Companion for Chapter 12
Climate Change

SUMMARY

- Climate change is the toughest public policy problem that humanity has ever faced for the following reasons:
  1. It is a global crisis: climate change affects every part of the planet, and every part of the world is contributing to it.
  2. When crises are global, as this one is, there are huge challenges in getting the world mobilized to take corrective action as there are sharp cross-country differences of opinion and interest on the proper way forward.
  3. It is a multigenerational crisis, and those who are going to be most affected are not yet born and therefore lack representation.
  4. The problem of GHG emissions goes to the core of a modern economy since the world economy has grown up as a fossil fuel-based economy.
  5. Climate change is a slow-moving crisis from the point of view of daily economic activities and the political calendar.
  6. The solutions to climate change are inherently complex; there is no single technology that would solve it, and the changes that are needed involve every sector of the economy.
  7. The energy sector is home to the world's most powerful companies, which are able to win political support through campaign financing and lobbying.
- The basic science of human-induced climate change was already worked out in the nineteenth century: in 1896, Swedish Nobel laureate Svante Arrhenius calculated by hand that a doubling of the CO_2 in the atmosphere would cause a rise in the mean Earth temperature of around 5°C.
- Solar radiation reaches the Earth as ultraviolet radiation; a large part reaches the surface, warming the Earth as a result. According to the concept of "black-body radiation," any warm body radiates electromagnetic energy, and the warmer the body, the greater the radiation. When the sun radiates energy to Earth, the Earth warms to just the temperature so that an energy balance is struck: the amount of energy radiated by the Earth equals the amount of energy radiated from the sun to the Earth.
- While the sun radiates ultraviolet radiations to the Earth's surface, the Earth radiates infrared radiation back to space, and the atmosphere contains molecules that trap part of that infrared radiation. These gases, called greenhouse gases (GHGs), change the energy balance: more ultraviolet hits the Earth than infrared radiation reaches space. The Earth then warms by just enough so that, at the higher temperature, the Earth radiates extra infrared radiation to balance the amount of solar radiation received.
- The major GHGs directly emitted by human activity are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Without the greenhouse effect, the average Earth temperature would be around -14°C; thanks to the greenhouse effect, it is around 18°C. Yet, if we put more GHGs into

the atmosphere, we warm the planet away from the fairly stable temperature range of the past 10,000 years.

- GHGs differ in their "radiative forcing" (heat-trapping capacity) and in their "residence time" (the time they spend in the atmosphere). CH_4 traps roughly 23 times more heat than CO_2, but its residence time is around 10 years rather than hundreds in the case of CO_2.
- The world is emitting around 55 billion tons of CO_2E (meaning the CO_2 equivalent tons, counting all six GHGs). The CO_2 part of that total is about 35 billion tons. CO_2 accounts for 77 percent of the greenhouse effect.
- In 1958, Charles Keeling started to measure seasonal levels of CO_2 in the atmosphere. The resulting record is known as the Keeling curve and shows that the atmospheric amount of CO_2 has been rising: from 330 ppm (one ppm or part per million means one CO_2 molecule per million of total molecules in the air) in 1958 to 400 ppm in 2013. This is a concentration of CO_2 not seen on the planet for 3 million years.
- Paleoclimate records show that when CO_2 concentrations were high as a result of natural processes, the Earth's temperature was also high. Since the Industrial Revolution until now, our planet has warmed by about 0.9°C. Even if we were to put no further GHGs into the atmosphere, the Earth would continue to warm by perhaps another 0.6°C because the oceans take a long time to warm up in response to the GHGs already emitted. This is called "thermal inertia."
- The consequences of a business as usual (BAU) trajectory for the planet could be absolutely dire. The temperature increase by the end of the century compared with preindustrial average temperature could be as much as 4-7°C. It is very difficult to determine how much GHGs humanity will emit on the BAU path, especially with a growing world economy. There are also uncertainties about the Earth's physical processes and the precise feedbacks from CO_2 to temperature increases. Yet, there is overwhelming evidence coming from many different directions that temperatures are increasing.
- The increase in temperature will have devastating effects including a major decline in crop yields, melting glaciers, rising sea levels threatening major cities, an increase in ocean acidification, loss of solid moisture, decline in rainfall, more frequent heat waves, droughts, floods, and extreme tropical cyclones. We shall note that certain regions like the Sahel, the U.S. Southwest, and the Mediterranean basin are extraordinarily vulnerable to higher temperatures and loss of solid moisture needed for agriculture.
- There are two different ways of responding to global warming. The first, mitigation, refers to reducing the GHGs causing human-induced climate change. The second, adaptation, refers to preparing to live more safely with the consequences of climate change. Mitigation is essential because there is a limit to how much we can adapt (e.g., if the global food supply is profoundly threatened). At the same time, it is important to adapt because climate change is happening and will continue to happen even if mitigation is highly successful.
- The highest mitigation priority is to reduce CO_2 emissions coming from the burning of fossil fuels. The second priority is to head off the deforestation which is causing CO_2 emissions from land-use changes. The third and fourth priorities are to reduce, respectively, methane and nitrous oxide emissions.
- One trajectory that would most likely avoid a 2°C increase holds CO_2 levels to around 450 ppm. A frequent assumption for a 2°C limit is that 2050 emissions should be somewhere between 10

and 15 billion tons of CO_2 compared with 35 billion tons in 2014. That would mean that emission per dollar of gross world product (GWP) would need to decline by a factor of six or more.

- The term decarbonization refers to a sharp reduction of CO_2 per dollar of GWP. There are three key steps for deep decarbonization: 1) *energy efficiency* to achieve greater output per unit of energy input; 2) *CO_2 emissions reduction per megawatt-hours of electricity* by increasing the amount of electricity generated by zero-emission energy; 3) *fuel shift* from direct use of fossil fuels to electricity based on clean primary-energy sources.
- Tapping renewable energy sources like wind and solar power faces two major challenges: 1) the greatest potential for renewable energy is often located far from population centers; 2) both wind and solar power are intermittent energy sources. As a result, tapping into renewable energy on a large scale will require: a) building new transmission lines to carry the power from remote locations to major population centers; b) developing technology for storing intermittent power sources; c) joining disparate renewable energy sources into a shared transmission grid, thereby helping to smooth out fluctuations. Large-scale, zero-carbon projects are within reach. Yet they are politically complex, require massive upfront investments, and need further R&D to bring them to fruition.
- Another potential way to reduce CO_2 emissions is carbon capture and sequestration (CCS), which can be done in two ways: 1) capture the CO_2 where is produced (e.g., the power plant) and then store it underground in a geological deposit; 2) remove the CO_2 from the atmosphere. This is called “direct air capture.” There are, however, vigorous technical and policy debates about the feasibility and cost effectiveness of large-scale CCS technologies.
- Geoengineering is another idea that suggests counteracting the effects of rising CO_2 by adding sulfate aerosol particles into the air to dim the incoming sunlight and thereby cool the planet. Another idea is to place a giant mirror in space to deflect some incoming solar radiation. A huge problem with these suggestions is that they might solve the "CO_2" problem only by introducing an even greater or more unpredictable problem.
- Due to the thermal inertia of the oceans and the inevitability of a further buildup of GHGs in the short-term, we need to prepare to live with at least some climate change. This implies more droughts, floods, heat waves, and extreme storms. Adaptation will require adjustments in many sectors. For example, crop varieties must be made more resilient to higher temperatures and more frequent floods and droughts; cities must be protected against rising oceans and storms.
- There is a need for corrective pricing to provide proper incentives for producers and consumers to reduce CO_2 emissions and avoid the externalities associated with CO_2 emissions: users of fossil fuels should be required to pay a higher price than users of clean energy in order to shift the incentives to a low-carbon economy. One way is to impose a carbon tax equal to the social cost of the CO_2 emitted by the fuel. A related alternative is to create a permit system in which emitters of CO_2 must buy a permit to do so.
- One of the greatest obstacles to an agreement on climate change is global politics. Negotiations have been largely stuck since 1992, when the world’s governments adopted the United Nations Framework Convention on Climate Change (UNFCCC) at the Rio Earth Summit. The Kyoto Protocol, signed in 1997, was the first major attempt to implement the treaty, but developing

countries were not obligated to meet specific emissions targets and the United States never signed it.

- China has now become the world's largest GHG emitter, and other countries are urging it to increase its climate mitigation. China is deeply vulnerable to climate change and thus has reasons to participate in a global mitigation effort.
- As the UNFCCC countries met for their annual meeting, the Conference of the Parties (COP), in 2011, they agreed that they would reach a more definitive agreement on climate control by 2015. Such agreement would include binding commitments to mitigate GHGs emissions for every country. There is therefore potential for the United States, China, and other major emitters to agree on a new approach, 23 years after the UNFCCC was signed.

EASY

REVIEW

Concepts and Definition

Can you define or explain the significance of these concepts?

Svante Arrhenius	Direct-air capture
Greenhouse gases (GHGs)	Geoengineering
Keeling Curve	Social costs of energy use
Parts per million (ppm)	Carbon tax
Mitigation	Permit system
Adaptation	Feed-in tariffs
Decarbonization	Liquefied natural gas (LNG)
Energy efficiency	Keystone XL Pipeline
Fuel shift	Hydrofracking
Photovoltaic system	Cap-and-trade
Wind power	United Nations Framework Convention on Climate Change (UNFCCC)
Geothermal energy	Conference of the Parties (COP)
DESERTEC	Kyoto Protocol
Grand Inga Dam Project	Annex I countries
Carbon capture and sequestration (CCS)	

Check your facts

1) Who performed the first calculation of how much temperature increase would result from a doubling of CO_2 in the atmosphere? When was this?
2) According to this first calculation, by how many degrees would the temperature increase?
3) What would the average Earth temperature without the greenhouse effect be?
4) What is the residence time of CO_2 molecules in the atmosphere?
5) What percent of the total greenhouse effect of the six GHGs does CO_2 account for?
6) Who started monitoring the amount of CO_2 in the atmosphere and when?
7) What level of atmospheric CO_2 concentration (in ppm) was reached in 2013?
8) How many ppm of CO_2 do 16 billion tons of CO_2 in the atmosphere equal to?
9) Approximately how much temperature increase (in °C) should we expect from a BAU path?

10) At present, by how much has the sea level already risen on the northern coast of the United States?
11) By how many degrees Celsius above pre-industrial mean temperature has the world agreed on several occasions to limit the increase in average global temperature?
12) How many billions of tons are one petagram?
13) What is the estimation of the additional warming of the average Earth temperature after the oceans warm in line with GHG concentrations?
14) In what range is the social cost of an extra 1-ton emission of CO_2 estimated to be?
15) When was the UNFCCC adopted?
16) When was the Kyoto protocol signed?
17) What was the agreed percentage reduction of CO_2 emissions for high-income countries under the Kyoto Protocol?

Answers: 1) 1896; 2) a 5°C rise; 3) around -14°C (6.8 °F); 4) 5-200 years; 5) 77%; 6) Charles Keeling in 1958; 7) 400 ppm; 8) 2 ppm; 9) 4-7°C; 10) by 1/3 of a meter; 11) 2°C; 12) one; 13) Additional 0.6°C warmer; 14) $25-100 per ton; 15) 1992; 16) 1997; 17) 20% reduction by 2012 compared with 1990

Review questions

What was the main concern expressed in 1972 at the UN Stockholm conference and in the book *Limits to Growth*?
What are some reasons why climate change is one of the toughest public policy problems?
Why does the fact that climate change is a global problem make it complicated to solve?
Why does the fact that climate change is an intergenerational problem make it complicated to solve?
What do we mean when we say that climate change is a "slow-moving crisis?"
What is the basic science behind climate change? Explain the greenhouse effect.
How do the different GHGs compare in terms of radiative forcing and residence time?
What are the implications of the Keeling curve?
What do the different oscillations on the Keeling curve mean?
What are the predicted consequences of climate change?
What are the risks involved in a 2°C increase? In a 3°C increase? In a 4°C increase?
Why is it necessary to pursue both mitigation and adaptation?
What are the three necessary steps to decarbonizing the global economy?
What are some of the challenges of renewable energy at a large scale?
What are some barriers to technological transition in the energy sector?
What are some of the implications of large-scale biofuels deployment?
What are some of the challenges of carbon capture and storage?
Provide examples of potential large-scale, low-carbon energy projects.
How does electricity produced with low-carbon energy sources offer a way to reduce carbon emissions in other sectors of the economy?
What are some of the ways the economy can adapt to a warming world?
Why do economists emphasize the need for corrective pricing of activities producing GHGs?
How could a tax or permit market be useful to solving climate change, and how would they differ from each other?
What do we mean by the "double-edged sword" of technological advance?

Why have the global politics of climate change been stuck since 1992?
What happened in Rio in 1992?
Why do we consider the Kyoto Protocol to have failed?
What are some of the reasons why China might want to reach a global agreement?
How can political systems hamper the reaching of an agreement?

DATA ACTIVITIES

EASY

A. CO_2 emissions per capita

Match each country with its correct level of CO_2 emissions per capita in 2010 (in metric tons per capita). Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacturing of cement in the country.

Brazil •	• 43.0
Canada •	• 17.5
China •	• 14.6
European Union •	• 12.2
India •	• 7.4
Mali •	• 6.2
Mexico •	• 3.8
Qatar •	• 2.2
Russian Federation •	• 1.6
United States •	• 0.1

Source: World Bank Indicator Database

Answers: 43.0 - Qatar; 17.5 - United States; 14.6 - Canada; 12.2 - Russian Federation; 7.4 - European Union; 6.2 - China; 3.8 - Mexico; 2.2 - Brazil; 1.6 - India; 0.1 - Mali.

EASY

B. Responsibility and vulnerability

Go to http://www.carbonmap.org/ and explore the different world maps. In particular, look at how the map changes when visualizing different types of responsibility (extraction, emissions, consumption etc.).

1) What are the top two countries with the highest levels of CO_2 emissions from fossil fuel use and cement production in 2013?
2) Which parts of the globe appear bigger on the map when we look at historical responsibility?
3) Using the "People at risk" tab, what are the two countries with the largest number of people already suffering from drought, floods, or extreme temperature in 2013?
4) What are the top 3 countries with highest fossil fuel reserves in 2013?

Answer: 1) China and the United States; 2) Europe and the United States; 3) China and India; 4) United States, Venezuela and Russia

EASY

C. Climate at a glance with NOAA

Explore the "Climate at a glance" database from the National Oceanic and Atmospheric Administration (NOAA) at http://www.ncdc.noaa.gov/cag/time-series. On the website, you can visualize global monthly data for temperature and precipitation since 1880. Often climate data is expressed in terms of "anomalies." The term temperature anomaly means a departure from a

reference value or long-term average. A positive anomaly indicates that the observed temperature was warmer than the reference value, while a negative anomaly indicates that the observed temperature was cooler than the reference value. For more information, read the NOAA FAQ on global surface temperature anomalies (https://www.ncdc.noaa.gov/monitoring-references/faq/anomalies.php).
Plot the time series of annual global land and ocean temperature anomalies from 1880 to 2010. Display a per-decade trend.

1) In what year did the anomalies all start to be positive?
2) What is the value of the trend slope?
3) What is the value of the highest anomaly and in what year was it?
4) Plot a similar graph for land and ocean separately. Do you see evidence that the land has been warming faster than the oceans?

Click on the tab "U.S." and plot a time series of annual Palmer Drought Severity Index from 1895 to 2015 for the United States. You can learn more about the various Palmer indexes at https://www.ncdc.noaa.gov/oa/climate/research/prelim/drought/palmer.html.

5) Do you observe a trend?
6) Now do the same thing but for the state of California. Do you observe a trend?

To learn about which states are affected by severe drought conditions, click on "Mapping" and then on "U.S. Mapping" to open the following map: http://gis.ncdc.noaa.gov/map/cag/#app=cdo.

7) Select "PDSI" in the right-hand side panel. What were the states with a PDSI of -3.01 or lower in June 2015? You can go back to the time series and check for yourself whether or not these states seem to have a trend for worsening drought conditions.
8) Finally, click on "State of the Climate" in the left-hand side panel, and click on the full report of global summary information for the last month. There, you should be able to see a map of selected significant climate anomalies and events for that month. Choose one of these events and write a short paragraph summary of what happened, using external sources as needed.

Answers: 1) 1977; 2) +0.07°C per decade; 3) 0.74°C in 2014; 4) Yes, the trend for land is +0.10°C/decade while it is +0.5°C/decade for the oceans; 5) Not really; 6) Yes, about -0.11/decade; 7) Florida, California, Oregon, Washington, Idaho, Montana, Utah, Connecticut

MEDIUM

D. Energy production and consumption

Using the US Energy Information Administration's website (http://www.eia.gov/beta/international/data/browser), download data for all countries of total primary energy production, total primary energy consumption per capita, total population, and per capita carbon dioxide emissions from consumption of energy.

1) Plot a cross-section of per-capita CO_2 emissions against per-capita energy use for the year 2011. Provide explanations for any observed trend and major outliers.
2) Using data on population and total primary energy production, create a new variable "per-capita energy production."
3) Plot a cross-section of per-capita energy use against per-capita energy production for the year 2011. Provide explanations for any observed trend and major outliers.

Using the World Bank Indicator database (http://data.worldbank.org/indicator/all), download data on "Pump price for gasoline (US$ per liter)." Using the US Energy Information Administration's website listed above, download data on total petroleum (and other liquids) production.

4) Using data on population and total petroleum (and other liquids) production, create a new variable "per-capita oil production."
5) Plot a cross-section of per-capita oil production against Pump price for gasoline (US$) for the year 2011. Provide explanations for any observed trend and major outliers.
6) Discuss why learning about energy production and consumption might be useful in the context of climate change.

MEDIUM

E. CO_2 emissions (idem to exercice in E in Chapter 6)

In this exercise, we will take a look at CO_2 emissions, CO_2 emissions per unit of GDP, and CO_2 emissions per capita, for high, middle and low-income countries, and for the whole world.
From the WDI database (http://data.worldbank.org/indicator/all), download as an excel document the following indicators for the whole time period available (1960s to today): CO_2 emissions (kt), CO_2 emissions (kg per 2011 PPP $ of GDP), and CO_2 emissions (metric tons per capita). We are interested in the data for High Income (HIC), Middle Income (MIC), Low Income (LIC), and World (WLD).

1) On the same graph, plot CO_2 emissions against time for high, middle, and low-income countries and for the whole world.
2) On the same graph, plot CO_2 emissions per capita against time for high, middle, and low-income countries and for the whole world.
3) On the same graph, plot CO_2 emissions per unit of GDP (2011 PPP $) against time for high, middle, and low-income countries and for the whole world.
4) Briefly discuss your findings in terms of decoupling.
5) Plot a cross section of CO_2 emissions per capita against GDP per capita for all the countries of the world in 2010. In the World Bank database, use the indicator GDP per capita, PPP (constant 2011 international $). Discuss. Do you see any interesting patterns?

HARD

F. Keystone XL Pipeline

Based on your own research and readings, write a 3-4 page paper about the costs and benefits of the Keystone XL Pipeline. Highlight the points that might have convinced the Obama administration to veto the bill on February 24, 2015.

HARD

G. The Ozone layer and the Montreal Protocol

Based on your own research and readings, write a 3-4 page paper about the lessons the world can learn from the challenge of ozone depletion and the Montreal Protocol in order to move toward a successful agreement for climate change.

HARD

H. Case study analysis

Select a policy, program, or project related to climate change mitigation or adaptation that has already been implemented or is in the process of being implemented. Write a paper (about 15 pages) to analyze the project. You will first briefly introduce the project. Then, spend most of the paper evaluating strengths and weaknesses, and conclude with lessons for the future.

DISCUSS AND DEBATE

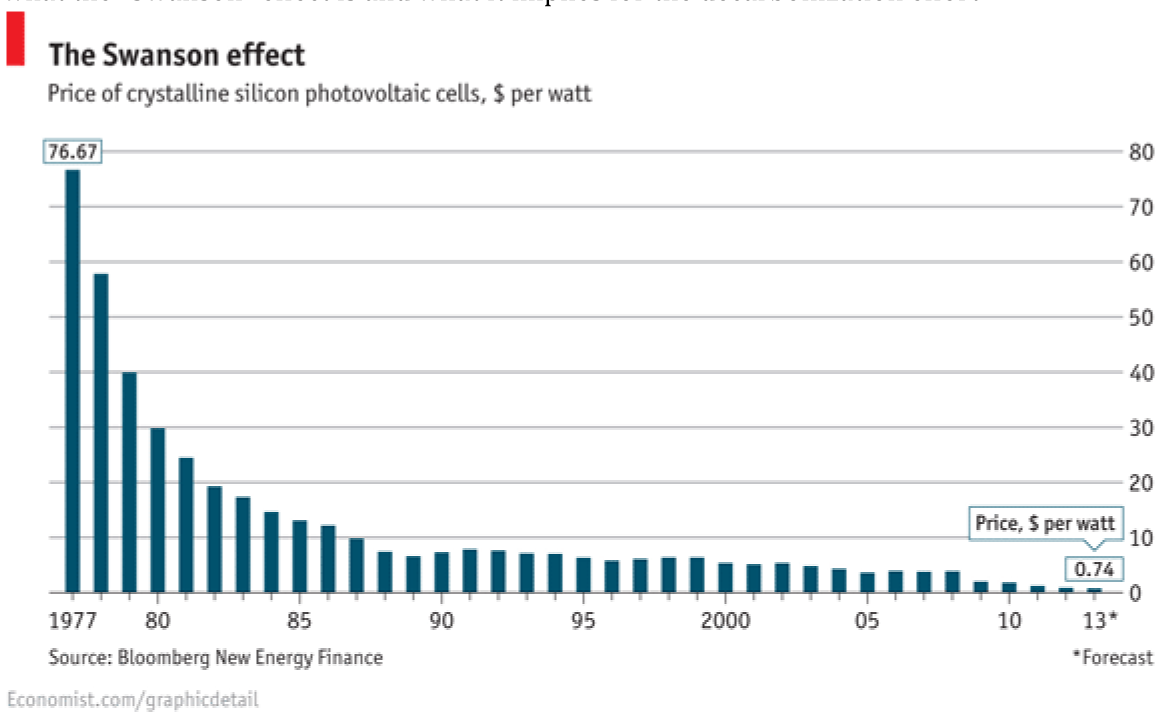
1) In your view, what are two of the biggest barriers for addressing climate change? How hopeful are you that humanity will find ways to overcome them?

2) Discuss the relationship between technological innovation and climate change.

3) How does climate change relate to the "tragedy of the commons" defined in Chapter 6?

4) To what extent can advances in low-carbon technologies be "directed"?

5) Take a look at the graph below, published in *The Economist* on December 28, 2012. Discuss what the "Swanson" effect is and what it implies for the decarbonization effort.



6) Using the case study below, discuss the various policy tools that can be used to tackle climate change.

7) President Reagan signed Executive Order 12291 on February 17, 1981, which stated "regulatory action shall not be undertaken unless the potential benefits to society from the regulation outweigh the potential costs to society**.**" In your opinion, what are the implications of this Executive Order for climate change?

8) What are some of the political or geopolitical factors that have stalled the UNFCCC negotiations?

9) Discuss some of the best strategies (in your opinion) to reaching a global agreement with binding commitments in 2015, taking into account the various levels of wealth, historical emissions, and proven reserves of fossil fuels of different countries?

10) Discuss whether or not it is feasible to avoid catastrophic climate change, considering technological, environmental, economic, and political perspectives. Support your answer with quantitative evidence as well as qualitative arguments, using the references from the book as well as any other relevant sources.

CASE STUDY

The growing use of emission trading

"Cap and trade" emissions trading systems allow environmental damage to be reflected in market prices. By capping emissions, they guarantee that the desired level of emission reduction is achieved; and by allowing trading, they give business the flexibility to find the cheapest solutions, while rewarding investment in low-carbon technologies and innovation.

Cap and trade systems work by setting a cap on total carbon dioxide emissions from the plants or countries covered. Emissions allowances are then created and form a common trading currency, with one allowance giving its owner the legal right to emit 1 ton of carbon dioxide. When the actual emissions of companies or countries are below the legal cap, they can sell their permits to actors with emissions above the cap — thus enabling them to profit from their carbon savings.

Cap and trade systems are already in place in the European Union, Norway, New Zealand, Switzerland and a number of north-eastern states of the United States. They are also being developed and implemented in Australia, China, India and the Republic of Korea, as well as in California and some Canadian provinces, and debated in Japan and elsewhere.

Where emissions allowances are allocated through auctioning, as occurs partially in the European Union emissions trading scheme and the Regional Greenhouse Gas Initiative system in the north-eastern United States, they provide an important source of revenue which can be used to fund climate action or other public goods.

The European Union emissions trading system is the largest cap and trade system, launched in 2005, covering carbon dioxide emissions from around 11,500 installations across Europe and around 40 per cent of European Union greenhouse gas emissions. The European Union-wide cap for 2008-2012 amounts to 2.081 billion allowances per year. Use of offset credits from outside the European Union (including from the Clean Development Mechanism and other sources) is allowed, subject to quantitative and qualitative limits, making the European Union emissions trading system the main driver of the international carbon market and providing a clear incentive for action.

India is working on an emissions trading scheme for key local pollutants in three large states as a new approach to environmental regulation in the country. A pilot project has been launched in three states. In addition, India has already launched an ambitious "Perform, Achieve and Trade" mechanism, which is intended to encourage 700 of the country's most energy-intensive units to become more energy-efficient and in the process help reduce India's greenhouse gas emissions by 25 million tons of carbon dioxide equivalent per year by 2014/15. About 700 of the most energy-intensive industrial units and power stations in India would be mandated to reduce their energy consumption by a specified percentage. The percentage reduction for a facility would depend on its current level of efficiency: the most efficient facility in a sector would have a lower percentage reduction requirement, while less efficient facilities would face larger percentage reduction requirements.

Australia recently introduced a carbon pricing mechanism as a key part of a plan for a clean energy future to underpin future national prosperity. Social equity is a key element of the scheme, which provides support to low-income households to assist with the impact of the carbon price.

In China, pilot projects on emissions trading have been launched in five cities and two provinces with the aim of gradually putting a regional carbon emissions trading system in place by 2015.

Source: Report of the Secretary General's Global Sustainability Panel. Resilient People, Resilient Planet: A Future Worth Choosing, Chapter 2: Progress Towards Sustainable Development pp. 15-27. Box 13.
https://en.unesco.org/system/files/GSP_Report_web_final.pdf

FURTHER READING

In this report released for the British government, economist Nicholas Stern examines the evidence on the economic impacts of climate change itself, and explores the economics of stabilizing greenhouse gases in the atmosphere.
Stern, Nicholas. 2006. The Stern Review Report: The Economics of Climate Change. London: HM Treasury. http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/media/4/3/executive_summary.pdf

- **Climate science**

This IPCC report considers new evidence of climate change based on many independent scientific analyses from observations of the climate system, paleoclimate archives, theoretical studies of climate processes, and simulations using climate models.
IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

This document summarizes the state of climate-change science, making clear what is well-established, where consensus is growing, and where there is still uncertainty.
National Academy of Sciences & Royal Society. (2014). Climate change evidence & causes.

Climate scientist James Hansen discusses whether human-induced global warming can cause ice sheet melting measured in meters in the coming centuries.
Hansen, James E. 2005. "A Slippery Slope: How Much Global Warming Constitutes 'Dangerous Anthropogenic Interference'?" Climatic Change 68(3): 269–279.

This study uses paleoclimate data to assess climate sensitivity and potential human-induced climate effects, and highlights implications for ice sheet melting.
Hansen, James, and Makiko Sato. 2012. "Paleoclimate Implications for Human-Made Climate Change." In Climate Change: Inferences from Paleoclimate and Regional Aspects, ed. André Berger, Fedor Mesinger, and Djordjie Šijački, 21–48. Heidelberg: Springer.

This article argues that we can state, with a high degree of confidence, that extreme anomalies such as those in Texas and Oklahoma in 2011 were a consequence of global warming because their likelihood in the absence of global warming was exceedingly small.
Hansen, James, Makiko Sato, and Reto Ruedy. 2012. "Perception of Climate Change." Proceedings of the National Academy of Sciences 109(37): E2415–E2423.

This is the original article in which Arrhenius argues that the concentration of carbon dioxide relates to the mean temperature of the planet.
Arrhenius, Svante. 1896. "On the Influence of Carbonic Acid in the Air Upon the Temperature of the Ground." *Philosophical Magazine and Journal of Science* 5(41): 237–276.

This website displays a daily record of atmospheric carbon dioxide from the Scripps Institution of Oceanography at UC San Diego.
Scripps Institution of Oceanography. 2014. "The Keeling Curve." Accessed June 4, 2014. https://scripps.ucsd.edu/programs/keelingcurve/

- **Impacts and Adaptation**

This IPCC report evaluates how patterns of risks and potential benefits are shifting due to climate change and considers how these risks can be reduced and managed through adaptation and mitigation.
IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

This 2010 edition of the world development report focuses on the implications of climate change for development.
World Bank. (2010). World development report: Development and climate change.

- **Mitigation and decarbonization**

This IPCC report assesses literature on the scientific, technological, environmental, economic, and social aspects of mitigation of climate change.
IPCC, 2014: Summary for Policymakers, In: Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

This report describes the deep decarbonization pathways project at a country level and presents preliminary findings on technical, feasible pathways to deep decarbonization.
SDSN Report: Pathways to Deep Decarbonization http://unsdsn.org/wp-content/uploads/2014/09/DDPP_Digit_updated.pdf

This study analyzes the infrastructure and technology path required to meet California's goal of an 80% reduction in greenhouse gases emissions below 1990 levels, using detailed modeling of infrastructure stocks, resource constraints, and electricity system operability.
Williams, James H., Andrew DeBenedictis, Rebecca Ghanadan, Amber Mahone, Jack Moore, William R. Morrow III, Snuller Price et al. 2012. "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity." Science 335(6064): 53–59.

This article argues that for conventional CCS to become a successful climate mitigation technology, it may need to be complemented with air capture, removing CO_2 directly from the atmosphere.
Lackner, Klaus S., Sarah Brennan, Jürg M. Matter, A.-H. Alissa Park, Allen Wright, and Bob van der Zwaan. 2012. "The Urgency of the Development of CO2 Capture from Ambient Air." Proceedings of the National Academy of Sciences 109(33): 13156–13162.

This report synthesizes the results of a two-year study of California's energy future. In particular, it assesses technology requirements for reducing greenhouse gas emissions in California to 80% below 1990 levels by 2050.
California Council on Science and Technology. (2011). California's energy future: the view to 2050: summary report. California Council on Science and Technology.

In this 2007 article, Pacala and Socolow argue that humanity already possessed the fundamental scientific, technical, and industrial know-how to solve the carbon and climate problem for the next half-century.
Pacala, S. and R. Socolow, 2004. "Stabilization wedges: Solving the climate problem for the next 50 Years with current technologies, *Science* 305: 968-972

- **International treaties**

United Nations Framework Convention on Climate Change (UNFCCC), 1992:
http://unfccc.int/resource/docs/convkp/conveng.pdf

United Nations Convention to Combat Desertification (UNCCD), 1992:
http://www.unccd.int/Lists/SiteDocumentLibrary/conventionText/conv-eng.pdf

Kyoto Protocol to the United Nations Framework Convention on Climate Change, 1998:
http://unfccc.int/resource/docs/convkp/kpeng.pdf