DECARBONISING HOUSING
The net zero fantasy

Michael Kelly

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About the author

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. He is a fellow of the Royal Society and the Royal Academy of Engineering.

From 2006–9 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, of which 27% was 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.

Executive summary

Approximately 45% of all the carbon dioxide emissions from the UK originate from heating air and water in buildings, of which 27% is from domestic homes and 18% from all other buildings. This ratio has not changed much this century. This means that, in reaching for an 80% reduction in CO_2 emissions, let alone a net zero emissions target, the built environment must put its house in order. There are two extremes to possible approaches: a total decarbonisation of all the energy used in buildings, or a deep reduction in energy use within buildings by improving the thermal envelope and the efficiency of appliances within.

This paper looks at the second of these options, because, under all scenarios that do not rely on unicorns for a major breakthrough in technology, fossil fuels will still be used to heat houses in 2050, in some form or other.

We have good data on what it might take to reduce the energy use in housing to near zero. A pilot project to retrofit over 100 social houses, with a target reduction in CO_2 emissions of 80%, has been carried out. However, with an average spend of order £85,000, the average reduction of CO_2 emissions achieved was only 60%, with only 3 of 45 projects where suitable data were collected reaching the 80% target. Moreover, social houses are smaller than average, and with the 80% target still in force it is estimated that around £150,000 will be needed per house for full insulation (internal and external, underfloor and in the roof space). Every house is unique, and therefore represents a bespoke project, there being no standard components, and imperfectly fitting insulation is often worse than no insulation at all. Optimistically, the energy savings might be of order £1,000 per year, representing a 150-year payback for the typical house.

Scaled up to the full housing stock, these figures represent a total raw cost of over £4 trillion. However, in a national roll out, economies of scale and learning by doing has the potential to reduce the cost to £75,000 per house, resulting in a total cost of £2.1 trillion. Another £1.4 trillion would be needed for non-domestic buildings, resulting in a total cost of £3.5 trillion.

The very poor return on investment means that a national retrofit of all existing buildings needs a government edict within a command economy. The opportunity cost of this retrofit is simply enormous, especially when viewed alongside other possible insurances: against supervolcanos, tsunamis, global financial collapse, and the like.

1 Introduction

In May 2019, the UK Climate Change Committee (CCC) presented a report: *Net Zero – The UK's contribution to stopping global warming*.[1] It was taken up within the month by the then Prime Minister, Theresa May, who rushed an amendment to the 2008 Climate Change Act through Parliament adopting its main recommendation, namely to target a net-zero-carbon economy for the UK by 2050. No cost-benefit analysis has been published, either by the CCC or by the Government, and indeed the costs involved remain a secret. Nor has there been any indication of the amount by which global temperatures will be reduced as a result of achieving the target. There is therefore no way of knowing whether the investment will succeed in its intention, much less whether it represents value for money against other calls.

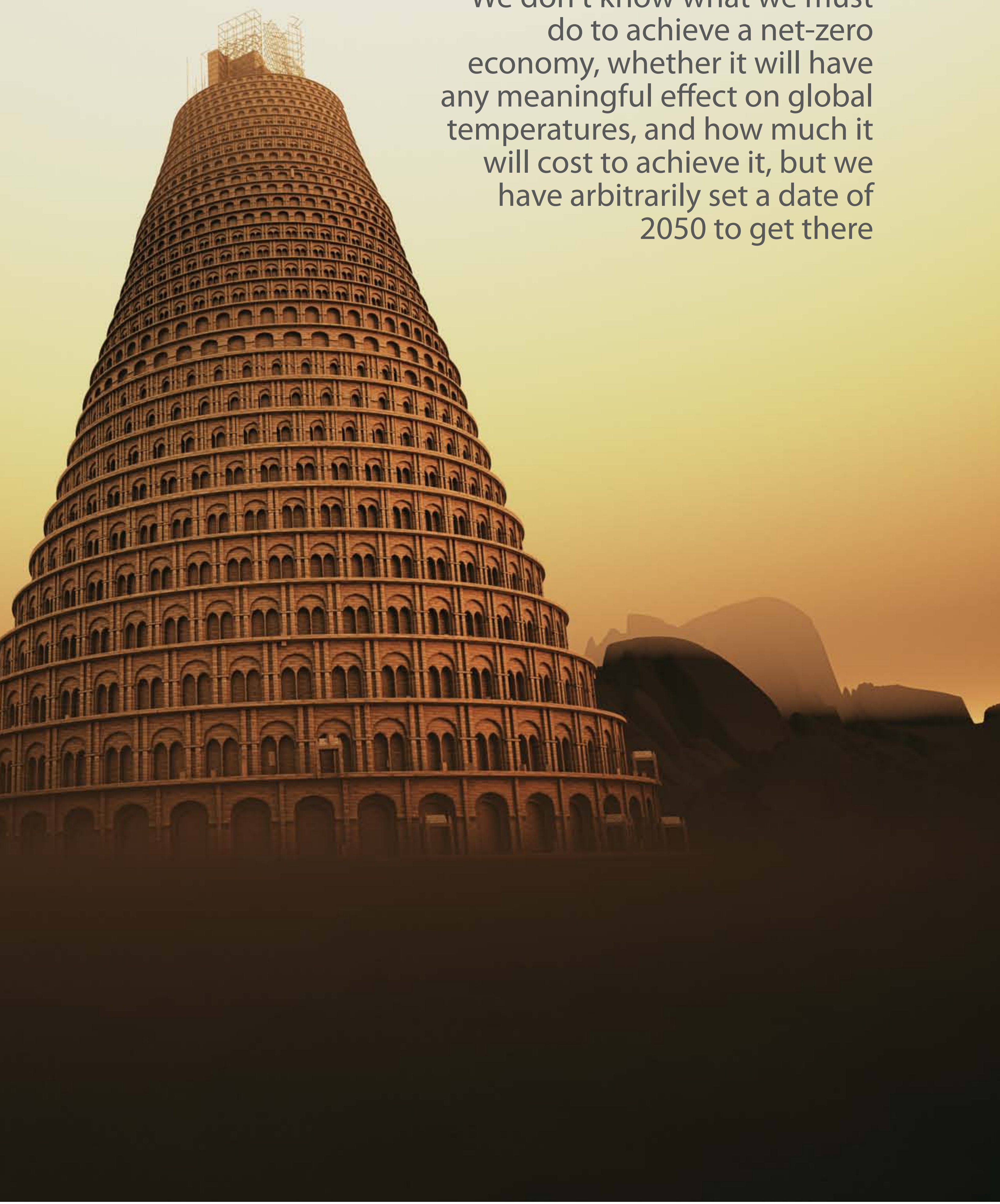
As of 2020, there remains a serious problem with the commitment to net zero carbon dioxide emissions (CDEs), which is best seen by considering the Old Testament story of the Tower of Babel (Genesis 11:1–9), from which engineering project managers drew fundamental lessons centuries ago. Mankind decided to build a tower to reach heaven. As they set out, they had no clear idea of what success would look like and when it would be achieved, nor how much the project would cost. The same can be said of the climate change project: we don't know what we must do to achieve a net zero economy, whether it will have any meaningful effect on global temperatures, and how much it will cost to achieve it, but we have arbitrarily set a date of 2050 to get there! The Babel project collapsed in a confusion of languages, and one can confidently anticipate a comparable failure this time round.

From the Digest of UK Energy Statistics (DUKES) 2019 data,[2] 45% of all CDEs come from the built environment, split 27% for domestic buildings and 18% for all other buildings (excluding any industrial processes in factories). These ratios have not changed over the last decade, since I first consulted DUKES. A serious alteration of the existing building stock is required. We cannot focus only on new buildings, as there is only approximately a 1% change to the building stock annually. In other words, approximately 85% of the UK's current buildings will still be extant in 2050, at which point they will represent 70% of the building stock. A deep retrofit of existing buildings is therefore needed to achieve an 80% reduction in CDEs, with a further contribution required to achieve net zero.

In February 2019, the CCC issued a report *UK Housing: Fit for the future?,*[3] which, rather than tackling the challenge of a deep retrofit of the existing building stock head on (probably because the authors understood the implications of the question), nibbles at it with a hundred and one small initiatives. Even if taken altogether, these steps do not come close to suggesting that the country could reduce the CDEs of the building sector by 80%, let alone 100%. The cost-benefit analysis is also piecemeal, and most interventions, whether using heat pumps or undertaking a programme of solid-wall cladding or any of the others, exhibit long payback times. There is no indication either of how much the CDEs of the UK built environment would actually decrease as a consequence, so we cannot determine value for money against the objective of slowing down climate change, as seen through the proxy of CDE reduction. Of course, this proxy itself gives no quantifiable indication of how much this spending would slow down climate change, so the desired result remains an unacknowledged act of faith throughout.

The achievement of net zero CDEs will be the final additional stage to the project once an interim 80% reduction has been achieved. But even the 80% CDE reduction of the original 2008 Act requires all buildings to achieve near-zero CDEs by 2050, according to the Government's 2011 report, *The Carbon Plan: Delivering our low carbon future*.[4] Therefore, this paper

> We don't know what we must do to achieve a net-zero economy, whether it will have any meaningful effect on global temperatures, and how much it will cost to achieve it, but we have arbitrarily set a date of 2050 to get there



casts achieving this 80% reduction of CDEs from the UK built environment (as per the 2008 Climate Change Act) as a giant civil engineering project and applies the engineering discipline of project definition to identify some of the implications.

Estimates of the resources required are necessarily uncertain, but previous pilot projects give us some real data with which to assess their validity. The cost, of more than £2 trillion, can be extrapolated up from costs to retrofit typical homes, as can the suggestion that the workforce and the supply chain required will be comparable in size with the NHS in terms of costs and headcount. Even if we could magic up the extra CDE reduction to achieve the net zero target in time for 2050, the cost savings in energy would only be £27 billion per annum (assuming the current £1,300 per annum annual household energy bill is reduced by a factor of four), with a payback period of over 75 years, much longer than any personal or institutional investor would countenance. The main conclusion of this paper is that an intrinsic, net-zero-carbon built environment will only come about by government fiat in a command economy. A 'war-footing' analogy is appropriate here, but few are convinced that the enemy we face is on a scale that demands such an overwhelming diversion of resources, when we still must retain some provision for other global emergencies such as pandemics, supervolcanoes, financial collapse and so on, as well as the cost of adapting to the climate change that actually occurs.

There is an important assumption that underlines this paper. If we could provide enough 100% net-zero-carbon primary energy by 2050, no action on the fabric of buildings would be necessary. All the realistic estimates that factor in changes in population and energy supply and demand suggest that well over 70% of the world's energy needs will still be provided by fossil fuels in 2050. Moreover, the built environment is such a big contributor to CDEs that it must achieve the net zero target within itself. One must also attack the additional 18% contribution to UK CDEs that comes from non-domestic buildings, many in the public sector. Yet progress since the 2010 CCC report on housing is nugatory,[5] and no doubt a third report will be written in 10 years' time, with similar pleas and no doubt with a similar result.

2 An initial estimate of retrofitting the housing stock

If we take a typical suburban semi-detached house and ask how much it would cost to reduce the CDEs by 80%, we must consider the various actions that would need to be taken, of which improving the thermal envelope to reduce energy usage is a major component – underfloor, loft, and external wall insulation, treble glazing or vacuum glazing of windows, elimination of draughts (while maintaining a non-zero flow of air to maintain the health of both the building and its occupants, as we do not want moulds and spores to proliferate), and the replacement of all appliances, including boilers, with the most modern and energy-efficient versions.

A sum of £5000 per house is clearly far too low, and would only pay for replacement of a few windows. With £500,000 to spend we could tear down the house and rebuild to the highest standards, so that figure is clearly far too high. The actual cost per house to achieve an 80% CDE reduction will be somewhere between these extremes and, given the level of uncertainty, the geometric mean of £50,000 per house will give a starting point. With 28 million homes in the UK, some bigger, others smaller than a semi-detached house, one arrives at an estimate of £1.4 trillion to retrofit the UK residential housing stock. Recalling the 27%/18% split of emissions between housing and all other buildings, and assuming the average costs of reduction scale with the total amount of CDE reductions, this would imply a total cost to achieve an 80% CDE reduction of £2.3 trillion!

3 A pilot project

But what about in practice? Faced with the scale of the problem, and the enormous costs and the level of uncertainty within the estimates, as Chief Scientific Adviser to the Department for Communities and Local Government, in 2009 I made a presentation to Lord Drayson, the then Minister of Science. As a result, his department launched the 'Retrofit for the Future' project through the Technology Strategy Board, wherein £17 million was spent on retrofitting over 100 social houses.[6]

The peak cost allowed per house was £150,000, and the average was £85,000.[7] This was well in excess of what a national retrofit project would cost, but this was a pilot project, delivered in the absence of a supporting cast of specialist suppliers – designers, builders, building materials suppliers and so on – who might be expected to deliver cost reductions. The target was to achieve an 80% CDE reduction by whatever methods were available: a combination of all the interventions described above.

It is important to note that the retrofitting of each house was essentially a bespoke project. This will be a feature of any national roll out. Standardisation is impossible, because every house is different and poorly fitted extra insulation is in some cases worse than no extra insulation at all, particularly in lofts.

The results were very interesting.[8] Detailed before-and-after data on energy consumption and CDEs were collected for 45 homes. Of these, only three met the 80% CDE reduction target. The average reduction was near 60%, and six projects achieved less than a 30% reduction in CDEs![9] If we were to insist on an 80% CDE reduction target, and £85,000 was insufficient for a successful pilot, perhaps another £50,000 would be enough. But at £135,000 per house, the total bill would be near £4 trillion!

Working out what would happen in a national roll out involves assessing two separate tendencies. On the positive side, there would be economies of scale to reap: learning by doing to speed up the process, and a set of standard solutions for each house type. The development of a specialist supply chain for the materials and a dedicated workforce would also help. Against this, the fact that every house would still be a bespoke project places limits on such cost savings. Moreover, social houses – as tested in the pilot project – tend to be smaller than the average home.

Before the pilot project, I estimated that costs could come down by 70–80%, but with the bespoke nature of each solution, I have come to agree with the estimate from the Energy Technologies Institute that the total cost to the nation will be of the order £2 trillion,[10] which is a factor of three saving. The cost per house will be nearer £75,000 than my initial estimate of £50,000 above. This shows that the guestimate above was in the right balk-park, before the pilot project had been undertaken. The revised estimate, based on the pilot study, is that the total cost to achieve an 80% CDE reduction across the entire UK housing stock would be £2.1 trillion, with a further £1.4 trillion needed for non-residential buildings.

It is noteworthy that all reports about actual whole-house retrofits are circumspect on the actual cost figures,[11] probably for fear of the total costs of a national programme being estimated and the value for money being shown to be woeful.

Note that a typical household's annual energy bill today is of the order of £1300, and since £150,000 per house achieved a 60% reduction in CDEs, the implied cost saving of energy

If we were to insist on an 80% emissions reduction target, and £85,000 was insufficient for a successful pilot, perhaps another £50,000 would be enough. But at £135,000 per house, the total bill would be near £4 trillion.

means that the investment would take 150 years to pay for itself. Typically, ten years is the upper limit for such a domestic intervention, so it is clear that no-one would make or lend towards such an investment. Capture of the improvement in the capital value may help but not completely. There would also be side benefits, such as improved health and reduced sickness costs, but these are small compared with the principal sum.

Only if there is a government edict will any significant inroads be made in energy reductions in existing homes. But no political party would commit to this level of spend on a national retrofit programme until the need was pressing and urgent. There is no ducking or diving from this conclusion. Such expenditure would compromise the ability of the nation to react to other potential harms, such as global financial collapse, or pandemics or wars.

4 Decarbonising a city

At the completion of my time as Chief Scientific Advisor, I returned full time to the University of Cambridge. At the time, the world faced the three interrelated challenges of energy security, sustainable consumption and resilience to future climates, just as it does now. The first of these was, and remains, particularly urgent, with older power stations being taken out of commission and nuclear plants approaching the end of their design lives. The gap between government rhetoric and action on the ground at the necessary scale was growing wider every day, with politicians deterred by the sheer magnitude of the challenge, and just where to start.*

My time in Whitehall had given me a new interest in climate policy, and I decided to refocus my efforts on assessing the practicality of decarbonising a city. Cambridge represented an ideal proving ground. The city has wealth of academic talent available to monitor all the processes and to take measurements of energy use before and after retrofit, as well as checking on changes in behaviour inside buildings, social attitudes towards the retrofit project and considering how to treat ancient buildings.† The prestige associated with 'Brand Cambridge' would mean that one could expect every civil engineering company with an interest in the built environment to come on board in order to get first-mover advantage. If the city were to commit to an early citywide retrofit of its building stock, it would represent an important experiment, at a moderate scale. Alternatively, if Cambridge showed that such a project could not be delivered, and why, it would be a most penetrating wake-up call to civil society.

Having made a preliminary assessment of the work involved, I delivered an 'amateur' prospectus to the city, which gave an estimated bill of £0.7–1.0 billion for retrofitting the building stock and thus halving its net CDEs.‡ I wanted this prospectus to be reviewed by the city and county councils, the university and the colleges, and the business and entrepreneurial communities in the area, so that they could give provisional approval. I thought

* Since that time, temporary relief has been found in a reduction in the demand for electricity, as energy-intensive industries such as iron and aluminium have moved away. Wind farms have filled much of the gap, even if their intermittency threatens grid stability.

† On this last point, just as we tolerate a few vintage cars on the road that do not meet all the modern vehicle standards, would we treat King's College Chapel, or the buildings on Trinity Great Court with the same exceptionalism, or would we insist on changes to windows and external cladding where necessary? Many of the ancient buildings have better thermal envelopes than buildings of the period 1800–2000.

‡ I have not updated the input figures. Whereas there were 49,000 dwellings in Cambridge in 2011, the 2018 local plan is for a further 14,000 homes over the period 2011–2030, a 28% increase. This is not factored into the detailed analysis here, but the results could easily be scaled slightly to do so.

this would encourage the Greater Cambridge Partnership to take ownership of the project and worked it up into a detailed proposal. However, all parties replied in a non-committal way, presumably hoping others would take the lead. The project was eventually shelved. Nevertheless, the details of the project are informative, as they show why deep retrofitting of buildings is so very hard.

Simple analysis

Although my focus was on decarbonising the building stock, at the time I started my research, work had already been done on determining the magnitude of decarbonising all sectors of the Cambridgeshire economy. Table 1 shows the CDEs of Cambridge and nearby local authorities in 2006 (the most recent available at the time), breaking the figures down into four areas: industrial and commercial, domestic, road transport and land use (and changes therein). There was no attribution of the usage within those sectors (heating, industrial processes, IT and other equipment etc).§

Table 1: Carbon dioxide emissions in Cambridge and nearby local authorities in 2006

kT carbon dioxide	In buildings		Transport	Land-use	Total
	Industrial & commercial	Domestic			
Cambridge	436	244	98	0	778
	56%	31%	13%	0%	
East Cambs	210	203	298	166	877
Fenland	532	231	191	157	1111
Huntingdonshire	601	406	742	139	1888
South Cambs	759	368	702	17	1846
	41%	20%	38%	1%	
National totals	245,076	153,605	135,007	−1,953	531,735
	46%	29%	25%	0%	

Source: Defra.[12]

While the City of Cambridge has CDEs lower than the national average, the county has higher levels.[13] It is also important to note that energy use in buildings accounted for 87% of CDEs in Cambridge but only 61% in Cambridgeshire. So, while a city-centric view would suggest it was best to focus on buildings alone, decarbonising the whole county would necessitate dealing with transport too. It is also worth noting that Table 1 does not explicitly include the carbon dioxide footprint of the stuff produced elsewhere but consumed in the region, other than the transport contribution.

§ The data given here differs from that held by the BEIS (DUKES), but Defra states that they have much greater detail of energy consumption from those entities use more than 100 kWh of energy per annum.

Sector impacts

Domestic buildings

Experts had advised the city council that £115 million would be needed to bring Cambridge's privately-owned housing stock (approximately 41,000 units) to 'Warm Front Standard', which, through loft and wall insulation, double glazing, and draught proofing, would deliver CDE reductions of 34%.[14] By taking extra steps, such as a programme of solid wall insulation, the cost would rise to £223 million, and the CDE savings would increase to 40%.[15] However, this latter figure was probably optimistic.

The figures were revealing, showing just how steeply costs rise as further incremental reductions in CDEs are demanded. The steepness of the cost curve would undoubtedly increase further, as CDE reductions reached 80% and then 100%.

Non-domestic buildings

There is a good correlation between the quantity of CDEs from non-domestic buildings and the aggregate floor space.[16] Table 2 shows floorspace for 3,269 non-domestic properties in Cambridgeshire.

Table 2: Floorspace in non-domestic buildings in Cambridgeshire

000 m^2	Retail	Offices	Factories	Warehouses	Other	Total
Cambridge	347	479	147	169	74	1,216
East Cambs	64	62	267	233	33	659
Fenland	144	58	507	406	45	1,160
Huntingdonshire	202	210	772	606	105	1,895
South Cambs	85	497	491	283	212	1,568

Source: These are properties subject to local body rates in the region, excluding churches, hotels, public houses, hospitals, universities, libraries, and leisure centres etc. There are about 5,600 non-domestic buildings in the city in total.[17]

Scaling published cost figures on domestic refurbishment[18] by the relative floorspace suggests that all non-domestic buildings could be C-rated with an expenditure of about £42 million on improved insulation methods, saving 0.11 million tonnes of carbon dioxide, or 13.7% of today's emissions. If one adds in all the other measures (heating systems and controls, and so on) the estimated cost comes to about £150/m^2, or about £182 million for Cambridge. The latter figure is broadly in line with the domestic housing figure, which involves many times the number of units, and has been independently arrived at for non-domestic buildings.[19] It has been estimated that better boilers and controls can reduce emissions by up to 20%, so that an estimated saving of over 25% from these measures is conservative. This figure also is in line with estimates from the Greater London Authority for refurbishment of its city-centre office blocks. Implicit in these figures is the effect of averaging over many different types of non-domestic buildings.

On 11 September 2008, after a public consultation, Cambridge had adopted a climate change strategy and action plan. It referred to a total of 5600 non-domestic buildings in the city, and covered the categories excluded above. If we were to assume (and it needs to be checked) that we can scale the costs and benefits pro rata to the full number of buildings, we would need £311 million to bring all non-domestic buildings up to a C rating.

Transport

As noted above, decarbonising transport was also a consideration. In 2007, Cambridge County Council had prepared a comprehensive bid to the Transport Innovation Fund for a set of measures including a high quality public transport network, a comprehensive cycling network, significant walking enhancements, extensive traffic management measures, an intensive programme of 'Smarter Choices' to promote these sustainable travel choices, and a Congestion Charging Scheme.[20] For an estimated cost of £498 million (at 2007 prices and a 2008 start), an estimated 16% reduction in CDEs would be delivered by 2021,[21] compared with a 12% increase on a do-nothing basis. There would also be a wide range of other social benefits including reduced journey times, and sustainable and attractive alternatives to the use of private vehicles.

Consequential savings

The total costs across the three sectors are shown in Table 3. With these figures in hand, crude estimates could be made of the consequential savings.[‖] For housing, annual energy

Table 3: Costs of decarbonisation plans for Cambridge

	£m
Domestic	223
Industrial and commercial	311
Transport	498

bill savings of £250 per household equated to £12 million across the housing stock. The estimate for non-domestic buildings was comparable, at £18 million. For transport, the net gain (including time saved less congestion charges etc) was £10 million. So the total annual saving was £40 million, although taking a broader approach to what savings might be delivered[22] could increase this figure to £60 million. This meant a cost of about £60 per ton of carbon dioxide saved in the buildings sector, but £800/tonne in the transport sector.

Execution

One initial analysis[23] indicated that we would need 4500 builders for 10 years to carry out the work, or approximately 100 person-days per dwelling.[24] However, in 2011 the local builder workforce was only 1500 strong. Similarly, the supply chain for building materials and its capacity would have needed to treble. It is noteworthy that Addenbrookes, Cambridge's main hospital, has a workforce of 10,000. It is clear that the workforce for the retrofit project would be on the same scale as healthcare in the area, and this is only to deliver a 25% CDE reduction.

‖ These assumed that there would be no rebound effect, such as citizens turning up thermostats.

Summary

The high cost per tonne of CDEs saved in the transport sector led us to remove it from further consideration. Allowing a contingency, this left us with expenditure of about £600 million[25] to reduce the carbon footprint of Cambridge buildings by something more than 25%. The cost equated to approximately £5000 per resident in Cambridge or £15,000 per family, or an average of £10,000 per building.

The prospectus to retrofit Cambridge building stock so as to reduce CDEs by 50% carried an estimated cost of £0.6 billion. This figure was arrived at before the DCLG pilot project on social housing was undertaken. However, it is clear that the estimates are in the right ballpark. Notice, however, that if 2050 is the target end date, we now have a 30-year instead of a 40-year project.

5 A nationwide roll out of a deep retrofit project

If we take (i) my initial estimates, (ii) the detailed results from the pilot study, and (iii) scale up the Cambridge study – in ambition from its original 25% CDE reduction to 80% and in extent from a single city to the whole country – a picture can be built up of the size and complexity of the civil engineering project required to decarbonise housing across the country. The cost of rolling out a project to deliver a 25% CDE reduction across the country is of order £0.4 trillion.[¶] With the greater number of homes now, the much greater spend per house needed to get an 80% CDE reduction and even more for a net-zero-carbon built environment, the cost easily exceeds the £2 trillion described in Sections 1 and 3. Also, the in-kind support of some of the civil engineering companies to the Cambridge programme would not be available for a national programme.

The estimate for the workforce scales up from 4,500 over 10 years in Cambridge, to 1 million over 30 years for a national programme. With the Addenbrooke's comparison in mind, a nationwide 80% CDE reduction project would require a workforce on the same scale as the NHS. This will hardly be a minor perturbation at the 1–5% level of the economy. The supply chain must be scaled up as well. Given that today most builders are subcontractors and work singly and/or in very small companies, the sector is not set up to grow the numbers in short order, as would be required by a deep retrofit of all the housing stock within 30 years; if this work were to be done by an army (including its provisioning), and was to be completed on the timescales demanded, the Cambridge project would have had to be done in six weeks!

It is hard to estimate the CDEs embodied in the materials used for the retrofitting, but external cladding will be as much as a 30% addition to the building fabric, with payback in terms of reduced CDEs taking around 30 years. This means that absolute emissions would not start to fall until 2050.

Finally, we should note that although the CCC has claimed that there are health co-benefits of retrofit projects, even a 10% (or £13 billion) reduction in the bill for the NHS would represent only a small fraction of the £67 billion needed annually to fund the retrofits. There is also the practical issue of how to capture and reassign that level of resource from health to retrofit.

¶ The assumption here, which can be questioned, is that the Cambridge housing stock in 2010 is representative of the national housing stock, but we know that homes in multiple occupation are over-represented.

The cost equated to approximately £5000 per resident in Cambridge or £15,000 per family, or an average of £10,000 per building.

6 Conclusions

The approach of the CCC to reducing CDEs from buildings is typical of a government quango: committee members have no personal skin in the game, and can afford to dance around the problem, nibbling at the edges. A professional engineering approach would size and scale the problem first, just as done here, then cost it and seek approval for the whole project.

The overriding consideration in assessing decarbonisation of buildings is the huge scale of the project required to achieve an 80% reduction of CDEs. Its impact on the UK economy and workforce would equal or exceed that represented by the armed forces in World War II. The added frustration is that what the UK might do in terms of CDE reductions has been undone, one hundred times over, for the last 20 years and almost certainly the next twenty, by the development of fossil-fuelled energy systems in underdeveloped countries.

Given the scale, the level of public debate about decarbonisation is appalling, as exemplified by the antics of middle-class Extinction Rebellion members. Their arguments about our grandchildren is also incredibly short-sighted. Can we think of anything done 200 or even 100 years ago by our grandparents (and I exclude world wars from this consideration, as gratuitously destructive) that has made us worse off, and that we now wish they had refrained from doing? Yet none of the deeds of our grandparents were predicated on making us, two generations later, better off.

From Thomas Malthus onwards, the worriers have been proven wrong; about food production, oil shortages, coal exhaustion and much else. We are 50 years into a demographic transition, the result of city-dwelling families being systematically smaller than rural families. The world population will peak in about 2050, or soon thereafter, and will shrink by more than 200 million by 2100. If people have to retreat from seaside dwellings there will be ample empty dwellings further inland. The regular revolutions in food technology, which have resulted in ten times as many people being fed than 250 years ago, will continue into the future, with heat- and drought-resistant species being developed. Megacities will be self-sufficient in greens and animal protein foods will be produced from factories within the city limits by 2100 or sooner. The resources that worriers would have us deploy to deal with problems that might, or might not, arise in hundred years' time would be better devoted to improving the lot of humanity in the round.

Notes

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11. See the references at the end of Reference 11, and google 'Retrofit for the Future'.
12. http://www.defra.gov.uk/corporate/about/what/localgovindicators/ni186.htm.
13. Cambridge (Cambridgeshire) is about 0.146% (1.22%) of the national total of CDEs. The 2001 census population of 108,863 (552,655) is 0.185% (0.939%) of a total of 58,789,000 in the UK.
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16. The conversion factor is 0.39 $tCO_2/m^2/yr$.
17. http://www.cambridge.gov.uk/ccm/navigation/environment-and-recycling/sustainable-city/climate-change/.
18. http://www.calebgroup.net/resources/documents/01CALEBNON-DOMESTICREFURBISHMENTREPORT-26Feb09_000.pdf.
19. https://members.ipf.org.uk/membersarealive/downloads/listings1.asp?pid=290.
20. http://www.cambridgeshire.gov.uk/NR/rdonlyres/07EE8F74-A6EF-48B9-ADB9-4528B2631405/0/FINALOutlineProposalforFunding.pdf.
21. Against a 2000 base figure.
22. Wider studies of savings (e.g. less illness, with reduced call on health-services or absence from work) treble the raw value above Clinch, J.P., Healy, J.D. Cost–benefit analysis of domestic energy efficiency. *Energy Policy* 29(2), 113–124, 2001.
23. Dr D Crawford-Brown (Land Economy, Cambridge University).
24. I recalculated the figures and came up with 20% higher numbers.
25. £223M+£311M+£50M contingency.

About the Global Warming Policy Foundation

The Global Warming Policy Foundation is an all-party and non-party think tank and a registered educational charity which, while openminded on the contested science of global warming, is deeply concerned about the costs and other implications of many of the policies currently being advocated.

Our main focus is to analyse global warming policies and their economic and other implications. Our aim is to provide the most robust and reliable economic analysis and advice. Above all we seek to inform the media, politicians and the public, in a newsworthy way, on the subject in general and on the misinformation to which they are all too frequently being subjected at the present time.

The key to the success of the GWPF is the trust and credibility that we have earned in the eyes of a growing number of policy makers, journalists and the interested public. The GWPF is funded overwhelmingly by voluntary donations from a number of private individuals and charitable trusts. In order to make clear its complete independence, it does not accept gifts from either energy companies or anyone with a significant interest in an energy company.

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