# PUTTING THE GENIE BACK

## Solving the Climate and Energy Dilemma

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## Solving the Climate and Energy Dilemma

BY

DAVID HONE

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‘ ... *there remains inevitability around political action and legislation to deal with carbon dioxide emissions. It’s not just politics that dictates this, but physics. Society can’t keep on adding carbon dioxide to the atmosphere and expect nothing to change*’.

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# GLOSSARY OF TERMS

**AAU** Assigned Amount Unit.

**AOSIS** Alliance of Small Island States.

**BECCS** Bioenergy Use with Carbon Capture and Storage.

**CBDR** Common but Differentiated Responsibilities.

**CCS** Carbon Capture and Storage.

**CDM** Clean Development Mechanism.

**CER** Certified Emissions Reduction.

**CFC** Chlorofluorocarbon.

**CLG** The Prince of Wales' Corporate Leaders Group (on climate change).

**COP** Conference of the Parties

**CORSIA** Carbon Offsetting and Reduction Scheme for International Aviation.

**CPLC** Carbon Pricing Leadership Coalition.

**DACCS** Direct Air Capture of Carbon Dioxide and Storage.

**ENSO** El Niño Southern Oscillation.

**EOR** Enhanced Oil Recovery.

**ERU** Emission Reduction Unit.

**ETS** Emissions Trading System.

**EU ETS** European Emissions Trading System.

| | |
|---|---|
| **EV** | Electric Vehicle (including hydrogen, battery electric and plug-in hybrid vehicles). |
| **GCCSI** | Global Carbon Capture and Storage Institute. |
| **GDP** | Gross Domestic Product. |
| **GHG** | Greenhouse Gas. |
| **HFC** | Hydro-fluorocarbon. |
| **HSFO** | High Sulphur Fuel Oil. |
| **ICE** | Internal Combustion Engine (vehicle). |
| **ICAO** | International Civil Aviation Organisation. |
| **IEA** | International Energy Agency. |
| **IETA** | International Emissions Trading Association. |
| **IGSM** | Integrated Global System Modelling. |
| **IPCC** | Intergovernmental Panel on Climate Change. |
| **ITL** | International Transaction Log. |
| **ITMO** | Internationally Transferred Mitigation Outcomes. |
| **JI** | Joint Implementation. |
| **LNG** | Liquefied Natural Gas. |
| **MBM** | Market Based Mechanism. |
| **MITJP** | Massachusetts Institute of Technology (MIT) Joint programme on the Science and Policy of Global Change. |
| **NDC** | Nationally Determined Contribution (but prefixed with 'I' for intended prior to the adoption of the Paris Agreement). |
| **NDRC** | National Development and Reform Commission. |

**NER** New Entrant Reserve (of the EU ETS).

**NET** Negative Emission Technology.

**NOAA** National Oceanic and Atmospheric Administration.

**PV** Photo Voltaic (solar cell).

**ROW** Rest of World.

**RPK** Revenue Passenger Kilometres.

**SLCP** Short Lived Climate Pollutants.

**UNEP** United Nations Environment Programme.

**UNFCCC** United Nations Framework Convention on Climate Change.

**WBCSD** World Business Council for Sustainable Development.

**WMO** World Meteorological Organization.

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# ENERGY DEFINITIONS AND UNIT ABBREVIATIONS USED

This book uses energy units in discussing the energy system. There are three that are most important.

| | |
|---|---|
| Joule | The joule, symbol J, is a derived unit of energy in the International System of Units. Approximately 4.2 J is required to heat 1 gram of water by 1°C. |
| Watt | The SI unit of power, symbol W, equivalent to 1 joule per second, it is the rate of consumption of energy. |
| Watt-hour | A measure of electrical energy, symbol Wh, equivalent to a power consumption of 1 watt for 1 hour. The Watt-Hour and Joule are interchangeable through a conversion factor of 3600 J/Wh, but Watt-Hour is used for electricity generation, whereas the Joule is used for energy more broadly. |

In addition, the energy system is described in terms of primary and final energy.

| | |
|---|---|
| Primary | Primary energy is an energy form found in nature that has not been subjected to any conversion or transformation process. It is |

energy contained in raw fuels such as coal, and other forms of energy received as input to a system. Primary energy can be non-renewable or renewable.

Final — Final energy is energy supplied to the final consumer for all energy uses. Electricity is final energy, as is natural gas when used directly for cooking and heating at home. But natural gas can also be classified as primary energy when taken directly from the ground into the energy system for use in a power station.

Barrel — A quantity of oil, 42 US Gallons or about 159 litres. Global oil production is about 95 million barrels per day.

EJ — Exajoules — one quintillion ($10^{18}$) joules. In 2015 global primary energy use was approximately 550 EJ.

Gt — Gigatonnes — one billion ($10^9$) tonnes. The largest coal fired power station in the world, a 5.5-GW facility in Taiwan, will emit about 2 billion tonnes of carbon dioxide over its lifetime.

GW — Gigawatt — 1 billion ($10^9$) watts. A 1-GW power station is the typical size for a modern coal, gas, or nuclear installation. The UK has about 50 GW of installed gas- and coal-fired power-generation capacity.

kg — Kilogramme, an SI unit of mass.

Mt — 1 million tonnes.

Mtpa — Million tonnes per annum.

| | |
|---|---|
| ppm | Parts per million by volume (of a gas in the atmosphere). |
| t | 1 tonne or 1000 kg. |
| TWh | Terrawatt hours – 1 trillion ($10^{12}$) Watt-hours. A 1-GW power station operating for 300 days per year will produce about 7 TWh. |
| °C | Degree Celsius, a measure of temperature. |

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# ABOUT THE AUTHOR

**David Hone** is Chief Climate Change Advisor at Shell International Ltd. He joined Shell in 1980 after graduating as a Chemical Engineer from the University of Adelaide in Australia, and previously held positions in refinery technology, oil trading, and shipping areas for Shell. David has been the principal climate change adviser for Shell since 2001 and has represented the company in that capacity in a wide variety of forums. He is a board member of the International Emissions Trading Association (IETA), was Chairman of IETA from 2011 to 2013, and is a board member of the Center for Climate and Energy Solutions (C2ES) in Washington.

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# FOREWORD: DONALD TRUMP AND THE PARIS AGREEMENT

As this book was being readied for publication, President Donald Trump announced that the United States would withdraw from the Paris Agreement. Heads of State from all corners of the world quickly responded, vowing to uphold the Agreement and ensure its continuance. But can the Paris Agreement, as discussed extensively in the pages that follow, survive?

There is an element of déjà vu to this event. Just days into my new job as climate change adviser in Shell, then President George W. Bush announced that the United States was withdrawing completely from the Kyoto Protocol and would follow an alternative path forward in terms of climate action. At the time, he proposed a significant step-up in technology development through the National Climate Change Technology Initiative and a leadership role by the United States to work within the United Nations framework and elsewhere to develop with its friends and allies and nations throughout the world an effective and science-based response to the issue of global warming.

The June 2001 Bush announcement was widely expected and indeed, it helped spell the end for the Kyoto Protocol. The UNFCCC process fractured as a result, with some Parties continuing to pursue the Kyoto

Protocol and all Parties brought back to the table to negotiate a new deal that worked for the United States. This gave birth to the Ad-Hoc Working Group on Long Term Cooperative Action, which together with the Kyoto Protocol arrangements could have potentially combined into a satisfactory global deal. Unfortunately, they didn't, with the meltdown in Copenhagen being the outcome. But the pieces were reassembled, in large part led by the United States under President Obama, with the result being the Paris Agreement in December 2015. That process took over 14 years to complete.

Sixteen years on from the Bush announcement and again from the White House lawn, President Trump has now declared that the United Stated will exit the Paris Agreement, once again with the caveat that the Administration would be open to a renegotiation or even an entirely new agreement. The reasons given are largely the same as those of President Bush; unfairness, competitiveness concerns, negative economic impact, layoffs of workers and price increases for consumers. But the circumstances are very different this time around.

Looking 14 years ahead from today we will be in the 2030s. My own analysis in Chapter 2 shows this as the time when we may start to see years in which the global average temperature rise could equal or exceed 1.5°C above the level in the mid-1800s. There isn't any grace period remaining to reorganise, negotiate and agree yet another climate deal. Nor should that happen; the Paris Agreement is structured to reflect what countries can offer, with no requirement other than that successive offers should improve over time and ratchet towards the end goal of net-zero emissions in the second half of the century. The Agreement isn't a good or bad deal for anyone; it simply reflects the progression required over time as nations either continue or begin to proactively manage emissions and eventually contain them.

The Paris Agreement is made up of national contributions, determined by nations per their domestic circumstances. This is the case for all countries, from the United States of America as the world's largest economy through to Zimbabwe as one of the poorest. Although the Agreement asks for developed countries to implement economy-wide absolute emission reduction targets, there is an expectation that all countries move in this direction and the Agreement encourages such movement. Several developing countries have structured their national contributions to reflect this and in the time since the negotiations concluded, more have implemented measures to that effect. For example, China is implementing a nationwide emissions trading system and emissions within their economy are now expected to peak well before 2030, ahead of their stated national contribution.

With all nations supposedly on a pathway towards absolute targets and eventually net-zero emissions, there is nothing left to negotiate other than the timeline along which this proceeds, although as I discuss in Chapter 3 the current timeline leaves the world well short of a 2°C outcome. Once again, the Agreement sets out the process for addressing this, rather than Parties having to resort to yet another negotiating process towards an alternative agreement. There is a transparency framework, a stocktake process and a mechanism to facilitate implementation of and promote compliance with the provisions of the Agreement. Although the proposed mechanism is facilitative in nature and should function in a manner that is transparent, non-adversarial and non-punitive, it nevertheless offers the opportunity for a country such as the United States to negotiate more rapid convergence of effort.

Both Chancellor Merkel and President Macron, along with UNFCCC Executive Secretary Patricia Espinosa, made it clear the morning after President Trump's announcement that there would be no renegotiation of the Paris Agreement. While anything is possible in theory, a renegotiation would put an end to the Agreement and probably not deliver a replacement for a decade or more. They were right to reject the proposal; in any case, it simply isn't necessary under the structure that exists.

Given all the above, the current Administration may still be concerned about the effort required by the United States to deliver its stated goal of a reduction of 26–28% in emissions by 2025 against a 2005 baseline, particularly when compared to some countries. Although the current surge in natural gas production and its replacement of coal for power generation, the advance of renewable energy and the roll-out of electric vehicles are all contributing to a fall in US emissions, the target remains ambitious. While the prospect of success is visible within the energy transition that is underway, the United States could simply resubmit its national contribution. Various parts of the Paris Agreement and the accompanying Decision Text open the door to such a step, and former Secretary of State John Kerry, who negotiated the Agreement for the United States, said as much on the BBC shortly after the Trump announcement. Although successive national contributions are required to demonstrate increased ambition under the Agreement, this is the first such submission and therefore can be revised.

By resubmitting its national contribution, some semblance of renegotiation would be achieved, at least in part. A new contribution from the United States would still require an absolute target as this is required of developed countries under Article 4.4, but the number could have a much wider margin, covering the expectation of economic growth that the President alluded to in his speech on June 1. Of course, this isn't an ideal outcome from an emissions perspective, but it would keep the United States in the frame for some time to come and allow them to pursue further equivalency of effort through the implementation mechanism.

Should the United States end up on a path of true departure, this will still take until November 2020 to execute. A Party cannot serve notice of termination until three years after the Agreement enters into force and then there is a period of one year before their participation ends. While such a period does not extend beyond the term of the current Administration, it nevertheless represents a long time in politics.

In the meantime, some 195 other countries will continue to implement their national contributions through a variety of approaches. The European Union, for example, is pursuing a reduction of 40% by 2030 against a 1990 baseline, utilising a cap-and-trade system for the large emission sources such as power stations. Even within the United States, the current energy transition will continue, with much the same result in terms of emissions in 2020 and possibly even 2025 as would have been the case with the national contribution in place. Deactivation of the contribution is unlikely to spur new construction of coal-fired power stations given the intense competitive pressure from natural gas and renewables. Even discounting current competition, there remains the prospect of future carbon constraints imposed at some point within the 50+ year lifetime of a new coal-fired power station.

But the energy transition is just one element of the Paris Agreement; emissions management is at its core. This will require more than just an energy transition to implement, probably requiring large-scale deployment of negative emissions technologies which I discuss at length in Chapters 3, 5 and 7, including geological storage of carbon dioxide. This latter step may be the one that suffers following the US announcement.

The Paris Agreement can and likely will survive the events of June 1. But if other nations don't step up and look beyond their own energy transitions, focussing squarely on the need for a net-zero emissions outcome within the next 50-80 years, then the goal of the Agreement may be at risk.

# INTRODUCTION

In mid-2008, the head of the Shell media team dropped by my desk with a proposal for the company to take an early step out of the world of traditional corporate communication and into the then new and emerging world of social media. The idea was to set up a regular blog series that discussed issues pertinent to the company and its stakeholders. With climate change a central issue for society, the plan was to start on this subject. As the leading climate change person within the company, I was asked to think about topics to kick off the initiative. A few months later I was up and running with my first posts covering emissions trading, policy development, and the energy transition. The opportunity was also a great fit with my role, which requires me to be something of an independent voice internally on climate change.

The blog is now heading towards a decade of posts and somewhat perversely, it has rather outlasted the initial enthusiasm for the idea. By 2017 there were nearly 400 posts, with several hundred thousand words of content covering almost every aspect of the climate issue. I have found that readership is quite wide, mainly through direct feedback from readers who I meet by chance at conferences and even socially.

As a chemical engineer with 37 years' experience in the oil and gas industry, my goal has always been to tackle the climate issue from an engineering perspective; based on data, built on facts and without the histrionics and emotion that have come to define this subject in many quarters. In 2014, I began work on a series of three short e-books that bought to life some of the ideas from my blog, succinctly covering many of the pertinent issues of climate change today, including carbon trading and the Paris Agreement.

This book brings together and builds on my blog and the e-books. It tells the story of the climate change issue and the transition in the energy system that must be implemented to finally address the issue. At its most ambitious, the Paris Agreement implies economic and societal change on a scale that sees carbon dioxide emissions fall rapidly from 40 billion tonnes per annum in 2016, to net-zero by the middle of the century. Yet our fossil fuel based energy system which ushered in the Industrial Revolution nearly 200 years ago continues to grow and evolve even as new sources of energy come into the market and compete.

The principal economic instrument for change is clear and has been for over two decades, but in 2017 only a fraction of the global economy actively employs government led carbon pricing policies and within that none of these systems operate at a level commensurate with the pace of change that is necessary. As deployment of new energy technologies accelerates, can solutions be found to cover the full range of services delivered by fossil fuels and can warming be limited to the agreed global goals? The book explores the climate issue from its very beginnings through to the end of the 21st century and looks in depth at the transition challenge that society faces.

Data from the book are sourced from Shell and from the University of Oxford, IEA, NASA, NOAA and CDIAC and all proceeds of the book will go to an NGO working on climate change-related issues.

# 1

# ENERGY AND CLIMATE CHANGE

In July 1912, in rural New South Wales, Australia, the *Braidwood Dispatch and Mining Journal* published a short article on the global use of coal. The same article appeared a month later in a similar local publication in New Zealand.

### COAL CONSUMPTION AFFECTING CLIMATE

> *The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.*

These stories were extracted from a longer article published in *Popular Mechanics* in March 1912. That article commented on the extreme weather of 1911 and drew on the late 19th-century work of Svante Arrhenius, a Swedish chemist who linked the average surface temperature of the Earth to the level of carbon dioxide in the atmosphere. From 1896 when Arrhenius began publishing his work, a number of similar stories appeared. At the time many cities, but famously New York and London, were also seeing the local impact of coal burning.

Just over 103 years later, when French foreign minister Laurent Fabius banged his gavel on the evening of Saturday 12 December 2015 in Paris, he ushered in a truly global deal on climate change. It embraces the spirit and ambition necessary to finally deal with the very issue that the *Braidwood* editor had noted with regards to the use of coal, but in the years that followed included all use of fossil fuels and many other practices in what has now come to be known as the Anthropocene[1] era. Less than a year later, on 4 November 2016, the Paris Agreement entered into force after the ratification criteria had been met.

But will the Paris Agreement really see us through to the end of this century, bringing an end to anthropogenic[2] emissions of greenhouse gases (GHG) and therefore limiting warming of the climate system?

The track record for confronting the climate issue is not good. The 21st Conference of the Parties (COP/COP21) in Paris also marked the last opportunity for most of us to breathe fresh air with a carbon dioxide level below 400 parts per million (ppm), compared with a level of 275 ppm before the start of the Industrial Revolution. This represented a near 50% increase in atmospheric carbon dioxide in less than 200 years. The first full day of 400 ppm carbon dioxide as recorded at the Mauna Loa Observatory in Hawaii was in May 2013, but because of the annual vegetation cycle that impacts the level of carbon dioxide in the atmosphere, there was still time to enjoy the heady days of the three hundreds. This date and the more recent last day at 399.9 ppm produced an outpouring of sentiment and grief from some environment correspondents, but the news has seemingly been forgotten.

From a human perspective, 400 ppm is little different from 300 or 500 ppm and in any case the level of carbon dioxide in a cramped meeting room can be much higher, but there is significance in the number nevertheless. The background level of carbon dioxide in the atmosphere moves slowly over millennia in response to gradual changes in ocean temperature, release from volcanic activity and uptake through weathering. The amount of carbon dioxide present in the atmosphere at any point in time is an important determinant in establishing the surface temperature of the planet, with higher levels of carbon dioxide linked to a higher temperature.

That relationship was established in the late 19th century and widely reported on after Svante Arrhenius published his landmark paper 'On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground'. Since the beginnings of collective agriculture and more recently with the onset of the Industrial Revolution, the level of carbon dioxide in the atmosphere has been rising. In 1958 Charles Keeling started collecting samples of air at Mauna Loa Observatory in Hawaii, which led to both the development of an instrument to accurately measure atmospheric carbon dioxide and the publication of the modern time series of carbon dioxide observations. Keeling found that the time series was rising year on year, but also fluctuated within a year as the northern hemisphere moved through the growing seasons.

Unfortunately, the arrival of this 400 ppm day had become inevitable. Since the early days of the Keeling Curve at 315 ppm, when it became clearly apparent that anthropogenic carbon dioxide emissions were accumulating in the atmosphere, the ppm have been counting up.

Before the start of the Industrial Revolution and as the modern coal era was just getting going, the level of carbon dioxide in the atmosphere was around 275 ppm. It had been at a similar level for some 10,000 years prior and fluctuated between 175 and 300 ppm over the previous million years, both as a driver of and in response to warmer and cooler climates.

So began the Industrial Revolution with James Watt inventing the steam engine at 278 ppm. By 300 ppm the internal combustion engine was powering the first tanks at the Battle of the Somme.

Despite a very clear recognition of the potential impact of rising carbon dioxide levels coming in the form of a White House report from the President's Science Advisory Committee during the Johnson Administration at 321 ppm, it wasn't long before there was a brief worry about global cooling. Then, with atmospheric chemistry growing as a discipline (probably on the back of concerns about a Cold War–induced nuclear winter), society was distracted at 332 ppm by the first major anthropogenic global concern, the hole in the ozone layer. But with a treaty negotiated and ratification underway by 349 ppm (only 17 ppm to sort that one out), it didn't take long for the science community to remember that another big issue was lurking in the shadows.

At 352 ppm and nearly 40 ppm on from the start of the Keeling Curve, NASA climate scientist James Hansen stated to a US Congressional Committee under the presidency of Ronald Reagan that the Earth was warmer in 1988 than at any time in the history of instrumental measurements. He argued that global warming is now significant enough that the greenhouse effect can be ascribed, with a high degree of confidence, as a cause and effect relationship and that computer simulation indicates that this enhanced greenhouse effect is already large enough to begin to affect the probability of extreme events such as summer heat waves.

The international diplomatic process that led to the Paris Agreement had taken 25 years (48 ppm), starting at the Second World Climate Conference in Geneva from 29 October to 7 November 1990. Sponsored by the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP) and other international organisations, the main objectives were to review the UNEP/WMO World Climate Programme and to recommend policy actions. The participants called for elaboration of a framework treaty on climate change and the necessary protocols, containing real commitments and innovative solutions, in time for adoption by the UN Conference on Environment and Development in June 1992. The latter event came to be known as the Rio Earth Summit and it did indeed result in the adoption of the United Nations Framework Convention on Climate Change (UNFCCC), which set out a framework for action aimed at stabilising atmospheric concentrations of GHG to ‘prevent dangerous anthropogenic interference with the climate system’.

But it was to be another 13 ppm on from the Hansen intervention before the Kyoto Protocol was adopted by parties to the UNFCCC and 14 ppm more before it was finally ratified at 380 ppm. That Protocol placed emission reduction obligations on developed countries and encouraged developing countries towards a cleaner energy future through an incentive mechanism linked to the goals adopted by the developed countries. 21 ppm later and with 400 ppm now in the rear view mirror, the Kyoto Protocol is a shadow of its former self, but with at least the legacy of the origins of a global carbon market. In the interim there was a valiant attempt at a new global deal in Copenhagen, although even that was 14 ppm before COP21.

The Paris Agreement sets out a goal to stay well below 2°C, so likely below 450 ppm, which on the face of it looks very ambitious, given that the atmospheric concentration was already at 400 ppm as the doors to the Le Bourget Conference Centre closed. But a lot can happen in 50 ppm; the first World Wide Web page posted in 1993 was only 43 ppm prior to COP21 in Paris.

As COP21 concluded, I was reminded of a quote by Otto von Bismarck, 'Laws are like sausages, it is better not to see them being made'. Yet, over the course of many years I had done just that. I could now reflect upon the complex and torturous course of modern diplomacy that had worked to deliver a deal and which hopefully represents renewed global leadership on climate change.

Having spent my entire career in the energy industry, I've had the opportunity to see and experience fossil fuel production and consumption in all its many forms. As a chemical engineering student I had the chance to work for a largely coal-based electricity company in Australia and briefly in a cement plant but on completion of my degree in 1980 I started with Shell, which is where I've remained until today.

Working in refineries, managing oil tankers and visiting Shell locations such as the Alberta Oil Sands has provided me with hands-on experience with the hardware involved in the energy industry. However, it was my 10 years in the world of crude oil trading and shipping that offered real insight into the size and complexity of the system society has collectively built to power the world. The Shell trading room in London is just one of many such trading centres scattered around the globe. Despite my refining experience, I was staggered by the ceaseless activity of buying and selling crude oil, chartering ships, discharging cargoes, liaising with loading terminals and transferring hundreds of millions of dollars in cargo payments.

Why then, in 2001 with over 20 years of experience in the oil industry, did I venture into the climate change debate? I decided to take up what was then the only job[3] in Shell dedicated exclusively to the climate issue, created some three years earlier in the wake of the agreement of the Kyoto Protocol.[4] My selling points were an industry background, commercial experience and a good knowledge of energy trading markets, which at the time aligned well with the aim of moving towards a globally traded carbon market. I also had a personal interest in environmental issues that were global in scale, which had started back in high school with an article I wrote for our science journal on the impact chlorofluorocarbons (CFC[5]) were having on the ozone layer. The fact that the ozone layer problem had been addressed and CFC production drastically curtailed as a result of the Montreal Protocol — the

1989 international treaty designed to protect the atmosphere by progressively eliminating substances responsible for ozone depletion — gave many climate-issue advocates hope that a similar deal could be reached for carbon dioxide emissions. But perhaps they had never stopped to meet the energy system.

In 2002, CEO of BP, Lord John Browne, gave a landmark presentation on climate change mitigation in the City of London that I was fortunate to attend. He took the opportunity to introduce the idea of stabilisation (or reduction) wedges to a mainly City audience (the work had already circulated in the academic sector). Stephen Pacala and Robert Socolow at Princeton had developed the wedge idea in a research programme supported by BP. Each wedge represented one of a number of quantifiable actions that when combined together were necessary to move from a business-as-usual global emissions trajectory to a particular atmospheric stabilisation of carbon dioxide. In the initial study that stabilisation was 500 ppm, well above what is now considered as the level not to breach.

Reduction wedges were on a very large scale (up to 1 Gt carbon/annum or nearly 4 Gt carbon dioxide) and consisted of actions such as:

- Increasing the fuel economy for 2 billion cars from 30 to 60 miles per gallon;
- Replacing 1400 1 GW 50%-efficient coal plants with gas plants (four times the then production of gas-based power);
- Introducing Carbon Capture and Storage (CCS) at 800 1 GW coal-fired or 1600 1 GW natural gas

(compared with 1060 GW coal operating globally in 1999) power plants;

- Adding 700 GW (twice the year 2000 capacity) of nuclear fission capacity.

At least a dozen reduction wedges were proposed of which four examples are given above. The task confronting the world was to implement all of them if anticipated energy needs were to be met and carbon dioxide emissions reduced; it wasn't a case of picking and choosing.

Lord Browne fully understood the issue and was trying hard to convey the enormity of the mitigation task. This was the first real attempt to quantify the physical changes in the energy system that were necessary and to turn them into a popular narrative. Many variations on the approach followed in subsequent years. Yet well over a decade later, incredibly, none of these proposals have been put into practice. The current growth in solar photovoltaic (PV) perhaps comes closest.

More recently, researchers from universities in the United States and China re-examined the wedges and concluded that the scale of the issue had grown and that an even more ambitious set of wedges would be required to address the climate issue. The team behind this analysis introduced the concept of 'phase-out' wedges, or wedges that represent the complete transition from energy infrastructure and land-use practices that emit carbon dioxide (on a net basis) to the atmosphere to infrastructure and practices that do not.

Understanding the climate issue today isn't just about recognising that atmospheric carbon dioxide levels are rising and therefore emissions must be reduced. While this is true, it oversimplifies a complex problem which now involves two huge and unwieldy beasts, the ocean/atmosphere system and the energy system. Neither is easily changed in a short space of time. The problem that society faces is the clash between the two. Our all-consuming demand for energy means that a delivery and use system has been built on a scale equivalent to the atmosphere itself, giving the former the capacity to affect the latter. And that is what is happening.

The scale of the global energy system isn't easy to grasp. Perhaps you need to see it. After four years studying chemical engineering, I took a few months off to travel to the United Kingdom and United States. In 1980 the flight from Melbourne to London involved a stop in Perth, then a second stop in Bombay (as it was then called), after which there was a final ten-hour leg to complete the journey. I recall the plane leaving Bombay at midnight with clear skies. It wasn't long before a string of brilliant orange beads of light appeared on the horizon. Given that we were over the Indian Ocean, with only water ahead of us, I was perplexed as to what this might be. For nearly an hour, perhaps two, the lights hovered in the distance, growing steadily more intense, without an obvious source.

The flight path took the plane over Oman and directly up the western coast of the Persian Gulf, at which point the source of the lights became apparent. These were gas flares coming from offshore oilrigs, oil terminals, refineries and chemical plants. The air was crystal clear. Such was the intensity of the light that even from 30,000 feet they produced an orange glow as fierce as the evening sun. Every detail of every installation for mile upon mile was visible.

This was the oil industry, as it then existed, where gas was an inconvenient by-product without a local market and the Liquefied Natural Gas (LNG)[6] industry that can take this by-product today was in its infancy. The industry has significantly reduced the practice of flaring natural gas that is brought to the surface with crude oil production, but the scale of the oil industry has only increased. Between 1980 and 2016 global oil production grew by about 50%.

Now, obviously, not everyone has the opportunity to witness large-scale energy production first-hand, so perhaps a few examples will help. In the two hours that you might spend watching the Leonardo DiCaprio climate change movie *Before the Flood*, a lot will happen in the world. It's become a very busy place powered by a lot of energy. Just to keep up with current energy demand, the next two hours will see:

- Four Very Large Crude Carriers (VLCC) of oil loaded somewhere in the world. In total, that's more than enough oil to fill the Empire State Building.
- About 2 million tonnes of coal extracted. Much of this moves by rail and if all this coal were carried in a single train, that train would be about 200 miles long.
- 800 million cubic metres of natural gas produced, which under normal atmospheric conditions would cover the area enclosed by London's M25 to a depth of about a foot; after half a day everyone in London would be breathing natural gas.
- 8–10 cubic kilometres of water passing through hydroelectricity stations, or enough water to more than fill Loch Ness.

Our immediate contact with this is the fuel for our cars, the electricity that lights our homes and powers our stuff and the oil or natural gas used in our boilers. But there is more, much more. This includes the unappealing, somewhat messy but nevertheless essential chemical plants where products such as sulphuric acid, ammonia, caustic soda and chlorine are made (to name but a few). Combined, about half a billion tonnes of these four products are produced annually. Manufactured by energy-intensive processes operating on an industrial scale, but concealed from daily life, these four products play a part in the manufacture of almost everything. Even the ubiquitous can of soft drink relies on sulphuric acid; the chemical is used to give the aluminium can the shiny look that is expected before opening it and consuming the contents. These core base chemicals rely in turn on various feedstocks. Sulphuric acid, for example, is made from the sulphur found in oil and gas and removed during refining and treatment processes. Although there are other viable sources of sulphur, they have long been abandoned for economic reasons.

Then there is the stuff we make and buy. The ubiquitous mobile phone and the much-talked-about solar PV cell are just the tip of a vast energy-consuming industrial system that relies on base chemicals such as chlorine, but also materials such as steel, aluminium, nickel, chromium, glass and plastics from which the products are made. The production of these materials alone exceeds 2 billion tonnes annually. All of this is made in facilities with concrete foundations, using some of the 3–4 billion tonnes of cement that is produced annually. The energy system transition that society is looking to as a solution to the rising level of carbon dioxide in the atmosphere is also dependent on these materials. The current formulation for the battery that powers a 2016 model Tesla includes some 35 kg of nickel. Scaling production to the extent that electric vehicles (EV) might quickly put paid to gasoline and diesel powered vehicles implies a rapid doubling in global nickel production, which also means more energy use.

The global industry for plastics is also rooted in the oil and gas industry. The big six plastics[7] all start their lives in refineries as base chemicals extracted from crude oil.

All of these processes are energy intensive, requiring gigawatt[8]-scale electricity generation, high-temperature furnaces and large quantities of high-pressure steam to drive big conversion reactors. The raw materials for much of this come from remote mines, another hidden key to modern life. These, in turn, are powered by utility-scale facilities, huge draglines for digging and 3 kilometre-long trains for moving the extracted ores. An iron ore train in Australia might be made up of 300–400 rail cars, moving up to 50,000 tonnes of iron ore, utilising six to eight locomotives. These locomotives run on diesel fuel, although many in the world run on electric systems at high voltage, e.g. the 25 kilovolt AC iron ore train from Russia to Finland.

This is just the beginning of the energy and industrial world we live in which is largely powered by the use and combustion of oil, gas and coal. These bring economies of scale to everything we do and use, whether we like it or not. Not even mentioned above is the agricultural world that now feeds over 7 billion people, uses huge amounts of energy and requires its own set of petrochemical-derived fertilizers and pesticides. The advent of technologies such as 3D Printing may shift some manufacturing to small local facilities, but even the material poured into the tanks feeding that 3D machine will probably rely on sulphuric acid somewhere in the production chain.

Despite all this, over 1 billion people in the world today have little or no access to modern energy services. Another 2 billion or so have just climbed onto the bottom rung of the energy ladder and will begin to consume in order to raise their living standards.

A related question is whether a country can develop without an accessible resource base of some description, but particularly an energy resource base. A few have done so, notably Japan (although even in that country coal mining rose to some 55 million tonnes per annum during the Second World War), but most economies have developed on the back of coal, oil, gas and minerals. It was the use of coal that supported the rise of industry in Germany, Great Britain, the United States and Australia and more recently in China, South Africa and now India. Of course, strong governance and institutional capacity are also required to ensure widespread societal benefit as the resource is extracted.

Coal is a relatively easy resource to tap into and make use of. It requires little technology to get going but offers a great deal, such as electricity, railways (in the early days), heating, industry and very importantly, smelting (e.g. steel making). For both Great Britain and the United States, coal provided the impetus for the Industrial Revolution. In the case of the latter, very easy-to-access oil soon followed, and mobility flourished, which added enormously to the development of the continent.

But the legacy that this leaves, apart from a wealthy society, is a lock-in of the resource on which the society was built. So much infrastructure is constructed on the back of the resource that it becomes almost impossible to replace or do without, particularly if the resource is still providing value.

As developing economies emerge, they too look at resources such as coal. Although natural gas is cleaner and offers many environmental benefits over coal (including lower carbon dioxide emissions), it also requires a higher level of infrastructure and technology to access and use, so it may not be a natural starting point. It often comes later, but in many instances it has been used as well as the coal rather than instead of it. Even in the United States, the recent natural gas boom has not completely displaced its energy equivalent in coal extraction; rather, some of the coal has shifted to the export market.

On the back of all this rests the issue of rising levels of carbon dioxide in the atmosphere and warming of the climate system.