C U R I O S I T Y

ALL HANDS TO THE PUMP

THE ECONOMICS OF CLIMATE CHANGE

When Frontier was launched in 1999, the world had just experienced the hottest year of the hottest decade in the hottest century of the millennium. Much of the debate in the following decade centred on the science: the complex relationship between the generation of greenhouse gases and the workings of the natural world. But economics should have helped to shorten the subsequent debate on what to do about it, since the generation of these by-products is a classic “externality” which needs to be priced into the market if it is not to be persistently over-produced. And economics tools continue to be badly needed to help prevent catastrophic consequences.

1990

1990S
THE HOTTEST DECADE IN THE HOTTEST CENTURY OF THE MILLENNIUM

The first in a run of "hottest" years

2000
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE PUBLISHES "EMISSIONS SCENARIOS"

The first IPCC report to provide formal scenarios linking emissions, climate change and economic development. The scenarios form the basis for thinking about the relationship between growth, emissions and climate

2001
EU RENEWABLE ENERGY DIRECTIVE

Sets 12% and 20% target share for gross renewable energy supply for 2010 and 2020 respectively

2004
PUBLICATION OF "HUMAN CONTRIBUTION TO THE EUROPEAN HEATWAVE OF 2003" BY STOTT AND ALLEN

The first publication to formally model the link between extreme events (heatwaves, hurricanes etc.) and human influence on the climate

2005
EU EMISSIONS TRADING SYSTEM INTRODUCED

One of the largest international schemes to trade carbon credits and establish a price for carbon, covering electricity and energy-intensive industrial sectors

2006
UK GOVERNMENT PUBLISHES STERN REVIEW: THE ECONOMICS OF CLIMATE CHANGE AND AL GORE RELEASES AN INCONVENIENT TRUTH

Stern report provides the most widely recognised cost–benefit analysis in support of tackling greenhouse gas emissions and Gore's movie cements many of the issues in the minds of the wider public

2007
FOURTH ASSESSMENT REPORT FROM THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

The first report to state that the evidence exists to confirm a likely link between global warming and human actions

2008
UK CLIMATE CHANGE ACT IS PASSED WITH BROAD CROSS-PARTY VOTE OF 465 IN FAVOUR AND 3 OPPOSED

Arguably the first act to enshrine in law all three elements of a national climate strategy: a medium-term, 2050, target; shorter-term carbon budgets and an independent, transparent monitoring process to hold government to account for progress

2009

COPENHAGEN ACCORD ADOPTED

Widely seen, correctly, as a failed attempt to agree international action following Kyoto, it was also the first international recognition of the need to cap global temperature rise at 2C

2011

DURBAN TALKS PRODUCE BREAKTHROUGH

Recovering from Copenhagen, these were the first talks that resulted in a commitment to adopt a universal agreement on climate change by 2015 (see below)

2013

IPCC UPDATES "LIKELY" TO "EXTREMELY LIKELY"

New evidence allows the IPCC to say it is extremely likely that there is a link between human actions and climate change (see 2007 above)

2014

TWENTIETH ANNIVERSARY OF THE UN FRAMEWORK CONVENTION ON CLIMATE CHANGE

UNFCC is the framework under which all international climate negotiations take place

2015

MEAN GLOBAL TEMPERATURE HIGHEST IN THOUSANDS OF YEARS, CO_2 CONCENTRATION IN ATMOSPHERE PASSES 400 PPM

Four of five hottest years on record between 2010 and 2015 (a pattern that extends further back and forward); and CO_2 concentration at its highest for millions of years

2015

PARIS AGREEMENT IS ADOPTED

Legally binding international treaty that incorporates commitments from all but a handful of nations and attempts to learn the lessons from the Kyoto process to allow global action

2016

PARIS AGREEMENT COMES INTO FORCE

Paris agreement comes into force after a record number of about 170 signatories formally signed the agreement

2018

MAJOR REFORMS TO EU EMISSION TRADING SYSTEM

In recognition of lessons learned from ten years of trading, scheme changes introduced to speed up reduction in emissions

2017

PRESIDENT TRUMP ANNOUNCES HIS INTENTION TO WITHDRAW THE USA FROM THE PARIS AGREEMENT

While announcing his intention to do so, in practice the USA cannot completely withdraw until 2020

The threats associated with rising concentrations of greenhouse gases were succinctly summarised in the report of the UK Independent Committee on Climate Change in 2017:

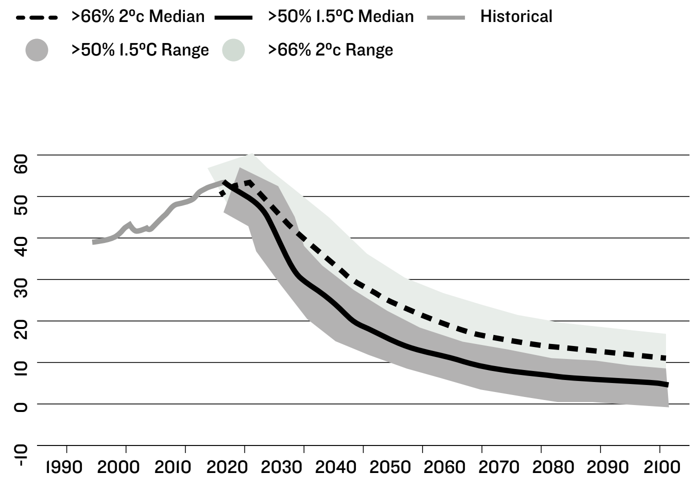
...Humanity has prospered in a largely stable global climate. That stability is now at risk. The climate is changing and human actions are causing the changes. Those actions mean that carbon dioxide levels are higher than at any time in human history, which will have an impact on all our lives. For example, rising sea levels threaten cities that have been built on the coast, changes in rainfall patterns will increase the risks of floods, and changes in water availability will affect agriculture and the crops that we rely on for food.

Greenhouse gas emissions will have to decline rapidly from their current peaks to avoid the worst impact of climate change, as reported in the 2019 report by the same Independent Committee on Climate Change see Figure 14.1. Even a reasonable (66%) probability of avoiding a 2C rise requires a reversal of a long trend of rising greenhouse gas emissions. The report notes that global net zero carbon dioxide emissions need to be reached by the 2070s, with wealthier (including European) countries reaching such limits much earlier.

The basic science has been known for over a century – and indeed the first recorded use of the "greenhouse" analogy dates back to 1827, when Jean-Baptiste Fourier deduced that the earth's atmosphere must have some property that was keeping it warmer than it would otherwise be. With the publication of "The artificial production of carbon dioxide and its influence on temperature" in 1938, Guy Callendar became the first scientist to demonstrate that rising CO2 levels were warming the atmosphere, estimating the change in Earth's temperature without any kind of computer to help with the calculations.

The Kyoto Protocol, signed in 1997, was the first major, legally binding international effort to reduce greenhouse gases. But it created a series of exceptions that undermined its effectiveness and meant the USA refused to sign. Others subsequently backed out, too. However, while the following decade saw some continuing dispute about global warming, or the extent to which it is man-made, in the past ten years the accumulation of evidence has whittled down the nay-sayers to an obstinate few (unfortunately – if inconsistently – including the current president of the USA).

FIGURE 14.1: GREENHOUSE GAS EMISSIONS ($GTCO_2E$/YR)



Source: IPCC, "Global Warming of 1.5C", Summary for Policymakers, 2018.

"HUMANITY HAS PROSPERED IN A LARGELY STABLE GLOBAL CLIMATE. THAT STABILITY IS NOW AT RISK"

That the evidence has built up so powerfully is thanks to greatly improved data on the build-up of greenhouse gases (carbon dioxide, methane, nitrous oxide and others) and step-changes in our ability to analyse such large datasets. Accurate measurements of CO_2, which are still improving, have had to wait for a combination of high-altitude monitoring stations, ocean buoys, satellites and other equipment to develop a global picture of temperature changes and a systematic record of CO_2 concentration. Meanwhile, the science of examining ice cores for trapped air has also been advancing, allowing us to extend the comparative record further back and with greater certainty.

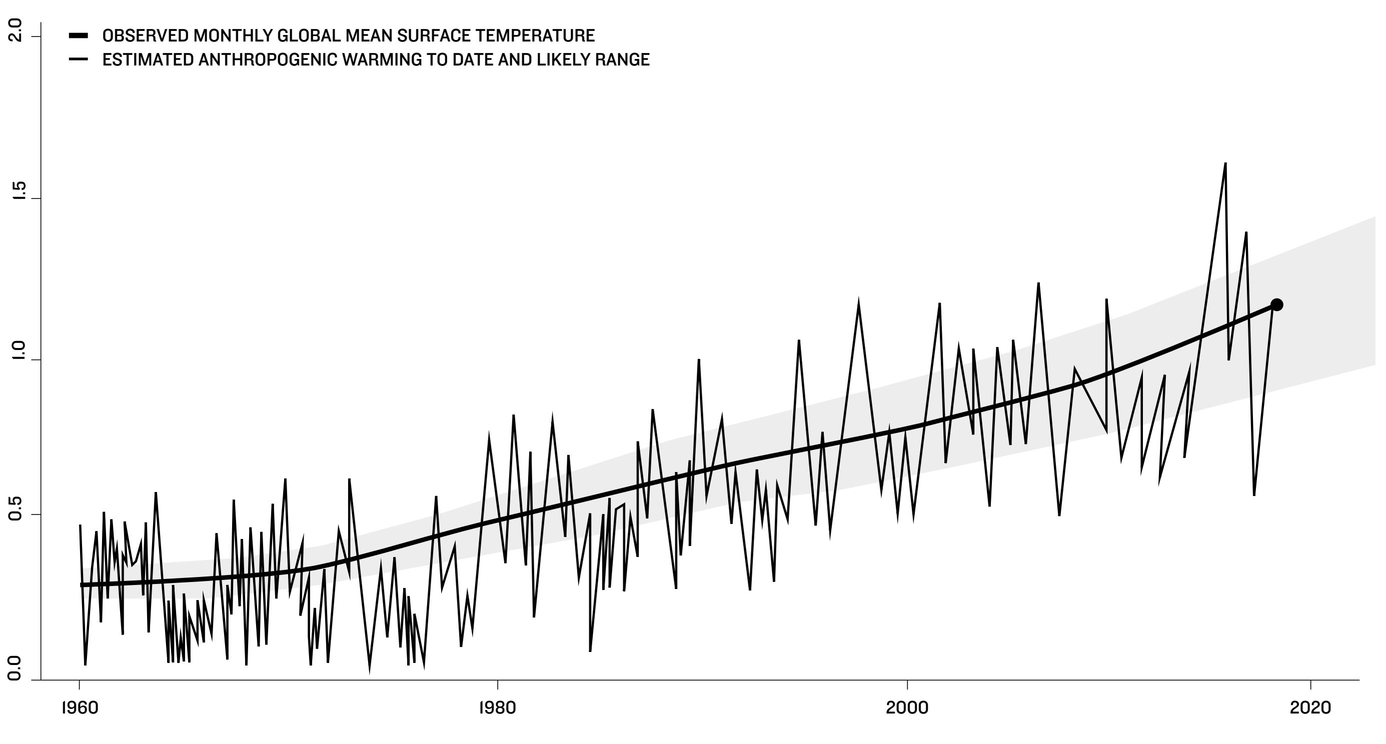
This combination of advances has enabled scientists to calculate that in 2016, concentrations of atmospheric CO_2 averaged over 400 parts per million for the first time in about 800,000 years. By 2018 they had passed 405 ppm and average global temperatures are now over 1C above pre-industrial levels. Better information on how greenhouse gas concentrations in the atmosphere have changed has been matched by an improved understanding of sea temperature and levels, as well as accompanying changes in the natural and human environment: changes in patterns of migration, behaviour and habitat range for some species (including humans), and changes in the patterns of storms of various types, local temperatures and sea levels.

The evidence of change was, in short, powerful enough to shift almost all policy-makers on to the issues that must be tackled rapidly if disaster is to be avoided. The first two were:

- **Attribution:** in a complex world where many factors determine outcomes, how can we attribute a particular event to one specific cause? What do greenhouse gas emissions have to do with my house being flooded?
- **Cost–benefit:** once we are convinced there are unwelcome consequences to greenhouse gas emissions, how should we assign a cost to those consequences, and use that as a basis for deciding how much we are willing to pay to avoid them? And, what are the current and future costs and benefits of adapting where we fail, or choose not, to reduce emissions?

These are questions which, in less apocalyptic situations, economists are used to answering systematically. Their tools are useful now, and the evidence to which they can be applied is accumulating rapidly. Indeed, economics can usefully start by explaining how we have got here in the first place.

FIGURE 14.2: GLOBAL WARMING RELATIVE TO 1850–1900 (ºC)



Source: IPCC, "Global Warming of 1.5C", Summary for Policymakers, 2018.

THE ULTIMATE EXTERNALITY

Greenhouse gases are an unpriced, uncosted, invisible, odourless and long lasting by-product of various forms of production. They are, in short, the quintessential "externality". Economics therefore teaches us that, without intervention to price them back into the market for output of which they are a by-product, we were bound to generate too much of them.

Economic progress has been intimately linked to energy use, and therefore to the by-product of most energy generation. Since the first fires were lit to give our ancestors an advantage over all their other competitors for food and shelter, through history's long series of industrial revolutions, economic development has depended on mastering the use of energy. Even today, we see the very close link between human progress and energy consumption – as illustrated in Figure 14.3 that shows the relationship between the UN's Human Development Index (HDI) and energy consumption per person.

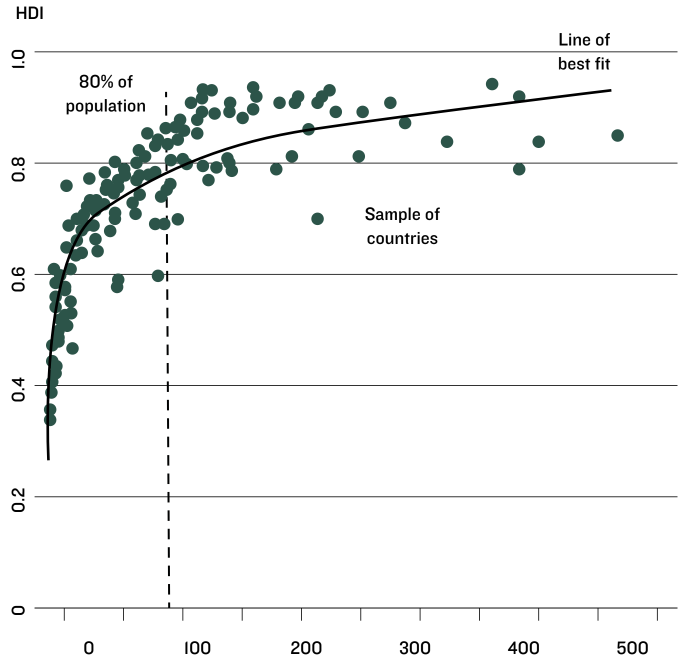
The very close historical link between GDP growth, energy and greenhouse gas emissions makes the changes in this pattern that have taken place, at least in some countries, over the past 20 to 30 years all the more remarkable. The British economy has grown by about 70% since 1990, but greenhouse gas emissions have fallen by over 40%. The record for the G7 largest economies as a whole is not quite as spectacular, but in the historical context still remarkable: they have enjoyed broadly comparable rates of economic growth without any increase in greenhouse gas emissions.

This unprecedented decoupling of economic growth from greenhouse gas emissions has, to date, been driven largely by two forces.

The first has been the use of some pretty blunt government instruments: the UK, USA, Germany and others have all used a range of policies, for example, to shift electricity generation from coal to renewables, as illustrated below. While market mechanisms have been used to help the process along, policy has been highly directive. Countries have used combinations of: specific regulations designed to reduce coal production, particular guarantees of market access for new forms of renewables and accompanying support to bring down production costs. Figure 14.4 illustrates the dramatic adjustments that have resulted in the UK.

This kind of intervention can be highly effective in sectors with a few, large, stationary sources of emissions (like power generation). But it is much more difficult to use in sectors where there are multiple, small and sometimes mobile sources of emissions (like transport, agriculture and home heating and cooling). Here more weight needs to be placed on market mechanisms and behavioural influences to drive change. More on those below.

FIGURE 14.3:
RELATIONSHIP BETWEEN THE UN'S HUMAN DEVELOPMENT INDEX AND ENERGY CONSUMPTION PER PERSON



Source: BP Energy Outlook, 2019 (https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf).

FIGURE 14.4:
LINK BETWEEN GDP GROWTH, ENERGY AND GREENHOUSE GAS EMISSIONS (1990–2015)

+72% GDP	UK	-43% EMISSIONS
+65% GDP	G7	-4% EMISSIONS

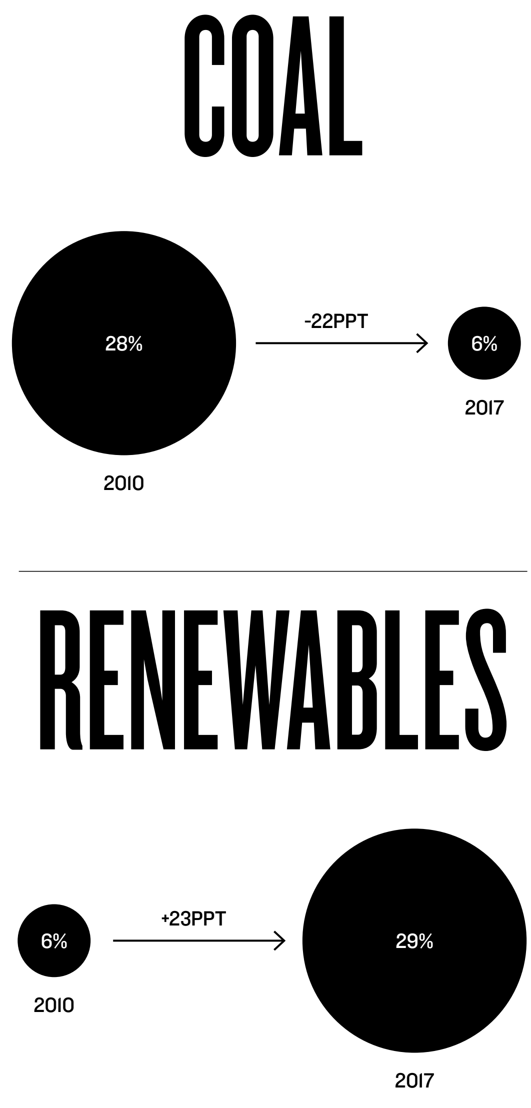
Source: UK Government, "Delivering Clean Growth", 2018.

"THE BRITISH ECONOMY HAS GROWN BY ABOUT 70% SINCE 1990, BUT GREENHOUSE GAS EMISSIONS HAVE FALLEN BY OVER 40%"

The second major factor explaining the performance of the most developed countries has been the changing pattern of international trade. Manufacturing has been shifting from these economies to those with lower labour costs. This is a less encouraging explanation, since it means emissions have shifted rather than reduced. Countries where growth has been more closely linked to manufacturing output have inevitably found it much more difficult to reduce emissions as rapidly, although in many cases (e.g. Germany, Poland, USA) that is linked to wider social issues (e.g. how to provide alternative employment for those working in fossil fuel industries).

The international mobility of the sources of emissions, particularly in sectors other than power generation, explains why a more sophisticated economic approach to decoupling is needed.

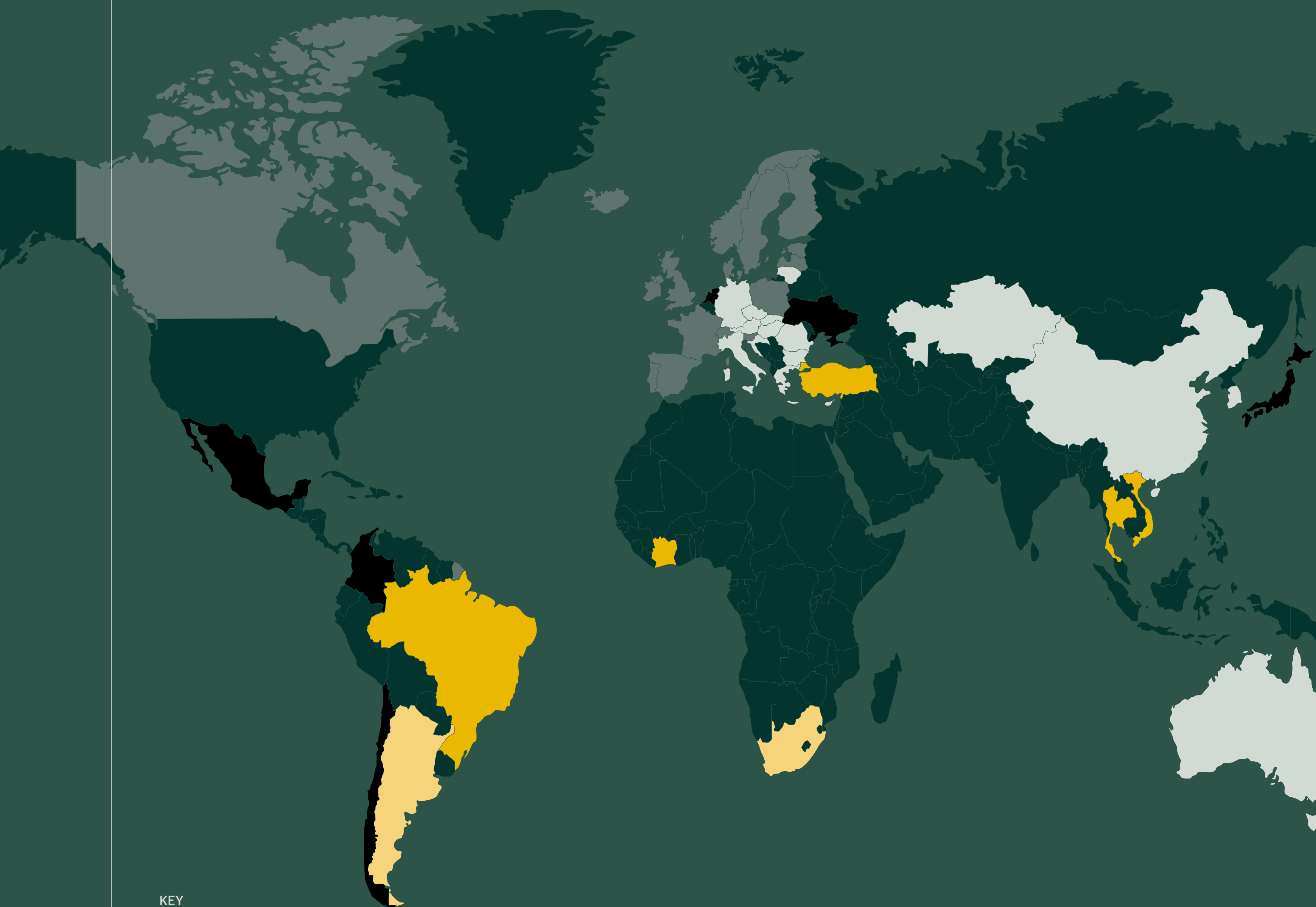
FIGURE 14.5: PERCENTAGE SHARE OF ELECTRICITY GENERATION



Source: UK Government, "Delivering Clean Growth", 2018.

A PRICE

FIGURE 14.6: REGIONAL, NATIONAL AND SUB-NATIONAL CARBON PRICING INITIATIVES (2019)



KEY

- ETS implemented or scheduled for implementation
- Carbon tax implemented or scheduled for implementation
- ETS or carbon tax under consideration
- ETS and carbon tax implemented or scheduled
- ETS implemented or scheduled, tax under consideration
- Carbon tax implemented or scheduled, ETS under consideration

Source: World Bank, Carbon Pricing Dashboard, 2019 (https://carbonpricingdashboard.worldbank.org/)

FOR

FIGURE 14.7: PRICE (€/tCO2)

Source: Sandbag. Available at: https://sandbag.org.uK/carbon-price-viewer/

A PRICE FOR EVERYTHING?

Faced with the invisible, odourless but damaging characteristics of greenhouse gas emissions, the natural reaction of economists is to say: put a price on them. To be more precise: set a price equal to the damage caused by the marginal unit of emissions, and watch the market solve the problem of minimising the effect of this on the costs of production or on lifestyles.

That usefully simple point has helped to drive the development of emissions pricing schemes. But the process is not, of course, as simple as it sounds. Even before we try to determine the "right" price, we have to agree on some important parameters:

- What emissions are we trying to "internalise"? CO_2, or all greenhouse gases? Emissions generated within the country concerned, or all emissions associated with goods and services consumed in that country, regardless of their source? (Are we prepared, or even allowed under trade rules, to introduce border taxes for emission-generating goods whose production takes place overseas?)
- What is our target? Are we trying to achieve an agreed percentage reduction in emissions? Or to achieve zero (or net zero) emissions? Or even to achieve "net negative" emissions?

Once we have agreed on these, we need to understand the cost of the technology that will deliver the last (i.e. most expensive) unit of emission reduction that is needed to meet our objectives. Setting the price at that level – through a carbon tax – would, in theory, result in sufficient reduction to meet our objectives, as producers and consumers respond by trying to find less emission-heavy means of production or to change their lifestyles. However, markets are complicated things. Once the price is set, producers, consumers and investors will try to find different ways of gaming the system. Several price iterations may be needed to achieve the "right" one.

EVERYTHING?

So far as the parameters are concerned, most emissions pricing schemes are concentrated on CO2; that is to say, they come under the general heading of “carbon pricing”. And so far as the target is concerned, in 2017 the High-Level Commission on Carbon Pricing, chaired by economists Joe Stiglitz and Nick Stern, concluded that reaching $40–$80 per tonne of CO2 by 2020 and $50–$100 per tonne by 2030 was consistent with the aims of the Paris Agreement on climate change.

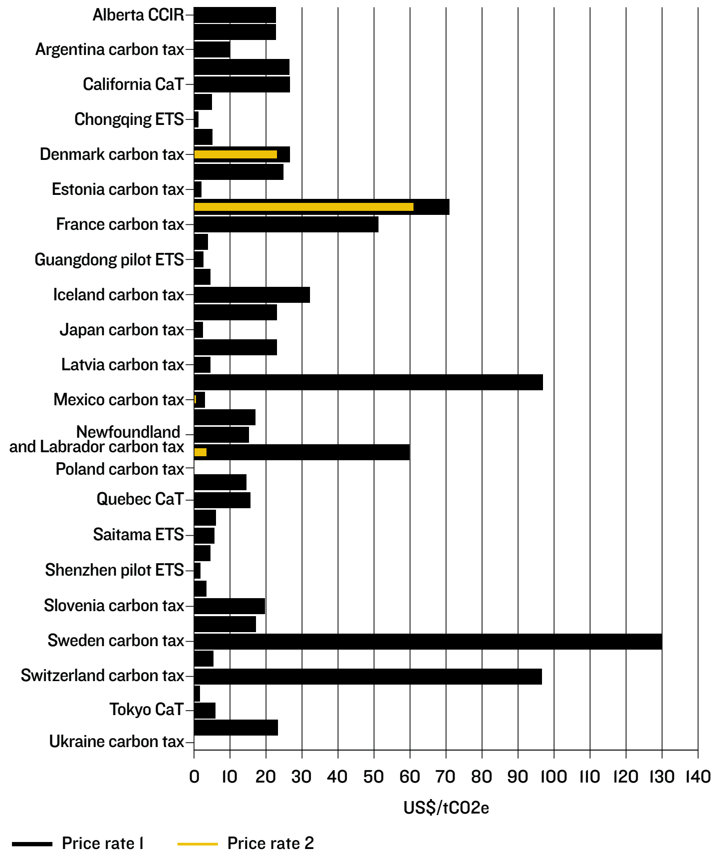
However, the uncertainty associated with estimating the correct price, or level at which to set carbon taxes, has led many governments around the world – including European governments, through the EU Emissions Trading Scheme – to go for a different form of carbon pricing (see Figure 14.6). They have instead set up systems of emissions permits, or allowances. Such emissions trading schemes (ETSs) allow governments to determine precisely the level of emissions they want in the future (and the speed with which this should decrease), leaving the market to determine the price at which the permits or allowances are traded.

Undoubtedly, these schemes have had some impact, and governments are continuing to introduce them worldwide. But these carbon pricing schemes too have had their problems – notably, erratic movements in permit prices that fail to send the correct signals to producers to undertake the level of investment in emission-reducing technology governments wish to see. To date, the EU Emissions Trading Scheme has suffered from low – and often unpredictable – prices because of the difficulty in accurately issuing the correct number of emissions allowances (see Figure 14.7).

The financial crisis and lobbying from firms and governments have combined to result in too many allowances being issued. Gradually the over-supply is being reined in; but it is a slow process that means other measures have been needed to supplement a price signal that has been too weak to stimulate the investment needed.

One of the lessons learned over the past 20 years has been that these schemes – whether price or permit based – have been more complicated to set up and administer than anticipated. In practice, prices have proved volatile, trading in permits has been thin and the market’s ability to signal future prices and costs limited. Policy-makers have regularly underestimated the time, rules and institutional structures needed to create the deep liquid markets that will provide credible signals to investors and households.

FIGURE 14.8: PRICES IN IMPLEMENTED CARBON PRICING INITIATIVES SELECTED

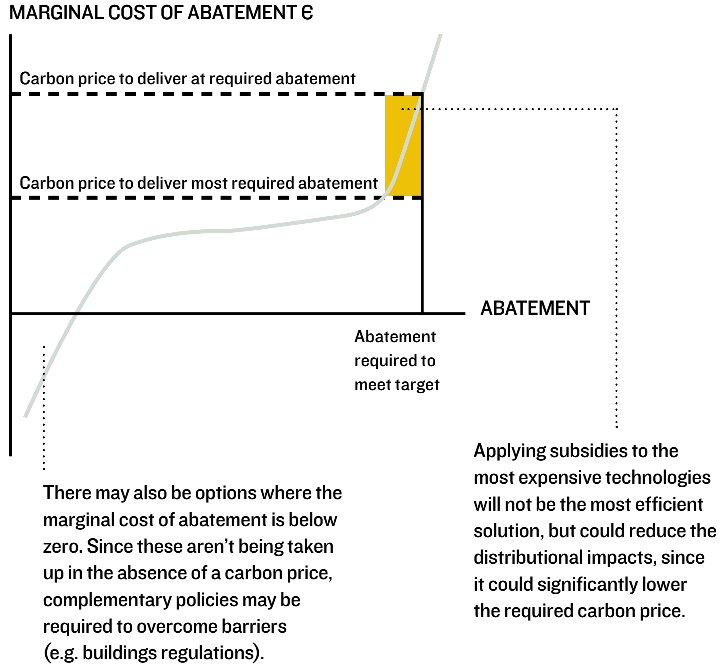


Note: Nominal prices on November, 01 2019.

Prices are not necessarily comparable between carbon pricing initiatives because of differences in the number of sectors covered and allocation methods applied, specific exemptions, and different compensation methods. Due to the dynamic approach to continuously improve data quality and fluctuating exchange rates, data of different years may not always be comparable.

FIGURE 14.9:

MARGINAL COST OF ABATEMENT €



BOX 1

DO COME AND JOIN US...

In an effort to encourage participation, the World Bank maintains an upbeat record of global progress in introducing carbon pricing schemes. It is an idea that has clearly had some traction. Twenty years ago, there were only six carbon pricing schemes in the world; a decade later, there were still only 16. Today, the World Bank's "Carbon Pricing Dashboard" lists 46 governments as having carbon pricing initiatives, together with 28 sub-national authorities – some of whose schemes, notably the Californian carbon tax in 2012, were potentially at least as important. Allowing for overlaps, that amounts to a total of 57 initiatives "implemented or scheduled for implementation".

The dashboard distinguishes between two different types of carbon pricing:

- Carbon taxes (CTs), which "price" emissions (or, more commonly, the carbon content of fossil fuels used) by adding to the cost of output of which these emissions are a by-product.
- Emissions trading schemes, whereby different entities can meet their targets for emissions either by changing production processes to reduce them, or by buying emissions units to cover the excess, depending on the relative costs of each option. There are two main types:

  (a) cap-and-trade – the regulator sets an absolute limit for emissions, and distributes allowances up to that limit through an auction

  (b) baseline-and-credit – emissions baselines are set for each entity and credits (which they can sell to others) are distributed to those which reduce emissions below their baselines.

The dashboard also identifies three relatively common types of market mechanisms:

- Offset mechanisms, which generate credits that can be earned by emissions reductions from specified programmes or projects, are tradable and can be used to achieve compliance with international or domestic policies. They have their own accounting protocol and registry.
- Results-based climate finance (RBCF), which makes payments after specified outcomes have been achieved and verified.
- Internal carbon pricing, whereby corporations allocate emissions allowances to different budget-holders within the company, which can be traded between them, or impose carbon taxes (often reflecting those faced externally) on different elements of the business.

Internal carbon pricing is increasing in major companies, as various regulatory authorities increase reporting requirements. But in 2017, only one-fifth of the Fortune 500 had implemented schemes. A separate initiative – the Task Force on Climate-Related Disclosures – has been gathering further momentum among financial companies whose investments are likely to be among the first affected by the disruptions linked to climate change. Over 500 financial companies – including most of the world's largest – have supported its recommendations and central banks are busy implementing them.

Although national and sub-national pricing or trading schemes are estimated to cover only 20% of global emissions, that is a five percentage point jump from 2017, an increase entirely accounted for by the inclusion of the Chinese national ETS, which is due to come into force in 2020. The Chinese scheme covers the largest chunk of emissions of any single scheme since the European ETS, launched in 2005.

However, there are huge variations in the explicit or implicit prices in these schemes, as Figure 14.8, World Bank estimates for 2019, demonstrates. Moreover, very few are within or above the range of $40–$80 per tonne of CO2 that the High-Level Commission on Carbon Pricing believed to be consistent with the Paris Agreement.

Achieving the required prices could have significant distributional effects: to begin with, they might endanger the competitiveness of some firms and increase costs for some households on low incomes. Many governments therefore choose to subsidise new technologies rather than to create incentives for them through a sufficiently high carbon price. This trade-off is illustrated in Figure 14.9.

Notwithstanding these difficulties, the World Bank points out that the average carbon price has risen: there were particularly sharp increases in 2018 in France (carbon tax rate increased from $38 to $55) and the EU allowance price ($7 to $16). Government revenues from carbon taxes are showing a corresponding increase. But the global total in 2017 was still estimated to be only $33 billion. ■

Pricing greenhouse gas emissions is intended to overcome the market failure associated with unpriced externalities. But placing a price on those emissions has revealed a series of related institutional failures.

At heart, the problems stem from the difficulty of creating a well-functioning market for a product whose price depends exclusively on the actions of government. Deep, liquid markets exist in goods for which there is sustained demand independent of government action (e.g. agricultural products, metals and minerals, houses and land). To date, the challenge of creating a market that is dependent solely on government backing for the ultimate value of the product being traded has proved a strain on our capabilities.

"GOVERNMENTS HAVE, IN SHORT, STOPPED THINKING MERELY ABOUT GETTING THE HORSE TO WATER"

HORSE TO WATER, HORSE TO DRINK?

The weaknesses revealed in pure market mechanisms intended to drive emissions reduction have led to the development of a series of additional solutions by governments. While the price mechanism has not been abandoned, it is being boosted (or, some would say, distorted) through a series of measures that put greater weight on the need to provide a long-term incentive for investment, innovation and new product development. Governments have, in short, stopped thinking merely about getting the horse to water, and begun to think more creatively about how to get it to drink.

Efforts have converged on four ways to boost a price-based policy:

01. **Strong political signalling:** this requires governments to make credible commitments to underpin their long-term aspirations to reduce emissions. Credibility is built up by evidence of broad-based support; legal backing; the use of specific, measurable targets; transparent monitoring and well-understood mechanisms for adjusting policy according to progress towards those targets. The 2008 UK Climate Change Act fulfils most of these criteria and is partly responsible for the decoupling of emissions from economic growth in the UK. Many other countries (e.g. Canada, France) are passing their own legislation or providing other signals. For example, in early 2019 the German Coal Commission set a date for Germany's exit from coal in an attempt to create a consensus on a very divisive issue.
02. **Internationalisation:** commitment by more than one government not only reinforces political signalling but creates a deeper market for emissions trading. The international Paris Agreement is the latest, and most sophisticated, international effort at political signalling; the World Bank is seeking to promote international carbon pricing schemes; the Task Force on Climate-related Financial Disclosures (TCFD) aims to bring together finance ministers and central banks with a common approach to financial risks from climate change; and other efforts (e.g. Powering Past Coal Alliance) are building international support for action.

03. **Innovation pump-priming:** this requires direct funding for research and development and related innovation in areas considered important for future emission-reduction efforts. Such programmes have included funding for early-stage development of technologies such as solar and wind power, battery storage, new industrial processes, carbon capture and storage, and other technologies.
04. **Deployment support:** this requires financial or regulatory assistance during the early stages of the application of new technologies to help reduce costs through learning-by-doing and achieve greater public acceptance (increasing demand) through greater familiarity with the technology or processes in question.

Each of these approaches is intended to address a distinct market failure: uncertainty about the policy framework, particularly at the global level; investor uncertainty and risk aversion with respect to the development of new technologies; and similar problems associated with market entry in the application of these technologies.

CHANGING THE AGENDA

Over the past 20 years, economists have followed behind the scientists: a largely engineering-based approach has dominated the discussion of what is required to check greenhouse gas emissions. This has had some considerable successes: it has created credible alternatives to coal-based generation, greatly improved batteries and encouraged a range of other important scientific advances (e.g. new generations of biofuels).

Economics has, however, played an increasing part, bringing market mechanisms to bear on the emissions challenge. But economists now need to raise their game. The nature of the challenge is changing, and the pace of response needs to quicken.

The twin challenges over the coming years are:

01. To spread the lessons learned to date around the world, replacing coal in energy generation, encouraging efficiency in production processes, and bringing in national zero emissions targets to help focus attention on sectors with major sources of emissions.
02. To achieve real emissions reductions in areas with a large number of smaller sources of emissions, and where consumer behaviour can play a much greater role (e.g. transport, agriculture, home heating and cooling).

The 2018 Nobel Prize in Economics was awarded to William Nordhaus for economic contributions to tackling climate change (and to Paul Romer for his work on technological innovation). The award recognised the integration of macroeconomic thinking and climate change. Nordhaus built the first models that tried to integrate the scientific evidence with economic mechanisms – to aid understanding of how the actions of people and firms might feed back into the environmental changes. His important step – linking physical and economics sciences systematically – can now be made with much greater sophistication. But one of the most important lessons from such work is that macro-models alone cannot answer the key policy-making questions: how to design and assess the impact of specific interventions?

Delivering the response to climate change demanded by the International Panel on Climate Change (the part of the United Nations tasked with developing the international scientific consensus on climate change and its impacts) will require more than macroeconomic policy. It will also require the use of microeconomic thinking to be properly integrated into policy-making. This is particularly relevant to the search for answers to three policy questions:

01. **First, how to design credible medium-term mechanisms for pricing greenhouse gas emissions**, a task that is beyond a single government. Efforts with tax and trading mechanisms must continue, but given their problems, we also need to find other ways to introduce a price for carbon. The development of a credible market in carbon offsets would help greatly. These involve the purchase of an equivalent amount of emission reduction to "offset" a carbon-emitting activity such as air transport – e.g. planting new forests that absorb the equivalent amount of carbon. The Paris Agreement provides the basis for greatly improving current schemes, and companies (particularly airlines) would support such measures. Economists could help deliver new, transparent markets that meet the criteria for a genuine offset (ensuring it is additional to reductions that would have happened anyway). This would help to establish an international benchmark price for carbon, to which other carbon taxes or permit-based schemes could be aligned.

02. **How to develop efficient support mechanisms for early-stage low-carbon technological solutions**. The "valley of death" between an innovation and its widespread deployment has been well documented. There is less agreement on how to bridge the valley but countries such as Germany, China, France, the USA and UK have been experimenting with different approaches (e.g. tax credits, deployment support, public sector procurement rules, standards). Understanding the conditions under which different approaches are more likely to work, and how to adjust their design accordingly, would be a big help – particularly in relation to some of the more difficult sectors (e.g. agriculture and heavy goods vehicles).
03. **How to bring behavioural economics to bear on lifestyle and consumption choices**, sensitising consumers to the need to reduce emissions. Governments can take a lead by changing the way in which they measure, report and discuss GDP and related measures of national "success" or individual "well-being". But other stimuli are needed to move us on to the virtuous circle, in which consumer demand stimulates carbon-free innovations in production, which in turn change patterns of consumption. One of the great challenges for higher-income countries will be shifts in diet, which are of course strongly influenced by a range of behavioural cues (given by advertising, in-store displays, or the perceived preferences of our friends and family, for example). We have also learned a lot from programmes to stop smoking, reduce the consumption of alcohol and encourage people to eat more fruit and vegetables. Trialling techniques based on insights derived from these programmes will help us plan how to move from a high-carbon equilibrium to a lower-carbon one.

GAMES NATIONS PLAY

Finally, there is a global question of political economy. In the end, emissions reduction depends on every country being convinced that every other country is also acting. As in the classical "prisoner's dilemma" favoured by game theorists, we only escape if we can find credible ways to co-operate. Economic theory and game theory provide some clues about how to improve the chances that national responses lead to lower emissions globally rather than an international race to use up fossil fuels as quickly as possible, in case they are more difficult to sell in the future.

Mechanisms that help to lock in decisions, to reinforce them and to provide positive feedback all help. They include independent, transparent monitoring and reporting of changes in the world's environmental assets and liabilities, as well as international agreement on the objectives of climate policy. The current international agreement is new and fragile: it is still in the process of getting established, and meanwhile threatened by new leaders and governments intent on undermining it.

Some of the newest economic thinking seeks to understand disruption – how new ideas, new entrants and new products disrupt incumbents. The success of the Paris Agreement will also depend on the disrupters in an international game whose prize is the underlying climatic and ecological stability that has been the foundation of humanity's success hitherto.