Introduction

Two Questions

Let us go then, you and I,
When the evening is spread out against the sky
Like a patient etherized upon a table

T. S. Eliot 'The Love Song of J. Alfred Prufrock' (1915)

In March of 2012, in a large-windowed conference hall on the snowy campus of the University of Calgary, I heard two simple questions. The man asking them was trying to help his audience get the most out of their day by giving them a clear understanding of where they, and others, stood when it came to action on climate change. To that end he asked them:

Do you believe the risks of climate change merit serious action aimed at lessening them?

Do you think that reducing an industrial economy's carbon-dioxide emissions to near zero is very hard?

Although this book is about more than climate change, it is because of the challenges of climate change that I have written it. And the two questions which were posed that morning by Robert Socolow, a physicist from Princeton University, seem to me a particularly good way of defining your position on the subject. So take a moment to answer them, if you would. The book's not going anywhere without you, and I think it will be a better read if you position yourself with respect to those questions before getting stuck in.

Here's a bit of context.

There is no serious doubt that the atmosphere's greenhouse effect is a key determinant of the Earth's temperature. Nor is there any serious doubt that carbon dioxide is a greenhouse gas, or that humans have been adding to the level of carbon dioxide in the atmosphere for the past few centuries by burning fossil fuels. In 1750, before the industrial revolution, the carbon-dioxide level was 280 parts per million. In 1950, when the great global boom of the second half of the twentieth century was taking off, it was about 310 parts per million. Today it is 400 parts per million. The bulk of that change has been due to the burning of fossil fuels. If you disbelieve any of those statements, you have been misled. I am not going to take the time to try and disabuse you in this book, and you should read on in expectation of frustration.

There is, however, a lot of room for doubt about the level of climate change the planet will see over the next decades and centuries. The best current estimate is that if fossil-fuel use continues on anything like current trends, the Earth is likely to end up at least two degrees Celsius warmer than it was before the industrial revolution, and possibly quite a lot warmer still. Change by one degree or two over a century or so may sound minimal, but it would be unprecedented in human history. Models of what happens to the climate in worlds in which fossil-fuel use is unconstrained point to severe, even cataclysmic, consequences in the form of damage to agriculture, greater harm done by extreme weather, the loss of biodiversity and sea-level rise over timescales of decades to centuries.

That said, different models provide different possible climates at any given carbon-dioxide level – some are more sensitive to the gas than others, in the language of modellers – and it is possible that the models on which warnings about climate change have mostly been based are, for some reason, skewed towards an unrealistically high sensitivity. It is also possible that humans and their natural world will be able to adapt to changed climates more easily and cheaply, and with less suffering, than most people concerned about climate change now believe. Thus it is possible that, even though carbon dioxide is unarguably a greenhouse gas, and a lot of it is being added to the atmosphere, climate change due to human action will not in the end be a planet-changingly big deal.

The question, though, is not about the possibility of benign outcomes. It is about your willingness to do something about the risks of bad or even catastrophic ones. A catastrophe does not have to be certain for steps to avoid it to be worth taking.

Now here's some context for the second question. The International Energy Agency, which compiles such statistics for governments, says that when the industrial nations committed themselves to cutting their carbon-dioxide emissions at the Kyoto climate-change conference in 1997, 80 per cent of the world's energy demand was met with fossil fuels. Renewable energy sources furnished just 13 per cent of the energy used; 10 of those 13 percentage points represented energy from biomass, including the wood burned on fires and in stoves by more than a billion people without other options. Wind, solar and hydropower provided just three percentage points.

In 2012, after 15 years of post-Kyoto political action on climate, wind, solar and hydro still provided 3 per cent of the world's energy needs; fossil fuels provided 81 per cent. Industrial carbon-dioxide emissions in 2013 were more than half as high again as they were at the time of Kyoto.

So how do you answer the two questions?

I answer them Yes and Yes. Yes, the risks posed by climate change are serious enough to warrant large-scale action. And Yes, moving from a fossil-fuel economy to one that hardly uses fossil fuels at all will be very hard.

To judge by what they say, and what policies they support, most people in favour of action on climate change are in the Yes/No camp: they want to act on the risks; they don't think that getting off fossil fuels is a terribly hard problem. Their way forward is to argue ever more strongly for emissions reductions; they believe these would be quite easily achieved were it not for a lack of political leadership willing to take on the vested interests of emitters.

Most of those against action on climate are in the No/Yes camp: they don't think climate is very much of a worry; but they do think that getting off fossil fuels is difficult, even impossible. Their leaders tend to focus on the weaknesses they see in the science and politics underlying the case for action on emissions, and on the drawbacks of renewable-energy systems.

Neither of these approaches works for people like me in the Yes/Yes camp. Yes/Yes people need different responses: responses which seek to lessen the risks of climate change without impractically rapid cuts in fossil-fuel use; or responses which seek to change society so deeply that such reductions become feasible. I think that deliberate modification of the climate – climate geoengineering – could offer a response of the first sort. It is to outline the promise and attendant perils of that idea, and to appreciate its antecedents and its implications, that I have written this book.

But that is not all I want to do. This is a book not just about a particular set of ways in which the world could be changed – it is about a world already changed in all sorts of ways that are not spoken of as clearly as they should be. It is a world in which the impact of the human is far greater than it used to be: a world in which the global economy has become something akin to a force of nature, in which the legacies of past generations and the aspirations of generations to come dwarf the impacts of hurricanes and volcanoes. Some people reject or denounce the implications of this change; others blithely accept them in a way that underplays their magnitude. I think those implications need to be opened up, inspected from different angles, interrogated, analysed, appreciated. Only then will it be possible to make the necessary judgements and choices.

Thinking about geoengineering is a worthwhile end in itself. But it is also an exercise in building up the imaginative capacity needed to take on board these deep changes the world is going through, and which it will continue to go through whether or not anyone ever actually attempts to re-engineer the climate. The planet has been remade, is being remade, will be remade. This book is an attempt to help people imagine the challenge those changes will bring.

Climate Risks and Responsibilities

Before going any further, though, let me justify my Yes/Yes. If you are already a Yes on either count, and impatient to boot, please feel free to skip ahead a section or two, as appropriate. If you are a No on one or the other count, let me see if I can bring you round, or at least clarify our disagreement.

First, the Yes as to risks from climate change that merit serious action. Some economic analysis suggests that there could be net benefits to the first degree or so of climate change, thanks to increased agricultural productivity in temperate zones, increased rainfall in some dry areas, less harm done by the cold at high latitudes and various other factors. If climate change due to carbon-dioxide emissions is a net benefit to the world, some people argue, countries should take no concerted action against it.

But in no such projections is everyone better off. And those who end up worse off are for the most part the people who start off poorer and who are responsible for fewer carbon-dioxide emissions, such as farmers and the urban poor in developing countries. I think that if carbon emissions do harm to those unfortunates, then people in rich countries and rich people in poor countries – the two groups, each about a billion strong, whose ways of life account for an overwhelming share of emissions – have a duty to act. That duty persists even if the emissions are somehow helping other people, such as rich-world farmers or old people at risk of death in cold winters. In most peoples' moral systems, you do not get a free pass to do harm to one set of people just because you are doing good to another set.

I understand that cutting emissions is by no means the easiest way to help the people whom those emissions put at risk. Easier immigration to rich countries; well-implemented development aid; political reform that puts more weight on the livelihoods of the poor; a more open trade system: all these policies offer more immediate solutions. But helping in those ways, while admirable and a good idea regardless of what else is done, would not fully excuse the climate harm. Just as it is wrong to help some people with one hand while hurting others with the other, you can't knock people down with impunity just because you are willing to slip them some cash first and pick them up off the floor afterwards.

Not everyone will accept this reasoning, and some who do accept it will, as a matter of pragmatism, feel justified in settling for net good even when it involves harm to some vulnerable people. But there are other reasons for believing that climate change merits a serious response. Climate change may be neither as big a problem nor as poorly tolerated as most of those who study it think; but even were this the case, there would remain a fair chance that it will be pretty bad, and a smaller chance that it will be very bad indeed. Let's say there is a 50 per cent chance of net harm, and a 5 per cent chance of this harm being very severe. To me, those odds justify serious action. A 5 per cent chance is one in twenty: pretty close to the odds that, on throwing a pair of dice, you will get either a double six or snake eyes. Not likely, but a long way from unheard of. When I was told on reasonable authority that my risks of a cardiac event in the next fifteen years or so were about 6 per cent, I resolved to make some changes in the way I lived my life. A little later I actually managed to act on those resolutions.

A straightforward reading of the latest assessment by the scientists of the Intergovernmental Panel on Climate Change (IPCC) would suggest that the risks are higher than those I just gave; many scientists and almost all environmental activists would put them much higher. But if you think, as I do, that figures as low as 50 per cent and 5 per cent justify action, it doesn't really matter for the purposes of this discussion if the figures are actually higher. Provided that threats to the world at large move you, you have already bought into the case for finding a way to act.

If you require more specific threats – threats to yourself, your loved ones, your descendants and theirs – things are not so clear-cut. I will not pretend that climate-change risks are all that high for reasonably well-to-do people in developed countries in the next half-century or so, and I imagine that describes most of my readers. My choice to worry about the more general threat is, I recognise, a choice. You may choose differently.

So those are my reasons for a Yes to the first question. What about those of you who answered No? Some, as mentioned, may find threats to humanity at large insufficiently motivating. Among the others, there seem to me to be two ways you might have come to your No. You may think that my one-in-twenty chance of catastrophe is small enough to live with. Alternatively, you may think that a 5 per cent chance would indeed justify serious attempts at risk reduction, but that the odds are actually longer than that – that the chance of catastrophic harm is, say, one in a hundred.

In the first case, the one where you are less risk-averse than I, there's probably not much I can do to change your mind. Please read on, though. I hope that readers do not have to agree with all the premises of this book to find its ideas stimulating and its effect on their imagination rewarding. I also suspect that some of those ideas are going to sound disturbingly risky to many readers. It will be nice to have a few people who laugh in the face of danger come along for the ride.

In the second case, the one where you think the risks are less than one in a hundred, I think you are displaying an indefensible level of certainty about how the climate works and how much carbon dioxide will be emitted over the next century. I can see that it would be nice to feel that level of certainty. But I just don't see how you can if you've looked at the issue seriously. Given the uncertainties involved, to be sure that a climate disaster is that unlikely shows a self-confidence so well developed as to be indistinguishable from folly.

The Second Fossil-Fuel Century

What about the other Yes? Why should moving off fossil fuels be so difficult? The answer lies in the scale of the problem and the speed of the change required, and – fair warning – it will take me rather longer to run through than the first Yes did.

The 30 billion tonnes of carbon dioxide emitted in 2013 came from burning three trillion cubic metres of gas over the year; from burning almost three billion barrels of oil in each of its months; from burning a bit less than 300 tonnes of coal in each of its seconds. The infrastructure needed for all that burning was almost as complex as it was essential.

To stabilize the climate by means of emissions reduction means replacing the whole lot.

The world has made huge investments in the facilities that extract fossil fuels from the ground and burn them – mines, oil wells, power stations, hundreds of thousands of ships and aircraft, a billion motor vehicles. Leaving aside the political lobbying power that such investment can command, there would be a limit to how quickly that much kit could be replaced even if there were perfect substitute technologies to hand that simply needed scaling up. If the world had the capacity to deliver one of the largest nuclear power plants ever built once a week, week in and week out, it would take 20 years to replace the current stock of coal-fired plants (at present, the world builds about three or four nuclear power plants a year, and retires old ones almost as quickly). To replace those coal plants with solar panels at the rate such panels were installed in 2013 would take about a century and a half. That is all before starting on replacing the gas and the oil, the cars, the furnaces and the ships.

And the challenge of decarbonization is not just a matter of replacing today's extraordinary planet-spanning energy infrastructure; you have to replace the yet larger system it is quickly growing into. The twentieth century began with a world population of 1.6 billion, none of whom enjoyed the energy-intense affluence of the citizens of today's modern industrialized states. Today's emissions are for the most part a result of the fact that two billion people now lead such lives.

But there are five billion more people in the poorer countries not leading such lives. About a quarter of those people lead lives illuminated only by sun, moon and fire, with no reliable access to modern energy supplies of any sort. They deserve better. All of those people should be able to lead the lives that the affluent two billion lead today, with access to the industrial and agricultural goods and services that copious energy makes possible. And so should their children and grandchildren.

The world's population is expected to grow from seven billion today to more or less ten billion by 2100. By that time the number of people enjoying rich-world energy privileges should also reach ten billion. So the challenge is to achieve for an extra eight billion people in the twenty-first century what was achieved for two billion in the twentieth century. Meeting that challenge implies a lot more energy use. It may be that a prosperous person of 2100 ends up using no more energy than a European did in 2000. That would be unprecedented, but it is perhaps not implausible. Energy use has, after all, plateaued in some places. Even under that assumption, though, the twenty-first century has to see either the continuation of a world divided into haves and have-nots or a massive expansion of the energy systems of developing countries.

It was the prospect of such an imminent expansion that made the grand agreement on climate change which much of the rich world was seeking at the Copenhagen climate summit of 2009 unattainable. The proposal that shaped those rancorous debates was that world carbon-dioxide emissions should halve by 2050, with developed countries going further and reducing their emissions by 80 per cent or more. The idea was that such deep reductions by rich countries would give developing countries a chance to go on using fossil fuels for a bit longer – a bit of room for growth. In shaping the proposal this way, its architects were recognizing the fact that, at the moment, developing countries are powering their growth with fossil fuels. Given the energy systems they have today, other technologies could not provide them with comparable amounts of power at the scale and cost they need.

The problem with the Copenhagen proposal was that while populations in the developed world are mostly stable, many of those in the currently developing world are still growing. At the time of Copenhagen, there were about six billion people in developing countries. In 2050 there will be more than eight billion in those countries. Take this into account and the Copenhagen deal offered no real room for growth; the extra fossil-fuel use envisaged in the developing world was only enough to balance its countries' increasing populations. In terms of carbon-dioxide emissions per person, the developing world would have had to stick very close to its then current levels, which were less than half of Europe's, less than a third of America's. Unsurprisingly, the deal did not get made. New fossil-fuel-burning capacity has been added round the world since Copenhagen at an even higher rate than it was being added before.

Though emissions from developing countries are unlikely to diminish any time soon, many rich nations remain committed to the reductions of 80 per cent that they spoke of at Copenhagen. Indeed, Britain has gone so far as to enshrine them in law. Such targets imply that emissions will be reduced by 4 per cent every year for 40 years. For comparison, when France converted its electricity infrastructure almost entirely to nuclear power between 1970 and 1995 it managed a reduction in emissions of just one per cent a year. Britain's 'dash for gas', a large-scale shift away from coal that followed the liberalization of the electricity market in the 1980s, reduced emissions by the same rate in the 1990s. America's dramatic shift to greater natural-gas use in response to the shale-gas revolution of the past decade has led to emissions reductions on a rather smaller scale. There are very few precedents for 4 per cent year-on-year emission reductions that don't also involve an economic collapse – and they can only last for so long.

This fits with the lessons that Arnulf Grübler, an academic at the International Institute for Applied Systems Analysis outside Vienna, has drawn from decades spent studying the history of energy systems, and in particular the 'energy transitions' in which one energy technology displaces another; the steam engine replacing the draft animal and the waterwheel, for example. One general principle, he says, is that energy transitions have been slow – they take about a century.

Things are different now, say the mainstream environmentalists and the environmentally conscious politicians in the Yes/No camp. Previous energy transitions were for the most part realized with no overarching plan. This one will be deliberate. And there has already been a renewables revolution on which the transition can be built. In the past couple of decades wind and solar power have been deployed on an industrial scale for the first time. There are now single installations with a capacity of between 100 megawatts and a gigawatt – facilities similar in size to advanced gas-turbine plants at the bottom end and nuclear plants at the top end.

(A note here on power and energy: power is the rate at which energy is made available or used over time; it is measured in watts, and multiples of watts. A human body burns up the energy in food at a rate of about 100 watts. The 1.5-litre engine in a compact car like a Toyota Corolla generates power from gasoline at about 50,000 watts, or 50 kilowatts (50kW). A really big wind turbine turns the energy of the wind into electricity at a rate of 5,000,000 watts, or five megawatts (5MW). A big power station typically runs at a billion watts or so – a gigawatt. The energy use of a major economy like America's, Europe's or China's is a thousand times larger still: something like a trillion watts, which is a terawatt (1TW). Energy is what you get if you multiply power by time. Use a kilowatt of power for an hour, and you have used a kilowatt hour.)

The attraction of renewables goes beyond drastically reduced greenhouse-gas emissions. Burning fossil fuels produces a wide range of 'aerosols' – tiny particles floating in the atmosphere (aerosol spray cans are so called because they turn their contents into such particles). Millions of lives are shortened each year because of the harm these aerosols do when inhaled; power plants that burn coal are particularly grievous offenders. Chemical contaminants created by generators and engines – nitrogen oxides and ozone – also do a lot of damage, both to people and to crops. And the supply of fossil fuels can fluctuate wildly, either because of changes in the market or because of politics. The fuel costs for some renewables, on the other hand, are fixed and very low – wind, sunshine and the tendency of water to flow downhill come for free, and the plants grown to burn as biomass can often be furnished pretty cheaply, too.

It is a fine list of benefits. But there is a second lesson from Grübler's studies of past energy transitions to be confronted. They have, in the main, been driven not by the availability of new ways of providing energy, but by new ways of using it: transitions are pulled by demand, not pushed by supply. Electricity and internal combustion engines were adopted because they allowed people to do things they hadn't done before, and people demanded those new energy services in ever-greater numbers. The requisite fuel supplies, generating technologies and distribution systems raced to catch up. There is simply no precedent for a wholesale change that doesn't offer users appealing new possibilities in terms of the way they use the energy – for a change that is pushed through rather than pulled along. And as far as the end user is concerned, renewable electricity is just another form of electricity – it offers no advantage as a means of powering things, even if generating the electricity that way has various charms. Its benefits are felt at the level of the system, not at the level of the individual buyer. That means a renewable-energy transition will need significant pushing.

As with Grübler's observations about the time transitions take, this points merely to decarbonization being unprecedented, not impossible. But the best example in recent history of an energy transition that governments tried to push through, rather than simply letting users pull, is not very encouraging. Governments in various countries pushed quite hard for a transition to nuclear power in the 1960s and 1970s. In many of them, though, the technology's early growth subsequently stalled.

This was in part an economic matter. In America, in particular, early promises of cheap and plentiful power failed to pay off as companies saw the costs of nuclear plants go through the roof at the same time as the growth in demand they had expected failed to materialize. But on top of this, the 1970s saw a catastrophic turn in the way people thought of and talked about the future; nuclear power played a role in this turn, and suffered from the consequences of it. I think it is worth looking at that process in a little detail, not just because of what it says about energy transitions, but because it throws light on our main themes. As will become apparent at various times in the course of this book, little else can hold a candle to the energies of the nucleus when it comes to imagining the impacts of world-changing technology.

In its early years nuclear power benefited from a carefully crafted position as the epitome of the scientific progress taking the world forward into a better future. Although there was a persistent undercurrent of cold-war anxiety, there was a general enthusiasm for the future that nuclear power was held to offer. Initial concern about nuclear power imagined it posing an insidious and ubiquitous threat, contaminating the world through its very existence in rather the same way that nuclear fallout did. It was neither a plausible concern nor one that gained much traction. Many environmentalists focused instead on the technology's environmental benefits; in terms of cleaning up the air people breathed nuclear plants promised to be a great step forward from coal plants.

In the 1970s, though, the original fear of nuclear business-as-usual was at first reinforced, and then displaced, by a fear of nuclear accidents. The notion of the meltdown focused nuclear anxiety on specific events, and relied on increasingly widespread concerns about the military-industrial complex and the technocratic hubris of governments. At the same time, it maintained the underlying sense of an invisible, intangible and global threat that makes all concerns about radiation so unsettling and prone to irrational exaggeration. The double vision in which specific accidents were also global threats reflected the sheer scope of the effects imagined: a ball of radioactive slag produced in a meltdown passing right through the Earth (the 'China Syndrome'); a meltdown poisoning its surroundings for geological periods of time. On top of these fears about what would happen if the nuclear-bomb-like energy of a reactor got out of control were worries about the levels of control that organs of state security might impose on the public to stop any saboteurs seeking to bring about disaster. The power needed to keep the genie bottled up was as worrying, to some, as the power of the genie unleashed – maybe more.

The new nuclear fear was not the only factor behind the stall in the transition to nuclear energy. In America, as noted, the technology proved to be far more expensive than its proponents had hoped, in part because of the rushed way in which it was rolled out. By the time of the Three Mile Island accident of 1979, which did a great deal to cement anti-nuclear fears in the American imagination, no new nuclear power plants had been ordered in America for more than three years. But the new fears added to nuclear power's woes, and indeed its costs, by making permission to build plants harder to gain; the current mixture of expense and public disquiet goes a long way to explaining why most nations with nuclear-power programmes get less than 20 per cent of their electricity from them and have expanded them little since the 1980s. (The great exception is France, which has a culture of technocratic planning, a trust of engineers on the part of both the public and the policy-making elite, a history of valuing its energy self-sufficiency, governments consistently happy to take a direct role in running the energy system and low fossil-fuel reserves. Nuclear reactors generate almost 80 per cent of its electricity.)

There are now environmentalists who would like to shock the stalled nuclear transition back to life as a way of fighting climate change. They argue that nuclear power's obvious problems – the risk of accidents, the production of radioactive waste and the facilitation of bomb building – are nothing like as bad as they have been painted, and pale compared to the damage climate change could do, and they are mostly right.

Only one nuclear accident – that at Chernobyl, in 1986 – has led to significant loss of life. Current assessments of the Fukushima meltdown suggest that there will be no discernible deaths as a result. Compare that with more than a million who die with coal-ruined lungs every year. New nuclear reactors built to the standards demanded by experienced government regulators with the power to have their decisions respected will be significantly safer than older designs. Long-term storage of waste has been politically mismanaged in many countries but is neither a particularly pressing problem – safe interim storage solutions that can last for decades, even a century, are tried and tested – nor a fundamentally intractable one. Though many civilian nuclear-power programmes have been linked to weapons development, those links have often proved breakable: neither Argentina nor Brazil is currently pursuing a bomb; South Africa gave its bombs up. Proliferation is a grave risk, but doing without nuclear electricity would not lead to a proliferation-free world. North Korea and Israel have produced nuclear weapons with no civilian power programme at all.

Despite all this, there seems little likelihood either that the green movement will pivot to nuclear power en masse or that the number of reactors will grow substantially. They remain more expensive watt-for-watt than fossil-fuel plants, most hydroelectric dams and some wind installations, and they only come in large sizes, which means you have to buy a billion watts or so at a time at costs of tens of billions of dollars. While smaller reactors would alleviate some of that problem, their development is difficult – nuclear power is, given the items involved and the regulations that surround them, a hard area in which to innovate. And nuclear energy enjoys none of the demand-pull that was crucial to earlier energy transitions; for a domestic or industrial user, nuclear electricity is no better than any other sort.*

* This is true for civilian power; in the military, however, nuclear electricity does have a key advantage, in that it can be used to power submarines which would otherwise have to take on air through a snorkel so that they could burn diesel. It was this small but crucial niche that led to nuclear reactors capable of generating electricity being developed in the first place.

Many of those pressing for a nuclear renaissance accept some or most of this. But they persevere despite knowing that their chances are slim. In part this is the willful blindness of the enthusiast – people who fully take on board how hard it is to change things often do not try. There is also a dislike of the irrational and a worry over seeing it dominate policy; the unrealistically exaggerated fear of radiation that drives mainstream green attitudes regarding nuclear power baffles and offends such people. They look askance at Germany's decision, after the Fukushima disaster, to listen to its long-standing anti-nuclear movement and close down a fleet of reactors that was producing safe, copious, clean and (because their capital costs were paid off) cheap electricity. Being pro-nuclear serves them as a badge of their willingness to break from green orthodoxy and to look at the world as it is. But most importantly, they have a deep-seated belief that renewables cannot on their own produce the sort of decarbonization that reductions in climate risk require, especially when the needs of the as-yet-undeveloped world are fully taken into account.

Renewables have constraints that go beyond their current costs. Wind and solar energy are intermittent. They become unavailable in ways both easily predictable – there is no solar energy at night – and less so. Sometimes the wind will fail to blow over quite large areas for days or weeks at a time. This need not be as much of a problem in the future as it would have been in the past; information technology will make it easier for 'smart grids', smart appliances and, indeed, smart people to cope with such fluctuations by managing demand; consumers will probably consent to such management if it lowers bills. But intermittency still drives up the costs and complexity of power supply if you want to get most or all of your electricity from renewables and you don't have access to a great deal of hydro-electric capacity – a largely zero-carbon source that can be ramped up or down very quickly to balance out the intermittencies of other supplies.

Wind, solar and biomass also all take up a lot of space. A wind farm on a moderately well-chosen site produces one or two watts for every square metre of land in its footprint. A square kilometre thus delivers about a megawatt, and so it takes a hundred square kilometres to deliver the 100MW you might expect from a gas turbine that fits into a plant not much larger than a warehouse. Crops grown to burn as biomass are an even more dilute source of energy – harvesting them provides at best a watt or so per square metre in temperate climes, though in the tropics things can be a bit better. Solar power does better, but still takes up quite a lot of land.

What does this mean for an industrialized country like the United Kingdom? The rate at which British people use electricity is about 40GW. To generate this at one watt per square metre would mean devoting 20 per cent of the area of the country to renewable energy (to be fair, you can graze sheep on the same land. But still . . .). If you want to deliver ever more of the nation's energy in the form of electricity (for example, if you want to replace fossil-fuel-powered cars with electric ones, or gas-fired domestic heating with electric heat pumps), you will need to be generating more electricity, and thus using even more land. Efficiency can help – efficiency can always help – but not enough to transform the situation. You also have to consider that, to some extent, more efficient energy systems encourage people to use more energy.

Even though they are intermittent and profligate in their use of space, renewables have a role to play; but the presence of fossil fuels will squeeze that role for as long as the fuels are allowed and affordable. Quite a lot of work on renewables in the 1970s and 1980s was premised on the idea that this would cease to be the case – that fossil fuels would become sparse and unaffordable. Similar ideas were prevalent in the mid-2000s when Europe framed an energy and climate strategy that gave pride of place to renewables: fossil-fuel prices, it was claimed, would in the long run both rise and become more volatile. At the time of the Copenhagen summit it was argued that if Europe were to become a renewables superpower it could avoid those costs and get ahead of the rest of the world.

But fossil fuels have become cheaper, not more expensive, and look likely to stay quite affordable for rich countries for decades to come. Attempts to make fossil-fuel prices higher through carbon taxes and similar schemes could, in principle, change this, forcing a lot of investment into alternatives. But in most places they have not attracted enough political support to stick, and it is not clear that they can. They would stand a better chance in a world that coordinated its actions internationally; when people talk about the low costs of a transition to renewables, they are imagining it taking place in such an optimal world. But that world has not yet been achieved.

Instead of increasing the costs of fossil-fuel generation through a carbon price or tax, governments have preferred to subsidize renewables. One problem with this is that it doesn't encourage people to stop using fossil fuels in existing plants; it just rewards people for building alternatives. Another problem is that the more renewables get built, the pricier the subsidies get. Germany's current *Energiewende*, a national policy which aims to cut carbon-dioxide emissions from the power sector drastically while at the same time retiring all of the country's nuclear plants, seems set to find out how far such subsidy approaches can go; they have cost well over 100 billion euros to date. In general, few economies have wind, solar or biomass supplying much more than 20 per cent of their electricity market (the same sort of level, possibly coincidentally, that has been achieved in the other push-not-pull attempt at an energy transition – that of nuclear power). That's a large enough fraction to transfer a significant amount of money to the builders and buyers of wind turbines and solar. But it is not enough to change the course of the planet's climate.

This reflects a general issue with environmental policies;

they are often aimed at pleasing voters and lobbies with green interests more than they are geared to achieving the stated environmental ends. People see wind turbines being built in prodigious numbers, and see solar cells on roofs, and think they are looking at a solution. In fact, in part because of the low energy-density of renewable energy, these impressive – and, to some, infuriating – sights are achieving very little in terms of providing enough power for a world of ten billion reasonably well-off people.

Renewable efforts do not have to be paltry. The *Energiewende* is no small thing. And it is possible that Germany – a rich, technologically potent country which is rather good at sustaining national consensus – may be able to convert itself almost entirely to renewable energy. That said, in 2013 Jane Long, formerly the associate director for energy and the environment at Lawrence Livermore National Laboratory in California, chaired a study of the prospects for emissions reduction in her state – also rich and technologically potent, though less adept when it comes to political consensus. Long's study found that by encouraging energy efficiency, completely replacing fossil fuels as a source of electricity and greatly reducing their use in industry and transportation, California might cut its emissions by 60 per cent over 40 years. With a justifiable pride in her home state's record on innovation and commitment to environmentalism, Long says that if California can't do better than that, no one else can. And compared with that scenario, which made use of nuclear power as well as copious renewables, Germany is aiming for a higher target with one arm tied behind its back.

But the challenge of decarbonization would not be met just by a few environmentally conscious economies cutting their emissions by 60 per cent, or 80 per cent, even if they could; all the big emitters need to get on paths that take them to 100 per cent if the level of greenhouse gas in the atmosphere is to be stabilized in this century, with the electricity sector carbon free a lot earlier. Just half of them doing so does not cut it – and perversely, by reducing demand, it might well reduce the cost of fossil fuels to the other half.

It was the fact that all the big emitters need to be involved that drove the hoopla over Copenhagen. But the belief that the world can in some way come together to agree to do as a whole what its large economies are not obviously willing to do individually is illusory. There is a value in international negotiations: they can help shore up a sense of purpose; they can provide something by way of sticks and carrots. But an international agreement will not lead any government to follow climate policies that are clearly not supported at home for reasons of ideology, cost, or any other factor. And an international agreement on climate questions is also peculiarly hard to come by.

There are many reasons why this is so, most of them linked to the fact that the people who do most of the emitting do not face most of the risks from climate change, and also to the fear that if some act but not all, then those who do not act will get as much of the benefit as those who do. Most crucial of all, though, is the problem that whatever benefits there are and to whomever they accrue, they will not be felt for decades. The climate depends on the cumulative carbon emissions – on the total stock that has been added to the atmosphere over centuries, not on the rate at which they are added at any particular time. Any plausible cuts in carbon-dioxide emissions made today would have more or less no effect until the mid-century. By that time the costs of inaction might be horribly plain – but there will be no time machine with which to come back and set the necessary cuts in motion on the basis of that future knowledge. As Hans Joachim Schellnhuber, an influential expert on climate-change impacts, puts it, 'climate change is too slow a problem to solve in time'.

The costs of action and the lack of an international mechanism do not mean there will be no decarbonization in the decades to come; but I suspect it will be more like that seen in China than on the scale imagined in Germany or California. China is building more renewable capacity than any other nation, and is ramping up a big nuclear programme, too. It is also enacting ambitious energy-efficiency measures. But this is only slowly reducing the proportion of its energy it gets from fossil-fuel use. Its current plans have its carbon-dioxide emissions continuing to rise until 2030 – at which point 80 per cent of Chinese energy will still be coming from fossil fuels. How quickly it might fall after that is anyone's guess.

As China, so the world. An investment in non-fossil-fuel sources of energy great enough simply to keep up with increasing demand is a huge commitment. An investment big enough to displace fossil fuels entirely does not look to be remotely on the cards under current conditions. Between 1750 and 2000 humans released half a trillion tonnes of the carbon that the Earth had stored up in fossil fuels. It is very hard to believe that, over the coming century, they will not release a trillion tonnes more.

Altering the Earthsystem

Yes/Yes is compelling to me, and I hope it now looks pretty reasonable to you. But as Rob Socolow pointed out in that big-windowed Calgary hall, it is a minority view.

Those who oppose climate action sit firmly in the No/Yes camp. For some of them, the Yes drives the No. If you understand that, Yes, action on fossil fuels is hard – hard technically and hard on people who get hit with higher electricity and fuel bills, as well as hard on people who have investments in oil, gas and coal – concluding that No, it isn't necessary is quite convenient. People in the No/Yes camp have a fair bit of motivation to search for reasons to doubt the science behind calls for action, a search with which organized lobbies have been happy to help.

The Yes/No camp saves its doubt for people who point out the impracticality of an energy transition on the scale required to make a big change in the risks. Politicians who accept the need for climate action insist that it will be relatively painless, maybe even an enjoyable improvement, bringing jobs and growth. The greens who accept that sharp reductions in fossil-fuel use will indeed have costs often imagine them falling predominantly on big businesses. Some also argue that the costs are, in a way, illusory. While less affordable energy and consequent drops in consumption look like a 'cost' to economists, some greens see the latter, in particular, as a benefit.

The rich world contains quite a few people who have found that they can lead happier lives with less stuff, and the same might be true of many more, if we could only see our way to making that choice (I say 'we' here because I accept that I may be among those who, because of the ingrained mindset of consumerism, are failing to follow a course of action which might make them happier). But as Pat Mooney of the Canadian environmental group ETC (it stands for Erosion, Technology and Concentration, and is pronounced 'et cetera') pointed out to me a few years ago, people who see some evidence that choosing a path of lowered consumption would make them happier and yet do not choose to act on that evidence are very unlikely to make the same choice for the benefit of others. And it is also unlikely that they will acquiesce in being forced down the path of happiness unchosen. 'Lead the life I want you to lead or the planet gets it' is not only an unattractive position, it is an ineffective one.

The world's political leaders are resolutely Yes/No or No/Yes, and most of the public seems OK with that. But the people Socolow was addressing in Calgary had pretty much declared for Yes/Yes simply by turning up. If they had not both taken responding to the risks of climate change seriously and believed fossil fuels were hard to get rid of they would not have bothered to attend a meeting on innovative chemical-engineering techniques for pulling carbon dioxide out of the air, a technology known in climate-change circles as 'direct-air capture'. Used at a scale large enough to have an appreciable effect of the atmospheric carbon-dioxide level, direct-air capture would be a form of geoengineering – which I define as the deliberate modification of the earthsystem on a global scale.

Where did that word 'earthsystem' come from? Why not just say modifying the Earth? Because I think people can sometimes be helped to see things afresh by expanding the language that they use, and this is one of those times. The Earth sounds and feels like a thing; when I say it – or rather, when you read it – in a context such as this, you like as not see a blue-and-white globe floating in space. When I say earthsystem instead, you probably see nothing at all. But it is my hope that, over time and through usage, you will come to feel something.

What I hope you come to feel, like wind on the skin, or the tremor in the ground from rushing water nearby, or lightning sensed through shut eyelids, is something dynamic. The earthsystem's essence lies not just in rock and water, or in air and plants, but in all the Earth's interplay of energy and matter. It lies in the flows of energy which drive the cycles of carbon, water, nitrogen and life's other essentials that roll ceaselessly round the planet and down through the eons. And it also lies in the way that those movements, and the transformations which they bring, shape the course of the flows of energy that drive them. These flows and cycles are the defining processes of the earthsystem.

The forces and feedbacks between these flows of energy and matter make the earthsystem subject to changes, just as other complex systems are. The system's processes can shift from one state to another quite quickly. Some of the biggest transitions that geologists see recorded in the rocks of the Earth, transitions which they use to distinguish one period of the planet's history from another, can be understood as shifts in the way the earthsystem works, shifts from one state to another.

Today human technology is driving change on a similar scale to that which has punctuated the story of the planet's past. What, at the beginning of the age of science, Francis Bacon dubbed 'human empire' – the expansion of power and knowledge, barely distinguishable from each other, out into the world – has become something like a force of nature. Dams are changing the flow of rivers, engineering works are altering the processes of erosion, agriculture is redefining the global cycling of nutrients and the patterns and pace of extinction – which is to say, evolution. And humankind's greenhouse gases are changing the rate at which energy flows through the planet's living systems. These effects on the earthsystem are now so marked that some scientists favour the idea of defining the current period of human empire as a new phase in the planet's history: they call it the Anthropocene.

And this is another reason for wanting to talk of the Earth as a system. Because the way that humans are imposing the Anthropocene on the planet is not just as a set of seven billion primates but as a system – the system that makes up the world in which we live, a world of social and economic and political and emotional forces just as real as the physical forces of the earthsystem, and quite as subject to feedback and changes of state. If you see the environment as just a thing – a planet, a lump of rock and water and air – then this socially mediated world, a world always, to a human, coloured by subjective experience, will perforce seem separate from the environment, as different in kind as a performance is from a stage. If you see the human world's context as the earthsystem, though, then the two systems begin to intermingle: the boundaries that have previously kept the social from the natural begin to blur. Neither has a monopoly on action. Both have impacts on the other. Economic feedbacks and climate feedbacks, political forces and radiative forcings, do not exist in different frames of reference. They all provide the settings for each other. It is through the earthsystem and its processes that the human world changes the geophysical facts of the planet; it is to changed states of the earthsystem that the human world finds itself responding.

When the change that humans bring to this new Anthropocene state of the earthsystem is deliberate, I see it as geoengineering; in this book, that term will cover any deliberate technological intervention in the earthsystem on a global scale, not just those aimed at countering, or ameliorating, the changes that people are making to the climate without deliberation. The notion of deliberation matters; to the earthsystem, a change made in passing may be no different to one made on purpose, but in the human world there is a difference between the changes you make and those that you plan, between having an effect on the future that you can foresee and having an effect that you intend. The extinction of the dodo is one thing; that of smallpox is another.

The effects of piling more and more carbon dioxide into the atmosphere can be foreseen, though not in as much detail as one might like. But they are not exactly intended. If the effects were to be reduced by machines capable of sucking carbon dioxide out of the atmosphere, like those under discussion in Calgary that morning, the resultant change would be intended, even if not all its impacts could necessarily be foreseen. Thus large-scale direct-air capture of carbon dioxide would be a way of giving the Earth a climate other than the one it would expect, given the amount of carbon dioxide that human activities have emitted. And that is what climate geoengineering aspires to more generally. Climate geoengineering can be pursued in very different ways, but the aim is always to decouple the climate from humanity's cumulative emissions of carbon dioxide. It is to unshackle, if only to a very limited extent, the future from the past.

Deliberate Planets, Imagined Worlds

If direct-air carbon-dioxide capture of some sort could be implemented safely on an arbitrarily large scale it is hard to imagine that it wouldn't be. Sucking carbon dioxide out of the atmosphere as fast as it was pumped in would seem to more or less solve the climate problem, as long as somewhere could be found to put the carbon dioxide thus sucked out. Maybe it could be stored in reservoirs underground; maybe it could be turned into solid carbonate rock; maybe it could be turned back into hydrocarbon fuel, so that such fuels would never run out.

Unfortunately, at the moment direct-air capture cannot be implemented on a remotely large enough scale because there is no proven technology for taking carbon dioxide out of the air that is practically or economically up to the job. And if your goal is to pull carbon dioxide out of the atmosphere at anything like the rate at which it is currently being pumped in, it's a very good bet that no such technology will ever exist. Some of the reasons why this is the case – as well as the promise direct-air capture might still offer while never meeting such an all-encompassing goal – will be discussed later. What I want to bring to your attention here is not the detail of the technology, but something about the people trying to make it real.

There were four groups actively working on the idea at the Calgary conference, and three of them had something striking in common. They were all fronted by charismatic North American physicists, the sort of people who impress and inspire students by showing the near-inexhaustible ability of physics to provide answers, and by encouraging them to ask questions to which the answers are truly interesting. They are the sort of men who make knowledge – both theirs and, once you learn from them, yours – feel like power. Men of human empire.

They are also the sort of men who can attract the interest and admiration of wealthier and more powerful men. All three of the physicists whose work was under discussion in Calgary were professors at prestigious universities, but their air-capture work has been mostly done under the aegis of companies they started for this purpose with the help of investments by rich sponsors. Klaus Lackner, of Columbia University, the first person to make a splash working on direct-air capture, was able to take his ideas about 'artificial trees' forward thanks to the backing of the late Gary Comer, the man who founded Lands' End clothing; Peter Eisenberger, also of Columbia, who dreams of using solar power to turn the carbon dioxide captured from the air back into fuel, attracted Edgar Bronfman of Seagram. David Keith, then at the University of Calgary and now at Harvard, landed the biggest fish of all. The main investor in his direct-air-capture company, Carbon Engineering, is Bill Gates.

To some, this will seem proof enough that climate geo-engineering is a pernicious capitalist plot. Further proof, if needed, might be adduced from Richard Branson's enthusiasm for such schemes (he has set up a prize to reward progress in pulling carbon-dioxide from the atmosphere). When Branson said, in 2009, 'if we could come up with a geoengineering answer . . . then Copenhagen wouldn't be necessary. We could carry on flying our planes and driving our cars' you could all but hear green hackles rise at such get-out-of-jail-free sentiments from an owner of airlines. But if it is all a plutocrats' plot, it is a very poorly contrived one. The Calgary meeting had been arranged by Keith to discuss the cost of the schemes in question. A report by a panel of the American Physical Society, chaired by Socolow, who has a long background in energy and climate studies, had derived costs for capturing carbon dioxide from the air of around $600 a tonne, possibly much more. That was far higher than the figures Eisenberger and Lackner had floated, and more than double the less ambitious figures Keith's company talked about. The meeting was intended to thrash out the differences.

It managed to get some way towards that goal; members of Socolow's panel admitted that their estimate might be slightly high, though they didn't think that would make any difference to the technology's feasibility. Keith still thinks that they are wrong, and that it is conceivable that his direct-air-capture technology might turn a profit in places where there is an industrial need for more carbon dioxide than can easily be brought in on trucks and where, in addition, the government has set a significant price on carbon. But he is talking tens of thousands of tonnes, not tens of billions. No one could have come away from Calgary thinking that direct-air capture was anywhere close to being a viable tool for large-scale climate geoengineering. Anyone investing in direct-air capture as part of a plot to take over the climate is making a mistake.

If, then, direct-air capture doesn't really matter, why think about it? Because it may matter, in time – and because knowing that helps put the present into context and lets you imagine the future more fully.

In the Yes/No and No/Yes camps, the details of the future don't much matter. The fear of bad outcomes motivates both climate activists and their foes, but the precise details don't matter. Both sides see themselves as averting a future that they don't like more than creating one that they do.

The Yes/Yes position requires a richer imagination – one that allows that the future may be quite different. It is in the Yes/Yes world that you will find people who are open about the need they see to fundamentally change the world economy so that it no longer demands or delivers constant growth – an option today's liberal democracies, even green-looking ones like Germany, scarcely countenance – or to return large numbers of people to a relationship with nature centred on the land. It is in the Yes/Yes world that you will find people who think, with regret but with clear eyes, that more or less all that can be done about the risks of climate change is to equip the afflicted with the means to ride those risks out, and that even then adaptation may be beyond the reach of billions. It is in the Yes/Yes world that you will find the most plaintive Cassandras, convinced that catastrophe is now inevitable.

And it is in the Yes/Yes world that you will find people imagining a planet where the earthsystem is manipulated in such a way that climate and carbon emissions are no longer so tightly bound. There is much to criticize in such thinking. It can be horribly simplistic. It can feed on, and give rise to, ideas about 'the control of nature' that are neither plausible nor palatable. It can be used to justify inaction. But I believe it can also open up doors, doors both practical and utopian. I think there may be ways in which climate geoengineering could really reduce harm. I also think that imagining geoengineered worlds that might be good to live in, in which people could be safer and happier than they would otherwise be, is worth doing. A utopia does not need to be attainable – indeed, by definition it cannot be. But that is not a reason to reject utopian thought. It is part of the reason for embracing it.

The possibilities of utopian imagination, though, are undercut, even betrayed, if the group doing the imagining is too small. That is currently the case, I think, for geoengineering. Listen to the discussion of the topic going on today and you will hear natural scientists who are cautiously curious about the ideas but have no real interest in trying to make them practical; you will hear social scientists and philosophers interested in providing critiques of the modes of thinking that shape the discourse; you will hear environmentalists who see in it, or project on to it, everything they dislike about centralized action, about capitalism, about mechanistic world views; you will hear the fantasies of the rich and powerful and the fears of the frightened and doctrinaire. It is too small a set of voices.

The way a society imagines its future matters. And who gets to do the imagining matters. The purpose of this book is to spread the tools with which to imagine a re-engineered earth-system a little more broadly. In doing so, it looks at the scientific possibilities under discussion. It also looks at the history of that discussion, at the beliefs people have held about the proper relationship between climate and humanity, at the political contexts that have grown up around those beliefs. I fear that may make it sound like the driest sort of imagining. I hope it will prove not to be. If nothing else, I think there is a particular appreciation of the wonder of the earthsystem that can be gained only by imagining how it could be changed.

The ultimate challenge is not just to picture what an earthsystem subject to some level of deliberate design might be like. It is to picture a world in which you would feel happy about such a design being realized. It is about finding happiness and exercising compassion on a planetary scale – a project that will have to be as political as it is scientific or technological. The goal is to help you imagine a world attractive enough that many would welcome it, but robust and provisional enough that its creation does not require everyone to agree on every aspect of it; a world that requires neither uniformity of outlook nor the suppression of dissent, but offers ways for justice and sympathy to spread out through the human world and into the earthsystem beyond.