Economics of Climate Change

Reading for Microeconomics class (Short)

The material is sourced from the following undergraduate textbooks :

Chiang, E. (2019). Microeconomics: Principles for a Changing World (5th ed.). Worth Publishers. ISBN 978-1319218393.

The CORE Econ Team (2023) The Economy 2.0: Microeconomics Open access e-text https://core-econ.org/the-economy/.

Hal R. Varian (2019). Intermediate Microeconomics: A Modern Approach (9th ed.). W.W. Norton & Co. ISBN: 978-0393689877.

Paul Krugman, Robin Wells (2018). Microeconomics (5th ed.). Worth Publishers. ISBN: 978-1-319-098780.

No additional content has been added. We modified the layout to fit the format of this document, adding three titles for the main sections. We also removed irrelevant details, such as references to page numbers or figures that are not included in this document.

I – The Science of Climate Change

[Chiang, 2019, pp. 799-802]

Among the most significant economic issues facing the world today is the effect of human actions on the environment. There is scientific consensus that without a significant reduction in the production of greenhouse gases, which engulf the atmosphere and lead to global warming, irreversible damage to the climate, ecosystems, and coastlines will result. However, the course of action needed to address climate change deals with equity issues that are difficult on which to achieve consensus.

Understanding climate change?

Climate change refers to the gradual change in the Earth's climate due to an increase in average temperatures resulting from both natural and human actions. It is largely irreversible, particularly in its effect on rising sea levels and on ecosystems. According to the Intergovernmental Panel on Climate Change (IPCC), the average temperature "from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere."[1] And the trend has not ebbed, as average temperatures in 2018 reached the highest ever recorded in modern times. Understanding the causes and effects of climate change is necessary to adopt appropriate actions to address the problem.

The causes of climate change

The primary causes of climate change are related to actions that emit greenhouse gases. Greenhouse gases created largely by human activities include carbon dioxide (CO_2) from fossil fuel and industrial processes, carbon dioxide (CO_2) from forestry and other land use (FOLU), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F).

The largest portion of greenhouse gases is carbon dioxide, which is created by fossil fuel usage, industrial production, and deforestation. Fossil fuel usage includes the use of automobiles and airplanes, electricity and home heating fuels, and the production of products such as plastics and tires

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[1] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

and even everyday items such as ink pens, cosmetics, and toothpaste. Deforestation contributes to greenhouse gases because trees absorb carbon dioxide, and when they are cut down or burned, the stored carbon dioxide is released into the atmosphere.

Other forms of greenhouse gases include methane, nitrous oxide, and fluorinated gases. Methane is generated largely from livestock farming, landfills, and the production and use of fossil fuels. Nitrous oxide is produced on farms from the use of synthetic fertilizers along with fossil fuel usage. Finally, fluorinated gases are created in products such as modern refrigerators, air conditioners, and aerosol cans. Because fluorinated gases do not harm the ozone layer and are energy efficient, products that emit these gases have grown in popularity over the past decade, though they still contribute significantly to global warming.

The consequences of Climate Change Today and in the Future

A sense of urgency surrounds climate change because the state of climate change science has advanced to the point where scientists are able to put probability estimates on certain impacts of warming, some of which are catastrophic. The major impacts of climate change are in the areas of food security, water resources, ecosystems, extreme weather events, and rising sea levels. The IPCC summarizes the consequences of climate change by listing five key "reasons for concern" as follows:

1. **Unique and threatened systems:** Many ecosystems are at risk, such as the diminishing Arctic sea ice and coral reefs, which leads to the extinction of species.
2. **Extreme weather events:** An increase in heat waves, heavy precipitation, and coastal flooding leads to major economic costs due to natural disasters and reductions in agricultural yields.
3. **Distribution of impacts:** The risks of climate change on disadvantaged people and communities are greater, especially those that depend on agricultural production.
4. **Global aggregate impacts:** Extensive biodiversity loss affects the global economy.
5. **Large-scale singular events:** Melting ice sheets will lead to rising sea levels, causing significant loss of coastal lands.

The difficulty with addressing these effects is that unlike air or water pollution that can be seen today, climate change has a cumulative effect. In other words, this year's CO_2 adds to that from the past to raise concentrations in the future. Once CO_2 levels reach a certain level, it may lead to extreme consequences that cannot be reversed. The global environment is essentially a common resource with many public goods aspects, and climate change is a huge global negative externality that extends long into the future.

[The CORE Econ Team, 2023, pp. 91-96]

New terms, new tools: Stocks and flows

To understand how the process of climate change could be contained, let’s consider the underlying scientific process.

Burning fossil fuels for power generation and industrial use emits CO_2 into the atmosphere. Greenhouse gases such as CO_2 allow incoming sunlight to pass through the atmosphere, but trap reflected heat on the earth, leading to increases in atmospheric temperatures and changes in climate. Some CO_2 also gets absorbed into the oceans, increasing the acidity of the oceans and killing marine life.

The amount of CO_2 in the atmosphere is called the **stock**, while the amount being added per year is called the **flow.** To better understand what the terms stock and flow mean, consider Figure 2.19. The stock of CO_2 is the amount in the bathtub.

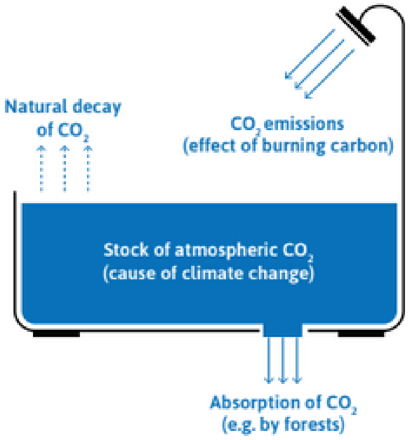


Figure 2.19 A bathtub model: the stock of atmospheric CO_2.

A flow is a measure based on a time period, like the number of tons of CO_2 per year. CO_2 emissions are an inflow that adds to the amount of atmospheric greenhouse gases, while the natural decay of CO_2 and its absorption (for example, by forests) are outflows that reduce the amount.

A key fact of climate science is that global warming results from the stock. It's what's in the tub that matters. The flow matters only because it will alter the stock. Figure 2.20 illustrates the movements in the stock of atmospheric CO_2 and annual temperatures.

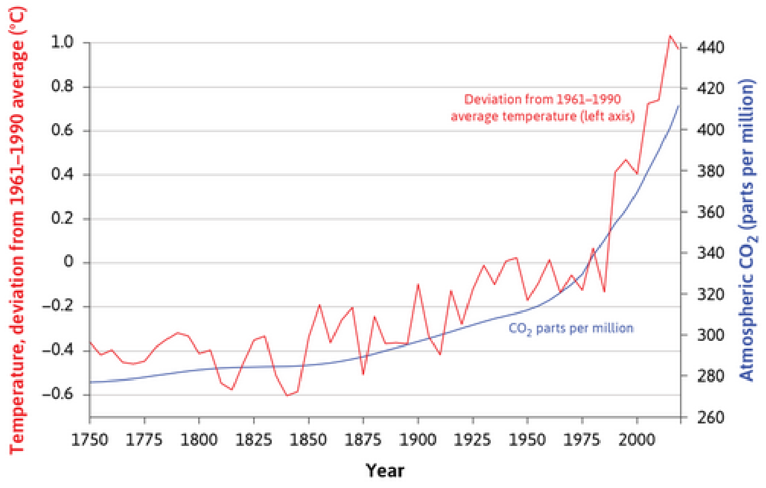


Figure 2.20 Global atmospheric concentration of carbon dioxide and global temperatures (1750 –2019).

The increase in the stock of atmospheric CO_2 is occurring because the outflows (natural decay, and absorption by forests and other carbon sinks) are far less than the new emissions that we add annually. Moreover, deforestation in the Amazon, Indonesia, and elsewhere is reducing the CO_2 outflows while also adding to CO_2 emissions. Forests are often replaced by agriculture, which produces further green house gas emissions—including methane from livestock, and nitrous oxide from fertilizer overuse.

The natural decay of CO_2 is extraordinarily slow. Of the carbon dioxide that humans have put in the atmosphere since the mass burning of coal that started in the Industrial Revolution, two-thirds will still be there a hundred years from now. More than a third will still be 'in the tub' a thousand years from now. The natural processes that stabilized greenhouse gases in pre-industrial times have been entirely over whelmed by human economic activity. And the imbalance is accelerating.

A future without fossil fuels

The GDP hockey sticks in Figure 1.1, tell a powerful story of the entry of country after country onto the path of continuously rising average living standards—and of the many countries that have not yet experienced the transition to broad-based growth.

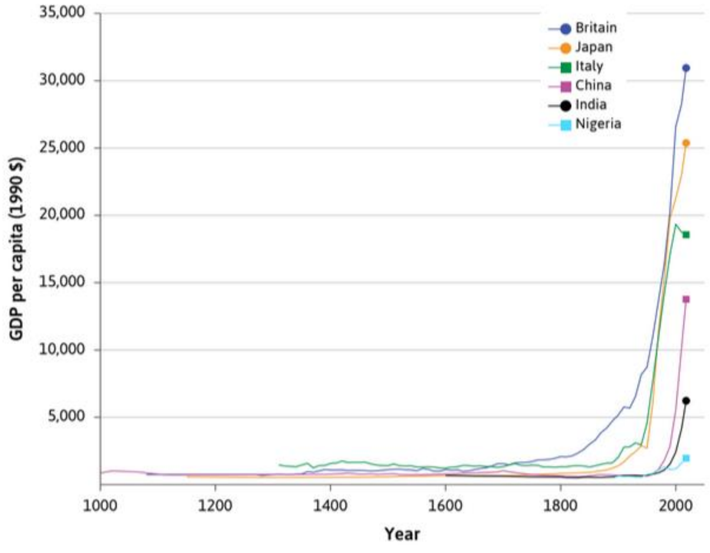


Figure 1.1 History's hockey stick: Gross domestic product per capita in five countries (1000–2018).

The production of energy is currently responsible for 87% of global greenhouse gas emissions. For the 85% of the global population who live below the level considered poor in a high-income country, is a fossil fuel-based transition to that standard of living in their future?

The evidence from climate science says that the growth in world production that would be required to raise incomes this much (estimated to be more than four times the size of today's total output) will have to be based on renewable energy combined with reduced energy input per unit of consumption.

How quickly this happens and at what cost depends critically on the policies that governments pursue; and these differ across countries. Figure 2.21 shows the link between rising living standards and CO_2 emissions: countries where GDP per capita is higher tend to have higher CO_2 emissions as well. This is to be expected because greater income per capita is the result of a higher level of production of goods and services per capita, involving greater use of fossil fuels. The upward-sloping 'line of best fit' shows the average emissions per capita for each level of GDP per capita. Low emissions by low-income countries signal energy poverty, not green energy or energy conservation.

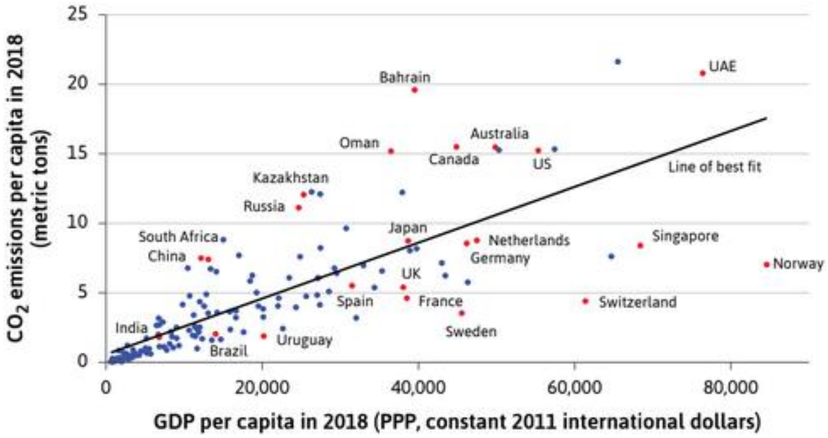


Figure 2.21 Carbon dioxide emissions are higher in richer countries.

But even among countries with similar per capita income, some emit much more than others. Compare the high emissions in the US, Canada, and Australia with the lower levels in France, Sweden, and Germany. Norway and Switzerland both have higher per capita incomes than the US but emit half as much CO_2.

This suggests that it is possible to organize production to offset, in part, the tendency for increased emissions as income rises. In low-emitting countries like France and Sweden, a substantial share of electricity is generated by non-fossil fuel sources (92% and 99% respectively) and petrol prices are much higher than in the countries with high emissions like the US and South Africa (above the line). For the poor countries on the left of the figure, their move to higher incomes needs to be a more nearly horizontal one rather than along the ‘line of best fit’.

A transition to low-carbon electricity could occur simply by governments ordering it, but it would be more likely to happen—either by government order or by private decisions—if the energy from these sources is cheaper than from fossil fuels. Until well into the twenty-first century, electricity generated from renewables was far more expensive than from fossil fuels. Even in the absence of a carbon tax which will —as intended— raise the price of fossil fuel-based energy, prices have changed dramatically more recently. In most parts of the world, power from new renewable facilities is cheaper than from new fossil fuel ones.

The collapse in the price of renewable electricity generation since 1976 is illustrated vividly in Figure 2.22 by the data on the cost of photovoltaic cells for producing solar energy. This chart uses a different scale from other charts so far: it is a ratio (or equivalently, logarithmic) scale. Each step up the vertical axis corresponds to a doubling of the price, and each step along the horizontal axis multiplies the installed capacity by ten. The data points form close to a straight line: its slope tells us that a 10-fold increase in capacity roughly halves the cost.

Concentrating on the last ten years, Figure 2.23 compares the changes in the costs of generating electricity using renewables and fossil fuels. It is the relative price of electricity generation over the lifetime of the power plant that affects decisions to switch to a new technology: the changes in ranking of wind, and especially solar (from the most expensive to the least) mean that by 2019, 72% of all new additions to capacity worldwide have been in renewables.

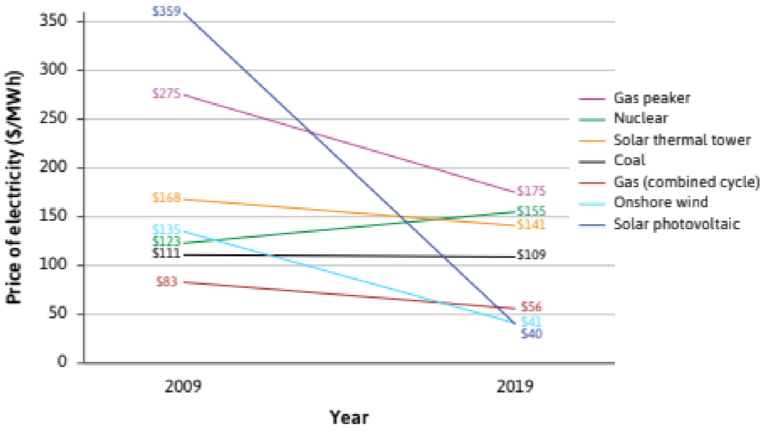


Figure 2.23 The price of renewable and non-renewable energy sources in 2009 and 2019.

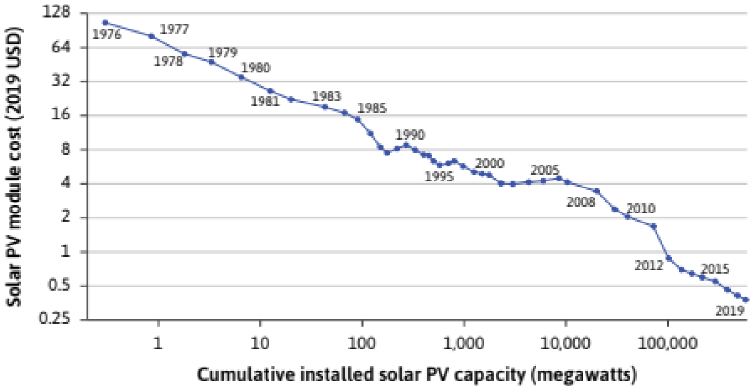


Figure 2.22 The price of photovoltaic cells (1976–2019).

It was government policies that initiated the exponential technological improvement in solar energy illustrated in Figure 2.22 above. Similarly rapid innovation characterized wind energy and lithium-ion batteries. The combined effect of government interventions and competitive markets drove progress. For example, subsidies for solar energy began in the 1970s in several countries including Japan, Germany, the US, and China. The schemes created incentives for energy providers to use solar and private companies to compete for market share. Equally important was government research funding (mainly in the US) leading to scientific advances that were applied to develop new solar cell materials and panel designs more efficient at converting sunlight to electricity.

The technological progress in renewables is a sign that a path to higher living standards without fossil fuels may be possible. But whether this is feasible on the scale required both to arrest climate change and make a serious dent in global poverty is doubtful.

II- Carbon pricing

[Chiang, 2019, p. 802]

Cleaning up pollution problems typically involves finding a level of abatement at which the marginal costs of abatement equal the marginal benefits. This can be achieved by taxing, assigning marketable permits, or using command and control policies to limit emissions.

[Varian, 2019, pp. 451-454]

Carbon Tax Versus Cap and Trade

Motivated by concerns about global warming, several climatologists have urged governments to institute policies to reduce carbon emissions. Two of these reduction policies are particularly interesting from an economic point of view: **carbon taxes** and **cap and trade.**

A carbon tax imposes a tax on carbon emissions, while a cap and trade system grants licenses to emit carbon that can be traded on an organized market. To see how these systems compare, let us examine a simple model.

Optimal Production of Emissions

We begin by examining the problem of producing a target amount of emissions in the least costly way. Suppose that there are two firms that have current levels of carbon emissions denoted by $(\bar{x}_1, \bar{x}_2)$. Firm i can reduce its level of emissions by x_i at a cost of $c_i(x_i)$. Figure 24.10 shows a possible shape for this cost function.

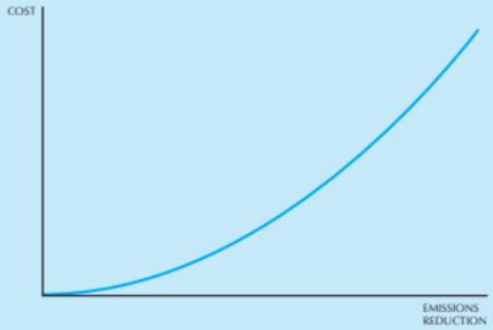


Figure 24.10 **Cost function for emissions.** The curve shows the cost associated with emission reductions.

The goal is to reduce emissions by some target amount, T, in the least costly way. This minimization problem can be written as

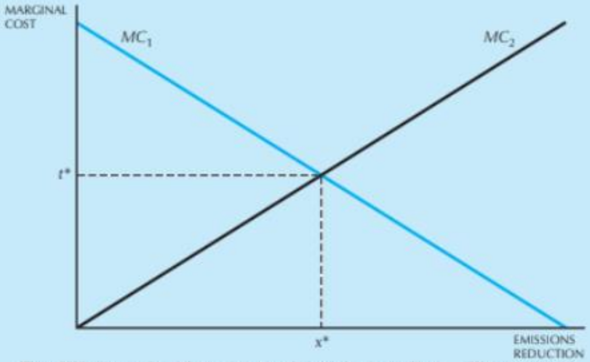
$$\min_{x_1, x_2} c_1(x_1) + c_2(x_2)$$

$$\text{such that } x_1 + x_2 = T.$$

If it knew the cost functions, the government could, in principle, solve this optimization problem and assign a specific amount of emission reductions to each firm. However, this is impractical if there are thousands of carbon emitters. The challenge is to find a decentralized, market-based way of achieving the optimal solution.

Let us examine the structure of the optimization problem. It is clear that at the optimal solution the marginal cost of reducing emissions must be the same for each firm. Otherwise it would pay to increase emissions in the firm with the lower marginal cost and decrease emissions in the firm with the higher marginal cost. This would keep the total output at the target level while reducing costs.

Hence we have a simple principle: at the optimal solution, the marginal cost of emissions reduction should be the same for every firm. In the two-firm case we are examining, we can find this optimal point using a simple diagram. Let $MC_1(x_1)$ be the marginal cost of reducing emissions by x_1 for firm 1 and write the marginal cost of emission-reduction for firm 2 as a function of firm 1's output: $MC_2(T - x_1)$, assuming the target is met. We plot these two curves in Figure 24.11. The point where they intersect determines the optimal division of emission reductions between the two firms given that T emission reductions are to be produced in total.



Equilibrium in the cap and trade market. The point t^* gives the optimal carbon tax and emissions license price.

Figure 24.11

A Carbon Tax

Instead of solving for the cost-minimizing solution directly, let us instead consider a decentralized solution using a carbon tax. In this framework, the government sets a tax rate t that it charges for carbon emissions. If firm 1 starts with $\bar{x}_1$ and reduces its emissions by x_1, then it ends up with $\bar{x}_1 - x_1$ emissions. If it pays t per unit emitted, its carbon tax bill would be $t(\bar{x}_1 - x_1)$.

Faced with this tax, firm 1 would want to choose that level of emission reductions that minimized its total cost of operation: the cost of reducing emissions plus the cost of paying the carbon tax on the emissions that remain. This leads to the cost minimization problem

$$\min_{x_1} c_1(x_1) + t(\bar{x}_1 - x_1)$$

Clearly the firm will want to reduce emissions up to the point where the marginal cost of further reductions just equals the carbon tax, i.e., where $t = MC_1(x_1)$.

If the carbon tax is set to be the rate t^*, as determined in Figure 24.11, then the total amount of carbon emissions will be the targeted amount, T. Thus the carbon tax gives a decentralized way to achieve the optimal outcome.

[Krugman & Wells, 2018, p. 1036]

The term emissions tax may convey the misleading impression that taxes are a solution to only one kind of external cost, pollution. In fact, taxes can be used to discourage any activity that generates negative externalities, such as driving (which inflicts environmental damage greater than the cost of producing gasoline) or smoking (which inflicts health costs on society far greater than the cost of making a cigarette). In general, taxes designed to reduce external costs are known as Pigouvian taxes, after the economist A. C. Pigou, who emphasized their usefulness in his classic 1920 book, The Economics of Welfare.

[Varian, 2019, p. 454]

Cap and Trade

Suppose, alternatively that there is no carbon tax, but that the government issues tradable emissions licenses. Each license allows the firm that holds it to produce a certain amount of carbon emissions. The government chooses the number of **emissions licenses** to achieve the target reduction.

We imagine a market in these licenses so each firm can buy a license to emit x units of carbon at a price of p per unit. The cost to firm 1 of reducing its emissions by x1 is $c_1(x_1) + p(\bar{x}_1 - x_1)$. Clearly the firm will want to operate where the price of an emissions license equals the marginal cost, $p = MC_1(x_1)$. That is, it will choose the level of emissions at the point where the cost of reducing carbon emissions by one unit would just equal the cost saved by not having to purchase a license.

Hence the marginal cost curve gives us the supply of emissions as a function of the price. The equilibrium price is the price where the total supply of emissions equals the target amount T. The associated price is the same as the optimal carbon tax rate t^*in Figure 24.11.

The question that remains is how to distribute the licenses. One way would be to have the government sell the licenses to firms. This is essentially the same as the carbon tax system. The government could pick a price and sell however many licenses are demanded at that price. Alternatively, it could pick a target level of emissions and auction off permits, letting the firms themselves determine a price. This is one type of “cap and trade” system. Both of these policies should lead to essentially the same market-clearing price.

Another possibility would be for the government to hand out the licenses to the firms according to some formula. This formula could be based on a variety of criteria, but presumably an important reason to award these valuable permits would be building political support for the program. Permits might be handed out based on objective criteria, such as which firms have the most employees, or they might be handed out based on which firms have donated the most to some political causes. From the economic point of view, it doesn’t matter whether the government owns the licenses and sells them to the firms (which is basically a carbon tax system) or whether the firms are given the licenses and sell them to each other (which is basically cap and trade).

III - International negotiations

[The CORE Econ Team, 2023, pp. 206, 208-212]

Modelling the global climate change problem

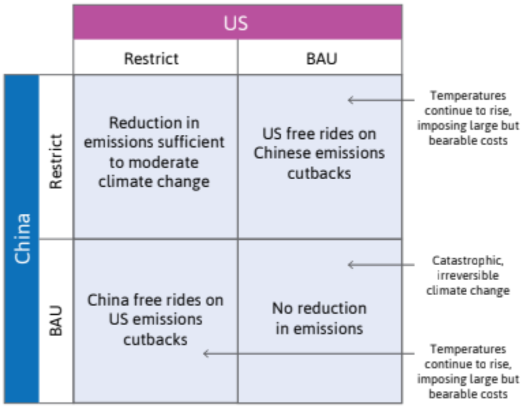
Why has it proved so difficult for international negotiations to make progress in limiting climate change? The success of the Montreal Protocol in protecting the ozone layer contrasts with the relative failure to reduce emissions responsible for global warming. The reasons are partly scientific. The alternative technologies to CFCs were well developed and the benefits relative to costs for large industrial countries, such as the US, were much clearer than in the case of greenhouse gas emissions.

Reducing carbon emissions requires much greater changes, across many industries and affecting all members of society. One of the obstacles at the United Nations' annual climate change negotiations has been disagreement over how to share the costs and benefits of limiting emissions between countries—and in recent years, the heavy costs some countries now face from the effects of past emissions elsewhere.

To explore the possible situations facing climate negotiators, we will model them as a game between two large countries, hypothetically labelled China and the US, each considered as if it were a single individual. First, we identify possible equilibria when each country behaves strategically; then we can think about how an agreed outcome might be achieved.

Figure 4.23a shows the outcomes of two alternative strategies: Restrict (taking measures to reduce emissions, for example by regulating or taxing the use of fossil fuels) and BAU (continuing with 'business as usual').

What we can expect to happen depends on the pay-offs in each outcome. The essential features of the problem can be captured using an ordinal scale from Best to Worst: it is the order of the pay-offs, not the size, that matters. Figure 4.23b shows two games, corresponding to different sets of hypothetical pay-offs.



		US	
		Restrict	BAU
China	Restrict	Reduction in emissions sufficient to moderate climate change	US free rides on Chinese emissions cutbacks
	BAU	China free rides on US emissions cutbacks	No reduction in emissions

Figure 4.23a Outcomes of climate change policies.

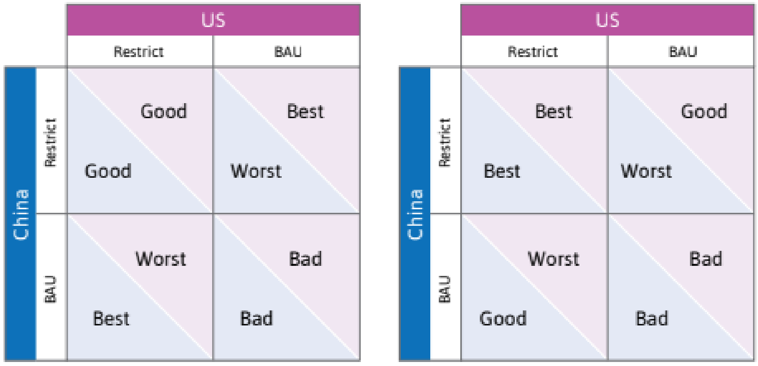
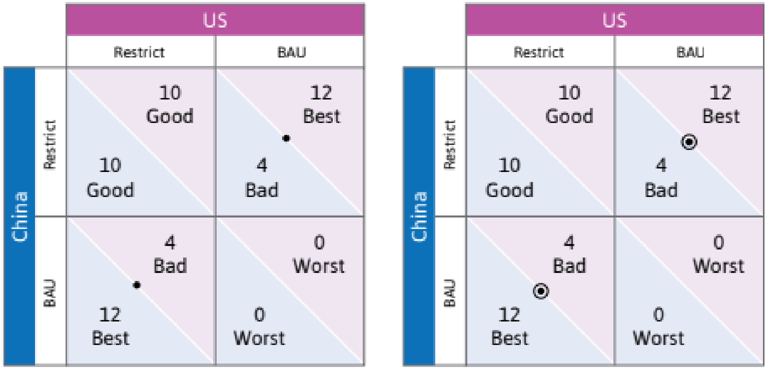


Figure 4.23b Two different climate policy games.

If you work out the best responses and find the Nash equilibria in each case, you will realise that the game on the left is a prisoners' dilemma, in which BAU is a dominant strategy for each country, leading to a Bad outcome for both. The game on the right is a coordination game, similar to the rice–cassava game in the box p.14 except that the players would like to coordinate on the same strategy, rather than the opposite one. There are two Nash equilibria: one is the Best outcome, in which both countries restrict emissions. But the Bad outcome in which neither do so is also an equilibrium, and if each country expects the other to choose BAU following their past behaviour, we can predict that they may be stuck in the (BAU, BAU) equilibrium.

Figure 4.23c presents a third model. It also shows the players' best responses, and hypothetical numerical pay-offs indicating the value of each possible outcome to the citizens of each country. The worst outcome for both countries is that both persist with BAU, thereby running a significant risk of human (and many other species') extinction. The best for each is to continue with BAU and let the other one Restrict. The only way to moderate climate change significantly is for both to Restrict.



China's best responses

US's best responses and
the two Nash equilibira

Figure 4.23c Best responses in a climate change game with a conflict of interest.

This is another coordination game with two equilibria, but now there is a conflict of interest between the players. This game is what is termed a **hawk–dove game**: players can act like an aggressive and selfish Hawk, or a peaceful and sharing Dove. In the climate change version, Doves Restrict and Hawks continue with BAU. The conflict of interest is that each country does better if it plays Hawk while the other plays Dove.

It captures a situation that is different from the previous two. Both countries have incentives to avoid catastrophic climate change. But they strongly prefer that the other should bear the costs of reducing emissions: each would like to wait to determine if the other will move first.

The Pareto-efficient allocation in which both countries restrict emissions also has the highest joint pay-offs. We can think of this as the best outcome for the world as a whole. But it is not an equilibrium.

Applying the hawk–dove game to climate policy

How do you think the hawk–dove game would be played in reality? Can the conflict of interest be resolved?

If one country could commit itself to BAU so that the other was certain that it would not consider any other strategy, then the other would play Restrict to avoid catastrophe. But this is true for both countries.

Negotiations are bound to be difficult, since each country would prefer the other to take the lead on restricting carbon emissions. The real climate negotiations are of course more complex—virtually all countries in the world are involved. Pay-offs may be different for these varied players. For example, in 2021 China produced 31% of the world's total carbon emissions, the US was second with 44% of China's level, followed by India. On a per-capita basis, China produced 55% of the emissions that the US did, and India produced 13% of US emissions.

Using public policy to change the game

How could the global social dilemma of climate change policy, as represented in this game, be solved? Could the governments of the world simply prohibit or severely limit emissions that contribute to the problem of climate change? This would amount to changing the game by altering available strategies by making BAU illegal. But who would enforce this law? There is no world government that could take a government that violated the law to court (and lock up its head of state!).

If the climate change social dilemma is to be addressed, Restrict must be in the interests of each of the parties. Consider the bottom-left corner (China plays BAU, US plays Restrict) equilibrium. If the pay-offs to China for playing Restrict were higher, when that is what the US is doing, then (Restrict, Restrict) might become an equilibrium. Indeed, in the eyes of many climate change scientists and concerned citizens, the aim of global environmental policy is to change the game so that (Restrict, Restrict) becomes a Nash equilibrium.

A number of mechanisms, aided by policy, could accomplish this:

- *Sustainable consumer lifestyles*: As a result of their concern for the wellbeing of future generations, people could come to prefer lifestyles that use fewer goods and services of the kind that result in environmental degradation. This would make the Restrict policy less costly and the BAU strategy less desirable.
- *Governments could stimulate innovation and the diffusion of cleaner technologies:* They might do this by, for example, raising the price of goods and services that result in carbon and other emissions, which would discourage their use. In the process, the use of cleaner technologies

would become cheaper, lowering the cost of Restrict. For example, renewable energy has become much cheaper. In some regions, it is now the cheapest energy option, which means Restrict is no longer more expensive than BAU. Self-interested behaviour will result in lower carbon emissions.

- *A change in norms:* Citizens, non-governmental organizations (NGOs), and governments can promote a norm of climate protection and sanction or shame countries that do nothing to limit climate change. This would also reduce the attractiveness of BAU.
- *Countries can share the costs of Restrict more evenly:* This is possible if, for example, a country for whom Restrict is prohibitively expensive instead helps another country where it is less expensive to Restrict. An example would be paying countries in the Amazon basin to conserve the rainforest.

Following the 2015 Paris Agreement (https://tinyco.re/8890909), almost all countries submitted individual plans for cutting emissions. Although there is no way that the agreement could be enforced, and these plans are not yet consistent with the goal of limiting the global temperature rise to 1.5°C, it is widely considered as a basis for further international cooperation. The Paris Agreement should:

- allow countries to better understand the costs of restricting emissions
- encourage economic players to innovate in order to further lower the costs
- strengthen norms that reduce the attractiveness of BAU
- establish a base of trust to share some of the costs of Restrict and negotiate more ambitiously in the future.

Anil's land is better for growing cassava, and Bala's for rice. But now if the two farmers produce the same crop, there is such a large fall in price that it is better for each to specialize, even in the crop they are less suited to grow. Follow the steps in Figure 4.21 to find the two equilibria.

Whatever their neighbour does, Anil and Bala each prefer to do the opposite. (Cassava, Rice) and (Rice, Cassava) are both Nash equilibria. This is a coordination game: each player would like to ensure that their action coordinates with their opponent's action.

Which equilibrium would we expect to observe in this game?

It is clear that the Nash equilibrium (Cassava, Rice), where they specialize in the crop they produce best, is preferred to the other Nash equilibrium, (Rice, Cassava), by both farmers.

Could we say, then, that we would expect Anil and Bala to engage in the best division of labour between the two crops? Not necessarily. Remember, we are assuming that they take their decisions independently, without communicating. Imagine that Bala's father had been especially good at growing cassava (unlike his son) and so the land remained dedicated to cassava even though it was better suited to rice. In response to this, Anil knows that Rice is his best response to Bala's Cassava: he decides to grow rice. Bala would have no incentive to switch to what he is good at: growing rice.

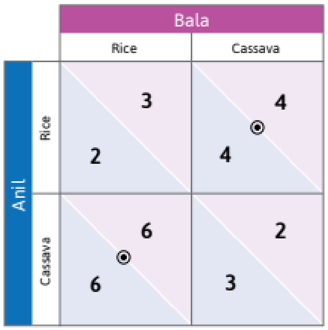


Figure 4.21 A third rice–cassava game: more than one Nash equilibrium.

1. Anil's best response to Rice
If Bala is going to choose Rice, Anil's best response is to choose Cassava. We place a dot in the bottom left-hand cell.

2. Anil's best response to Cassava
If Bala is going to choose Cassava, Anil's best response is to choose Rice. Place a dot in the top right-hand cell. Anil does not have a dominant strategy.

3. Bala's best responses
If Anil chooses Rice, Bala's best response is to choose Cassava, and if Anil chooses Cassava, Bala should choose Rice. The circles show Bala's best responses. He doesn't have a dominant strategy either.

4. There are two Nash equilibria
If Anil chooses Cassava and Bala chooses Rice, both of them are playing best responses (a dot and a circle coincide). So (Cassava, Rice) is a Nash equilibrium. But so is (Rice, Cassava).

The example makes an important point. If there is more than one Nash equilibrium, and if people choose their actions independently, then the players can get 'stuck' in an equilibrium in which all players are worse off than they would be at the other equilibrium. We would not call the game in Figure 4.21 an invisible hand game —the players may not reach the outcome that is best for both of them.

Notes to the figures

Fig 1.1

Stephen Broadberry. 2021. 'Accounting for the great divergence: recent findings from historical national accounting'.; Total Economy Database (https://tinyco.re/1587851).; S. N. Broadberry, B. Campbell, A. Klein, M. Overton, and B. van Leeuwen, B. 2015. British Economic Growth, 1270–1870 (https://tinyco.re/6743321). Cambridge: Cambridge University Press.; S. Broadberry, H. Guan, and D. Li. 2018. 'China, Europe and the Great Divergence: A Study in Historical National Accounting' (https://tinyco.re/9902110) Journal of Economic History 78: pp. 955–1000.; J. P. Bassino, S. Broadberry, K. Fukao, B. Gupta, and M. Takashima, M. 2019. 'Japan and the Great Divergence, 730–1874' Explorations in Economic History 72: pp. 1–22.; S. Broadberry, J. Custodis, and B. Gupta, B. 2015. 'India and the Great Divergence: An Anglo-Indian Comparison of GDP per Capita, 1600–1871' (https://tinyco.re/ 3221560) Explorations in Economic History 55: pp. 58–75.; P. Malanima. 2011. 'The Long Decline of a Leading Economy: GDP in Central and Northern Italy, 1300–1913'. European Review of Economic History 15: pp. 169–219.; S. Broadberry and L. Gardner. 2022. 'Economic Growth in Sub-Saharan Africa, 1885–2008: Evidence From Eight Countries' (https://tinyco.re/8802100). Explorations in Economic History 83: 101424. Note: The historical data is being improved continuously and the best data is provided in Figure 1.1 for the six countries shown. An alternative source of data is available for many more countries in the interactive chart.

Fig 2.20

Pieter Tans, NOAA/GML, and Ralph Keeling, Scripps Institution of Oceanography. 2022. Trends in Atmospheric Carbon Dioxide (https://tinyco.re/8976788); D. Gilfillan, G. Marland, T. Boden, and R. Andres, R. 2021. Global, Regional, and National Fossil-Fuel CO_2 Emissions (https://tinyco.re/4356621). Carbon Dioxide Information Analysis Center (CDIAC) Datasets. Accessed: September 2021.; Michael E. Mann, Zhihua Zhang, Malcolm K. Hughes, Raymond S. Bradley, Sonya K. Miller, Scott Rutherford, and Fenbiao Ni. 2008. 'Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia' (https://tinyco.re/ 1009800). Proceedings of the National Academy of Sciences 105 (36): pp. 13252–13257.; C. P. Morice, , J. J. Kennedy, N. A. Rayner, and P. D. Jones. 2012. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset (https://tinyco.re/6765840). Journal of Geophysical Research 117. D08101, doi:10.1029/2011JD017187. Note: This data is the same as in Figures 1.2a and 1.2b. Temperature is average northern hemisphere temperature.

Fig 2.21

The World Bank. 2021. 'World Development indicators (https://tinyco.re/ 1998076)'.; EPI. 2018. 'Environmental Protection Index 2018 (https://tinyco.re/5473228)'. Yale Center for Environmental Law and Policy (YCELP) and the Center for International Earth Science Information Network. Note: Three small very high-income countries (Kuwait, Luxembourg, and Qatar) are not shown.

2.22

F. Lafond, A. G. Bailey, J. D.Bakker, D.Rebois, R. Zadourian, P. McSharry, P., and J. D. Farmer. 2017. 'How well do experience curves predict technological progress? A method for making distributional forecasts'. (https://tinyco.re/6990876); Inter- national Renewable Energy Agency (IRENA)

Resource. 2020. Global solar PV installed capacity and solar PV model prices (https://tinyco.re/2667654).

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Our World in Data (https://tinyco.re/2209091). Lazard's Levelized Cost of Energy Analysis (https://tinyco.re/7666512). Version 13. 2019.