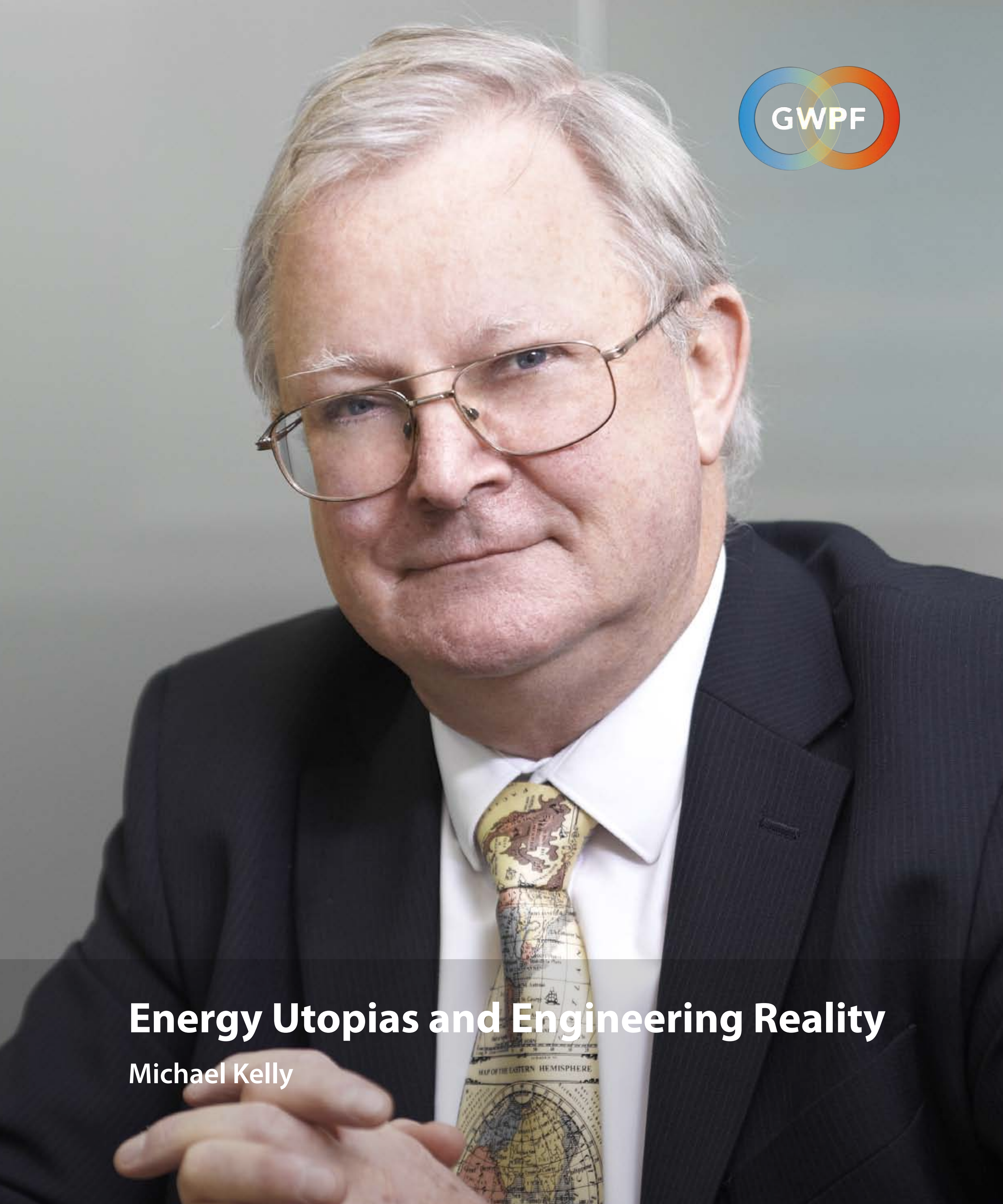

Energy Utopias and Engineering Reality

Michael Kelly

The Global Warming Policy Foundation

2019 Annual Lecture
London, 11 November 2019

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About the lecturer

Michael Kelly ended his academic career as the inaugural Prince Philip Professor of Technology at the University of Cambridge. His main research focus was in new semiconductor physics and technology for ultra-high-speed electronic devices and the manufacturability of semiconductor structures at the nanoscale.

His interest in the topic of this lecture was roused during 2006–9 when he was a part-time Chief Scientific Adviser to the Department for Communities and Local Government. When the Climate Change Act 2008 was signed, he pointed out to Ministers that 45% of UK carbon dioxide emissions came from heating air and water in buildings, 27% from homes and 18% from all others. He persuaded Lord Drayson as Science Minister to undertake a pilot programme called 'Retrofit for the Future', in which over 100 social houses were retrofitted to reduce their emissions. More on that in the lecture.

On his return full-time to Cambridge he was asked by his engineering colleagues to lead the teaching of final-year and graduate engineers on present and future energy systems, which he did until he retired in 2016. The introductory lecture of that course was on the scale of any energy future transition and is the forerunner to this lecture. This last point is to dismiss the cavilling critics who suggest that an electronic engineer should not be able to address these matters.

He regards the invitation to deliver the GWPF annual lecture as a singular honour, being able to inject the concerns of real-world engineering firmly into the public debate, in front of an audience with a strong representation of parliamentarians.

The 2019 Annual GWPF Lecture

Energy Utopias and Engineering Reality

Michael Kelly

Introduction

I want to begin by presenting four examples that show how clearly the world is better off today as opposed to thirty or one hundred years ago because of, among other things, a sufficient supply of energy. The incidence of hunger, poverty, illiteracy and child mortality have all been reduced by more than a factor of two over the period 1990–2015 (Figure 1a). Death rates associated with gas and nuclear energy production are less than a sixth those of oil and coal (Figure 1b). Deaths from natural disasters have dropped by 90% over the 20th century, excepting the Sri Lanka and Fukushima tsunamis in 2004 and 2011 (Figure 1c). Warnings by radio and telephone are the main reason.

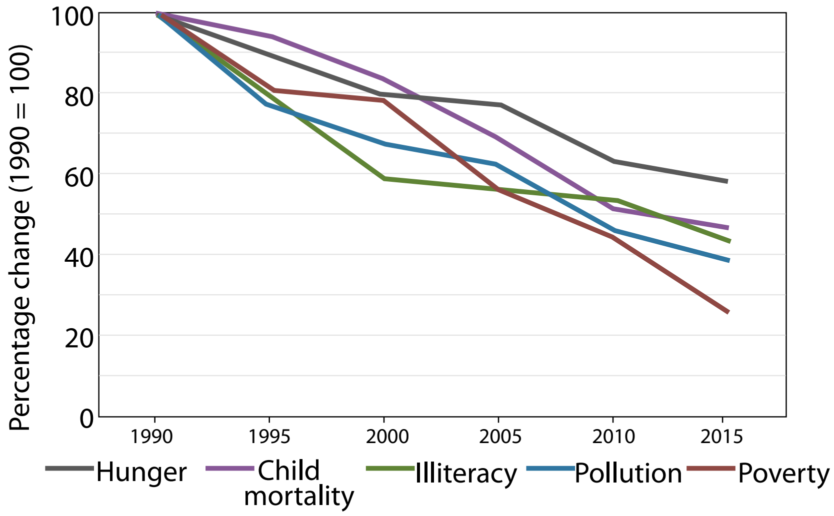
More people live in safer and better conditions and are better fed than at any previous time in human history. The United Nations has played an important role, first with the Millennium Development Goals over the period 2000–2015 and now the Sustainable Development Goals over the period 2016–2030.

I now have a simple pragmatic question to ask. Suppose I agree to pay you £100 to dig a two-metre-deep hole for me to bury family treasure. You set about digging, but find your progress thwarted by a hundred people with wheelbarrows full of earth coming to fill in your hole. What would you do? Keep on digging regardless or stop and try to find out what is going on? To your protest that you are being paid to dig a hole, you are told that the others are being paid much more to fill in any holes that appear!

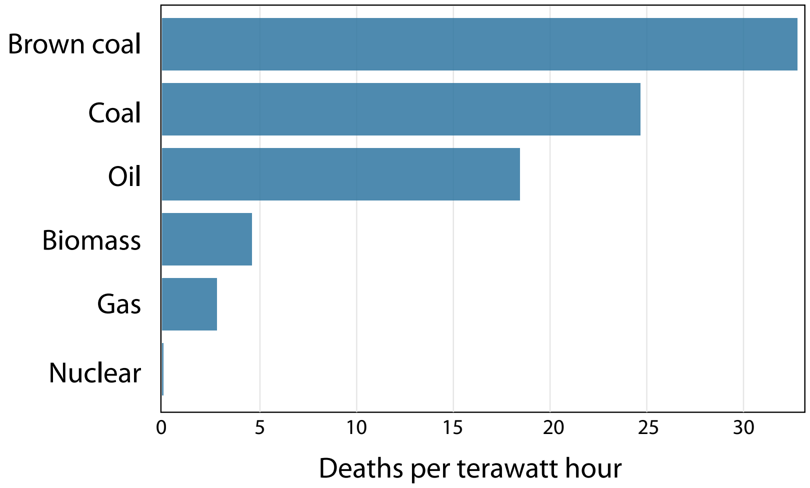
At this time there are people in several countries, including both the United Kingdom and New Zealand, both of whose passports I hold, who are straining to turn off the last coal-fired power stations in the cause of climate change mitigation. But the Chinese Belt and Road Initiative, the largest civil engineering project in the world, will help over 2 billion people in West Asia and Africa out of poverty and hunger over the next 30 years, just as earlier projects took 600 million people in China from rural squalor to middle-class comfort over the last 20 years. The initiative will include 700 new coal-fired power stations, over a third of which are currently being built. I do not support the neo-colonialist tendencies associated with the initiative, but it will go further than any other project to deliver the first and second of the UN's Sustainable Development Goals: the elimination of world poverty and hunger. The climatic Sustainable Development Goal is number 13 on the list.

Biblical scholars will recall the story of the Tower of Babel, with key lessons which engineers have long since learned. When people set out to build a tower to heaven, they had no way of knowing how to determine that they had in fact completed the tower by reaching heaven. Nor did they know in advance how much it would cost. Climate mitigation shares the same two characteristics – no one can define what it means to have averted climate

(a) Human welfare



(b) Mortality in energy production



(c) Mortality in natural disasters

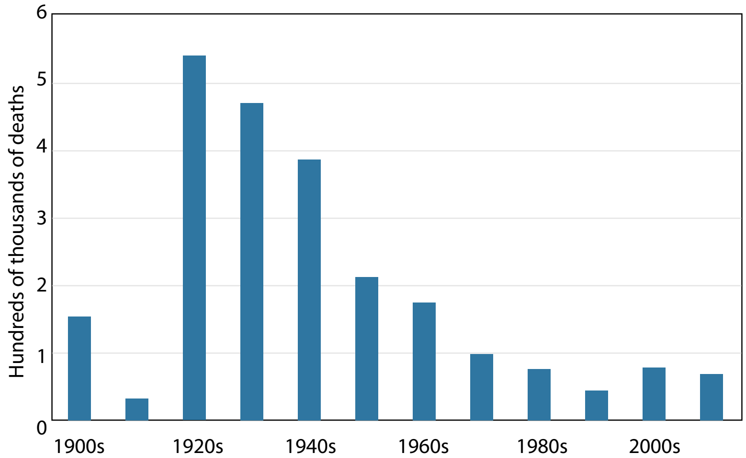


Figure 1: Energy brings improvements in human welfare

Sources: (a) Johan Norberg, FAO, World Bank, UNESCO, EPA; (b) Markandya and Wilkinson (2007) via Our World in Data; (c) OFDA/CRED International Disaster Database and Our World in Data.

change, nor how much it will cost. Extinction Rebellion simply have no idea of the scale of cost of what they are demanding by 2025: if they did, they would back away.

Next, I refer to germane speeches from three US presidents. In his farewell address in 1961, Dwight Eisenhower said:

> …in holding scientific research and discovery in respect, as we should, we must also be alert to the equal and opposite danger than public policy could become the captive of a scientific-technological elite.

That is where we are now. The following year, John F. Kennedy used the famous expression 'We choose to go to the Moon', while speaking to a crowd in Houston. As he was saying this, his key advisors could have confirmed that there were no known scientific or technological impediments to this project – it just needed will and support.

But contrast this with Richard Nixon, who said, during his 1971 State of the Union address:

> I will also ask for an appropriation of an extra $100 million to launch an intensive campaign to find a cure for cancer, and I will ask later for whatever additional funds can effectively be used. The time has come in America when the same kind of concentrated effort that split the atom and took man to the moon should be turned toward conquering this dread disease. Let us make a total national commitment to achieve this goal.

When Nixon said those words, no advisors would have suggested a cure for cancer was around the corner, as we must recognise 50 years later.

So the recent academic plea for mass leave of absence to 'save the planet' was quite misleading in appealing to the moon-shot as an exemplar – climate is more akin to the cancer example.

Just so that there can be no doubt whatsoever, the real-world data shows me that the climate is changing, as indeed it has always changed. It would appear by correlation that mankind's activity, by way of greenhouse gas emissions, is now a significant contributory factor to that change, but the precise percentage quantification of that factor is far from certain. The global climate models seem to show heating at least twice as fast as the observed data over the last three decades. I am unconvinced that climate change represents a proximate catastrophe, and I suggest that a mega-volcano in Iceland that takes out European airspace for six months would eclipse the climate concerns in short order.

The detailed science is not my concern here. The arguments in this lecture would still apply if the actual warming were twice as fast as model predictions. Project engineering has rules of procedure and performance that cannot be circumvented, no matter how much one would wish it. Much of what is proposed by way of climate change mitigation is simply pie-in-the-sky, and I am particularly pleased to have so many parliamentarians here tonight, as I make the case for engineering reality to underpin the public debate.

I plan to describe (i) the global energy sector, (ii) the current drivers of energy demand, (iii) progress to date on decarbonisation, and the treble challenges represented by (iv) factors of thousands in the figures of merit between various forms of energy, (v) the energy return on energy invested for various energy sources, and (vi) the energising of future megacities. I make some miscellaneous points and then sum up. The main message is that our present energy infrastructure is vast and has evolved over 200 years. So the chances of revolutionising it in short order on the scale envisaged by the net-zero target of Parliament is pretty close to zero; zero being exactly the chance of the meeting Extinction Rebellion's demands.

The energy sector – its scale and pervasiveness

As society evolves and civilisation advances, energy demands increase. As well as increasing demand for energy, the Industrial Revolution led to an increase in global population, which had been rather static until about 1700. Since then, both the number of people and the energy consumption per person have increased, and from Figure 2 we can see the steady growth of gross domestic product per person and energy consumption through the 19th and 20th centuries until now.

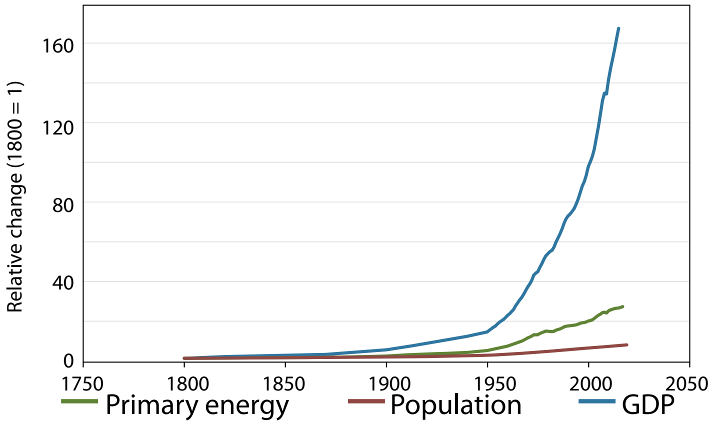


Figure 2: Growth in energy and GDP are correlated
Data source: Our World in Data.

At the same time, the relative size of the energy sector as a function of the whole economy has shrunk, from a dominant contribution (especially if we regard food as a fuel) to just 9% for the energy and 3% for the food sectors in developed countries today, for example Sweden (Figure 3).

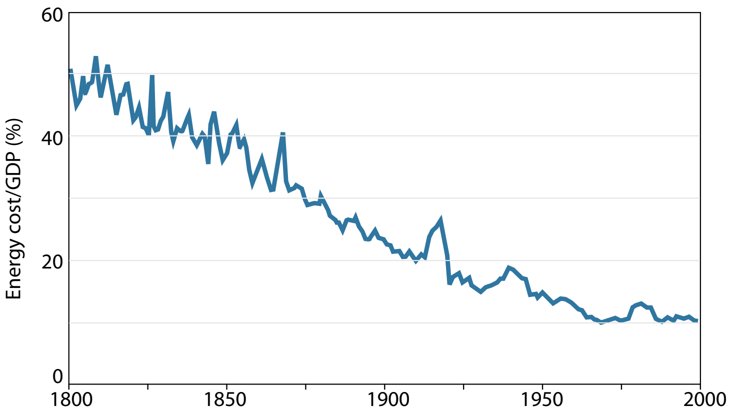


Figure 3: Swedish energy as a proportion of output
Source: Stern and Kander (2011)

Energy is the essential driver of modern civilisation. World GDP this year is estimated at $88 trillion, growing to $108 trillion by 2023, with the energy sector then being of order $10 trillion. But renewables have played, and will continue to play, a peripheral role in this growth. Industrialisation was accompanied by a steady and almost complete reduction in the use of renewables (Figure 4).

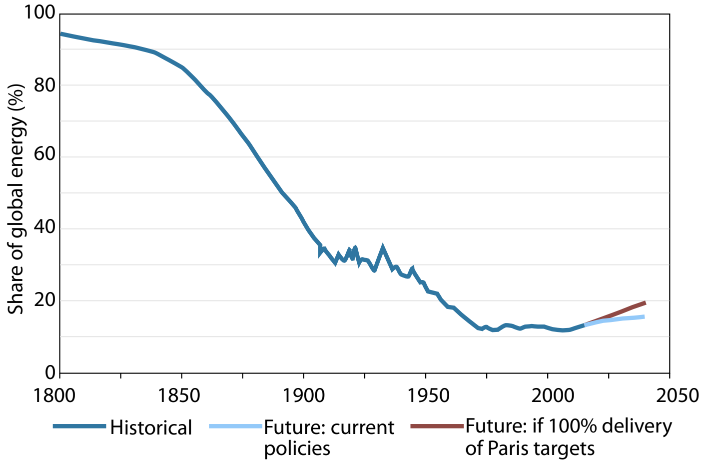


Figure 4: Getting off renewables 1800–2000…and on again?
Source: http://cait.wri.org/profile/World.

Then, in response to the oil crises in the 1970s, there was a big increase in research into wind and solar photovoltaics, as the US tried to wean itself off dependence on foreign fossil fuels, but this had little impact on the economy, and the pressure to achieve energy independence waned during the 1980s, although R&D continued. In recent years, there has been an uptick in renewables use, but this has been entirely the result of the pressure to decarbonise the global economy in the context of mitigating climate change, and the impact has again been nugatory. Modern renewables remain an insignificant share of the energy supply (Figure 5). Indeed MIT analysts suggest the transition away from fossil fuel energies will take 400 years at the current rate of progress.

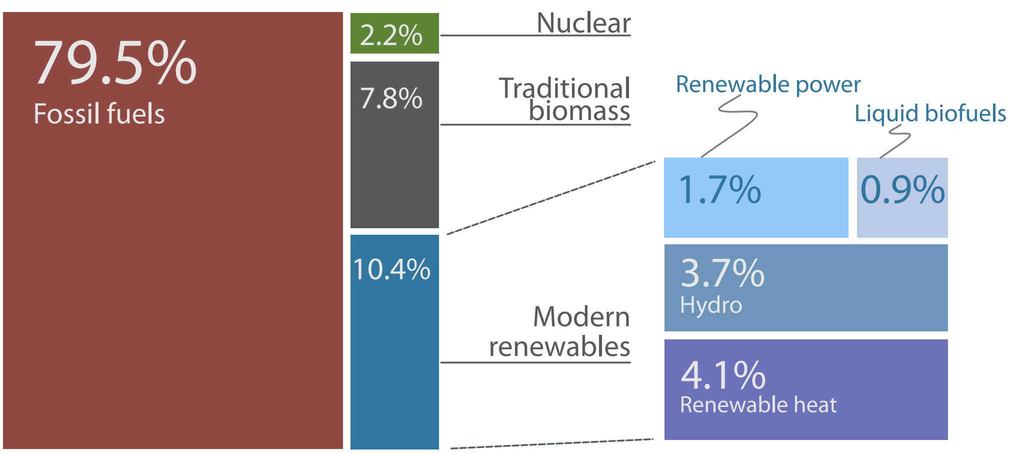


Figure 5: Modern renewables are insignificant in energy supply
Source: http://www.ren21.net/wp-content/uploads/2017/06/GSR2017_Highlights_FINAL.pdf

In order to keep global temperatures to within 1.5°C of pre-industrial levels, we intend to eliminate emissions of greenhouse gases (mainly carbon dioxide) by replacing all the energy developments since about 1880 with zero-carbon alternatives. This is to be achieved by 2050. Figure 6 shows the scale of what has been proposed. Even reaching the old target of an 80% reduction in carbon dioxide emissions would be miraculous; this is a level of emissions not seen since 1880. I assert that a herd of unicorns will be needed to deliver this target, let alone full decarbonisation. I also point out the utter nonsense of Extinction Rebellion's demands to complete the task by 2025.

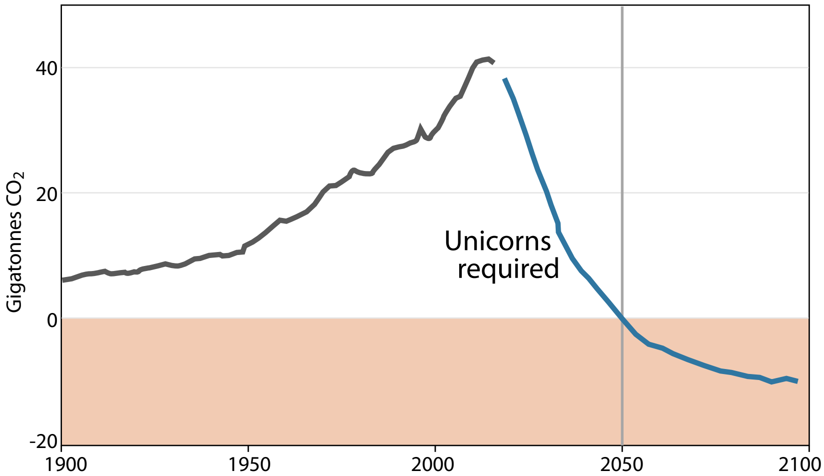


Figure 6: The scale of the task
Source: After Glen Peters,
https://www.slideshare.net/GlenPeters_CICERO/can-we-keep-global-warming-well-below-2c.

Contemporary drivers of energy needs 1995–2035

I wish to focus on the drivers of global energy demands today by looking back and forward twenty years. Figure 7 shows data from BP covering the period 1965–2035 on the demand for global energy by fuel type. The data to 2015 is historic and not for challenge.

One notes that we have not had an 'energy transition': fossil fuels have continued to grow steadily at a rate about 7–8 times that of renewable technologies over the last 20 years. The energy demand of the major developed countries has been static or in small decline over that period. Most of the increase has come from growth in the global middle class, which increased by 1.5 billion people in the 20 years to 2015. The World Bank is anticipating a further increase of 2.5 billion by 2035, much of it the result of China's Belt and Road Initiative, and BP estimate a further 40% growth in global energy demand by then. The whole of Figure 7 can be explained quantitatively if one assumes that a middle class person (living in a high-rise building with running water and electricity, without any mention of personal mobility – the World Bank definition of middle class existence – uses between three and four times the amount of energy per day as a poor person in a rural hovel or urban slum.

You should be under no illusions: this is a humanitarian triumph. It is the delivery of the top Sustainable Development Goals – the elimination of poverty and hunger – that has been and will remain the main driver of energy demand for the foreseeable future.

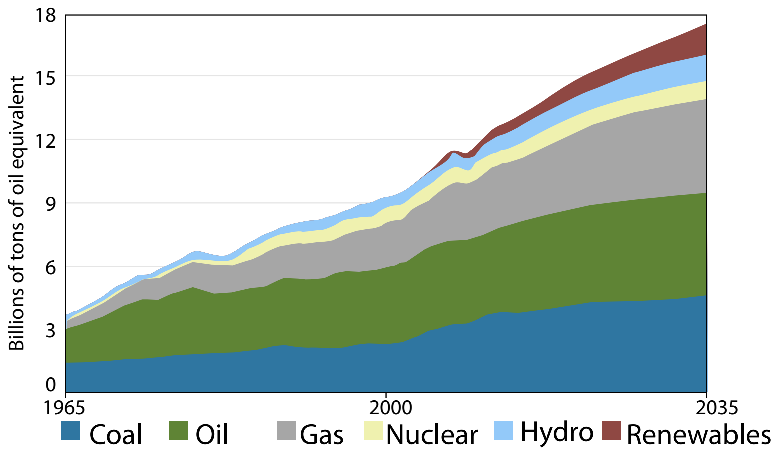


Figure 7: Energy supply by type
Source: BP.

And this improvement in human welfare will be driven almost entirely by fossil fuels. BP suggest that by 2035, renewables will still only be delivering about 10% of energy demand, less than one sixth of fossil fuel provision. And one sees a smooth evolution rather than any break points that would indicate major advances or abrupt changes in the energy sector.

Decarbonisation progress to date

The UK

In the UK, the Climate Change Committee has, on the face of it, overseen a steady fall in UK emissions of carbon dioxide since its formation in 2008. However, the fall started in 1990 and has continued at a very steady rate since (Figure 8a).

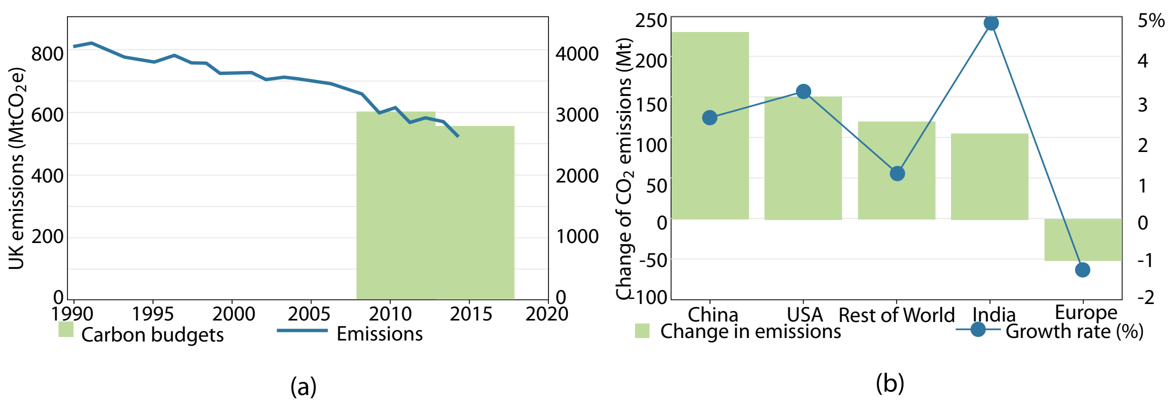


Figure 8: UK and global emissions
(a) UK emissions were falling before major climate policies introduced (b) Growth in global emissions dwarfs UK reductions. Source: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming.

However, UK decreases are dwarfed by global increases. After no-growth years in 2016 and 2017, global carbon dioxide emissions grew by 3% in 2018 (Figure 8b). European emissions fell but the growth in all the other parts of the world was 17 times greater. The emissions reductions in the UK have also come at a considerable cost. Figure 9 shows the increasing deficit of the UK balance of payments with respect to manufactures since then. In other words, a significant proportion of our emissions have been exported to China and elsewhere. Indeed, over the period 1991– 2007, the emissions associated with rising imports almost exactly cancelled the UK emissions reduction!

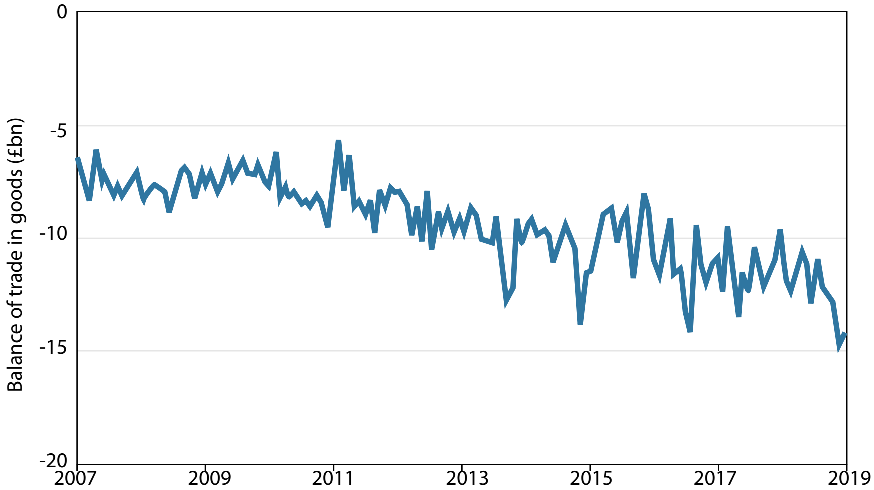


Figure 9: UK deficit in manufactured goods
Source: https://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN02815.

Some of the measures introduced by the Climate Change Committee have actually made global emissions worse. Where we once smelted aluminium using electricity generated from a mixture of nuclear, gas and coal, we now import our aluminium from China where electricity is nearly all made from coal. What is worse, the smelter in Anglesey had a contract to use more electricity when the local demand was low (at night and on weekends); costs were kept lower for everyone. Now the smelter has gone, local consumers have to pay more for their electricity as the generators are less efficiently used.

There was much publicity in late summer this year when 50% of the UK's electricity was (briefly) generated from renewables. Few people realised that electricity is only 16% of our total energy usage, and it is a common error, even in Parliament, to think that we are making enormous progress on the whole energy front. The real challenge is shown in Figure 10, where the energy used in fuels, heating and electricity are directly compared over a three-year period. Several striking points emerge from this one figure.

First, we use twice as much energy in the UK for transport as we do for electricity. Little progress has been made in converting the fuel energy to electricity, as there are few electric vehicles and no ships or aircraft that are battery powered. Note that if such a conversion of transport fuel to electricity were to take place, the grid capacity would have to treble from what we have today.

Second, most of the electricity use today is baseload, with small daily and seasonal variations (one can see the effect of the Christmas holidays). The more intermittent wind and solar energy is used, the more back-up has to be ready for nights and times of anticyclones or both: the back-up capacity could have been used all along to produce higher levels of

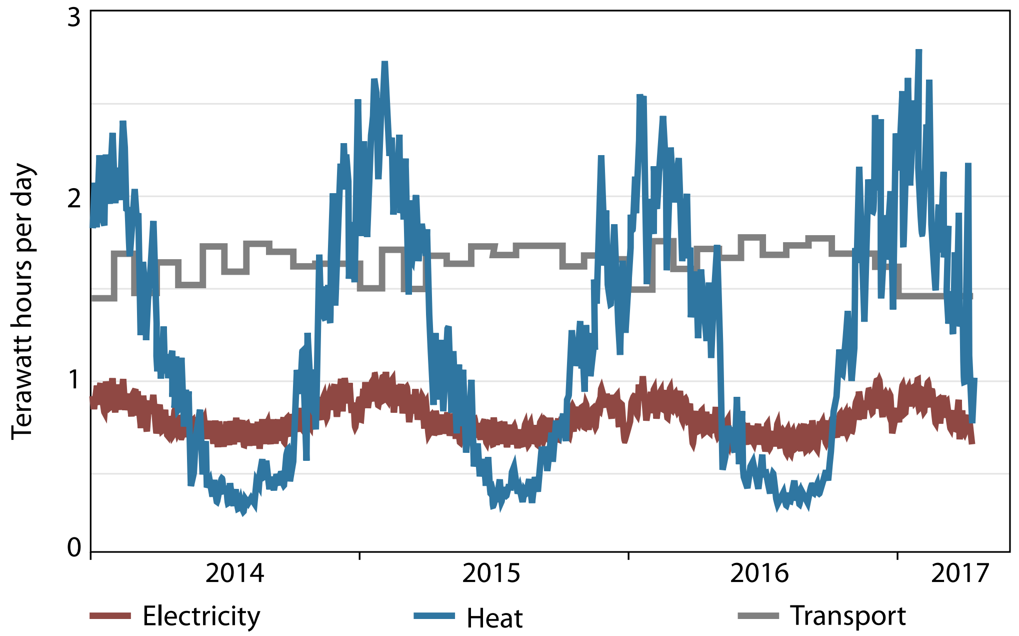


Figure 10: UK energy demand by type over three annual cycles
Source: John Loughhead, BEIS.

baseload electricity, and because it is being used less efficiently, the resulting back-up generation costs more as it pays off the same total capital costs.

But in fact it is the heating that is the real problem. Today that is provided by gas, with gas flows varying by a factor of eight between highs in winter and lows in summer. If heat were to be electrified along with transport, the grid capacity would have to be expanded by a factor between five and six from today. How many more wind and solar farms would we need?

Germany

Germany is often held out as the European leader, with over €800 billion invested in the 'Energy Transition'. However, as in the UK, electricity is a small fraction of German energy demand, and despite the vast expenditure, only about one seventh of total energy supply is currently from renewable sources. Meanwhile, reductions in carbon dioxide emissions have been proportionally less than in the UK in recent years, in part because Germany has maintained more of its industrial manufacturing base.

Germany's renewables leadership has mostly been in demonstrating the difficulties of using renewables on the grid. The successes of renewables are usually reported in summer when electricity demand is at its lowest. But in winter, when the solar panels are covered with snow and there are week-long anticyclones, the German grid gets very little electricity from renewables. Indeed, over the winter of 2016–7 there were two periods, each of ten days, when little or no renewable energy was generated. Germany's power storage capacity – mostly hydroelectricity – was woefully inadequate to meeting this shortfall. Total electricity consumption in both of these periods was 800 times what dams could store and generate. This is not atypical in developed countries. The total pumped storage capacity in the USA would run its grid for three hours, while the installed battery storage would run it for five minutes.

Consumers in Germany have paid a high price for this leadership too. An electricity grid with high penetration of renewables is necessarily inefficient because of the intermittency and unreliability of wind and solar power. German electricity prices are among the highest in the world.

China

To conclude this section, Figure 11a shows that renewables are not even close to meeting the growth in demand, let alone reducing existing levels of fossil fuel use. Renewable energy's contributions remain small compared with fossil fuels in relative terms, even if in absolute terms they are large compared with values elsewhere in the world. The forward projections show a constant value of coal and gas used for electricity through to 2040.

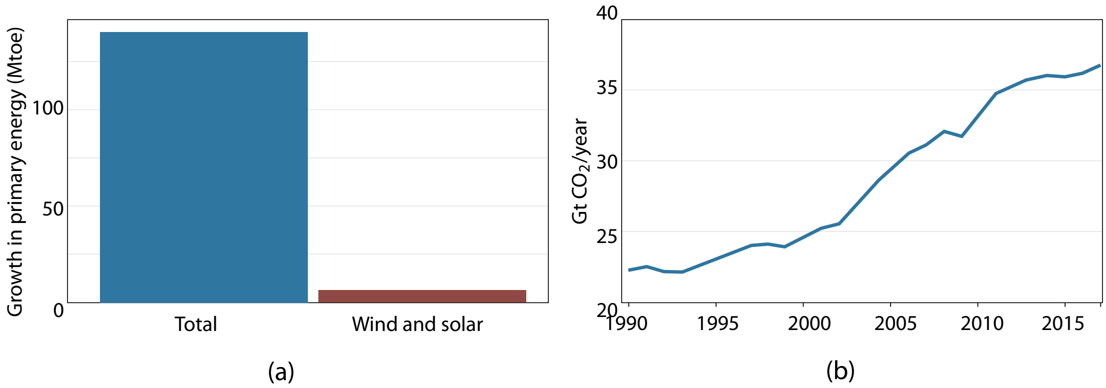


Figure 11: Fossil fuels are driving China's growth
(a) Average annual growth (2004–14) for wind and solar against all energy (b) Emissions of CO_2.
Sources: (a) BP; (b) Global Carbon Project.

China's carbon dioxide emissions have been rising inexorably, with little sign of a slow-down (Figure 11b).

Initial conclusions

So far, I have described the scale of the global energy sector, how it has come to be the size it is, the current drivers for more energy and the current status of attempts to decarbonise the global economy. I can draw some initial conclusions at this point.

- Energy equals quality of life and we intervene there only with the most convincing of cases.
- Renewables do not come close to constituting a solution to the climate change problem for an industrialised world.
- China is not the beacon of hope it is portrayed to be.
- There is no ground shift in energy sources despite claims to contrary.

For the rest of this lecture I shall delve further into engineering issues.

The engineering challenges implied by factors of hundreds and thousands

Many people do not realise the very different natures of the forms of energy we use today. But energy generation technologies can differ by factors of hundreds or thousands on key measures, such as the efficiency of materials use, the land area needed, the whole-life costs of ownership, and matters associated with energy storage.

Here are four statements about the efficiency with which energy generation systems use high-value advanced materials:

- A Siemens gas turbine weighs 312 tonnes and delivers 600 MW. That translates to 1920 W/kg of firm power over a 40-year design life.
- The Finnish PWR reactors weigh 500 tonnes and produces 860 MW of power, equivalent to 1700 W/kg of firm supply over 40 years. When combined with a steam turbine, the figure is 1000 W/kg.
- A 1.8-MW wind turbine weighs 164 tonnes, made up of a 56-tonne nacelle, 36 tonnes for the blades, and a 71-tonne tower. That is equivalent to 10 W/kg for the nameplate capacity, but at a typical load factor of 30%, this corresponds to 3 W/kg of firm power. A 3.6-MW offshore turbine, with its 400-tonne above-water assembly, and with a 40% load factor, comes out at 3.6 W/kg over a 20-year life.
- Solar panels for roof-top installation weigh about 16 kg/m^2, and with about 40 W/m^2 firm power provided over a year, that translates to about 2.5 W/kg energy per mass over a 20-year life.

The figures are shown in Figure 12, although the wind and solar bars are all but invisible.

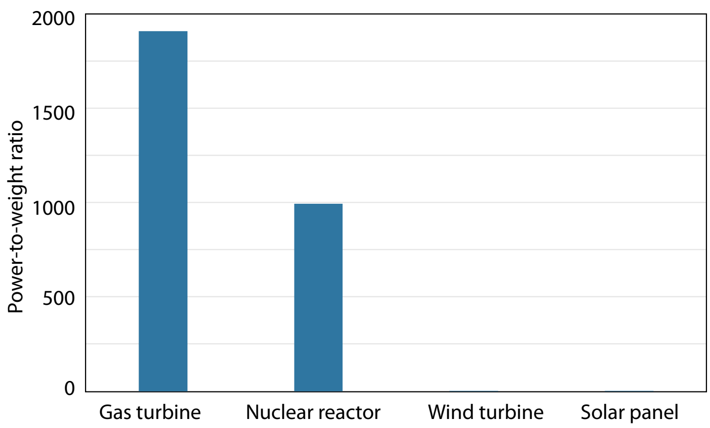


Figure 12: Power-to-weight ratios for various generation technologies

Now the gas turbines and nuclear power stations need fuels, but these are not subject to energy-intensive processing in the way that steels, silicon wafers and fibre-composites are. Moreover, in the case of wind, I have not mentioned the plinth, which is comparable in size to the one required for a combined cycle gas turbine or nuclear reactor, but you'd need 360 5-MW wind turbines (of 33% efficiency) to produce the same output as a gas turbine, each with concrete foundations of comparable volume. The concrete requires high-energy processing of large quantities of cement, and the plinths must be removed at the end of life.

The requirement for land is another consideration. Both wind and solar energy are intrinsically more dilute than fossil fuels, in which past sunlight has been concentrated many times over, or nuclear fuels where the nuclear energies involved are much greater than the chemical energies in fossil fuels which are in turn much greater than the solar and wind energies.

The late David MacKay showed that the land areas needed to produce 225 MW of power were very different: 15 acres for a small modular nuclear reactor, 2400 acres for average solar cell arrays, and 60,000 acres for an average wind farm (Figure 13).

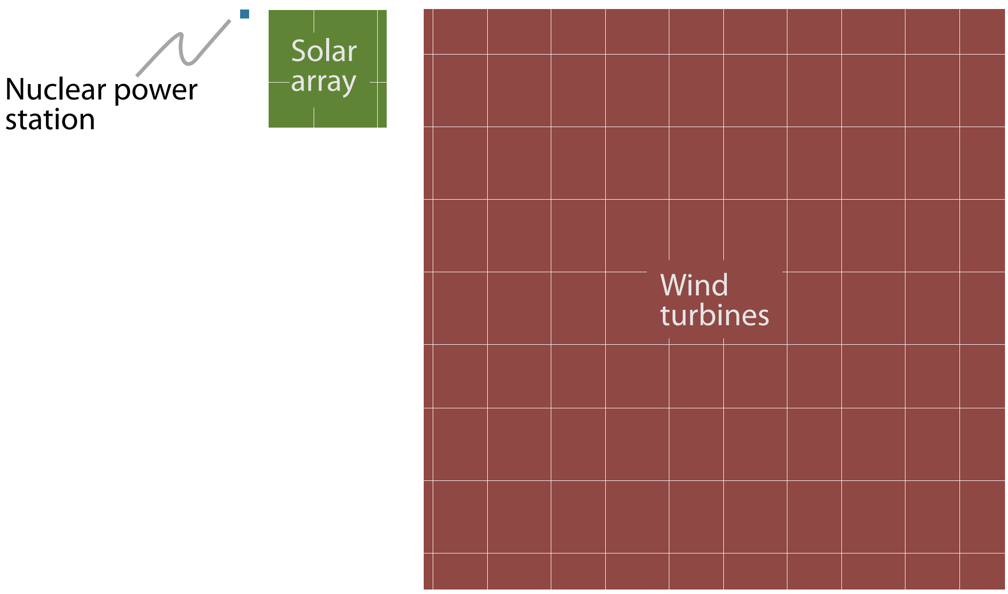


Figure 13: Areas required for different 225-MW power stations
Data per David MacKay.

My own example takes the 4000 km^2 of the Fen country, currently used to provide some of the food for London. If it was used instead to grow miscanthus grass, year-round, to be harvested and burned to drive a steam generator for electricity, one would get 2 GW of continuous electricity. However from a land area of 0.1 km^2 (300m by 300m), the Sizewell B nuclear reactor produces 1.3 GW continuously. The ratio of land areas involved is 40,000 to 1! Note that if state-of-the-art solar panels were used, the ratio of land needed to produce the same electricity continuously is 1000:1. Land in the UK is too highly valued, even as a rural amenity, to be given over to wind turbines or solar panels.

Technologies for storing energy are also very different. Table 1 shows the energy density of different fuels. The battery in the table is the lead-acid type. Petrol can store 50,000 times more energy per kilogram. Modern lithium-ion batteries are better, but not much: all the R&D over the last 40 years has given a 50-fold increase in energy density, but we are now approaching the limits allowed by the materials as we know them. In other words, there is not another 1000-fold improvement to be had that might allow batteries to compete with petrol. The reason is clear: all the chemical energy in all the relevant chemical bonds in petrol is available when the fuel is burned. In a battery, most of the weight is not converted to useable energy.

Table 1: Energy densities of different fuels

Technology	Energy density MJ/kg
Wind turbine	0.00006
Battery	0.001
Hydro	0.72
Wood	5.0
Petrol	50
Hydrogen	143
Nuclear fission	88,250,000
Nuclear fusion	645,000,000

Source: M J Kelly, 'Lessons from technology development for energy and sustainability' *MRS Energy and Sustainability* 2016; 3: 2-13.

The productivity of renewables

If a cheetah exerts more energy chasing a rabbit than it gets by eating it, its future is not assured. If the cheetah is supporting a family, then the ratio of energy expended to energy obtained had better be much less than unity. A similar calculation can be performed for energy generation technologies. This is known as the energy return on investment. The solar farms installed in Spain during 2006–9 expect to collect 250% of the energy used in their manufacture, installation and operation over their 25-year lifetimes, so in energy terms or money terms, the return on investment is 2.5:1. If the panels were free and their efficiency up 50% on the actual solar panels of a decade ago (reaching the absolute limit imposed by the physics of solar interactions with one semiconductor interface), the EROI rises to about 5:1. Data from the first-of-its-kind wind farm at Vindeby shows that the lifetime revenue is only 140% of the construction cost, reduced to 100% when lifetime maintenance costs are added. For the Hornsea 1 offshore windfarm, due to be completed next year, the expected lifetime revenue is only five times the total lifetime costs. The figure for the Hinkley Point nuclear power station is 7:1, or more if there is any life extension as is common with nuclear power plants.

These numbers for wind and solar are worryingly low. Mankind has a so-called hierarchy of energy needs and desires, running from basic requirements like heat and cooking, through to more sophisticated requirements like education and 'nice-to-haves' like the arts (Figure 14). It is progressively higher returns on energy investments that allow us enjoy these progressively greater benefits of civilisation.

Every £1 of coal generates £10 of electricity, and every £1 of natural gas generates £15 of electricity. With these factors one can see how the modern world can run with an energy sector that is only 9% of the world economy. The question remains – are renewable energies productive enough to maintain a modern global economy as we know it? If we need to have

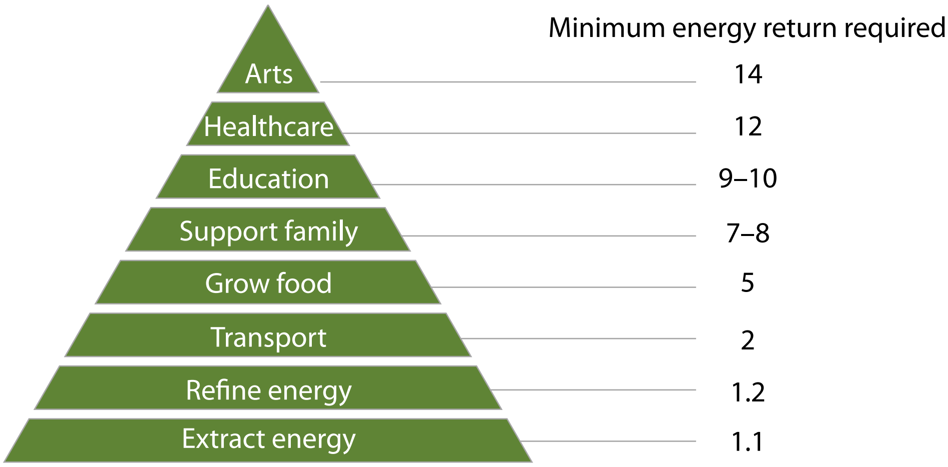


Figure 14: Energy returns required for human welfare
Source: Pedro A Prieto and Charles A S Hall, *Spain's Photovoltaic Revolution: The Energy Return on Investment*, Springer 2013

a rather larger energy sector as a fraction of the global economy, we will be taking a reverse step in terms of the trajectory of Figure 3.

The challenge of megacities

In 2050 over half the world's population will be living in megacities with populations of more than 5 million people. The energising of such cities at present is achieved with fossil and nuclear fuels, as can the cities of the future. The impact of renewable energies will be very small, as the vast areas of land needed, often taken away from local areas devoted to food production as in London or Beijing, will limit their contribution. The extreme examples are Hong Kong and Singapore, neither of which have any available hinterland.

Recent progress on the vertical farming of leaf vegetables and the development of meat grown in laboratories means that megacities could be self-sufficient in both these contributions to the human diet from factories within the limits of these megacities. Only grain still needs the large areas of agriculture.

In the UK, 45% of carbon dioxide emissions come from heating air and water in buildings (27% in the domestic sector, and 18% in all others). In 2010, as chief scientific advisor to the then Department of Communities and Local Government, I convinced Lord Drayson, the Science Minister, to fund a pilot programme in which over 100 social houses would be retrofitted with external and internal cladding, double glazing and new appliances.* We targeted a reduction of 80% in emissions. However, of 45 specific projects where full before-and-after data is available, the average spend of £85,000 achieved an average emissions reduction of only 60%, with only three projects meeting the 80% target and some not even reaching 30%. Social houses are smaller than the average, and there are fewer detached houses, so it is clear that an average spend of as much as £150,000 may be required to

* R. Gupta et al. 'Intent and outcomes from the Retrofit for the Future programme: key lessons', *Building Research & Information* 2015; 43:4: 435–451.

achieve the 80% target. While in a national roll-out there may be some cost reduction from learning by doing, nearly every house will need a bespoke solution, as poor or imperfect insulation is worse than no insulation. The cost to the country will be of order £2-3 trillion and will require a workforce on the same scale as the NHS to deliver a total retrofit over 30 years. No one has discussed the opportunity costs of such a major commitment.

Miscellany

Before drawing my conclusions, I want to make a few miscellaneous points.

A history of gloom

There is a history of gloomy predictions about mankind that coincides with the industrial revolution.

- In 1798 Thomas Malthus FRS said: 'The power of population is so superior to the power in the earth to produce subsistence for man, that premature death must in some shape or other visit the human race.'
- In 1868, William Stanley Jevons FRS wrote *The Coal Question*, the key message of which was to halt the industrial revolution since the collapse of society upon the exhaustion of coal reserves was too terrible to contemplate.
- In 1970, Paul Ehrlich ForMemRS suggested that European civilization would collapse before 2000 because of overpopulation and mass starvation.

The irony of all these examples is that the solution to the problem was at hand at the very time the Jeremiahs spoke. The combine harvester trebled the efficiency of the harvest and – apart from the potato famine (a political famine) – no one starved in Europe. The discovery of oil and gas greatly expanded the availability and expected duration of fossil fuels. The green revolution of Norman Borlaug ForMemRS introduced new strains of wheat, and hunger now appears to be in terminal decline. In contrast to all this, in 1830 the 1st Baron Macaulay FRS asked:

> On what principle is it that, when we look we see nothing but improvement behind us, we are to expect nothing but deterioration before us?

I have some sympathy with this point of view.

Future demographics

I suggest that the demographic transition that started 70 years ago is the solution to those who cry wolf about the climate now. In the countryside, another child is a useful pair of hands from the age of 6, while a child in a city is a burden until they are 15. Everywhere in the world where more people live in cities than the countryside (North America, Europe, Japan and Australasia), the local population (excluding immigration) is in decline, with fewer than 2.1 children per family. Globally, the number of children per family has halved since 1970 from 5 per family to 2.3 today. China's population will peak in the early 2030s and will be less in 2060 than it was in 2000.[†] There will be 200 million fewer people on earth in 2100 than at the peak in the 2060s.[‡] There will be plenty of empty houses for people who are actually displaced by any sea level rise at that time.

† Data quoted in *The Financial Times*, 3 December 2018.

‡ D Bricker and J Ibbotson, *Empty Planet: The shock of global population decline*. Robinson (2019)

The climate change imperative

In the 1990s the global average surface temperature had been rising sharply for 15 years, and many predicted that this rate of warming would continue, when in fact it has halved. This lesson of history is regularly ignored as the current level of climate alarm is cranked up.

The upsides of more carbon dioxide in the atmosphere

The historical character of science was a dispassionate evaluation of all the relevant facts on a particular issue. It is sad that the upsides of increased carbon dioxide levels in the atmosphere (such as the greening of the biosphere) are systemically ignored or discounted, while those matters which are neutral, such as storm frequency and severity are spun to be hostile to humanity. All the data shows that extreme events were more extreme and more common in the first half of the 20th century, but climate change is supposed to have started in 1960 – in most accounts.

Dematerialisation

The smart phone is an epitome of dematerialisation of the world economy. The services now fitting in the palm of the hand would thirty years ago have required a table full of equipment – phone, TV, video recorder and player, alarm clock, dictaphone, newspapers and magazines, TV, answerphone, letters.

Sense of balance

For £1 devoted to mitigating climate change, how much money should be set aside for mitigating Carrington events, pandemics, global financial collapse, volcanoes, earthquakes and tsunamis, and other threats? What is the appropriate level of global insurance, and indeed the insurance for poorer countries?

Mitigating climate change as a civil engineering project

If I were able to raise £1 trillion a year for ten years, and devote it to mitigating climate change, there is no answer to date to the simple questions that are the starting point of any engineering project. What are the specific projects that should best be funded and to what level? How do we measure the consequential reductions in climate change so that we can assess the value for money after the event, if not before? No-one has any clue how to assess value for money in advance.

Conclusions

It is clear to me that for the sake of the whole of mankind we must stay with business as usual which has always had a focus on the efficient use of energy and materials. We must de-risk the major infrastructure projects, such as mass decarbonisation, as they are too serious to get wrong.

Human lifestyle changes can have a greater and quicker impact if implemented: we can all promise and deliver a 10% drop in our energy consumption from tomorrow. It would not be without consequences.

Who owns the integrity of engineering in the climate debate in the United Kingdom? Globally?

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Further reading

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