WHAT ARE THE LIKELY IMPACTS OF CLIMATE CHANGE ON INFRASTRUCTURE?

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The UK's national infrastructure systems will be threatened by the impacts of climate change, including sea level rise, increased temperatures, and changing frequency of droughts and floods. We need to be acting now to ensure that national infrastructure systems are adapted to the climatic conditions they will be experiencing in future.

Recent natural disasters, like the widespread flooding across the UK in the summer of 2007 and again in Cumbria in November 2009, illustrated the vulnerability of infrastructure systems in the UK to climatic extremes. Flooding in New Orleans due to hurricane Katrina demonstrated how fragile modern society is in the face of devastating natural hazards. There are social as well as technical reasons for this fragility. From a technical point of view, there are high levels of inter-dependence between the infrastructure networks that we rely upon for energy, water, transport and telecommunications, which leads to the potential for cascading failures. Meanwhile, an emphasis upon cost reduction and optimising efficiency, in particular in the privatised utilities, has progressively removed redundancy, which was intended to provide fall-back capacity in the event of failure.

Complex systems can be designed to have very high levels of reliability, even when they are occasionally subject to extreme environmental loads – witness the safety record in the civil aerospace industry– but to do so requires careful analysis of the *resistance* of the system to extreme loading, its *robustness* to potential unforeseen loads and the system's capacity to recover from disruption, or in other words its *resilience*. Having originated in ecology and been extensively elaborated in the social sciences, the notion of resilience is rapidly gaining currency in engineering as a motif for the design and management of critical infrastructure systems. The threat of climate change implies the need to extend analysis of system resilience to understand processes of long term change and adapt systems so that they will in future be less vulnerable to failure from natural hazards in a changing climate.

INFRASTRUCTURE VULNERABILITY TO WEATHER-RELATED HAZARDS

A multitude of functions of society and industry are influenced by weather, and thus also potentially by future climate change. Many industries are in a good position to adapt to changing climatic conditions year on year – insurers can modify the premiums for weather-related hazards and farmers can modify when and what they plant, though even in these instances longer term planning is also necessary. Adaptation, however, becomes of utmost importance in long term climate-sensitive decisions that are hard to reverse. These include major infrastructure investments, such as water supply reservoirs, highways and power stations. Land use planning decisions influence the vulnerability of people and properties to climate-related hazards, such as flooding, now and in the future. Building regulations help to determine how houses and other buildings will cope with future climates.

There have now been many studies that have explored the potential scope of climate impacts on infrastructure. Table 1 (see www.sciencein parliament.org.uk) summarises some of the most important potential impacts. Under the Climate Change Act, infrastructure providers are required to report on the climate risks to which they are exposed and the steps they are taking to reduce those risks. The Climate Change Risk Assessment (published in January 2012) provides a national analysis of risks to the UK, including to national infrastructure systems. The proliferation and diversity of potential impacts can be an obstacle to well targeted action. Yet in the UK, the top adaptation priorities for infrastructure are now quite well established:

• *Flooding:* The frequency of river flooding, along with surface water flooding from heavy rainfall, is expected to increase. Though mean sea levels around the UK are unlikely to rise by more than a metre before the end of the 21st Century, sea levels will continue to increase for hundreds of years thereafter, with very long term implications for coastal settlements and nuclear facilities.

• *Water scarcity:* Water resources in many UK river basins are already over-exploited. Climate change will exacerbate this problem, especially in the south of England, by reducing summer precipitation and potentially increasing demand.

• *Heat:* The heat wave in 2003 is estimated to have caused 2139 excess deaths in the UK. Excessive heat in buildings and transport systems (including the London Underground) that are not designed for very hot weather causes discomfort that reduces productivity.

At a global scale, Working Group II of the Intergovernmental Panel on Climate Change reports on *Impacts, Adaptation and Vulnerability* including summaries of published literature for various sectors and global regions. The impacts of climate change will vary greatly worldwide. The impacts depend not only on the magnitude of the change in climate but also on the capacity of societies and individuals to cope with climate change, in other words, their adaptive capacity. Hotspots of vulnerability are in low-lying coastal locations and areas that are already water-stressed. The implications of climate change in these locations has the potential to be felt world-wide via increased disaster relief costs, migration and insecurity.

RECENT PROJECTIONS OF CLIMATE CHANGE FOR THE UK

The latest climate scenarios for the UK were released in June 2009 and are known as the UK Climate Projections (UKCP09). The projections are based upon over 300 runs of the Met Office Hadley Centre's global climate model, combined with more detailed modelling to provide results for the UK on a 25km grid. Each model run was scored by the quality of reproduction of observations of past climate change and weighted accordingly. This procedure enabled the generation of probability distributions that represent the uncertainty surrounding future climate changes.

The science of climate projection has continued to advance since the publication of UKCP09. Improving resolution of climate models will enable more accurate prediction of localised processes like precipitation and wind. Improved modelling is also providing predictions of temperature that include the effect of urban areas. Such developments are to be welcomed, but they do mean that decision makers need to be ready to accommodate intermittent updating of climate information, and to accept that whilst the broad global trends are now well established, predictions of local climatic patterns and associated uncertainties may well change as the science progresses.

DELIVERING ADAPTATION

It is in individuals' and businesses' interests to prepare for a changing climate. Doing so will yield immediate benefit in terms of risk reduction, as well as preparing for longer term changes. However, as Lord Stern observed in his report on the economics of climate change, "in some cases the benefits of adapting could extend beyond those who have paid for them, and provide benefits to the wider economy and society. In this case the private sector is unlikely to invest in the amount of adaptation society would desire, because they cannot capture the full benefits of the investment." Government therefore has a role in making adaptation happen by:

- Providing of climate information, as has been done in UKCP09, and guidance on adaptation decision making.
- Incorporating adaptation in legal and regulatory arrangements, for example land use planning, building regulations and regulation of privatised utilities.
- Including climate change adaptation in government's own decision making, for example in investments in buildings and infrastructure.

The Climate Change Act 2008

In November 2008, the UK became the first country in the world to introduce a Climate Change Act – a legally binding, long-term framework for both mitigation and adaptation. With respect to adaptation:

• Government is to assess the risks climate change poses to the UK every five years. The first Climate Change Risk Assessment was published in January 2012

• Government is to publish and regularly update a national adaptation programme to address climate risks. The first statutory Programme is expected in 2013

• The Adaptation Sub-Committee of the independent Committee on Climate Change was brought into being in order to monitor and report on progress on the National Adaptation Programme and advise on the Climate Change Risk Assessment

• Government is to require public authorities and statutory undertakers to assess, where necessary, the risks of climate change to their work and set out what action they need to take in response (the "Reporting Power").

In the Climate Change Act and the UKCP09 scenarios the UK has taken purposeful steps to ensure that the country is well adapted to a changing climate. Yet in many respects the UK is still at the outset of a process that will see climate change adaptation becoming embedded in all aspects of decision making. Engineers have particular responsibility with respect to adaptation of infrastructure so as to ensure that these systems are resilient to future threats and adaptable in the face of climate uncertainties.

What are the implications of the Engineering the Future "Infrastructure, engineering and climate change adaptation" report?, February 2011[1]

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Earlier this year the Engineering the Future group published a report on how infrastructure should be adapted to meet the challenges of climate change and of rapidly-evolving technology.

A major element in the answer to this concern centres on 'smart' infrastructure, which implies the blending of information and communications ('ICT') infrastructures with all others. This is fine and helpful but does mean that all the 'blended' infrastructures will start to see the world more as ICT does. And for ICT, as we are all aware, the world is a highly dynamic place quite apart from climate change. ICT technology is still rapidly developing and all infrastructures are becoming 'smarter', that is more precisely and rapidly monitored, and more swiftly adaptive to changes in user needs and external conditions. This helps efficiency and reduces costs but also increases the interdependencies between the various infrastructures. Essentially, as with any improvement in efficiency, insofar as smart technology works its effects will get built in to expectations and we will consequently come to depend on it. Less obviously the rapidly-changing technical and demand environment typical of ICT will become typical also of other infrastructures which have traditionally operated on much longer change cycles. But this will also make all smart infrastructures more adaptive to changing conditions, including climate change, which could be very helpful. And in fact the track record for ICT systems in coping with disruptions is generally good – see the later comments on the Japanese tsunami recovery.

But this does need to be considered at the time of design. So future infrastructure systems do need to be overtly designed for adaptation, that is designed to allow bits of themselves and bits of other infrastructures on which they depend to be changed or improved later without altering the fundamentals of their behaviour in unexpected ways. This tends to involve the use of (international) standard interfaces and a 'modular' approach to the logical (but not necessarily physical) design.

This is one example of the growing interdependencies between the various infrastructures (particularly between all infrastructures and IT & Comms) which can mean that failure in one area can very quickly spread in unexpected ways and in extreme cases can lead to cascade failure. To handle this the infrastructures should be dealt with as a system of systems (as opposed to as independent units).

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Although this has nothing particular to do with climate change I note that there are some new hazards associated with smart infrastructures, for example there may be some danger of 'hacking' in mixed infrastructures, as perhaps demonstrated by a recently-reported example[2]. This emphasises the need for a proper approach to security and resilience.

One expected effect of climate change is that **there will be more emergencies**, such as major storms, floods and the like, though of course other things can also cause such events. These will now be more multi-system than in the past because of the growing interdependencies referred to above and thus less easily dealt with within a limited context. The 'system of systems' needs to be resilient. Specifically standards should be adapted to allow resumption of a partial service after an emergency where a full service is still unavailable, and research and experiences from each sector need to be shared.

There is also a need for greater understanding of, and therefore research into, the behavioural changes which are likely as a result of climate change. People are part of the system of systems.

We will be, even more than today, living in a world in which certainty is not possible, but we can aim to know as much as possible about it, and this is easier and cheaper than it was in the past.

Such information as we have is likely to be probabilistic, and this will require some changes of approach. For example engineers need to develop further their skill in to embracing probabilistic methods and flexible solutions, and in dealing with complex risk scenarios. And regulations must be developed to deal with probabilistic rather than absolute scenarios. The use of continuous monitoring will allow reactive and timely maintenance across all infrastructure and this can increase resilience.

However, in general getting more resilient is not easy and the best strategies are often counter-intuitive. For example a common reaction to concern over resilience is to set up one's own centralised system under one's own control. But such systems are actually less resilient than dispersed and diverse systems, even when the latter are multi-owned (ask RIM!). A better approach involves careful network design and diversity of supply, even though this may be harder to manage.

But it is not all bad news; modern smart infrastructure is much more adaptable than older 'dumb' versions, and the expected impacts of climate change in the UK will lead to conditions no more extreme than those currently experienced and dealt with elsewhere in the world. And there are other advantages –for example we have ever-greater real-time knowledge of the world in which we live because of an explosion in the number of smart sensing devices ('The Internet of Things'); and this trend has a long way to go. And the UK is already a serious player here. For example in a lecture at the IET on 13th October last [3] Warren East, CEO of ARM, pointed out that there were nearly as many ARM processors shipped last year as there are people in the world, and sales are still rising strongly. About half are for smartphones, but the rest are for other smart devices such as meters.

To maximise resilience we need both smartness and diversity, so that systems can cover for each other. RIM is a lesson here not only because their system was highly centralised but also because people had alternatives, like iPhones & email. Think of smart metering or other infrastucture communications (or health) for public systems which have diversity issues, any one of which is probably much more critical than RIM.

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And as more reassurance it is worth noting that the Japanese tsunami ICT infrastructure recovery experience is in many ways heartening – though complacency would be a mistake. For example, according to a colleague Hiromichi Shinohara of NTT the immediate damage was enormous; 18 offices demolished and 23 flooded, 65,000 poles demolished, 90 routes (~6,300 km total) disrupted and 375 mobile base stations unserviceable. But 90% of the system was recovered in about two weeks and the vast majority within two months (basically almost all except for areas inaccessible because of radiation hazards). But the experience did also highlight interdependency effects – for example the number of failed systems (both mobile and fixed) more than doubled in the 48 hours following the disaster as the backup power systems failed, though these were mostly restored in another few days. And a key 'lesson learned' is the difficulties caused by disruption to other infrastructure such as roads that made repair difficult. But here again there is some good news – for example in the face of severe congestion in the traditional telephone service (caused by high demand as well as by damage) internet and e-mail services were invaluable. And there are tales of adaptive innovation; for example a colleague Will Franks of Ubiquisys reports that Softbank (a Japanese mobile company) restored some local mobile coverage by combining 'femtocell' technology with satellite phones and generators to create mobile temporary communications base stations.

In conclusion the opportunity exists to react intelligently to climate change and its impact on the increasingly complex, smart, 'system-of-systems' infrastructures. But this will require considerable care and skill, and a meeting of historically very different cultures, even within engineering & science.

Footnotes

1 Available online at www.raeng.org.uk/adaptation

2 http://www.bbc.co.uk/news/technology-15817335 BBC water pump hacking (US)

3 available for re-viewing at http://tv.theiet.org/technology/communications/11869.cfm

“WHAT ARE THE ISSUES AND ACTIONS REQUIRED?”

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You will note that the title of this article collapses neatly to “WWW”. That is intended to highlight the World Wide Web as an intrinsic part of what we will need in order to exploit opportunities to deal with a Wetter, Windier and Warmer climate in the future. I will touch on some of the issues raised in the Infrastructure UK plan prepared by the Treasury.

We lack information about infrastructure assets that are between 50 and 150 years old. Collecting data on them has not been at the forefront of anyone’s mind. As a result the asset data is inadequate and in some cases inaccurate. And that is causing us a considerable problem in thinking about what we then do with the adaptation of it or the modernization of it in order to cope with climate change. An added complication is that a lot of the infrastructure is regulated and hence data is only collected if either the regulator says so, or it is commercially required; collection for the public good does not happen by default.

The regulatory frameworks are not coherent with regard to resilience. The interdependence between these various infrastructure components means that if one is not resilient it can cause a cascade failure into another, and if you do not have regulations to take this into account before those instances occur, they may indeed occur. The design of infrastructure is disaggregated largely because it is privatized into sectors which are siloed from each other. So the governance of design related to resilience is equally difficult to deal with because of this disaggregation.

We don’t do whole life value appraisal. We tend to do cost appraisal of the capital investment (CAPEX) that goes into creating the infrastructure. We don’t measure the value of the infrastructure when it is providing a public good and public services. The operational expenditure that is required in order to achieve that is seen as “too difficult”. The whole life value appraisal is therefore not done. We live in a risk-averse culture, so technology, innovation and exploitation is difficult. It is changing, as has been indicated already, but it is changing relatively slowly. The effects of climate change are not slow to have impact.

Academia has been doing a lot of what is called multi-scale modelling for some decades. It has involved taking individual components of infrastructure and aggregating them and taking the aggregated effect in order to extrapolate further and understand the consequences. We have done a lot of that particularly around cities but also in other domains such as transport. There is a lot of knowledge in academia that industry is not taking a huge amount of notice of in this country at the moment. This is not true in other countries.

The economic models need to be more accurate; the financial models, such as public-private partnership funding, seem to be somewhat discredited as a result of recent experience. There is little trust or confidence on how to invest in and pay for all of this. We do not have a mechanism whereby the market knows how to value the public sector. And the public sector is very cautious about what the market may or may not choose to do.

You may think that I am being really negative about all of this. But there is a unanimity of feeling out there that we need to do something about this issue. Everyone is now trying to solve adaptation and modernization at the same time. We need to solve the problems and we need to solve them quickly. I am an optimist. But there is no point in trying to hide from the fact that the list of things to do is not complete and that there is a lot we do not understand. We cannot just tick them off in isolation because they may have relationships between each other. The actions in my view that are now required are holistic, but can be broadly compartmentalized into government, commerce and academia.

Government had firstly to set up Infrastructure UK. It was initiated two and a half years ago and it survived the general election. It is located in the Treasury. It has considerable visibility, not only now in the Treasury but also in the Cabinet Office and increasingly in No.10. So Infrastructure UK is a body that is gaining attention, not only because of what it is doing to deliver the current political agenda, but also because it is moving the agenda ahead more quickly than in the past which is good news.

In the same context is the cost review, carried out by a combination of the Cabinet Office and the Enterprise Reform Group, where we need to look and see why it costs as much as it does to build infrastructure in this country, because we know that it costs more in this country than it does elsewhere. Identifying those factors is one thing. Doing something about them is something else.

There is considerable investment by the Technology Strategy Board (TSB) and by RCUK representing all the Research Councils, of which three are predominant in this field, principally Engineering and the Physical Sciences Research Council (EPSRC), Natural Environment Research Council (NERC) and the Economic and Social Research Council (ESRC), in creating a body of knowledge and some innovative capability to change the way we research infrastructure. That body of knowledge has been invested in already and EPSRC, in particular, is looking to increase its investment. I am talking here about hundreds of millions–not a small amount of money–across a broad range of different areas of science, technology and engineering. In the Department for Business Innovation and Skills (BIS), across a range of regulatory aspects, there is work to see what reform is feasible and what the migration route would be to deliver more coherent frameworks by making more data available, and to ensure that the data that is available can be exploited.

There is also a lot of work on planning reform and the issue of planning and localism and how they interact. This has been seen as one of the major impediments to progressing infrastructure investment and the planning reform activity is aimed at trying to do something about it. Of course this is contentious. I am not suggesting that it is not! It is one of those areas that we need to think about from a number of different viewpoints to see where the consensus ends up. That is for government to pursue.

What commerce is doing is gathering data about the assets, because most of them are run by private sector organizations. So they are being persuaded, using a number of mechanisms, that asset data is good for them and on top of that to manage the information they have got in a much more coherent way. If we can do this really well, and we have some of the best information management academics in the world, we could export this know-how in a way that would be very beneficial to our economy.

Programme management is also important, such as how we invest in power stations, utilities, and railways – such as Crossrail for example. Programme managers are required to deliver engineering, civil, mechanical and information technology, both on budget and on time. Sir John Armitt has provided an excellent example with the Olympic Park and we are learning from John in order to take that message elsewhere.

Understanding where the skills are going to come from is crucial, and commercial organizations are now mounting apprentice training schemes with considerable government encouragement in order to provide themselves with what they need for the future so that they can survive. They are beginning to embrace innovation. So having said that industry is risk averse, it is now moving in a direction to becoming less risk averse.

Academia has a large amount to offer, I believe. We are looking at how you govern these infrastructure activities that are by definition multidisciplinary. We do not know yet how to govern them. And this is not trivial due to the knowledge required, the complexity of their structures, and commercial objectives using value-based economics. What are the social aspects of infrastructure as an emotional as well as a live-able experience is an extant research question.

Many of us live in and around cities. It is one thing to think about the rural economy we used to have in this country–but actually now most of our GDP comes from cities. We also have to continue to think about whether that is where we want to continue to go in lifestyle terms by exploiting our interdependent and networked infrastructure and also deciding where we are internationally. Academic studies of issues such as these add a body of knowledge that provides evidence to politicians and helps leaders of commerce decide what they want to do.

So what are the urgent specifics? How should we manage cities and underground infrastructure? What will be the effect of (unusually cold) winter weather? The previous Secretary of State for Transport asked me, "How often will this occur in the future?" It was a very easy question for him to ask but it was absolutely impossible to answer. It comes back to questions of probability, uncertainty and distribution. Health, finance and logistics are all influenced by information and communications technology (ICT), which is a crucial part of the infrastructure and affects everything else if it fails, such as the unknown effects of Wetter Warmer Windier (WWW) on the World Wide Web (WWW).

So what are the world wide effects which may mean that our infrastructure closes down? It may mean that available services are reduced, with a repair time that could be days or months. It may be cascade failure that may be un-repairable. We do not know in advance which one of these situations applies as these phenomena have not been modelled at this level of sophistication and complexity. When the snow hit Heathrow three questions were asked by the Secretary of State for Transport: "Who is responsible?" to which the response was: "BAA!" "Who has authority to do something about it?" Again: "BAA!" "Who is accountable?" "Probably in the minds of the general public, the Secretary of State for Transport!" At the end of the day the public like to hold the appropriate Secretary of State accountable for the wellbeing of all of these infrastructural components. The lack of alignment between responsibility, authority and accountability is absolutely crucial for governing resilience in abnormal circumstances and managing and maintaining normal operations. We currently do not have that and we need to do something about it.