* magazine finds that the oceans are turning acidic at what may be the fastest pace in 300 million years, with potential severe consequences for marine ecosystems.[15] Among the first victims of ocean warming and acidification are coral reefs, because corals can form only within a narrow range of temperature and acidity of seawater. Oyster hatcheries are also affected, and have been referred to as "canaries in a coal mine" since they may predict effects on a wide range of ocean ecosystems as ocean acidification increases.[16]

Future projections of climate change depend upon the path of future emissions. Even if all emissions of greenhouse gases were ended today, the world would continue warming over the next few decades because the ultimate environmental effects of emissions are not realized immediately. Based on a wide range of models with different assumptions about future emissions, the IPCC estimates that:

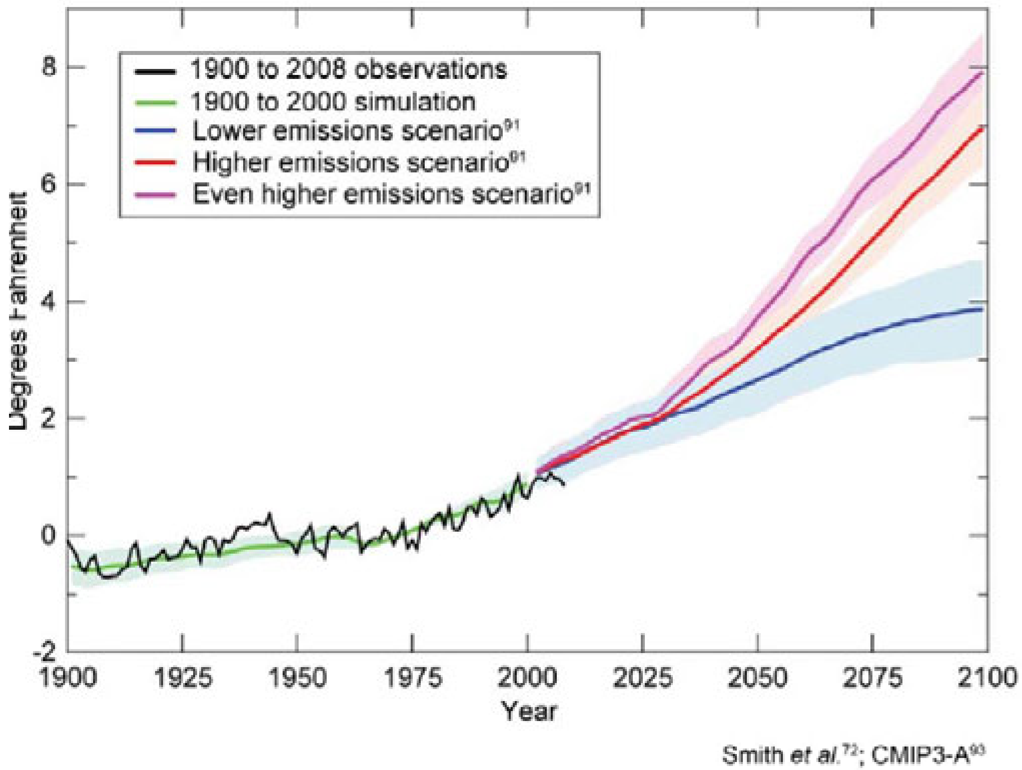
> Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to likely exceed 1.5°C (2.7F) and might be as high as 4.8°C (8.6F).

The Arctic region will warm more rapidly than the global mean, and mean warming over land will be larger than over the ocean. The range of possible temperature increases is shown in Figures 6 and 7, with Figure 7 showing the probable distribution of temperature increases across the planet for low-end and high-end temperature increase scenarios.

---

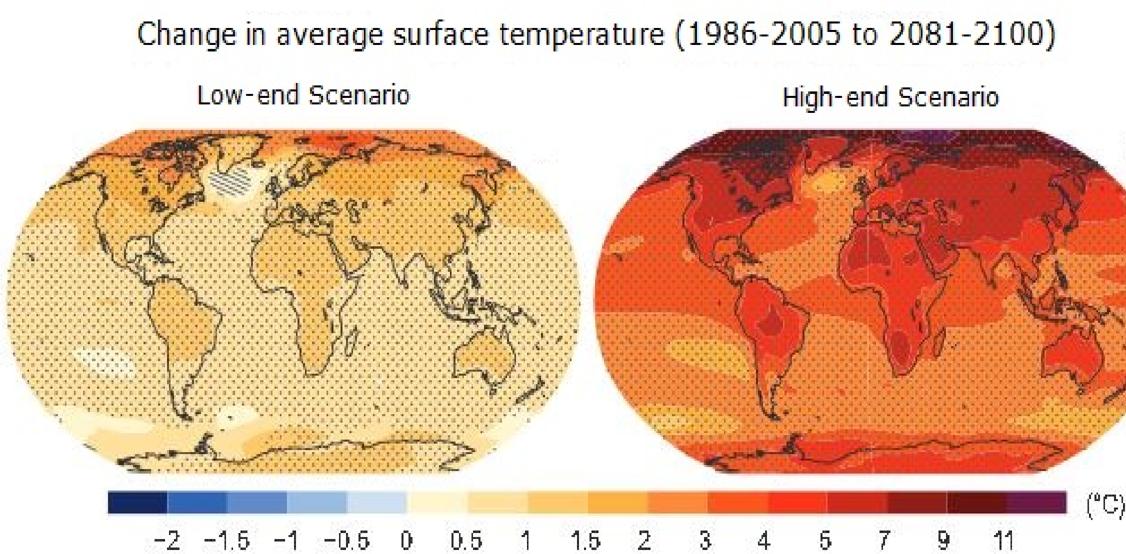
[14] National Oceanic and Atmospheric Administration (NOAA), 2010.
[15] Deborah Zabarenko, "Ocean's Acidic Shift may be Fastest in 300 Million Years," *Reuters* March 1, 2012.
[16] Roger Bradbury, "A World without Coral Reefs," *New York Times* July 14, 2012; NOAA, 2010, "Scientists Find Rising Carbon Dioxide and Acidified Waters in Puget Sound" http://www.noaanews.noaa.gov/stories2010/20100712_pugetsound.html and http://www.pmel.noaa.gov/co2/story/Going+Green%3A+Lethal+waters

Figure 6. Global Temperature Trends Projected to 2100



Source: U.S. Global Change Research Program, available at: http://www.globalchange.gov/

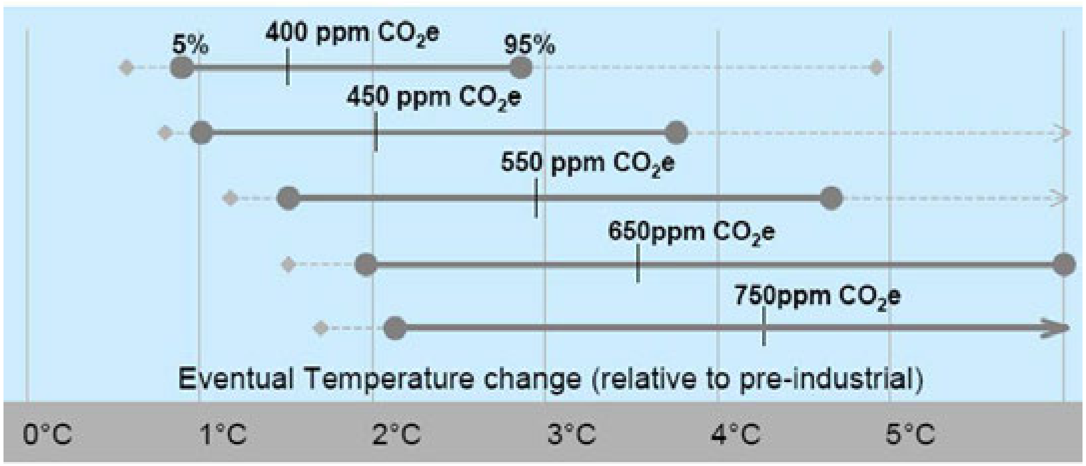
Figure 7. Global Temperature Trends Projected to 2100 – two scenarios



Source: IPCC, 2013

Figure 8 below relates the stabilization level of greenhouse gases, measured in CO_2 equivalent, or CO_2e, to the resulting rise in global average temperatures, incorporating the degree of uncertainty. The solid bar at each level of CO_2e represents a range of temperature outcomes that is likely to occur with a 90% probability. The dashed line extending beyond this interval at either end represents the full range of predicted results from the major existing climate models. The vertical line around the middle of each bar represents the mid-point of the different predictions.

Figure 8. The Relationship between the Level of Greenhouse Gas Stabilization and Eventual Temperature Change



Source: Stern, 2007.

This projection suggested that stabilizing greenhouse gas concentrations at 450 ppm CO_2e would be 90% likely to eventually result in a temperature increase between 1.0 and 3.8°C, with a small probability that the rise could be significantly more than this. With greenhouse gas concentrations in the atmosphere that are already almost at 450 ppm CO_2e in 2013, stabilization at 450 ppm is very unlikely to be achieved. As we will see later, even stabilization at 550 ppm CO_2e, which is a challenging target, would require dramatic policy action.

In its fifth report (2013), the IPCC stresses that the elevation of global temperature will very likely be above 2° Celsius: "Since the fourth report (2007) annual global GHG emissions have continued to grow and reached 49.5 billion tons (gigatons or Gt) of carbon dioxide equivalents (CO2eq) in the year 2010, higher than any level prior to that date. The current trajectory of global annual and cumulative emissions of GHGs is inconsistent with widely discussed goals of limiting global warming at 1.5 to 2 degrees Celsius above the pre-industrial level. Deep cuts in emissions will require a diverse portfolio of policies, institutions, and technologies as well as changes in human behavior and consumption patterns."[17]

[17] IPCC 2013, Working group III, Mitigation of Climate Change, Chapter 1, p.3-4

2. ECONOMIC ANALYSIS OF CLIMATE CHANGE

Scientists have modeled the effects of a projected doubling of accumulated carbon dioxide in the earth's atmosphere. Some of the predicted effects are:

- Loss of land area, including beaches and wetlands, to sea-level rise
- Loss of species and forest area, including coral reefs and wetlands
- Disruption of water supplies to cities and agriculture
- Health damage and deaths from heat waves and spread of tropical diseases
- Increased costs of air conditioning
- Loss of agricultural output due to drought

Some beneficial outcomes might include:

- Increased agricultural production in cold climates
- Lower heating costs
- Less deaths from exposure to cold

In addition to these effects, there are some other, less predictable but possibly more damaging effects, including:

- Disruption of weather patterns, with increased frequency of hurricanes and other extreme weather events
- A possible rapid collapse of the Greenland and West Antarctic Ice Sheets, which would raise sea levels by 12 meters or more, drowning major coastal cities
- Sudden major climate changes, such as a shift in the Atlantic Gulf Stream, which could change the climate of Europe to that of Alaska
- Positive **feedback effects,**[18] such as an increased release of carbon dioxide from warming arctic tundra, which would speed up global warming

The IPCC projects that with increasing emissions and higher temperatures, negative effects will intensify and positive effects diminish (Table 1). As shown in Figure 6, there is considerable uncertainty about the expected global warming in the next century. We need to keep such uncertainties in mind as we evaluate economic analyses of global climate change.

In its fifth report, the IPCC estimates impacts by continent and gives a medium to high likelihood for the following events to take place increasingly in the coming decades:

- Africa will be significantly impacted by more severe droughts in some regions with very strong adverse effects on regional, national and household livelihood and food security; whereas other regions will be subjected to more floods and increased associated water-borne diseases (malaria and other infectious diseases) that will result in a higher death toll. Asia will be

[18] A feedback effect occurs when an original change in a system causes further changes that either reinforce the original change (positive feedback) or counteract it (negative feedback).

submitted to similar increased risks of drought related water and food shortages in the in-land continental regions, while the coastal regions will be impacted by increased floods caused by the rising of sea levels, causing damage to infrastructures and livelihood, at potentially very large scales (hundreds of millions of people live on the shores of the Indian and Pacific Oceans).

- Europe will be impacted by flooding and increasing sea levels and coastal erosion, as well as significant reduction in water availability particularly in Southern Europe; extreme heat events will impact health and labor productivity, crop production and air quality, while increasing the frequency of wildfires in Southern Europe and in the Russian boreal regions.

- Australasia and Oceania will be severely impacted by the frequency and intensity of flood damage, as well as by the significant changes in the composition of coral reef systems in the oceans; Several Small Islands in the Pacific and Indian Oceans will disappear under sea-level rise and others will become inhabitable.

- Central and South America will be impacted by a reduction of water availability in semi-arid and glacier-melt-dependent regions, while urban and rural areas in lower altitudes will be subjected to increased flooding and landslide, which will result in a decrease in food production and food quality.

- North America will be impacted by a high frequency of hurricanes and cyclones, urban floods in riverine and coastal areas, public health impacts and social system disruption, while increased drying trends in the West of the United States will result in wildfire-induced loss of ecosystem integrity, property loss, and higher rates of human morbidity and mortality.

- Biodiversity will decrease in all the oceans, with a distributional shift in fish and invertebrate species, a decrease in fisheries abundance due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, and accompanied by a reduced ecological resilience of coastal ecosystems. This will seriously impact livelihoods of all communities relying on fisheries as their main food intake. [19]

[19] IPCC Working Group 2, Summary for Policymakers, p 27-30, 2013.

Table 1. Possible Effects of Climate Change[20]

Type of Impact	Eventual Temperature Rise Relative to Pre-Industrial Temperatures				
	1°C	2°C	3°C	4°C	5°C
Freshwater Supplies	Small glaciers in the Andes disappear, threatening water supplies for 50 million people	Potential water supply decrease of 20-30% in some regions (Southern Africa and Mediterranean)	1-4 billion more people suffer water shortages Serious droughts in Southern Europe every 10 years	Potential water supply decrease of 30-50% in Southern Africa and Mediterranen	Large glaciers in Himalayas possibly disappear, affecting ¼ of China's population
Food and Agriculture	Modest increase in yields in temperature regions	Declines in crop yields in tropical regions (5-10% in Africa)	150-550 million more people at risk of hunger Yields likely to peak at higher latitudes	Yields decline by 15-35% in Africa Some entire regions out of agricultural production	Increase in ocean acidity possibly reduces fish stocks
Human Health	At least 300,000 die each year from climate-related diseases Reduction in winter mortality in high latitudes	40-60 million more exposed to malaria in Africa	1-3 million more potentially people die annually from malnutrition	Up to 80 million more people exposed to malaria in Africa	Further disease increase and substantial burdens on health care services
Coastal Areas	Increased damage from coastal flooding	Up to 10 million more people exposed to coastal flooding	Up to 170 million more people exposed to coastal flooding	Up to 300 million more people exposed to coastal flooding	Sea level rise threatens major cities such as New York, Tokyo, and London
Ecosystems	At least 10% of land species facing extinction Increased wildfire risk	15-40% of species potentially face extinction	20-50% of species potentially face extinction Possible onset of collapse of Amazon forest	Loss of half of Arctic tundra Widespread loss of coral reefs	Significant extinctions across the globe

Sources: Stern, 2007; IPCC, 2007.

[20] According to the fifth report of IPCC (2013) there is a strong likelihood that the increase in average global temperature will be more than 2° Celsius.

Cost-Benefit Studies of Global Climate Change

Some economists have attempted to place the analysis of global climate change in the context of **cost-benefit analysis**. Others have criticized this approach as an attempt to put a monetary valuation on issues with social, political, and ecological implications that go far beyond dollar value. We will first examine economists' efforts to capture the impacts of global climate change through cost-benefit analysis, and then return to the debate over how to implement greenhouse gas reduction policies.

In performing a cost-benefit analysis, we must weigh the consequences of the projected increase in carbon emissions versus the costs of current policy actions to stabilize or even reduce CO_2 emissions. Without policy intervention, carbon emissions can be expected to continue to rise approximately as projected in Figure 2. Aggressive and immediate policy action would be required first to stabilize and then to reduce total CO_2 emissions in the coming decades.

Strong policy action to prevent climate change will bring benefits equal to the value of damages that are avoided.[21] These benefits must be compared to the costs of taking action. Various economic studies have attempted to estimate these benefits and costs. The results of five such studies for the U.S. economy are shown in Table 2.

When monetized costs are added up, the total annual U.S. damages are estimated at between $60 billion and $140 billion (1990 dollars). This is about 1% - 3% of U.S. GDP. Although different economic studies come up with different estimates, most of them are in the range of 1-3% GDP. Cost estimates for larger temperature change over the longer term rise to around 10% of global GDP.

Note, however, that there are also some "Xs" in the totals—unknown quantities that cannot easily be measured. The damages from species extinctions, for example, are difficult to estimate in dollar terms: the estimates shown here indicate a cost of at least $1.4 - 5 billion, with additional unknown costs which rise with additional warming.

In addition to the Xs, other monetized estimates could also be challenged on the grounds that they fail to capture the full value of potential losses. For example, oceanfront land is more than just real estate. Beaches and coastal wetlands have great social, cultural, and ecological value. The market value of these lands does not reflect the full scope of the damage society will suffer if they are lost.

Valuing human health and life is very controversial. These studies follow a common cost-benefit practice of assigning a value of about $6 million to a life, based on studies of the amounts people are willing to pay to avoid life-threatening risks, or are willing to accept (for example in extra salary for dangerous jobs) to undertake such risks.

In addition, these estimates omit the possibility of the much more catastrophic consequences that *could* result if weather disruption is much worse than anticipated.

[21] These benefits of preventing damage can also be referred to as **avoided costs**.

Table 2. Estimates of Annual Damages to the U.S. Economy from Global Climate Change (Billions of 1990 $)

	Cline (2.5°C)	Fankhauser (2.5°C)	Nordhaus (3°C)	Titus (4°C)	Tol (2.5°C)
Agriculture	17.5	3.4	1.1	1.2	10
Forest loss	3.3	0.7	X	43.6	X
Species loss	4	1.4	X	X	5
Sea level rise	7	9	12.2	5.7	8.5
Electricity	11.2	7.9	1.1	5.6	X
Nonelectric heating	-1.3	X	X	X	X
Mobile air conditioning	X	X	X	2.5	X
Human amenity	X	X	0.75% of GDP	X	12
Human mortality and morbidity	5.8	11.4		9.4	37.4
Migration	0.5	0.6		X	1
Hurricanes	0.8	0.2		X	0.3
Leisure activities	1.7	X		X	X
Water supply availability	7	15.6		11.4	X
Water supply pollution	X	X		32.6	X
Urban infrastructure	0.1	X		X	X
Air pollution	3.5	7.3		27.2	X
Total in billions	**61.1**	**69.5**	**55.5**	**139.2**	**74.2**
Total as percent of GDP	**1.1**	**1.3**	**1**	**2.5**	**1.5**

Source: Nordhaus and Boyer, 2000, p. 70.
Note: "X" denotes items that are not assessed or quantified.

The third US National Climate Assessment (2014) has stressed the fact that United States economy is already suffering significant costs related to climate change impacts, such as the unprecedented climatic events of the likes of Hurricane Katrina and Hurricane Sandy, the increased frequency of devastating tornados in the Midwest, and the worsening droughts in the hot spring and summer seasons in recent years, which count has record highs in the history of climate.

Hurricane Katrina in August 2005, for example, caused the loss of over 1800 lives in addition to imposing a cost estimated at $125 billion in damage[22]. Hurricane Sandy on October 31, 2012, killed 159 people and caused over $50 billion in damage.[23] If climate changes cause severe hurricanes and Typhoons (such as Typhoon Haiyan that hit the Philippines in November 2013) to become much more frequent, the estimate given in Table 2 of less than one billion annual losses could be much too low. Another of the unknown values – human morbidity, or losses from disease – could well be enormous if tropical diseases extend their range significantly due to warmer weather conditions.

In a 2008 study, the total cost of damages to the U.S. economy in a Business-As-Usual case in 2025 is predicted to be $271 billion dollars or 1.36% of total GDP. The cost of damages rises over time (Table 3). Higher ranges of temperature change lead to dramatically increased damage estimates.

Table 3. Damages to the U.S. Economy from Climate Change

	in billions of 2006 dollars				as a percentage of GDP			
	2025	**2050**	**2075**	**2100**	**2025**	**2050**	**2075**	**2100**
Hurricane Damages	10	43	142	422	0.05%	0.12%	0.24%	0.41%
Real Estate Losses	34	80	173	360	0.17%	0.23%	0.29%	0.35%
Energy Sector Costs	28	47	82	141	0.14%	0.14%	0.14%	0.14%
Water Costs	200	336	565	950	1.00%	0.98%	0.95%	0.93%
Total Costs	**271**	**506**	**961**	**1873**	**1.36%**	**1.47%**	**1.62%**	**1.84%**

Source: Ackerman and Stanton, 2008.

Clearly, these damage estimates are not precise, and are open to many criticisms. But suppose we decide to accept them – at least as a rough estimate. We must then weigh the estimated benefits of policies to prevent climate change against the costs of such policies. To estimate these costs, economists use models that show how economic output is produced from factor inputs such as labor, capital, and resources.

[22] http://www.livescience.com/32181-how-much-did-hurricane-katrina-cost.html
[23] http://www.huffingtonpost.com/2013/02/12/hurricane-sandy-second-costliest_n_2669686.html

To lower carbon emissions, we must cut back the use of fossil fuels, substituting other energy sources that may be more expensive. In general, economic models predict that this substitution would reduce GDP growth. The IPCC has used macroeconomic models to estimate the costs of **mitigation** policies (i.e. policies aimed at reducing climate change impacts) in terms of changes of consumption globally. Those reductions in consumption are estimated at around 1 to 4% by 2030, 2 to 6% by 2050 and 3 to 11% by 2100, relative to consumption baseline scenarios that grow anywhere from 300 to 900% over the century. The IPCC emphasizes that the longer we wait in adopting additional mitigation measures, the higher the costs of mitigation would be in the medium to long term.[24] Other studies have shown estimates for the costs of cutting emissions by 70% below "business as usual" ranging from a loss of 3.5% of GDP to a *gain* of 1% in GDP.[25]

Several economic studies have also estimated the many **co-benefits** (benefits in other areas) of curbing greenhouse gases emissions, [26] including:

- Cleaner air: the benefits for health and ecosystems of reduced air pollution from a reduction in the use of fossil fuels

- Greener land: the benefits of climate policy in reducing deforestation and improving the sustainability of agriculture

- Safe and secure energy: reducing the impacts of fossil fuel extraction on health and the environment while providing renewable sources of energy that are safer, more affordable, and reduce dependency on fossil fuels produced in politically volatile regions (Middle East).

- Less waste: the numerous benefits of moving to a more resource-efficient economy, including conservation of scarce resources, financial savings and reduction of the impacts of waste disposal.

- A stronger economy: redesigning the economy so as to minimize negative impacts and maximize benefits of moving away from fossil fuels on jobs, growth, productivity, fuel poverty, and development.

- Health and well-being: the large benefits of low-carbon lifestyles for health and well-being, including the benefits of more walking and cycling, eating less meat, and a "buy less, work less" higher quality lifestyle.

How can we weight the costs of taking action on global warming against the benefits in terms of avoided damage? Much depends on our evaluation of future costs and benefits. The costs of taking action must be born today or in the near future. Many of the benefits of taking action (the avoided costs of damages) are further in the future. How can we decide today how to balance these future costs and benefits?

---

[24] IPCC 2014, Summary for Policymakers, in Climate Change 2014, Mitigation of Climate Change, contributions of working group III to the Fifth Assessment Report of the IPCC, p.15.
[25] Stern, 2007, Chapter 9: "Understanding the Costs of Mitigation".
[26] Co-benefits are benefits of a given policy in other areas. This list is drawn from Smith, 2013.

Economists evaluate future costs and benefits by the use of a **discount rate**. Costs and benefits in the future are considered to have a lower dollar value than the same costs and benefits today, with the size of the difference depending on the choice of discount rate (see Box 4). What justifies the use of discounting? Partly, it is based on the natural human tendency to focus on the present more than the future. Most people would prefer to receive a benefit now than a similar benefit in the future. This may be a simple matter of personal preference, or it may be based on the economic logic that having resources in the present allows for investment to receive greater benefits in the future.

Economists incorporate this concept into CBA through discounting. Discounting effectively reduces the weight placed on any cost or benefit that occurs in the future, relative to the same impact occurring now. The further the cost or benefit occurs in the future, the less weight is given to that impact. As the time period under consideration becomes longer, this effect of discounting becomes more significant in lowering the value that is placed on well-being in the future, leading to a continuing controversy over the proper use of discounting.

The problems and implicit value judgments associated with discounting add to the issues of ethics and judgment that we have already noted in valuing costs and benefits. Can we really say that damages to future generations should be weighed much less heavily than the same damages today? This suggests that we should consider some alternative approaches – including techniques that incorporate ecological as well as economic costs and benefits.

BOX 4: DISCOUNTING

Economists calculate the present value of a cost or benefit of \$X that occurs in years in the future using the equation:

Present Value (\$X) = \$X / (1 + r)^n

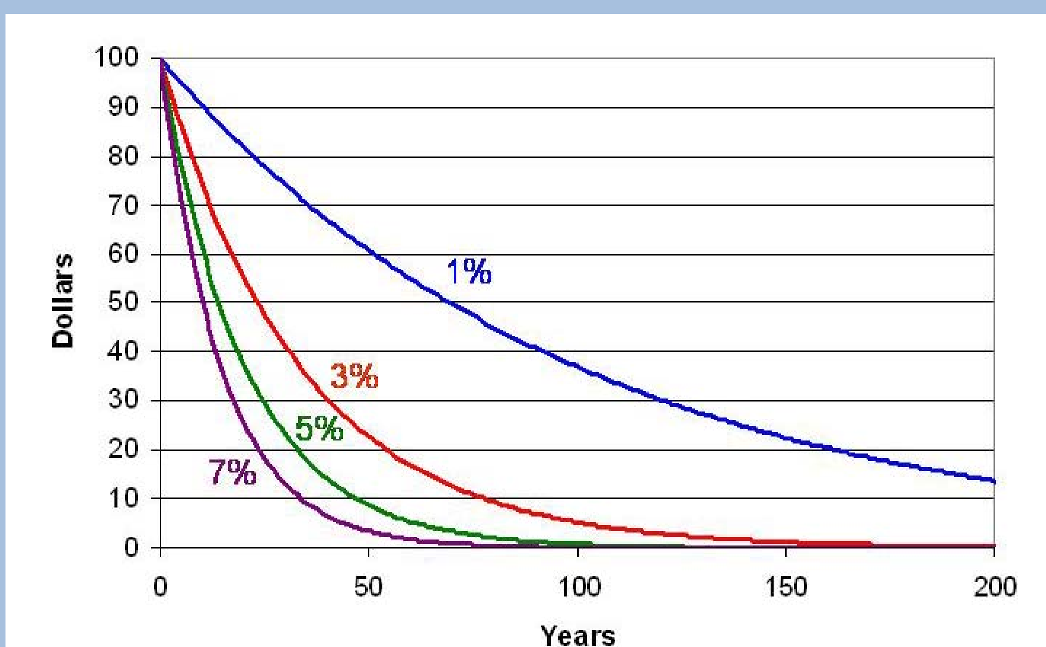
where *r* is the discount rate. So, for example, if we want to determine the present value of a benefit of \$50,000 received 25 years from now with a discount rate of 5%, it would be:

$\$50,000 / (1 + 0.05)^{25} = \$14,765$

The choice of a discount rate becomes more important the further out in time one goes. Figure 9 below shows the present value of \$100 of costs or benefits experienced at different times in for different time periods into the future using several discount rates that have been used in climate change cost-benefit analyses.

We see that when a discount rate of 5% or 7% is used, costs or benefits that occur 100 years into the future are negligible in terms of present value – worth only \$0.76 and \$0.12 respectively. Even with a discount rate of 3%, the value of \$100 is only \$5.20 after 100 years. But when the discount rate is 1%, impacts 100 years into the future are still significant – worth about \$37 in present value; even when discounting over a period of 200 years, the present value is still nearly \$20.

Figure 9. Present Value of a Future \$100 Cost or Benefit: The Effects of Different Discount Rates



3. ANALYZING LONG-TERM EFFECTS OF CLIMATE CHANGE

Economic studies dealing with cost-benefit analysis of climate change have come to very different conclusions about policy. According to studies done by William Nordhaus and colleagues, the "optimal" economic policies to slow climate change involve modest rates of emissions reductions in the near term; followed by increasing reductions in the medium and long term.[27]

Until recently, most economic studies of climate change reached conclusions similar to those of Nordhaus, although a few recommended more drastic action. The debate on climate change economics altered in October 2006, when Nicholas Stern, a former chief economist for the World Bank, released a 700-page report, sponsored by the British government, titled "The Stern Review on the Economics of Climate Change".[28] Publication of the Stern Review generated significant media attention and intensified the debate about climate change in policy and academic circles.

While most previous economic analyses of climate change suggested relatively modest policy responses, the Stern Review strongly recommends immediate and substantial policy action:

> The scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response. This Review has assessed a wide range of evidence on the impacts of climate change and on the economic costs, and has used a number of different techniques to assess costs and risks. From all these perspectives, the evidence gathered by the Review leads to a simple conclusion: the benefits of strong and early action far outweigh the economic costs of not acting.
>
> Using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more. In contrast, the costs of action – reducing greenhouse gas emissions to avoid the worst impacts of climate change – can be limited to around 1% of global GDP each year.[29]

What explains the difference between these two approaches to economic analysis of climate change? One major factor is the choice of the discount rate to use in valuing future costs and benefits.

The present value (PV) of a long-term stream of benefits or costs depends on the discount rate. A high discount rate will lead to a low present valuation for benefits that

[27] Nordhaus, 2007 and 2013.
[28] Available in book form (Stern, 2007). The full Stern Review is available online at http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/sternreview_index.htm , including both a 4-page and 27-page summaries.
[29] Stern Review, Short Executive Summary, page vi.

are mainly in the longer-term, and a high present valuation for short-term costs. On the other hand, a low discount rate will lead to a higher present valuation for longer-term benefits. The estimated net present value of an aggressive abatement policy will thus be much higher if we choose a low discount rate (see Box 4).

While both the Stern and Nordhaus studies used standard economic methodology, Stern's approach gives greater weight to long-term ecological effects. The Stern Review uses a low discount rate of 1.4% to balance present and future costs. Thus even though costs of aggressive action appear higher than benefits for several decades, the high potential long-term damages sway the balance in favor of aggressive action today. The use of a standard discount rate of in the 5-10% range, in contrast, has the effect of reducing the present value of significant long-term future damages to relative insignificance.

Another difference between the two studies concerns their treatment of uncertainty. Stern's approach gives a heavier weighting to uncertain, but potentially catastrophic impacts. This reflects the application of a **precautionary principle**: if a particular outcome could be catastrophic, even though it seems unlikely, strong measures should be taken to avoid it. This principle, which has become more widely used in environmental risk management, is especially important for global climate change because of the many unknown but potentially disastrous outcomes possibly associated with continued greenhouse gas accumulation (see Box 5).

A third area of difference concerns the assessment of the economic costs of action to mitigate climate change. Measures taken to prevent global climate change will have economic effects on GDP, consumption, and employment, which explain the reluctance of governments to take drastic measures to reduce significantly emissions of CO_2. But these effects will not all be negative.

The Stern Review conducted a comprehensive review of economic models of the costs of carbon reduction. These cost estimates are very much dependent on the modeling assumptions that are used. The predicted costs of stabilizing atmospheric accumulations of CO_2 at 450 parts per million range from a 3.4 percent decrease to a 3.9.percent *increase* in GDP. The outcomes depend on a range of assumptions including:

- The efficiency or inefficiency of economic responses to energy price signals
- The availability of non-carbon "backstop" energy technologies
- Whether or not nations can trade least-cost options for carbon reduction
- Whether or not revenues from taxes on carbon-based fuels are used to lower other taxes
- Whether or not external benefits of carbon reduction, including reduction in ground-level air pollution, are taken into account[30]

Depending on which assumptions are made, policies for emissions reduction could range from a minimalist approach of slightly reducing the rate of increase in emissions to a dramatic CO_2 emissions reduction of 80%.

[30] Stern Review, Chapter 10: "Macroeconomic Models of Costs".

BOX 5: CLIMATE TIPPING POINTS AND SURPRISES

Much of the uncertainty in projections of climate change relates to the issue of feedback loops. A feedback loop occurs when an initial change, such as warmer temperatures, produces changes in physical processes which then amplify or lessen the initial effect (a response that increases the original effect is called a positive feedback loop; a response that reduces it is a negative feedback loop). An example of a positive feedback loop would be when warming leads to increased melting of arctic tundra, releasing carbon dioxide and methane, which add to atmospheric greenhouse gas accumulations and speed up the warming process.

As a result of various feedback loops associated with climate change, recent evidence suggests that warming is occurring faster than most scientists predicted just 5 or 10 years ago. This is leading to increasing concern over the potential for "runaway" feedback loops which could result in dramatic changes in a short period. Some scientists suggest that we may be near certain climate tipping points which, once exceeded, pose the potential for catastrophic effects.

Perhaps the most disturbing possibility would be the rapid collapse of the Greenland and West Antarctic Ice Sheets. While the IPCC forecasts a sea level rise of 0.2 to 0.6 meters by 2100, the melting of these two ice sheets would raise sea levels by 12 meters or more. Such a scenario is still controversial, and considered unlikely to occur in the 21st century, but new research suggests that changes can occur much faster than originally expected.

In recent studies, scientists found that methane emissions from the Arctic have risen by almost one-third in just five years. The discovery follows a string of reports from the region in recent years that previously frozen boggy soils are melting and releasing methane in greater quantities. Such Arctic soils currently lock away billions of tones of methane, a far more potent greenhouse gas than carbon dioxide, leading some scientists to describe melting permafrost as a ticking time bomb that could overwhelm efforts to tackle climate change. They fear the warming caused by increased methane emissions will itself release yet more methane and lock the region into a destructive cycle that forces temperatures to rise faster than predicted.

Sources: "Melting Ice Turns up the Heat," Fred Pearce, *Sydney Morning Herald*, November 18, 2006; "Arctic Permafrost Leaking Methane at Record Levels, Figures Show", David Adam, *The Guardian*, 2010 http://www.guardian.co.uk/environment/2010/jan/14/arctic-permafrost-methane

Climate Change and Inequality

The effects of climate change will fall most heavily upon the poor of the world. Regions such as Africa could face severely compromised food production and water shortages, while coastal areas in South, East, and South-East Asia will be at great risk of flooding. Tropical Latin America will see damage to forests and agricultural areas due to drier climate, while in South America changes in precipitation patterns and the disappearance of glaciers will significantly affect water availability.[31] While the richer countries may have the economic resources to adapt to many of the effects of climate change, poorer countries will be unable to implement preventative measures, especially those that rely on the newest technologies.

Recent studies have used geographically-distributed impacts models to estimate the impacts of climate change across the global domain. As Table 4 indicates, number of coastal flood victims and population at risk of hunger by 2080 will be relatively larger in Africa, South America and Asia, where most developing countries are located. [32]

Table 4. Regional-scale impacts of climate change by 2080 (millions of people)

Region	Population living in watersheds with an increase in water-resources stress	Increase in average annual number of coastal flood victims	Additional population at risk of hunger (figures in parentheses assume maximum CO_2 enrichment effect)
Europe	382-493	0.3	0
Asia	892-1197	14.7	266 (-21)
North America	110-145	0.1	0
South America	430-469	0.4	85 (-4)
Africa	691-909	12.8	200 (-2)

Source: adapted from IPCC, 2007b, http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch20s20-6-2.html
Note: These estimates are based on a business-as-usual scenario. The CO_2 enrichment effect is increased plant productivity, which at maximum estimates could actually decrease the number at risk of hunger.

The way in which economists incorporate inequality into their analyses can have a significant impact on their policy recommendations. If all costs are evaluated in dollars, a loss of, say, 10% of GDP in a poor country is likely to be much less than a loss of 3% of GDP in a rich country. The Stern Review asserts that the disproportionate effects of climate change on the world's poorest people should increase the estimated costs of climate change. Stern estimates that, without the effects of inequity, the costs of a BAU scenario will be 11-14% of global GDP. Weighing the impacts on the world's poor more heavily gives a cost estimate of 20% of global GDP.

[31] IPCC, 2007b; Stern, 2007, Chapter 4: Implications of Climate Change for Development.
[32] This table and data are available at http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch20s20-6-2.html

4. POLICY RESPONSES TO CLIMATE CHANGE

Two types of measures can be used to address climate change; **mitigation** or **preventive measures** tend to lower or mitigate the greenhouse effect, and **adaptive measures** deal with the consequences of the greenhouse effect and trying to minimize their impact.

Preventive or mitigation measures include:

- Reducing emissions of greenhouse gases, either by reducing the level of emissions-related economic activities or by shifting to more energy-efficient and renewable energy technologies that would allow the same level of economic activity at a lower level of CO_2 emissions.
- Enhancing **carbon sinks**.[33] Forests and soils store carbon and recycle CO_2 into oxygen; preserving forested areas, expanding reforestation, and using carbon-storing agricultural techniques have a significant effect on net CO_2 emissions.[34]

Adaptive measures include:

- Construction of dikes and seawalls to protection against rising sea level and extreme weather events such as floods and hurricanes.
- Shifting cultivation patterns in agriculture to adapt to changed weather conditions in different areas, and relocating people away from low-lying coastal areas.
- Creating institutions that can mobilize the needed human, material, and financial resources to respond to climate-related disasters.

For any particular preventive or adaptive measure, an economic approach suggests that we should apply **cost-effectiveness analysis** in considering which policies to adopt. The use of cost-effectiveness analysis avoids many of the controversies associated with cost-benefit analysis. While cost-benefit analysis attempts to offer a basis for deciding whether or not a policy should be implemented, cost-effectiveness analysis accepts a goal as given by society, and uses economic techniques to evaluate the most efficient way to reach that goal.

In general, economists favor approaches that work through market mechanisms to achieve their goals (see Box 6). Market-oriented approaches are considered to be cost-effective; rather than attempting to control market actors directly, they shift incentives so that individuals and firms will change their behavior to take account of external costs and benefits. Examples of market-based policy tools include **pollution taxes** and **transferable, or tradable, permits**. Both of these are potentially useful tools for greenhouse gas reduction. Other relevant economic policies include measures to create incentives for the adoption of renewable energy sources and energy-efficient technology.

---

[33] Carbon sinks are areas where excess carbon may be stored. Natural sinks include the oceans and forests. Human intervention can either reduce or expand these sinks through forest management and agricultural practices.

[34] See Harris and Birjandi Feriz, 2011.

BOX 6: ECONOMISTS' STATEMENT ON CLIMATE CHANGE

As early as 1997, over 2,500 economists including eight Nobel laureates had signed the following public statement calling for serious steps to deal with the risks of global climate change:

I. The review conducted by a distinguished international panel of scientists under the auspices of the Intergovernmental Panel on Climate Change has determined that "the balance of evidence suggests a discernible human influence on global climate." As economists, we believe that global climate change carries with it significant environmental, economic, social, and geopolitical risks, and that preventive steps are justified.

II. Economic studies have found that there are many potential policies to reduce greenhouse-gas emissions for which the total benefits outweigh the total costs. For the United States in particular, sound economic analysis shows that there are policy options that would slow climate change without harming American living standards, and these measures may in fact improve U.S. productivity in the longer run.

III. The most efficient approach to slowing climate change is through market-based policies. In order for the world to achieve its climatic objectives at minimum cost, a cooperative approach among nations is required -- such as an international emissions trading agreement. The United States and other nations can most efficiently implement their climate policies through market mechanisms, such as carbon taxes or the auction of emissions permits. The revenues generated from such policies can effectively be used to reduce the deficit or to lower existing taxes.

Source: Originally organized by Redefining Progress, currently available at http://dieoff.org/page105.htm.

While most of this module focuses on mitigation policies, it is becoming increasingly evident that mitigation policies will need to be supplemented with adaptation policies. The IPCC classifies adaptation needs into seven sectors of water, agriculture, infrastructure, human health, tourism, transport and energy[35]. Changing precipitation and temperature patterns have significant implications for agriculture. With moderate warming, crop yields are expected to increase in some colder regions, including parts of North America, but overall the impacts on agriculture are expected to be negative, and increasingly negative with greater warming.

The impacts of climate change on human health are already occurring. The World Health Organization has estimated that over 140,000 people per year are already dying as a direct result of climate change, primarily in Africa and Southeast Asia.[36]

Various estimates exist for the cost of appropriate adaptation measures. The United Nations has estimated that the total cost of adapting to climate change will cost

[35] IPCC, 2007.
[36] World Health Organization, 2009.

between about $60 billion and $190 billion annually by 2030. [37] A review of the United Nations' estimates conclude that their costs were probably too low by a factor of two to three, and even more when the costs for excluded sectors, such as tourism and energy, are also considered.[38]

Further, adaptation costs would be expected to increase beyond 2030 as warming and other impacts become more severe. In 2010 the World Bank estimated the costs of adaptation in developing countries only to be between $75 billion and $100 billion annually over the period 2010 to 2050.[39] The report notes that funding for adaptation measures could be met by doubling current foreign aid from developed countries. It also mentions that fostering economic development will provide developing countries with greater internal resources to adapt to climate change.

Economic Policy Options: Carbon Taxes

The release of greenhouse gases in the atmosphere is a clear example of a negative externality that imposes significant costs on a global scale. In the language of economic theory, the current market for carbon-based fuels such as coal, oil, and natural gas takes into account only private costs and benefits, which leads to a market equilibrium that does not correspond to the social optimum. From a social perspective the market price for fossil fuels is too low and the quantity consumed too high.

A standard economic remedy for internalizing external costs is a per-unit tax on the pollutant. In this case, what is called for is a **carbon tax**, levied exclusively on carbon-based fossil fuels in proportion to the amount of carbon associated with their production and use. Such a tax will raise the price of carbon-based energy sources, and so give consumers incentives to conserve energy overall, as well as shifting their demand to alternative, non-carbon sources of energy (which are not taxed). Demand may also shift from carbon-based fuels with a higher proportion of carbon, such as coal, to those with relatively lower carbon content, such as natural gas.

> "Carbon taxes would appear to consumers as energy price increases. But since taxes would be levied on primary energy, which represents only one part of the cost of delivered energy (such as gasoline or electricity) and more important, since one fuel can in many cases be substituted for another, overall price increases may not be jolting. Consumers can respond to new prices by reducing energy use and buying fewer carbon-intensive products (those that require great amounts of carbon-based fuels to produce). In addition, some of these savings could be used to buy other less carbon-intensive goods and services.
>
> "Clearly, a carbon tax creates an incentive for producers and consumers to avoid paying the tax by reducing their use of carbon-intensive fuels. Contrary to other taxed items and activities, this avoidance has social benefits – reduced

[37] UNFCCC, 2007.
[38] Parry et al., 2009.
[39] World Bank, 2010.

energy use and reduced CO_2 emissions. Thus, declining tax revenues over time indicate policy success – just the opposite of what happens when tax policy seeks to maintain steady or increasing revenues."[40]

Table 5 shows the impact that different levels of a carbon tax would have on the prices of coal, oil, and natural gas. Based on energy content, measured in Btus,[41] coal is the most carbon intensive fossil fuel, while natural gas produces the lowest emissions. Calculating the impact of a carbon tax relative to the standard commercial units for each fuel source, we see that a $10/ton carbon tax, for example, raises the price of a barrel of oil by about a dollar. This is equivalent to only about two cents per gallon.[42]

Table 5. Alternative Carbon Taxes on Fossil Fuels

	Coal	Oil	Natural Gas
Tons of carbon per billion Btu	25.6	17.0	14.5
Tons of carbon per standard unit of fuel	0.574/ton	0.102/barrel	0.015/Mcf (thousand cubic feet)
Average price (2012)	$76.30/ton	$95.55/barrel	$3.20/Mcf
Carbon tax amount per unit of fuel:			
$10/ton of carbon	$5.74/ton	$1.02/barrel	$0.15/Mcf
$100/ton of carbon	$57.42/ton	$10.15/barrel	$1.49/Mcf
$200/ton of carbon	$114.85/ton	$20.31/barrel	$2.98/Mcf
Carbon tax as a percent of fuel price:			
$10/ton of carbon	13%	1%	4.7%
$100/ton of carbon	132%	11%	47%
$200/ton of carbon	265%	21%	93%

Source: Carbon emissions calculated from carbon coefficients and thermal conversion factors available from the U.S. Department of Energy. Oil price is August 2012 world average. Natural gas price is August 2012 average U.S. wellhead price. Coal price is August 2012 U.S. average over 5 different types of coal. All price data from the U.S. Energy Information Administration.

A $100/ton carbon tax would equate to an increase in gasoline prices of about 24 cents per gallon. Even though natural gas has a lower carbon content than oil, its relatively low price in 2012 means that a carbon tax would increase its price by a greater percentage. The impact of a carbon tax would be most significant for coal prices.

[40] Dower and Zimmerman, 1992.
[41] A Btu (British thermal unit) is approximately the amount of energy needed to raise the temperature of one pound of water one degree Fahrenheit (from 39 to 40 degrees).
[42] There are 42 gallons in a barrel of oil.

Will these taxes affect people's driving or home heating habits very much? This depends on the **elasticity of demand** for these fuels. Elasticity of demand is defined as:

$$Elasticity\ of\ demand = \frac{Percent\ change\ in\ demand}{Percent\ change\ in\ price}$$

Economists have measured the elasticity of demand for different fossil fuels, particularly gasoline. One study[43] surveyed all the available research on the elasticity of demand for motor fuels and found that within the short-term (about one year or less) elasticity estimates averaged -0.25. [44] This means that a 10% increase in the price of gasoline would be expected to decrease gasoline demand in the short term by about 2.5%.

In the long-term (about 5 years or so) people are more responsive to gasoline price increases as they have time to purchase different vehicles and adjust their driving habits. The average long-term elasticity of demand for motor fuels was -0.64[45]. According to Table 5, a $200 carbon tax would increase the price of gasoline by 48 cents per gallon. Assuming a retail price of $3 per gallon, this would translate to a 16% price increase. A long-term elasticity of -0.64 suggests that once people have time to fully adjust to this price change, we would expect the demand for gasoline to decline by about 10%.

Figure 10 shows a cross-country relationship between gasoline prices and per capita consumption. (Since the cost of producing a gallon of gasoline varies little across countries, variations in the price of gallon in different countries is almost solely a function of differences in taxes.)

Notice that this relationship is similar to that of a demand curve: higher prices are associated with lower consumption, lower prices with higher consumption. The relationship shown here, however, is not exactly the same as a demand curve; since we are looking at data from different countries, the assumption of "other things equal", which is needed to construct a demand curve, does not hold. Differences in demand may, for example, be partly a function of differences in income levels rather than prices. Also, people in the United States may drive more partly because travel distances (especially in the Western U.S.) are greater than in many European countries. But there does seem to be a clear price/consumption relationship. The data shown here suggest that it would take a fairly big price hike – in the range of $0.50- $1.00 per gallon or more – to affect fuel use substantially.

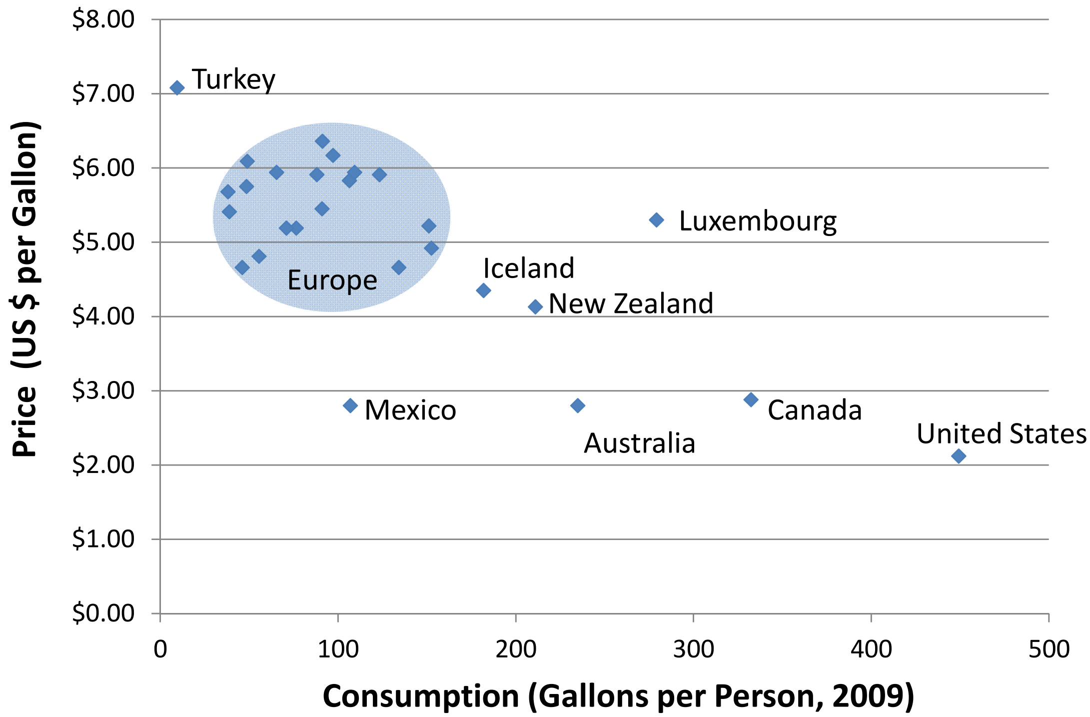
---

[43] Phil Goodwin, Joyce Dargay, and Mark Hanly. "Elasticities of Road Traffic and Fuel Consumption with respect to Price and Income: A Review," *Transport Reviews*, 24(3):275-292, May 2004.

[44] Goodwin et al., 2004. The short-run price elasticity of demand for gasoline may have declined significantly in recent years. Hughes et al. (2008) estimate an elasticity of demand for 2001-2006 of -0.03 to -0.08, compared with their estimate of an elasticity of demand for 1975-1980 of -0.21 to -0.34.

[45] Goodwin et al., 2004.

Figure 10. Gasoline Price versus Use in Industrial Countries, 2009



Note: Shaded area represents price/consumption range typical of West European countries.
Sources: U.S. Energy Information Administration database; GTZ, 2009

Would such a tax ever be politically feasible? Especially in the United States, high taxes on gasoline and other fuels would face much opposition, especially if people saw it as infringing on their freedom to drive. As Figure 9 shows, the U.S. has by far the highest consumption per person and the lowest prices outside of the Middle East. But let's note two things about the proposal for substantial carbon taxes:

- First, revenue recycling could redirect the revenue from carbon and other environmental taxes to lower other taxes. Much of the political opposition to high energy taxes comes from the perception that they would be an *extra* tax – on top of the income, property, and social security taxes that people already pay. If a carbon tax was matched, for example, with a substantial cut in income or social security taxes, it might be more politically acceptable. The idea of increasing taxes on economic "bads" such as pollution, while reducing taxes on things we want to encourage, such as labor and capital investment, is fully consistent with principles of economic efficiency[46]. Rather than a net tax increase, this would be **revenue-neutral tax shift** - the total amount which citizens pay to the government in taxes is unchanged. Some of the tax revenues could also be used to provide relief for low-income people to offset the burden of higher energy costs.

[46] To encourage higher investment, carbon tax revenues could be used to lower capital gains or corporate taxes.

- Second, if such a revenue-neutral tax shift did take place, individuals or businesses whose operations were more energy-efficient would actually save money overall. The higher cost of energy would also create a powerful incentive for energy-saving technological innovations and stimulate new markets. Economic adaptation would be easier if the higher carbon taxes (and lower income and capital taxes) were phased-in over time.

Economic Policy Options: Tradable Permits

An alternative to a carbon tax is a system of tradable carbon permits. A carbon trading scheme (also known as **cap-and-trade**) could be national in scope, or include several countries. An international permit system would work as follows:

- Each nation would be allocated a certain permissible level of carbon emissions. The total number of carbon permits issued would be equal to the desired national goal. For example, if carbon emissions for a particular country are currently 40 million tons and the policy goal is to reduce this by 10%, then permits would be issued to emit only 36 million tons. Note that different nations could be obliged to meet different targets, which is the case under the Kyoto Protocol.
- Permits are allocated to individual carbon-emitting sources in each nation. Including all carbon sources (e.g., all motor vehicles) in a trading scheme is clearly not practical. Instead, under most proposals permits would be allocated to the largest carbon emitters, such as power companies and manufacturing plants, or else to the suppliers through which carbon fuels enter the country – oil importers, coal mines, etc. These permits could initially be allocated for free on the basis of past emissions, or could be auctioned to the highest bidders.
- Economic theory indicates that the effectiveness of the trading system should be the same regardless of how the permits are allocated. However, there is a significant difference in the distribution of costs and benefits: giving permits out for free essentially amounts to a government subsidy to the polluters, while auctioning permits imposes real costs upon firms and generates public revenues.
- Firms are able to trade permits freely among themselves. Firms whose emissions exceed the number of permits they hold must purchase additional permits or else face penalties. Meanwhile firms that are able to reduce their emissions below their allowance at low cost will seek to sell their permits for a profit. Firms will settle upon permit prices through free market negotiations. It may also be possible for environmental groups or other organizations to purchase permits and retire them – thus reducing overall emissions.
- Nations and firms could also receive credit for financing carbon reduction efforts in other countries. For example, a German firm could get credit for installing efficient electric generating equipment in China, replacing highly polluting coal plants.

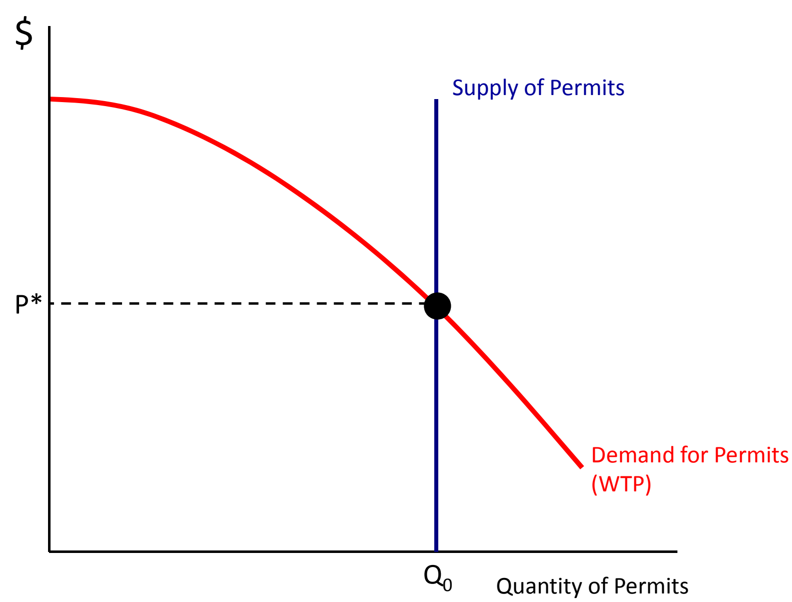
A tradable permit system encourages the least-cost carbon reduction options to be implemented, as firms will implement those emission-reduction actions that are cheaper than the market permit price. Tradable permit systems have been successful in reducing sulfur and nitrogen oxide emissions at low cost. Depending on the allocation of permits, it might also mean that developing nations could transform permits into a new export commodity by choosing a non-carbon path for their energy development. They would then be able to sell permits to industrialized nations who were having trouble meeting their reduction requirements.

While the government sets the number of permits available, the permit price is determined by the market for permits. In this case, the supply curve is fixed, or vertical, at the number of permits allocated, as shown in Figure 10. The supply of permits is set at Q0. Firms' demand curve for permits represents their willingness to pay for them. In turn, their maximum willingness to pay for permits is equal to the potential profits they can earn by emitting carbon.

Assume that the permits will be auctioned off one-by-one to the highest bidders. Figure 11 shows that the willingness to pay for the first permit would be quite high, as a particular firm stands to make a relatively large profit by being allowed to emit one unit of carbon. For the second permit, firms that failed to obtain the first permit would be expected to simply repeat their bids. The firm that successfully bid for the first permit could also bid for the second permit, but would be expected to bid a lower amount assuming their marginal profits are declining (i.e., their supply curve slopes upwards, as is normal). Regardless of whether the same firm wins the bid for the second permit, or a new firm, the selling price for the second permit would be lower.

This process would continue, with all successive permits selling for lower prices, until the last permit is auctioned off. The selling price of this permit, represented by P* in the graph, is the market-clearing permit price. We can also interpret P* as the marginal benefit, or profit, associated with the right to emit the Q_0th unit of carbon.

Figure 11. Determination of Carbon Permit Price

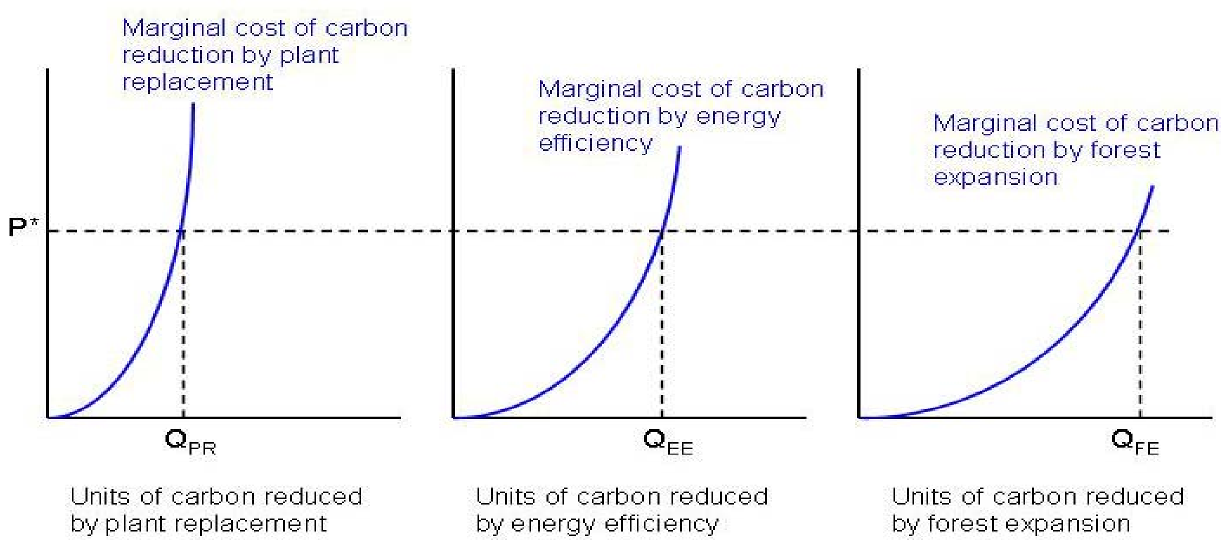


While all permits could theoretically sell for different prices, tradable permit markets are normally set up so all permits sell for the market-clearing price. This is the case for the acid rain program in the United States, operating since 1995 and widely-considered to be a successful emissions trading program. In that program, all parties interested in purchasing permits make their bids, indicating how many permits they are willing to purchase at what price. Whoever bids the highest gets the number of permits that they requested. Then the second-highest bidders get the number of permits they applied for, and so on until all permits are allocated. The selling price of all permits is the winning bid for the very last permit available. This would be P* in Figure 11. All bidders who bid below this price do not receive any permits.

Another important point is that each firm can choose to reduce their carbon emissions in a cost-effective manner. Firms have various options for reducing their carbon emissions. Figure 12 shows an example where a firm has three carbon reduction strategies: replacing older manufacturing plants, investing in energy efficiency, and funding forest expansion to increase carbon storage in biomass. In each case, the graph shows the marginal costs of reducing carbon emissions through that strategy. These marginal costs generally rise as more units of carbon are reduced, but they may be higher and increase more rapidly for some options than others.

In this example, replacement of manufacturing plants using existing carbon-emitting technologies is possible, but will tend to have high marginal costs—as shown in the first graph in Figure 12. Reducing emissions through greater energy efficiency has lower marginal costs, as seen in the middle graph. Finally, carbon storage through forest area expansion has the lowest marginal costs. The permit price P* (as determined in Figure 10) will govern the relative levels of implementation of each of these strategies. Firms will find it profitable to reduce emissions using a particular strategy so long as the costs of that option are lower than the cost of purchasing a permit. In this example, we see that forest expansion would be used for the greatest share of the reduction, while plant replacement would be used for the lowest share.

Figure 12. Carbon Reduction Options with a Permit System



Note: Marginal costs shown here are hypothetical.

This system combines the advantages of economic efficiency with a guaranteed result: reduction in the overall emissions level Q*. The problem, of course, is to achieve agreement on the initial allocation of permits. There may also be measurement problems, and issues such as whether to count only commercial carbon emissions, or to include emissions changes resulting from land use patterns.

Nations and corporations that participate in such a trading scheme can decide for themselves how much of each control strategy to implement, and will naturally favor the least-cost methods. This will probably involve a combination of different approaches. Suppose one nation undertakes extensive reforestation. It is then likely to have excess permits, which it can sell to a nation with few low-cost reduction options. The net effect will be the worldwide implementation of the least-cost reduction techniques.

Other Policy Tools: Subsidies, Standards, R&D, and Technology Transfer

There is an ongoing debate about the relative merits of carbon taxes and transferable permits (see Box 7). Although political problems may prevent the adoption of sweeping carbon taxes or transferable permit systems, there are a variety of other policy measures which have potential to lower carbon emissions. These include:

- *Shifting subsidies from carbon-based to non-carbon-based energy sources*. Many countries currently provide direct or indirect subsidies to fossil fuels. If these subsidy expenditures were redirected to renewable sources, especially in the form of tax rebates for investment, it could promote a boom in investment in solar photovoltaic, fuel cells, biomass and wind power – all technologies which are currently at the margin of competitiveness in various areas.
- *The use of efficiency standards to require utilities and major manufacturers to increase efficiency and renewable content in power sources*. A normal coal-fired generating plant achieves about 35% efficiency, while a high-efficiency gas-fired co-generation facility achieves from 75% to 90% efficiency. Tightening standards over time for plants, buildings, vehicles, and appliances would hasten the turnover of existing, energy-inefficient capital stock.
- *Research and development (R&D) expenditures promoting the commercialization of alternative technologies*. Both government R&D programs and favorable tax treatment of corporate R&D for alternative energy can speed commercialization. The existence of a non-carbon "backstop" technology significantly reduces the economic cost of measures such as carbon taxes, and if the backstop became fully competitive with fossil fuels, carbon taxes would be unnecessary.
- *Technology transfer to developing nations.* The bulk of projected growth in carbon emissions will come in the developing world. Many energy development projects are now funded by agencies such as the World Bank and regional development banks. To the extent that these funds can be directed towards non-carbon energy systems, supplemented by other funds dedicated specifically towards alternative energy development, it will be economically feasible for developing nations to turn away from fossil-fuel intensive paths, achieving significant local environmental benefits at the same time.

BOX 7. CARBON TAXES OR CAP-AND-TRADE

There is a lively debate regarding which economic approach should be used to reduce carbon emissions. There are important similarities, but also important differences, between carbon taxes and a transferable permits or cap-and-trade approach.

Both pollution taxes and cap-and-trade can, in theory, achieve a given level of pollution reduction at the least overall cost, with the same magnitude of price increases to final consumers, and the same amount of government revenue if all permits are auctioned off. Both approaches create a strong incentive for technological innovation, and can be implemented upstream in production processes to cover the same proportion of total emissions. Yet there are several important differences between the two approaches. Some of the advantages of a carbon tax include:

- In general, a carbon tax is considered to be simpler to understand and more transparent than a cap-and-trade approach.
- With technological change, a carbon tax will automatically further reduce carbon emissions. With a cap-and-trade program, technological change will instead reduce the price of permits.
- Perhaps the most important advantage of a carbon tax is that it provides greater price predictability. If businesses and households know what future taxes will be on fossil fuels and other greenhouse gas-emitting products, they can invest accordingly.

The advantages of a cap-and-trade system include:

- Even though a cap-and-trade system ultimately results in the same level of price increases to consumers and businesses, it avoids the negative connotations of a "tax." So a cap-and-trade system seems to generate less political opposition than a carbon tax.
- Some businesses favor cap-and-trade because they believe they can successfully lobby governments for free permits, rather than having to purchase them at auction. Distributing permits for free in the early stages of a cap-and-trade program can make it more politically acceptable to businesses.
- The greatest advantage of a cap-and-trade approach is that emissions are known with certainty because the government sets the number of available permits. Since the policy goal is ultimately to reduce carbon emissions, a cap-and-trade approach does this directly while a carbon tax does it indirectly through price increases.

The choice of instrument -- carbon tax or cap-and-trade – mainly depends on whether policymakers are more concerned with price uncertainty or emissions uncertainty. Price certainty is important because it allows for better long-term planning, but if the relevant policy goal is to reduce carbon emissions by a specified amount with certainty, then a cap-and-trade approach is more reliable, although it may lead to some level of price volatility.

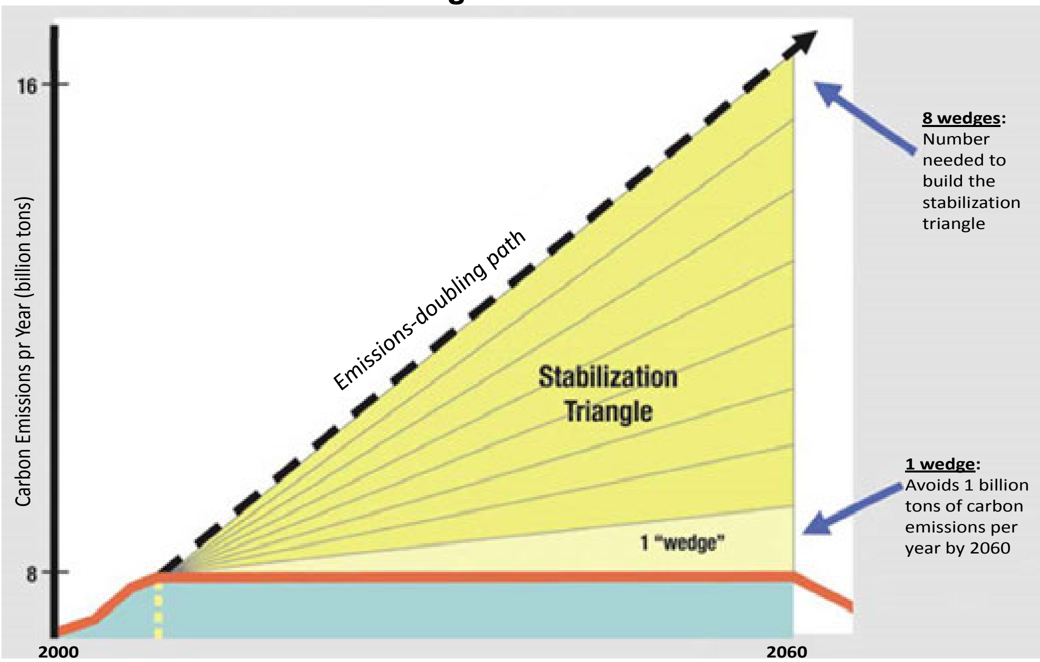
Source: Carbon tax advantages summarized from http://www.carbontax.org/faq/. For more detailed comparative analysis of carbon taxes versus cap-and-trade see Metcalf, Gilbert E. "Market-based policy options to control US greenhouse gas emissions." Journal of Economic Perspectives **23**, 2 (2009): 5-27.

The Technical Challenge

Meeting the climate change challenge requires economic policy instruments, but we can also evaluate policy effectiveness from a technical perspective. Some proposals for carbon mitigation require significant technological advancement, such as the widespread use of artificial photosynthesis or nuclear fusion. The future cost and technical feasibility of these technologies remains uncertain. Ideally, we could reduce carbon emissions sufficiently using existing technologies, or those reasonably expected to be available in the near future. In 2004 physical scientists Stephen Pacala and Robert Socolow determined that the carbon emissions could be stabilized over the next 50 years by scaling up existing technologies.[47]

In their analysis,[48] they take as the Business As Usual (BAU) scenario, an approximate doubling of carbon emissions over the next 50 years, from about 8 billion tons of carbon per year to16 billion tons.[49] They consider what actions could be taken that would effectively reduce total emissions by one billion tons by 2060. Each of these actions produces a **climate stabilization wedge** that moves emission down by one billion ton from the BAU scenario. Thus if eight of these wedges were implemented, carbon emissions would remain steady over the next 50 years, even as population expands and economies grow, as shown in Figure 13.

Figure 13. Climate Stabilization Wedges



Source: Pacala and Socolow, 2004

[47] Pacala and Socolow, 2004.
[48] See http://cmi.princeton.edu/wedges/intro.php
[49] At the time Pacala and Socolow wrote their paper, global carbon emissions were about 8 billion tons per year. Global carbon emissions in 2012 were approximately 9 billion tons.

They then reviewed a range of technological options, focusing on those technologies that were already available on an industrial level. Their proposed actions are broadly divided into three categories: increased energy efficiency, energy supply-side shifts, and carbon storage. These technologies would need to be implemented on a global scale.

Possible "wedges" include:

- Doubling automobile fuel efficiency
- Decrease the number of car miles traveled globally by half
- Doubling efficiency of coal-based electric plants
- Replacing coal plants with efficient natural gas plants
- Increasing wind capacity 10 times relative to 2004 levels
- Installing 100 times the 2004 capacity of solar electric generation
- Eliminating tropical deforestation
- Instituting carbon-saving conservation tillage in global agriculture
- Retrofitting buildings for maximum energy efficiency
- Capturing and storing carbon emissions from coal plants
- Doubling nuclear generating capacity
- Increase ethanol production twelve-fold through biomass plantations
- Using solar-produced hydrogen for fuel-cell cars

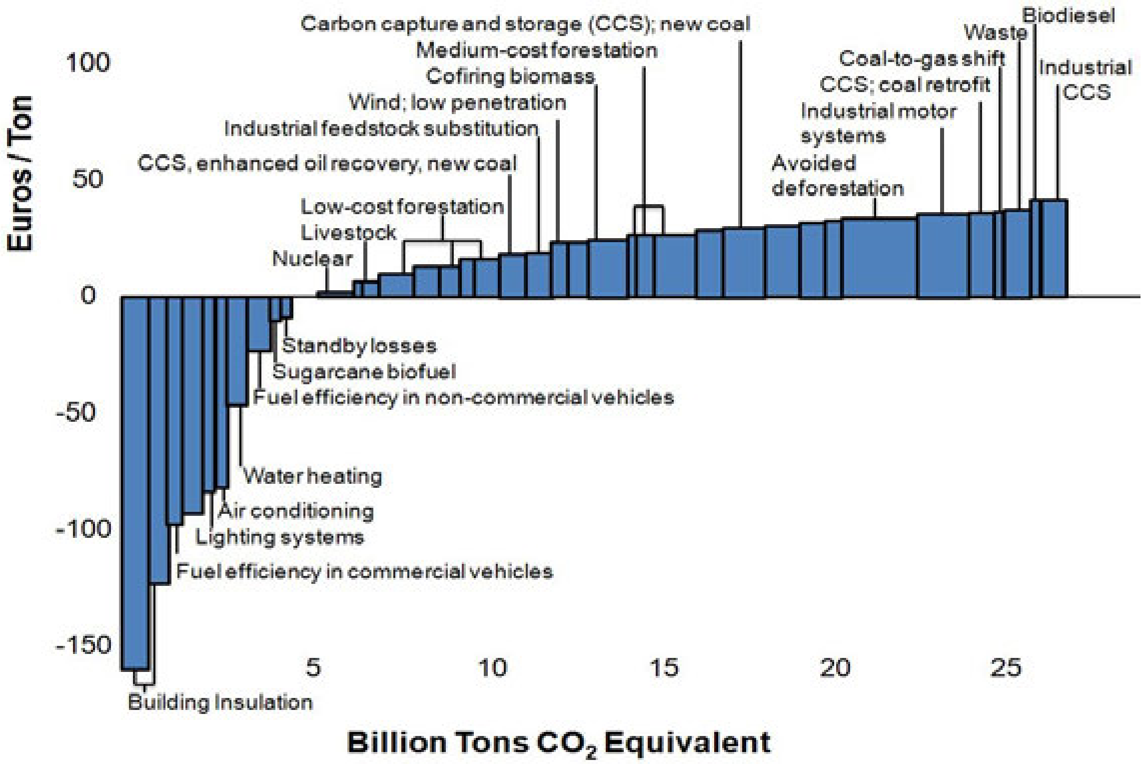
No one strategy will suffice to build the entire stabilization triangle. We should also note that the climate stabilization wedges analysis does not address the costs of each wedge, nor other environmental implications of options such as nuclear and biofuels. And if the goal is emissions reduction, rather than simply stabilization, more than eight wedges would be needed.

Obviously some wedges would be cheaper to implement than others. Depending on the social cost of carbon emissions, some wedges may not provide net benefits to society. For a more complete economic analysis, we need to also consider costs.

Another well-known analysis estimates both the costs and potential carbon reduction of more than 200 greenhouse gas mitigation, or abatement, options on a global scale.[50] Then the various options are arranged in order of cost, from lowest-cost to highest. The economic logic is that it makes sense to implement those actions that reduce carbon at the lowest per-unit costs first, and then proceed to more costly actions. The results of their analysis are presented in Figure 14.

[50] McKinsey & Company, 2009.

Figure 14- Global Greenhouse Gas Abatement Cost Curve to 2030



Source: McKinsey & Company, 2009.

The Y-axis indicates the cost of each abatement option, measured in euros per ton of carbon dioxide reduction per year and The X-axis tells us the cumulative reduction in CO_2 emissions relative to a BAU scenario, resulting from all those actions to the left.

How reliable is this abatement cost curve analysis? The McKinsey study has been subject to criticism both for underestimating and overestimating costs. Some actions that are technically feasible, like reducing emissions from agricultural and forestry practices, may be difficult to achieve in practice due to political and institutional barriers. Nonetheless, abatement costs curves such as those presented in the McKinsey study illustrate the basic principle that there are many low-cost or no-cost actions that could be taken to reduce carbon emissions.

Research, Development and Dissemination (RD &D) in the field of fuel efficiency is particularly important to implementing technological potential. One of the key policy tools that governments have in order to influence and encourage the private sector to invest more in the kind of RD & D that would have the desired impacts, is to impose standards, in particular on fuel efficiency. The US Government, which had been particularly lax in terms of standards for the past four decades, has recently, under the Obama Administration, taken much stringent measures to improve fuel efficiency in all the sectors of the American economy (Box 8).

BOX 8: THE US CORPORATE AVERAGE FUEL ECONOMY STANDARD

In the U.S. Corporate Average Fuel Economy (CAFE) standard was first enacted by Congress in 1975 to reduce energy consumption by increasing the fuel economy of cars and light trucks and recently the Obama Administration set standards to increase CAFE levels rapidly over the next several years.[1] As of 2009, automobile fuel-efficiency standards in the United States did not exceed 27.8 miles per gallon.

In 2009, President Obama proposed a new national fuel economy program that covers model year 2012 to model year 2016 and ultimately requires an average fuel economy standard of 35.5 miles per US gallon in 2016[1], a jump from the then average for all vehicles of 25 miles per gallon. In addition, in August of 2012, the Obama Administration finalized new standards that will increase fuel economy to the equivalent of 54.5 mpg for cars and light-duty trucks by Model Year 2025.

When combined with previous standards set by this administration, this move will nearly double the fuel efficiency of those vehicles compared to new vehicles currently on our roads. In total, the administration's national program to improve fuel economy and reduce greenhouse gas emissions will save consumers more than $1.7 trillion at the gas pump and reduce U.S. oil consumption by 12 billion barrels.[1]

Climate Change Policy in Practice

Climate change is an international environmental issue. Each individual nation has little incentive to reduce its emissions if other nations do not agree to similar reductions, because unilaterally reducing emissions could impose significant costs while having a negligible effect on overall emissions. Thus a binding international agreement is necessary, especially if the policy goal is to reduce emissions by 50-80%.

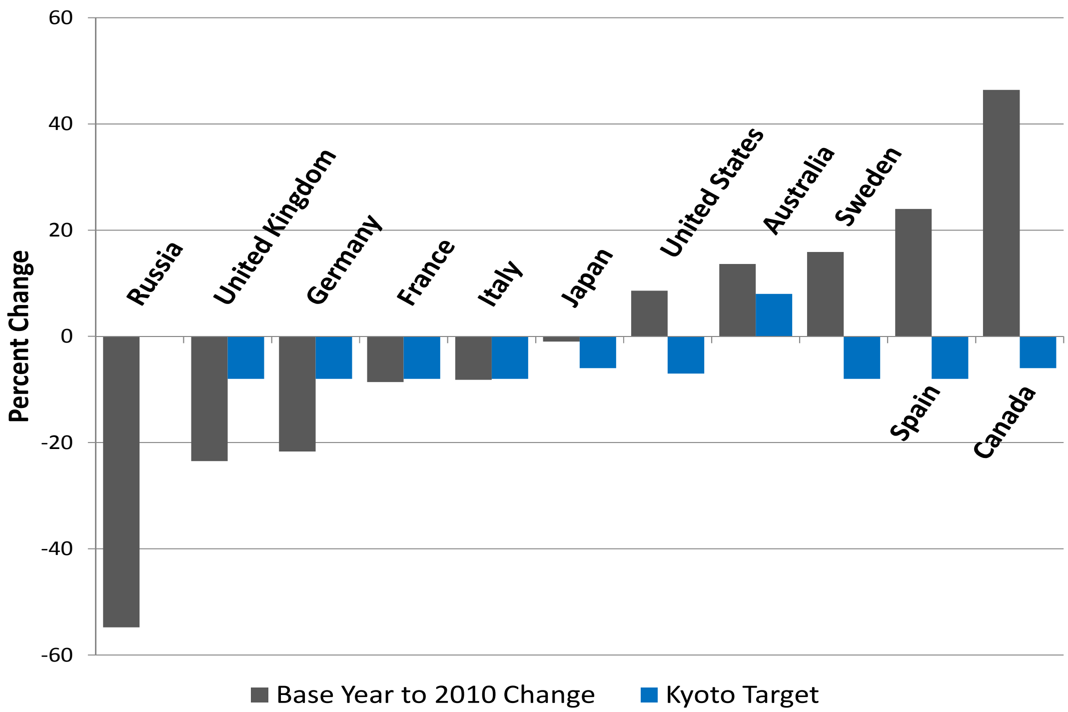
The most comprehensive international agreement on climate change has been the Kyoto Protocol. Under this treaty industrial countries agreed to emission reduction targets by 2008-2012 compared to baseline emissions in 1990. For example, the United States agreed to a 7% reduction, France to an 8% reduction, and Japan to a 6% reduction. Developing nations such as China and India are not bound to emissions targets under the treaty, an omission that the United States and some other countries protested. The Kyoto Protocol nonetheless entered into force in early 2005 after Russia ratified the treaty in November 2004. By 2012, 191 nations had signed and ratified the Kyoto Protocol. The United States signed the treaty in 1998 but has never ratified it.

To achieve the goals of the Protocol in a cost effective manner, the treaty includes three "flexibility mechanisms". One is the trading of emissions permits among nations that are bound by specific targets. Thus one nation unable to meet its target could purchase permits from another nation that reduces its emissions below its requirements. The European Union has set up a carbon trading system that went into effect in 2005 (see Box 9).

Another flexibility mechanism is **joint implementation**, whereby an industrial nation receives credit for financing emission-reducing projects in other countries bound to emissions targets, mainly in transitional countries such as Russia and Lithuania. The third is the **clean development mechanism**, whereby industrial nations can obtain credit for financing emission-reducing or emission-avoiding projects in developing nations not bound to specific emissions targets, including China and India.

As of early 2015, it seemed the Kyoto Protocol target of a 5% overall reduction for participating countries would be met. But as we see in Figure 15 the results for individual countries vary significantly. The figure compares each country's target to their actual emission change between their baseline year and 2010. For example, Germany's target under the Protocol was an 8% reduction, but by 2010 it had already achieved a 22% reduction, largely due to emissions reductions in former East Germany.

Figure 15. Progress toward Meeting Kyoto Protocol Targets



Source: UNFCCC greenhouse gas data (Note: includes land use and forestry adjustments)

Other countries on target to meet their Kyoto commitments include the Russian Federation, the United Kingdom, and France. Russia's dramatic decline in emissions is a result of its economic collapse in the early 1990s rather than a result of policies to reduce emissions. Without the significant drop in Russian emissions, the overall Kyoto target would clearly not be met. Russia has been able to gain income through trading emissions reductions under the flexibility mechanism, but these emissions reductions would have occurred anyway.

Countries not on target to meet their Kyoto commitments include Australia, Sweden, Spain, and Canada. In December 2011 Canada formally withdrew from the agreement because it would obviously fail to meet its obligation. The United States agreed to a 7% reduction in emissions relative to its 1990 baseline when it initially signed the treaty, but by 2010 its emissions had instead increased by 8%. In addition, Kyoto placed no restrictions on emissions from developing countries, meaning that overall global emissions have continued to grow.

Countries that fail to meet their commitments will need to make up for it during the post-Kyoto commitment period. Negotiations have been underway for several years to draft a successor to the Kyoto Protocol, as shown earlier in Box 2. Previous international climate change meetings have set deadlines to reach a post-Kyoto agreement, yet without success.

While progress on an international agreement continues to languish, climate change policies are being put into effect at other levels, from multinational agreements down to individual municipalities. To help it meet its obligations under the Kyoto Protocol, the European Union has set up a carbon trading system which went into effect in 2005 (see Box 9). Carbon taxes have been enacted in several countries including a nationwide tax on coal in India (about $1/ton, enacted in 2010), a tax on new vehicles based on their carbon emissions in South Africa (also enacted in 2010), a carbon tax on fuels in Costa Rica (enacted in 1997), and local carbon taxes in the Canadian provinces of Quebec, British Columbia, and Alberta that apply to large emitters or motor fuels.

In the United States, there have been numerous state and local-level initiatives to reduce emissions. The Regional Greenhouse Gas Initiative (RGGI) is a cap-and-trade program for emissions from power plants in nine Northeastern states.[51] Permits are mostly auctioned off (some are sold at a fixed price), with the proceeds used to fund investments in clean energy and energy efficiency. Permit auction prices have ranged from about $2-$4 per ton of CO_2. In California, a cap-and-trade program took effect in early 2012. At the local level, over 1,000 U.S. mayors have signed on to the U.S. Conference of Mayors' Climate Protection Agreement, setting a goal of meeting or beating Kyoto targets in their cities.[52]

While the United States has dropped out of the Kyoto Protocol, it has set its own climate change goals. Unlike the Kyoto Protocol, these goals are voluntary rather than binding. In 2009 President Obama set a goal of reducing **greenhouse gas emissions** by 17% below 2005 level by 2020[53]. As discussed in Box 8, the Obama administration has significantly tightened automobile emissions standards, with a goal of nearly doubling fuel efficiency by 2025. In June 2014, the U.S. Environmental Protection Agency (EPA) announced new standards to cut carbon pollution from power plants by 30% by 2030.[54] The Obama administration has also announced plans to cut methane

[51] http://www.rggi.org/
[52] http://www.usmayors.org/climateprotection/agreement.htm
[53] US Department of Energy, EERE News, 2009, available at http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=15650
[54] "EPA Seeks to Cut Power Plant Carbon by 30%," *New York Times*, June 1, 2014.

emissions from oil and gas production by up to 45% from 2012 levels, and committed the Federal Government, which produces more greenhouse gases than any other U.S. company or organization, will reduce greenhouse gas pollution from direct sources by 28% and indirect sources such as employee travel and commuting by 13% by 2020.[55]

The IPCC's Fourth Assessment Report (2007) suggested that industrialized countries need to reduce emissions between 25 and 40 percent below 1990 levels by 2020. IPCC's Fifth Report (2014) indicates that these trends were met by industrialized countries only because the great recession produced by the financial meltdown of 2008 significantly slowed down the economic growth of these countries.[56]

In the wake of the recession, efforts at economic recovery have come into conflict with previous climate goals. The European Union, which had led the way in terms of regulation, has already signified a reverse of commitment, facing declining industrial competitiveness and a recognition that its economy is unlikely to rebound. In January 2014, the EU's Commission proposed an end to binding national targets for renewable energy production after 2020, responding to business groups that argued that more stringent emissions targets could endanger Europe's feeble economic recovery. "Europe pressed ahead on other fronts, aiming for a cut of 40 percent in Europe's carbon emissions by 2030, double the current target of 20 percent by 2020 but the proposals were seen as a substantial backtrack by environmental groups." [57]

[55] The White House Statement, 2010, available at http://www.whitehouse.gov/the-press-office/president-obama-expands-greenhouse-gas-reduction-target-federal-operations and http://www.fieldtechnologies.com/us-government-committed-to-reducing-greenhouse-gas-emissions/; Coral Davenport, "Obama Administration Plans New Rules on Oil and Gas Industry's Methane Emissions," *New York Times*, January 13, 2015.

[56] IPCC 2007, 2013, 2014.

[57] Stephen Castle, Europe, Facing Economic Pain, May Ease Climate Rules, New York Times, Jan. 22, 2014

BOX 9: THE EUROPEAN UNION CARBON TRADING SYSTEM

In 2005 the European Union launched its Emissions Trading Scheme (EU-ETS), which covers more than 11,000 facilities that collectively emit nearly half of the EU's carbon emissions. The system works by putting a limit on overall emissions from high-emitting industry sectors which is reduced each year. Within this limit, companies can buy and sell emission allowances as needed. This 'cap-and-trade' approach gives companies the flexibility they need to cut their emissions in the most cost-effective way.

Under the EU-ETS, each nation develops a National Allocation Plan to determine the overall number of permits available in the country. Whereas the vast majority of emission allowances were previously given away for free by governments, from 2013 auctioning has been the main method of allocating allowances. Each allowance or permit gives the holder the right to emit one tonne (= metric ton) of CO_2, the main greenhouse gas, or the equivalent amount of two more powerful greenhouse gases, nitrous oxide (N_2O) and perfluorocarbons (PFCs).

The initial phase (2005-2007) of the EU-ETS produced disappointing results as permits were over-allocated, leading to a drop in the permit price from over €30 per tonne to less than €1 by the end of 2007. In the second phase (2008-2012), fewer permits were initially allocated, leading to relatively stable prices of around €15-€20/tonne for a few years. But by mid-2012 prices had fallen to €5-€10/tonne as the market again experienced a glut of permits.

Despite the volatility in prices, according to the EU the EU-ETS led to a reduction in emissions from large emitters of 8% between 2005 and 2010. Also, the costs of the EU-ETS have been less than expected, around 0.5% of European GDP. The third phase of EU-ETS will require more of the permits to be auctioned, include more greenhouse gases, and set an overall EU cap (reduced by 1.74% each year) rather than allowing individual nations to determine their own cap. By the end of the third phase, the program's goal is to reduce overall EU emissions 20% relative to 1990 levels.

New data demonstrate that the EU-ETS is genuinely contributing to reducing the EU's greenhouse gas emissions. In 2010 average emissions per installation were more than 17,000 tons CO_2e lower than in 2005, when the EU ETS was launched. This emission reduction corresponds to burning 7,500 tons of hard coal less per installation. Although emissions increased slightly in 2007 as Romania and Bulgaria joined the EU, and again in 2010 in line with the recovery from the economic crisis, average annual emissions per installation are now 8.3% below 2005 levels.

Sources: EU-ETS website (http://ec.europa.eu/clima/policies/ets/index_en.htm); Grubb, et al., 2009 ; Also from http://ec.europa.eu/clima/publications/index_en.htm#Ets

The Future of Climate Change Policy

Will the limited policy measures now being taken to control greenhouse emissions be sufficient? Recent evidence of increased rapidity of climate change suggests that the cumulative impact of emissions may be more severe than anticipated. Arctic ecosystems have shown clear signs of breakdown as temperatures rise, raising the possibility of feedback effects from tundra melting, which would further accelerate global warming.[58] A report prepared for the U.S. Department of Defense cited the possibility of large-scale drought in critical agricultural regions; a collapse of the North Atlantic Gulf Stream, causing an abrupt shift to much colder temperatures in Europe and the Northern U.S.; and widespread civil unrest and mass migration caused by disruption of water and food supplies.[59] The costs of such developments would be clearly very high, well into the higher range of estimates in Table 2, amounting to hundreds of billions of dollars per year.

The Intergovernmental Panel on Climate Change has estimated that the stabilization of atmospheric CO_2 levels would require reduction of CO_2 emissions to a small fraction of current levels. This goal is far beyond the Kyoto Protocol targets, and would require major policy intervention to redirect the world's economies towards non-carbon energy sources. The IPCC also finds, however, that opportunities for reductions of 30-70% in greenhouse gas emissions are available at a net cost below $100 per ton of carbon equivalent; a substantial portion of these cuts would have low or even zero marginal cost (reflecting the cost patterns shown in Figure 14). According to these figures, the IPCC's maximum estimated reduction, of 5 billion tons, could be achieved at a net cost of several hundred billion dollars – a large amount, but probably less than the cost of the high-scenario damages, even using standard discount rates.[60] Certainly the low-cost or no-cost cuts look like a good investment from an economic point of view.

Economic analysis could thus justify much more aggressive climate change policy, but significant political barriers stand in the way of such policies. One positive indication for continuation and strengthening of climate policies is that public opinion broadly favors action on climate change. In an international poll commissioned by the World Bank with 13,518 respondents in 15 countries— Bangladesh, China, Egypt, France, India, Indonesia, Iran, Japan, Kenya, Mexico, Russia, Senegal, Turkey, the United States, and Vietnam – majorities in all countries polled saw climate change as either "very serious" or "somewhat serious", with larger majorities in low-income countries (Bangladesh, Kenya, Senegal, and Vietnam), which are already experiencing destructive climatic events, viewing climate change as a very serious problem (World Bank,2010). In the U.S., a poll in early 2015 found that:

> An overwhelming majority of the American public, including nearly half of Republicans, support government action to curb global warming, according to a

---

[58] Richard B. Alley, "Abrupt Climate Change," *Scientific American* November 2004; Clifford Kraus, "Eskimos Fret as Climate Shifts and Wildlife Changes," *New York Times*, September 6, 2004.
[59] Peter Schwartz and Doug Randall, "An Abrupt Climate Change Scenario and Its Implications for U.S. National Security," October 2003, available at http://www.ems.org/climate/pentagon_climate_change.html.
[60] IPCC 2001, 2007, 2013, 2014.

poll conducted by *The New York Times*, Stanford University and the nonpartisan environmental research group Resources for the Future   the poll also found that two-thirds of Americans say they are more likely to vote for political candidates who campaign on fighting climate change.[61]

In another ground-breaking development, the U.S. and China reached agreement in November 2014 on a climate pact committing the two largest emitters to significant carbon reductions (see Box 10).

If significant progress is to be made in combatting climate change, the economic policy measures discussed in this module will play a central role. Political leaders and the public will determine how strongly we will respond to this major issue of the twenty-first century, but economic policies will be central to accomplishing the goals we choose.

BOX 10: U.S.-CHINA CLIMATE AGREEMENT

"China and the United States made common cause against the threat of climate change, staking out an ambitious joint plan to curb carbon emissions as a way to spur nations around the world to make their own cuts in greenhouse gases. The landmark agreement, jointly announced by President Obama and President Xi Jinping, includes new targets for carbon emissions reductions by the United States and a first-ever commitment by China to stop its emissions from growing by 2030."

It was hoped that the agreement could spur efforts to negotiate a new global climate agreement in Paris in December 2015. A climate deal between China and the United States, the world's No. 1 and No. 2 carbon polluters, was seen as essential to concluding a new global accord: "Unless Beijing and Washington can resolve their differences, climate experts say, few other countries will agree to mandatory cuts in emissions, and any meaningful worldwide pact will be likely to founder." In addition, the U.S. announced at the Group of 20 industrial powers meeting in November 2014 that it would commit $3 billion to a new international fund to help the world's poorest countries respond to the effects of climate change.

Although these developments were positive steps in the long and tortuous path towards global action on climate, many hurdles remained to be surmounted. India, another major developing nation, has indicated unwillingness to make any commitments that might impeded its economic growth. Nonetheless, indications that the U.S. and China are prepared to lead the way struck a more positive note in the run-up to the 2015 Paris talks.

Sources: Mark Landler, "U.S. and China Reach Climate Accord after Months of Talks," *New York Times*, November 11, 2014; Coral Davenport and Mark Landler, "U.S. to give $3 billion to climate fund to help poor nations, and spur rich ones," *New York Times* November 14.

[61] Coral Davenport and Marjorie Connelly, "Most Americans Support Government Action on Climate Change, Poll Finds," *New York Times*, January 30, 2015

5. SUMMARY

Climate change, arising from the greenhouse effect of heat-trapping gases, is a global problem. All nations are involved in both its causes and consequences. Currently developed nations are the largest emitters of greenhouse gases, but emissions by developing nations will grow considerably in coming decades. The most recent scientific evidence indicates that effects during the twenty-first century may range from a global temperature increase of 1.5°C (2.7F) to 4.8°C (8.6F). In addition to simply warming the planet, other predicted effects include disruption of weather patterns and possible sudden major climate shifts.

One approach to economic analysis of climate change is cost/benefit analysis. The benefits in this case are the damages potentially averted through action to prevent climate change; the costs are the economic costs of shifting away from fossil fuel dependence, as well as other economic implications of greenhouse gas reduction. Cost-benefit studies have estimated both costs and benefits in the range of several percent of GDP. However, the relative evaluation of costs and benefits depends heavily on the discount rate selected. Since the damages are expected to increase with time, the use of a high discount rate leads to a lower evaluation of the benefits of avoiding climate change. In addition, some effects such as species loss and effects on human life and health are difficult to measure in monetary terms. Also, depending on the assumptions used in economic models, the GDP impacts of policies to avoid climate change could range from a 3.5% decrease to a 1% increase in GDP.

Policies to respond to global climate change could be preventive or adaptive. One of the most widely discussed policies is a carbon tax, which would fall most heavily on fuels causing the highest carbon emissions. The revenues from such a tax could be recycled to lower taxes elsewhere in the economy, or they could be used to assist people in lower income brackets, who will suffer most from higher costs of energy and goods. Another policy option is tradable carbon emissions permits, which could be bought and sold by firms or nations, depending on their level of carbon emissions. Both these policies have the advantage of economic efficiency, but it has been difficult to obtain the political support necessary to implement them. Other possible policy measures include shifting subsidies away from fossil fuels and towards renewable energy, strengthening energy efficiency standards, and increasing research and development on alternative energy technologies.

The Kyoto Protocol mandating reductions of greenhouse gases by industrialized nations went into force in 2005, and Kyoto reduction targets have been partially met. Negotiations are continuing for a post-Kyoto climate regime including all countries, and a U.S.-China deal on climate policy was announced in 2014. Effective climate change policy in the future will require involvement of the U.S. as well as China, India, and other developing nations. Much more ambitious reduction targets will be needed to avoid the costs associated with long-term climate change.

KEY TERMS AND CONCEPTS

Adaptive measures: policies intended to adapt to adverse environmental impacts.

Avoided costs: costs avoidable through environmental preservation or improvement.

Cap-and-trade: see **Transferable permits**.

Carbon sinks: portions of the ecosystem with the ability to absorb certain quantities of carbon dioxide, such as forests, soils and oceans.

Carbon tax: a per-unit tax on goods and services based on the quantity of carbon dioxide emitted during the production or consumption process.

Clean development mechanism: a component of the Kyoto Protocol that allows industrial countries to receive credits for helping developing countries to reduce their carbon emissions.

Climate stabilization wedge: a policy action calculated to reduce carbon emissions by one billion tons.

Co-benefits: benefits gained from a policy, such as a carbon reduction policy, in other areas such as public health or national security.

Common property resource: a resource not subject to private ownership and available to all, such as a public park, or the oceans, or the capacity of the Earth and its atmosphere to absorb carbon.

Cost-benefit analysis: a tool for policy analysis that attempts to monetize all the costs and benefits of a proposed action, in order to determine the net benefits.

Cost-effectiveness analysis: a policy tool that determines the least-cost approach for achieving a given goal.

Discount rate: the annual rate at which future benefits or costs are discounted relative to current benefits or costs.

Elasticity of demand: the sensitivity of the quantity demanded to prices.

Externality: an effect of a market transaction on individuals or firms other than those directly involved in the transaction.

Feedback effects: the process of changes in a system leading to other changes that either counteract or reinforce the original change.

Global climate change: the changes in global climate, including temperature, precipitation, and storm frequency and intensity, that result from changes in greenhouse gas concentrations in the atmosphere.

Global commons: global common property resources such as the atmosphere and the oceans.

Greenhouse effect: the effect of certain gases in the earth's atmosphere trapping solar radiation, resulting in an increase in global temperatures and other climactic changes.

Greenhouse gas: gases such as carbon dioxide and methane whose atmospheric concentrations influence global climate by trapping solar radiation.

Greenhouse gas intensity: the amount of greenhouse gas emissions per unit of economic output.

Joint implementation: a component of the Kyoto Protocol whereby industrial nations can obtain credit for financing carbon-reducing projects in other industrial nations.

Marginal net benefit: the net benefit of the consumption or production of an additional unit of a resource; equal to marginal benefit minus marginal cost.

Mitigation: the effort to reduce the human sources of climate change, notably the emission of greenhouse gases (GHGs), including efforts to capture GHGs in natural or artificial sinks (areas where carbon and other GHGs can be stored).

Ocean acidification: increasing acidity of ocean waters as a result of dissolved carbon from CO_2 emitted into the atmosphere.

Pollution taxes: a per-unit tax based on the pollution associated with the production of a good or service.

Public goods: goods available to all, whose use by one person does not reduce their availability to others.

Precautionary principle: the principle that policies should take steps to avoid outcomes damaging to health or environment, even if the damaging outcomes cannot be predicted with certainty, and especially when such outcomes are potentially catastrophic or irreversible.

Preventive measures: policies intended to prevent adverse environmental impacts.

Revenue-neutral tax shift: policies designed to balance tax increases on certain products or activities with reductions in other taxes, such as a reduction in income taxes that offset a carbon-based tax.

Stock pollutant: a pollutant that accumulates in the environment, such as carbon dioxide and chlorofluorocarbons (CFCs).

Technology transfer: the process of sharing technological information or equipment, particularly among nations.

Transferable (tradable) permits: permits that allow a certain quantity of pollution and that may be traded among firms or nations; also known as cap-and-trade.

REFERENCES

Ackerman and Stanton, 2008, The Cost of Climate Change, Natural Resource Defense Council, available at http://www.nrdc.org/globalwarming/cost/cost.pdf

American Geophysical Union, 2014. Human-Induced Climate Change Requires Urgent Action. www.agu.org

Boden, T.A., G. Marland, and R.J. Andres, 2011. *Global, Regional, and National Fossil-Fuel CO2 Emissions*. Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, http://cdiac.ornl.gov/trends/emis/tre_glob_2008.html

Bradbury, Roger "A World without Coral Reefs," *New York Times* July 14, 2012*;* NOAA, 2010, "Scientists Find Rising Carbon Dioxide and Acidified Waters in Puget Sound" http://www.noaanews.noaa.gov/stories2010/20100712_pugetsound.html and http://www.pmel.noaa.gov/co2/story/Going+Green%3A+Lethal+waters

Cline, William R. *The Economics of Global Warming*. Washington D.C.: Institute for International Economics, 1992.

Dower, Roger C. and Zimmerman, Mary. *The Right Climate for Carbon Taxes, Creating Economic Incentives to Protect the Atmosphere*. Washington D.C.: World Resources Institute, 1992.

Ellerman, A. Denny et al., The European Union's Emission Trading System in Perspective, Pew Center on Global Climate Change, 2008,available at http://www.c2es.org/docUploads/EU-ETS-In-Perspective-Report.pdf

Fankhauser, Samuel. *Valuing Climate Change: the Economics of the Greenhouse*. London: Earthscan Publications, 1995.

Goodwin, Phil, Joyce Dargay, and Mark Hanly, 2004. "Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review," *Transport Reviews*, **24**(3): 275-292.

Harris, Jonathan M. and Brian Roach. *Environmental and Natural Resource Economics: A Contemporary Approach*. New York: Routledge, 2014.

Harris, Jonathan M. and Maliheh Birjandi Feriz, *Forests, Agriculture, and Climate: Economic and Policy Issues*. Tufts University Global Development And Environment Institute2011, http://www.ase.tufts.edu/gdae/education_materials/modules/REDD.pdf

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2013, The Physical Science Basis*, Summary for Policymakers. IPCC, 2013. http://ipcc.ch/

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014, Synthesis Report*. IPCC, 2014. http://ipcc.ch/

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2001, Volume 1: The Scientific Basis.* Cambridge, UK: Cambridge University Press, 2001.

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2007, Volume 1: The Physical Science Basis*. Available at http://www.ipcc.ch/

McKinsey & Company, 2009. *Pathways to a Low-Carbon Economy.* http://www.mckinsey.com/Client_Service/Sustainability/Latest_thinking/Pathways_to_a_low_carbon_economy

Nordhaus, William D., and Joseph Boyer, *Warming the World: Economic Models of Global Warming*. Cambridge, Mass: The MIT Press, 2000.

Nordhaus, William, "The Stern Review on the Economics of Climate Change, 2007", available at http://nordhaus.econ.yale.edu/stern_050307.pdf

Nordhaus, William. *The Climate Casino: Risk, Uncertainty and Economics for a Warming World.* New Haven and London: Yale University Press, 2013.

Parry, Martin, Nigel Arnell, Pam Berry, David Dodman, Samuel Fankhauser, Chris Hope, Sari Kovats, Robert Nicholls, David Satterthwaite, Richard Tiffin, and Tim Wheeler, 2009. "Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates." Report by the Grantham Institute for Climate Change and the International Institute for Environment and Development.

Roodman, David M. *Getting the Signals Right: Tax Reform to Protect the Environment and the Economy*. Worldwatch Paper # 134. Washington, D.C.: Worldwatch Institute, 1997.

Schwartz, Peter and Doug Randall, "An Abrupt Climate Change Scenario and Its Implications for U.S. National Security," October 2003, available at http://www.ems.org/climate/pentagon_climate_change.html

Smith, Alison. *The Climate Bonus: Co-benefits of Climate Policy.* New York: Routledge, 2013.

Socolow, Robert H., and Stephen W. Pacala, 2006. "A Plan to Keep Carbon in Check," *Scientific American*, p. 50-57, September 2006.

Stern, Nicholas, *The Economics of Climate Change: The Stern Review*. New York and Cambridge, U.K.: Cambridge University Press, 2007. http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/sternreview_index.htm

United Nations Framework Convention on Climate Change (UNFCCC), 2007.

Investment and Financial Flows to Address Climate Change. Climate Change Secretariat, Bonn.

U.S. Department of Energy, Energy Information Administration. *International Energy Outlook 2011*, Report No. DOE/EIA-0484 (2011).

World Bank, *World Development Report 2010: Development and Climate Change.* Washington, D.C.: The World Bank, 2010.

World Health Organization, 2009. "Protecting Health from Climate Change: Connecting Science, Policy, and People."

Zabarenko, Deborah "Ocean's Acidic Shift may be Fastest in 300 Million Years," *Reuters* March 1, 2012.

DISCUSSION QUESTIONS

1. Do you consider cost-benefit a useful means of addressing the problem of climate change? How can we adequately value things like the melting of arctic ice caps and inundation of island nations? What is the appropriate role of economic analysis in dealing with questions that affect global ecosystems and future generations?

2. Which policies to address climate change would be most effective? How can we decide which combination of policies to use? What kinds of policies would be especially recommended by economists? What are the main barriers to effective policy implementation?

3. The process for formulating and implementing international agreements on climate change policy has been plagued with disagreements and deadlocks. What are the main reasons for the difficulty in agreeing on specific policy actions? From an economic point of view, what kinds of incentives might be useful to induce nations to enter and carry out agreements? What kinds of "win-win" policies might be devised to overcome negotiating barriers?

EXERCISES

1. Suppose that under the terms of an international agreement, U.S. CO_2 emissions are to be reduced by 200 million tons, and those of Brazil by 50 million tons.

Here are the policy options that the U.S. and Brazil have to reduce their emissions:

USA:

Policy options	Total emissions reduction (million tons carbon)	Cost ($ billion)
A: Efficient machinery	60	12
B: Reforestation	40	20
C: Replace coal fueled power plants	120	30

Brazil:

Policy options	Total emissions reduction (million tons carbon)	Cost ($ billion)
A: Efficient machinery	50	20
B: Protection of Amazon forest	30	3
C: Replace coal fueled power plants	40	8

a) Which policies are most efficient for each nation in meeting their reduction targets? How much will be reduced using each option, at what cost, if the two nations must operate independently? Assume that any of the policy options can be partially implemented at a constant marginal cost. For example, the U.S. could choose to reduce carbon emissions with efficient machinery by 10 million tons at a cost of $2 billion. (Hint: start by calculating the average cost of carbon reduction in dollars per ton for each of the six policies).
b) Suppose a market of transferable permits allows the U.S. and Brazil to trade permits to emit CO_2. Who has an interest in buying permits? Who has an interest in selling permits? What agreement can be reached between the U.S. and Brazil so that they can meet the overall emissions reduction target of 250 million tons at the least cost? Can you estimate a range for the price of a permit to emit one ton of carbon? (Hint: use your average cost calculations from the first part of the question.)

2. Suppose that the annual consumption of an average American household is 2000 gallons of oil in heating and transportation and 300 ccf (hundred cubic feet) of natural gas. Using the figures given in Table 5 on the effects of a carbon tax, calculate how much an average American household would pay per year with an added tax of $10 per ton of carbon. (One barrel of oil contains 42 gallons.) Assume that this relatively small tax initially causes no reduction in the demand for oil and gas. Figuring 100 million

households in the United States, what would be the revenue to the U.S. Treasury of such a carbon tax?

What would be the national revenue resulting from a tax of $200 per ton of carbon? Consider the issue of the impact of increased prices on consumption – a reasonable assumption about consumption elasticity might be that a $200 per ton tax would cause the quantity of oil and gas consumed to decline by 20%. How might the government use such revenues? What would the impact be on the average family? Consider the difference between the short-term and long-term impacts.

WEB LINKS

1. http://epa.gov/climatechange/index.html The global warming web site of the U.S. Environmental Protection Agency. The site provides links to information on the causes, impact, and trends related to global climate change.

2. http://www.ipcc.ch/ The web site for the Intergovernmental Panel on Climate Change, a United Nations-sponsored agency "to assess the scientific, technical, and socioeconomic information relevant for the understanding of the risk of human-induced climate change." Their web site includes assessment reports detailing the relationships between human actions and global climate change.

3. http://www.wri.org/our-work/topics/climate World Resource Institute's web site on climate and atmosphere. The site includes country studies and a link to the U.S. Climate Action Plan.

4. http://www.unfccc.de/ Home page for the United Nations Framework Convention on Climate Change. The site provides data on the climate change issue and information about the ongoing process of negotiating international agreements related to climate change.

5. http://rff.org/focus_areas/Pages/Energy_and_Climate.aspx Publications by Resources for the Future on issues of energy and climate change. The site includes several research papers on the trading of greenhouse gas emissions permits.

6. http://www.globalcarbonatlas.org/?q=emissions Global Carbon Atlas is a platform to explore and visualize the most up-to-date data on carbon fluxes resulting from human activities and natural processes. The scientific team responsible for this site includes scientists from around the world, many of whom are also associated with the IPCC report.