multi-scale infrastructure systems analytics

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Response by the Infrastructure Transitions Research Consortium to the Call for Evidence by the National Infrastructure Commission on the National Infrastructure Assessment

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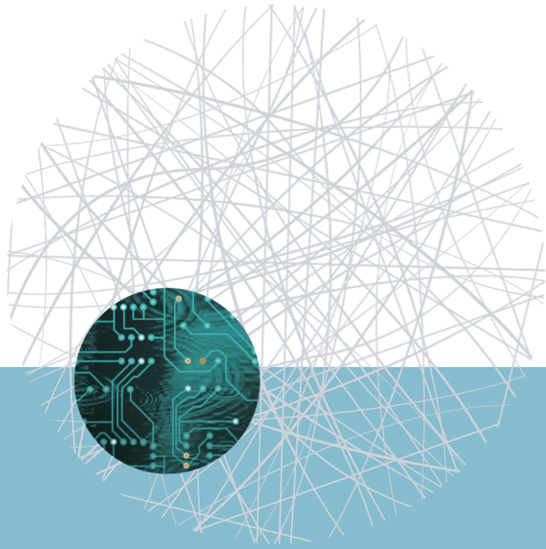

Engineering and Physical Sciences Research Council

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Introduction

This response to the National Infrastructure Commission's call for evidence for the National Infrastructure Assessment (NIA) has been produced by the UK Infrastructure Transitions Research Consortium (ITRC). The UK Infrastructure Transitions Research Consortium (ITRC) is a consortium of seven UK universities (Oxford, Cambridge, Cardiff , Leeds, Newcastle, Southampton, Sussex) funded by the Engineering and Physical Sciences Research Council (EPSRC) to "develop and demonstrate a new generation of simulation models and tools to inform the analysis, planning and design of national infrastructure". Since beginning in 2011 the ITRC has developed the NISMOD national infrastructure system model, along with a series of other innovations in interdisciplinary systems research. In this response to the call for evidence on the NIA we draw the Commission's attention to the most relevant aspects of that research. We offer our continued support as the NIA proceeds.

In our research we have emphasised the importance of taking a 'system-of-systems' perspective that integrates across infrastructure sectors based on general frameworks and principles. The consultation on the National Infrastructure Assessment that was published in 2016 proposed a framework for the NIA that was closely aligned with the approach that we have developed, whilst advancing upon it in some important ways. The consultation questions in this Call for Evidence are wide-ranging and align less rigorously with a logical framework. We trust that the NIC will adopt a coherent logical structure for the analysis and recommendations in the NIA.

All of the cited references can be made available on request. For further information contact Prof Jim Hall: jim.hall@eci.ox.ac.uk or Miriam Mendes miriam.mendes@ouce.ox.ac.uk

Our response is structured around the questions in the consultation document.

Cross-cutting issues

1: What are the highest value infrastructure investments that would support long-term sustainable growth in your city or region?

In ITRC we have adopted a multi-attribute perspective on value, based around the dimensions of the 'trilemma':

1. Security of supply, accessibility and quality of service
2. Affordability and economic efficiency
3. Environmental impact and sustainability

Value for money should be considered in these broad terms, to help navigate inevitable trade-offs between alternative investments/policies and in space and time (Hall et al., 2017b). We have sought to apply a consistent set of metrics across infrastructure sectors (Hall et al., 2016) based upon the dimensions of the trilemma.

We welcome the focus upon the long term and upon sustainability. Most infrastructure planning and investment decisions have long term implications. They are difficult decisions because of the uncertainties in factors that will influence the long term performance of infrastructure (like climate change and population growth) (Otto et al., 2014, Hall et al., 2012b). In the face of these uncertainties, attention to flexibility in infrastructure assets can provide opportunities to increase economic, environmental and social returns (Young and Hall, 2015). Careful consideration should be given to incorporating designs and practices (even in the event of higher installation costs) that enable system adaptation to changing policy, economic and social conditions (Hino and Hall, 2017). What is considered the highest value investment now might not be so in 5 or 10 years' time due to changes in demand, technology or policy goals. Examples include modularity in design and openings for experimentation (this could be in policy, operation, design, usage, governance, regulation… etc.). Using the example of low-carbon infrastructure Hiteva et al. (2017) identify a key opportunity for successfully matching infrastructure investments to societal needs. This advocates addressing the often described investment gap in infrastructure simultaneously with an institutional gap in infrastructure development and decision-making. Where possible, decision making should avoid technological lock-in and prevent path dependence, building in system flexibility. An example of missed opportunities for creating value from infrastructure investment is the construction of unilateral transmission connections with limited capacity between offshore wind farms and the onshore grids under the OFTO regime, thus precluding their usage as connectors and part of a Supergrid (Hiteva, 2013).

2. How should infrastructure most effectively contribute to the UK's international competitiveness? What is the role of international gateways for passengers, freight and data in ensuring this?

In the first phase of the ITRC programme we focussed upon national infrastructure networks with rather simplified treatment of the interface between the UK's infrastructure networks and the rest of the world. Exceptions related to our analysis of the role of trans-national energy interconnectors (Baruah et al., 2014, Baruah et al., 2016), airports (Blainey and Preston, 2016) and export of solid waste (Watson et al., 2016). Within the ITRC's MISTRAL programme, which began in 2016, we are looking more explicitly at the interconnectivity between the UK, its geographical neighbours and the rest of the world, including connectivity for energy, transport (passenger and freight), digital (cable and satellite) and solid waste systems. The results from that analysis are not yet available but we will be generating scenarios for international connectivity and the role of gateways in enabling that connectivity.

3: How should infrastructure be designed, planned and delivered to create better places to live and work? How should the interaction between infrastructure and housing be incorporated into this?

ITRC has adopted a service-based view of infrastructure, focussing upon the services that infrastructure systems deliver (Otto et al., 2014). Reliable, affordable and environmentally sustainable infrastructure services are one aspect of "better places to live and work".

Demand for all sorts of infrastructure service comes from houses, so it is important to take an integrated view of infrastructure and housing. The ITRC's research has therefore focussed upon characterising the nature of demand, for example for energy (Baruah et al., 2016), digital (Oughton et al., 2016, Oughton et al., 2015, Oughton and Frias, 2016), water (Simpson et al., 2016), waste water (Manning et al., 2016) and solid waste services (Watson et al., 2016) at a household or community scale. That analysis has illustrated the significant range of possible demands for infrastructure services at a household scale and the potential for innovation to reduce demand.

Our intra-zonal traffic model (Blainey and Preston, 2016) provides some insights into urban congestion, but at a highly aggregate level. The new transport model being developed in the MISTRAL programme will provide more detailed insights into this aspect of urban liveability. The more geographically refined research in MISTRAL will also explore the role of urban green spaces in urban drainage

In the MISTRAL programme we will be using individual buildings as the lowest level of resolution in our modelling. We are developing a methodology to characterise all of Britain's building stock and household occupants. We have developed a microsimulation model that simulates the evolution of household composition over the coming decades. That simulation has been conducted for Newcastle and we are ready to extend nationally. We offer this evidence base to the NIC.

Our research on building characterisation combines GIS data with evidence from remote sensing to characterise buildings in terms of their age and type (Barr and Barnsley, 2004). This approach has been applied in London and is being rolled out nationally. Further research will develop spatial optimisation methodologies so that we can allocate future infrastructure (like CHP plants or photovoltaic panels) according to a set of objectives and constraints. A version of this was developed for allocating new housing in London (Walsh et al., 2011) according to objectives (e.g. prioritising brownfield sites) and constraints (e.g. avoiding floodplains). This methodology may be of interest to the NIC in developing spatial scenarios of demand for infrastructure services.

A further strand within the MISTRAL programme is the development of an agent-based model of the housing market, which is being extended to make it spatially explicit. This is still work in progress and we do not expect robust results on the timescale require for the NIA, but we hope it will provide worthwhile evidence for future rounds of the NIA.

4. What is the maximum potential for demand management, recognising behavioural constraints and rebound effects?

The ITRC has developed modules for projecting demand for different infrastructure services, including household and industrial energy demand (Baruah et al., 2016), water demand (Simpson et al., 2016, Water UK, 2016), transport trip generation (Blainey and Preston, 2016) and generation of solid waste (Watson et al., 2016). We are now in the process of generating a new geographically resolved model of demand for digital connectivity. Each of these models can be used to explore the potential for demand management strategies.

The potential for improved energy efficiency is very large. It has been estimated that the global thermodynamic potential is a reduction of approximately 85% (Cullen et al., 2011). The economic and practical potential is clearly smaller. Most reliable estimates (Lucon et al., 2014, NAS, 2010) are 20%-50%, which is the range that we modelled in the ITRC analysis as achievable by 2050. The lower end of the range would probably be achieved by market forces alone; the upper end requires significant policy intervention. The difference is clearly hugely important for energy infrastructure policy.

Meta-analysis of energy efficiency evaluation studies shows that energy efficiency programmes tend to deliver significant benefits and to be highly cost effective, but to achieve less than simple engineering estimates (Wade and Eyre, 2015). The reasons are diverse. Rebound effects are relatively well understood. They can be significant where there is large unmet demand for energy services, but in an advanced economy like the UK, direct rebound effects are small, typically ~10%. Under-performance of more complex technical solutions is also a factor, implying that skills and training in supply chains and installation need to be an important parts of energy efficiency policy (Killip, 2013). Behavioural, cultural and institutional factors are also important in understanding the reason for under-investment in energy efficiency and in policy design.

For road and rail transport we have modelled the response of demand to economic and population change, as well as the negative feedback from congestion (Blainey and Preston, 2016). In fact, in our simulations self-limiting congestion is only avoided by decoupling demand from the economic and population drivers, which might be achieved by demand management. However, there is a risk that such demand management will lead to sub-optimal outcomes for the economy and the environment we have not yet modelled these effects. It should also be noted that in many circumstances capacity investment and pricing are joint decisions, and the optimal balance between thesewill vary between contexts. The potential for demand management by limiting supply is noteworthy for modes where absolute limits on capacity apply (in other words where additional users can not attempt to use infrastructure which is effectively full), such asairports.

5: How should the maintenance and repair of existing assets be most effectively balanced with the construction of new assets?

In our analysis in ITRC using NISMOD we have incorporated operation as well as capital costs of infrastructure. However, we have not yet quantified the role of maintenance. Some worthwhile examples of this do exist, for example in the Environment Agency's Long Term Investment Scenarios (LTIS) which we are now incorporating within NISMOD (Hall et al., 2017b). LTIS models the deterioration of flood defences and triggers investment decisions when decisions when assets have deteriorated badly (Environment Agency, 2014).

6: What opportunities are there to improve the role of competition or collaboration in different areas of the supply of infrastructure services?

The ITRC's analysis of governance has explored the role of competition in infrastructure provision. In the right circumstances, competition has been shown to yield more efficient production, control costs and/or motivate innovation. However there are many instances within the infrastructure sectors where competition may not lead to the most efficient/cost effective/high performance solutions (for example where capital intensive assets and technologies exhibiting strong network effects lead to characteristics of a natural monopoly). Examples of the limitations of commercial competition in parts of infrastructure provision include the roll out of smart meters in electricity and the application of a franchising model to passenger rail services (e.g. mismatch between vehicle asset lives and franchise lengths led to additional organisations and misaligned incentives in vehicle provision). If competition is useful in an infrastructure setting, care should be taken to select appropriate mechanisms for competition for the sector, technology and processes being delivered. Mechanisms to co-ordinate and motivate the work of organisations without using competition can be more efficient in some circumstances.

Given the importance and long-life of infrastructure systems, it is often not an efficient use of resources to have more than one organisation developing knowledge or expertise that is either duplicated elsewhere or isolated from other complimentary knowledge bases (as might be the case if knowledge is being built for commercial exploitation in a competitive setting). There are opportunities for investment in the development and maintenance of common and cross-sector knowledge bases/sets of expertise that can be applied across sectors, supporting learning between sectors and offering the basis for tackling inter-sector interdependencies. The building up of knowledge/expertise can be located in several places, for example in universities, businesses operating across sectors (such as construction firms or management/engineering consultancy firms) and policy and regulation arenas (such as through the National Infrastructure Commission and UKRN) (Hiteva et al., 2016).

7. What changes in funding policy could improve the efficiency with which infrastructure services are delivered?

It is generally acknowledged that the introduction of a road user charging system where the cost of driving on a road varies by time, place, and vehicle type would improve the operational efficiency of the road network (Walker, 2011, Eddington, 2006). If the income from such a system was then allocated to offset the various externalities on which charges were based (such as congestion, air pollution, and infrastructure damage) it would also improve the financial efficiency of the network, providing that the implementation costs of the scheme were not excessive. Forms of user-based congestion charging already exist for air, rail and sea, meaning that the lack of such charges on the road system leads to serious market distortions.

8. Are there circumstances where projects that can be funded will not be financed? What government interventions might improve financing without distorting well- functioning markets?

9: How can we most effectively ensure that our infrastructure system is resilient to the risks arising from increasing interdependence across sectors?

The ITRC has worked extensively on analyzing risks and resilience of national infrastructure systems. Our approach incorporates:

1. spatial representation of climate hazards, for example flooding (Pant et al., 2017) and cooling water shortages for power plants (Byers et al., 2016, Byers et al., 2015),
2. analysis of infrastructure network performance during extreme events,
3. network disruption (Pant et al., 2016a),
4. interdependencies with other infrastructure networks (Thacker et al., 2017c) and
5. the indirect economic consequences of infrastructure failure (Pant et al., 2016b).

The methodology has been used to identify geographical 'hotspots' of infrastructure vulnerability, where a hotspot is defined as a concentration of infrastructure assets with a large number of users directly or indirectly dependent on those assets (Thacker et al., 2017a). Analyzing potential failure scenarios and the direct and indirect economic consequences provides the starting point for making the business case to invest in resilience. It also helps to target investments where they will most efficiently reduce the consequences of infrastructure network failure (Thacker et al., 2017b).

Our analysis of governance indicates that economic regulators may need to move beyond recent initiatives like the U.K. Regulators Network and towards more comprehensive and proactive collaborative arrangements. These could not only bring together economic regulators and relevant national government departments, but could also include other actors, such as environmental regulators (e.g. the Environment Agency), and different levels of government including Local Authorities. Working across levels of governance in this way will require rebalancing between the better co-ordination by central government and more context specific processes, resources and actions at a local level. Multi-agency organisations such as Resilience Forums (for example the Lincolnshire's Critical Infrastructure and Essential Services Group) at local and regional level, facilitate the development of closer relationships and cooperation between infrastructure providers (such as Anglian Water, CE Electric and British Telecom) and Local Authority bodies (such as local drainage boards) through regular meetings on the resilience of critical infrastructure along the coast. These meetings are thought to significantly improve the knowledge of infrastructure assets held by national government agencies. They could also help to build trust and facilitate the flow of information between local industry, infrastructure owners and local authorities, through activities such as the development of Information Sharing Protocols (Hiteva and Watson, 2016).

10: What changes could be made to the planning system and infrastructure governance arrangements to ensure infrastructure is delivered as efficiently as possible and on time?

The ITRC has developed an approach to infrastructure planning that examines the performance of existing infrastructure networks, the drivers of future need for infrastructure services and the alternative investments and policies that might be implemented to address those needs. That is closely aligned with the approach to the NIA that has been proposed by the NIC. Nonetheless, it represents a significant departure from conventional infrastructure planning practice:

1. Our focus is upon the assessment of the performance of national infrastructure systems as a whole, not the appraisal of individual projects.

2. We consider a wide range of possible scenarios of changing drivers of demand for infrastructure services. A straightforward but significant contribution has been the adoption of a set of consistent scenarios that are used across infrastructure sectors.

3. We have tested sets of alternative strategies for infrastructure provision, including investments and policy instruments.

This process is not intended to provide a deterministic masterplan for infrastructure delivery, but it provides a sense of direction, whilst being flexible enough to adapt to uncertainties. In our analysis of adapting cities to climate change, we have demonstrated how an 'adaptive pathways' approach can provide robustness to a range of future uncertainties (Kingsborough et al., 2017).

In our analysis for the National Needs Assessment study (ICE, 2016), we emphasised the importance of accompanying investments in new capacity with more vigorous action to manage demand.

Approaches that emphasise efficiency, innovation and using existing assets more effectively are likely to have lower costs.

Our analysis of infrastructure governance has exposed how a range of potential economic, social and environmental gains could be made by strategic and positive infrastructure coordination between infrastructure sectors. Potential benefits include more coordination, greater information about interdependencies; and fostering greater trust between different stakeholders (public and private actors, and national, regional and local authorities). To realise these benefits, further co-ordination may be required between the individual sectors at multiple levels (international, national and local); the removal of regulatory and investment barriers to cross-sectoral infrastructure investment. For example, this could include further regulatory actions to ensure that innovation in smarter electricity networks and learning is sustained beyond the life of current regulatory incentives provided by Ofgem (which have included the Low Carbon Network Fund). Another example is the weakening of incentives for water companies to invest in on-site renewable energy projects because the costs of such projects cannot be recovered from water consumers, and they do not count towards some of those companies' emissions reduction obligations (Watson and Rai, 2013).

The evidence suggests that increasing the amount of engagement and consultation, and taking account of the views of stakeholders within infrastructure plans, can lead to more legitimate outcomes. Examples include research on low carbon infrastructure (Hiteva et al., 2017) and research on energy system change (Parkhill et al., 2013).

11: How should infrastructure most effectively contribute to protecting and enhancing the natural environment?

The ITRC's analysis has analysed environmental impacts from two perspectives:

1. Taking environmental metrics as an output variable (the third pillar of the trilemma), by which alternative infrastructure strategies can be compared, alongside metrics of security of supply and cost.
2. Taking the environment as a constraint on the set of possible options. We understand that this is the approach that the NIC will take with the UK's legal carbon targets. We have taken this approach with respect to water abstraction licencing, though there is some ambiguity in how licences may change in future (Water UK, 2016).

We welcome the NIC's development of indicators of infrastructure performance, which we believe should be constructed around the dimensions of the 'trilemma': (1) security of supply, reliability, accessibility and quality of service (2) affordability and economic efficiency and (3) environmental impact and sustainability of resource use. We suggest in particular that environmental protection, including meeting statutory climate change targets (see Q11) should be central to any future national infrastructure assessments and plans.

Hiteva et al. (2017) argue that environment protection for low carbon infrastructure should adopt a holistic approach, taking into consideration trade-offs, network effects and integrated thinking in infrastructure. Since infrastructure underpins the choices and behaviours of decision-makers and users, they also argue that a more progressive approach could include a focus on outcomes (e.g. low carbon living) rather than being confined to the means to deliver such outcomes.

12. What improvements could be made to current cost-benefit analysis techniques that are credible, tractable and transparent?

Current CBA techniques contain plenty of flexibility to include multiple versions of valuation (including wide economic, social and environmental benefits) and to analyse programmes as well as projects and network effects. In practice, relatively few CBA studies make use of this flexibility. In part this may be because estimates of wide economic and environmental benefits are quite uncertain, and because of the complexity of appraising adaptive sequences of investments and policies (Young and Hall, 2015, Borgomeo et al., 2016). Our aim in the MISTRAL programme is to provide a platform and datasets that will make system-scale appraisal process more straightforward, whilst recognising inevitable uncertainties.

Transport

13. How will travel patterns change between now and 2050? What will be the impact of the adoption of new technologies?

It is clearly impossible to predict with any certainty how travel patterns will change between now and 2050, as this depends on how a range of other factors change and play out over this time period, ranging from growth in population, through developments in technology, to the impacts of political events such as 'Brexit'. However, while definite predictions may be impossible, flexible modelling systems can be used to examine how travel patterns might change in future in response to a range of different future strategies and scenarios. This is exemplified by the ongoing research work being carried out by the ITRC using its NISMOD system, which has so far examined future travel patterns under 3 external scenarios (covering demographic economic change and fuel prices) and 7 transport strategies (covering technological development, infrastructure investment, and policy- related decisions) (Blainey et al., 2013, Hickford et al., 2015, Blainey and Preston, 2016). Further work is currently ongoing to develop a typology of transport strategy components, to permit more flexible investigation of transport futures using the updated NISMOD system.

14. What are the highest value transport investments to allow people and freight to get into, out of and around major urban areas?

With respect to urban and inter-urban transport there are no magic formulae. Each infrastructure investment is context specific (as WebTAG stresses), and each urban area will have specific transport needs. Furthermore, the quality and effectiveness of existing transport systems varies significantly from place to place, meaning that a bespoke approach will be needed in each case. It should also be noted that a focus on enabling accessibility might in some circumstances deliver a greater increase in productivity at lower cost than a more 'traditional' focus on enabling mobility through the construction of additional transport infrastructure. Investments in ICT infrastructure enabling virtual mobility to substitute for physical mobility may also prove to be of high value, particularly if combined with economic and fiscal policies which encourage flexible/home working. Agglomeration diseconomies should also be considered, including excessive specialisation (and a mono-cultural economy), adverse knowledge spill-over effects, congestion (London as a barrier for links within the UK and between the UK and Europe) and pollution.

15. What are the highest value transport investments that can be used to connect people and places, as well as transport goods, outside of a single urban area?

See response to Q14

16. What opportunities does 'mobility as a service' create for road user charging? How would this affect road usage?

The answer to this question depends on what exactly is meant here by 'mobility as a service' (MaaS). As the recent Transport System Catapult (Transport Systems Catapult, 2016) report makes clear MaaS might be either based around private transport (and tantamount to car leasing with added value services) or multi-modal (and based around national and local public transport networks).

There are also important distinctions depending on the balance between public and private sector involvement. Road charging would have most relevance for a MaaS system based around car sharing, whereas a public transport focused MaaS might deliver greater efficiency and environmental benefits. However, it is difficult to see how even a MaaS system based on car-sharing would create direct opportunities for road user charging unless the charging system that was applied meant that travel using MaaS vehicles was cheaper for the users than travel by private car and hence MaaS was used to overcome equity issues. For travel in congested areas (where the greatest benefits from road user charging might be expected) this would only be the case if the road user charging system applied to private cars as well as to MaaS vehicles, or if MaaS vehicles were charged a fee which was far below the full economic cost they imposed on society. This is because under the current system of road taxation the only charge perceived at point of use is the cost of fuel, meaning that drivers do not face any penalty for driving in highly congested areas compared to driving on uncongested roads, whereas with an efficient road user charging system vehicles would pay significantly more for driving in congested areas than in uncongested areas. This would mean that if the road user charging system applied only to MaaS vehicles it would be significantly cheaper to drive into a congested area using a conventional vehicle than to use MaaS. This means that MaaS is only likely to have a significant impact on reducing traffic congestion if time and place-variant road user charging is introduced for all vehicles using the road network. However, it is not obvious how the existence of MaaS would help overcome the political barriers which have previously prevented the introduction of comprehensive road charging. Even if such a scheme was introduced, then there is still a risk that a road-based MaaS system could in some circumstances make congestion worse by diverting passengers away from more space-efficient public transport systems. There is therefore a need for a multi-modal MaaS that encourages use of the most efficient modes at different times of the day.

Digital communications

17. What are the highest value infrastructure investments to secure digital connectivity across the country? When would decisions need to be made?

With constrained annual capital investment, there is a capacity-coverage trade-off in the delivery of digital infrastructure.

Gruber et al. (2014) make an assessment of the economic benefits of broadband investment across the EU and find that the overall future benefits outweigh the investment costs, but that the private sector is reluctant to invest because investors only partially appropriate the benefits.

They suggest the public sector has a role therefore in subsidising the build-out of high speed broadband infrastructure. We believe this role should be focused at the bottom end of the market where the costs of delivery are unviable through normal market methods.

Near-ubiquitous coverage is important because past evidence of telecoms technologies has shown that the largest network externalities only accrue once a critical mass of infrastructure is present.

This critical mass has been found to be near universal service (Roller and Waverman, 2001). Hence, the true economic and social benefits of online content, applications and services only take place when practically all of the population can make use of them.

We believe large headline speeds are not necessarily required currently (e.g. 1 Gbps), based on existing bandwidth demand forecasting (Kenny and Broughton, 2013, Kenny and Kenny, 2011). However, deployment of high-capacity infrastructure (e.g. Fibre/FTTP) does provide a future proof solution, and if we do end up requiring this solution in decades to come, it would be cheaper in the long-run to install now.

The decision therefore needs to be made as to whether we (i) use a 'big bang' investment approach to digital infrastructure investment (with heavy state support), or (ii) use an incremental rollout of digital infrastructure, that sweats assets, uses minimal public funding, but may cost more over the long run as it will be a less efficient way to use available capital allocations.

18. Is the existing digital communications regime going to deliver what is needed, when it is needed, in the areas that require it, if digital connectivity is becoming a utility? If not, how can we facilitate this?

The question of 'need' is central. Economic theory implies that if there is a 'need' for specific goods or services, consumers will be prepared to pay for them. However, broadband services are widely regarded as having a 'broken value chain'.

Briglauer (2014) finds that the Digital Agenda for Europe targets can be best achieved by focusing on supply-side rather than demand-side policies. This includes deregulation, and encouraging favourable competitive market conditions.

However, Nardotto et al. (2015) finds no evidence that unbundling increased broadband adoption, except for in early years before the market reached maturity. The data instead found that inter- platform competition from cable always leads to market expansion.

This is comparable with the work of Oughton et al. (2015) who also found that inter-platform competition had the largest effect on network investment in the UK. Hence, encouraging greater inter-platform competition via expansion of the Virgin Media cable network (e.g. via Project eLightning) will deliver better quality digital infrastructure.

With regards to mobile, under current baseline scenario conditions, Oughton and Frias (2016) find that it will take significant time and resources to rollout ultrafast mobile broadband to rural areas if one wishes to deliver superfast broadband speeds (50 Mbps). While this may be a viable option using small cells in urban and suburban areas (if planning rules can be relaxed for deployment), wide area coverage in rural areas will be challenging to deliver data rates above 10 Mbit/s. In areas where there is spare capacity in infrastructure assets, infrastructure sharing is a viable option worth exploring (Ibid.).

Fund et al. (2016) undertook an economic analysis of spectrum and infrastructure sharing in millimetre wave cellular networks, concluding that 'open' deployments of neutral small cells serving subscribers of any service provider encourage market entry by making it easier for networks to get closer to critical mass. Infrastructure sharing is one way in which the costs of deploying network upgrades can be reduced.

However, analysis by Ovando et al. (2015) of LTE rollout in rural areas shows that passive infrastructure sharing does not necessarily constitute a single-cost solution for meeting required coverage obligations in low population density areas, but sharing a single network does begin to make deployment more feasible for operators. A package of measures should be explored including market-based, regulatory and policy strategies to increase coverage and capacity.

Energy

19. What is the highest value solution for decarbonising heat, for both commercial and domestic consumers? When would decisions need to be made?

For the ITRC's analysis we assumed decarbonisation of heat for one of our key strategies (Baruah et al., 2016). We exclusively looked at electrification of heat demand. On the supply side we looked at the options for supplying the increased electrical demand through Nuclear/ renewables/CCS. Supplying this demand was cheapest through building big nuclear plants and reinforcing a number of transmission lines (modelling output). With regards to when decisions need to be made, this was exogenous to the ITRC modelling.

Our broad conclusion from the ITRC analysis and subsequent work is that decarbonisation of heat using electrification as the only mechanism is very unlikely to be a cost effective or acceptable strategy (Eyre and Baruah, 2015). Not all buildings are suitable for electric heating systems. And even using efficient heat pumps, such a strategy would require at least an additional 40GW of power generation, all of which would operate at a load factor of less than 25%, much of it very much lower as it would only be used on the coldest days. This analysis concludes that strategies using more diverse fuel mixes will be more resilient and lower cost. Medium term options that are robust against uncertainty include greater use of biogas (although the resource is limited to a fraction of heat demand) and more concerted efforts to improve building efficiency and reduce demand (see our response to question 4 above).

However, there is currently no consensus on the optimum strategy for heat decarbonisation. We endorse the broad conclusions of the recent report of the Committee on Climate Change (Committee on Climate Change, 2016) to which we provided expert advice. We interpret the key conclusions as being:

1. There is a need to integrate heat decarbonisation and energy efficiency policies with increased urgency for energy efficiency in the short term.

2. There are some no regrets options for decarbonising heat, including the deployment of ground source heat pumps off the gas grid and the development of heat networks in urban centres.

3. That choices between hydrogen and electricity for decarbonisation of existing on gas grid homes need to be made in the early 2020s, with evidence collected to support the decision during this Parliament, including through trials.

It seems likely that hydrogen will form part of the optimum solution, but with uncertainty about the relative roles of natural gas (with CCS) and electrolysis in that process.

Within the MISTRAL programme we are extending NISMOD to explicitly represent local electrification and the potential role of heat and hydrogen networks. This will is being achieved through the development of a local Energy Hub model, which is embedded in our national CGEN+ electricity and gas model.

20. What does the most effective zero carbon power sector look like in 2050? How would this be achieved?

The ITRC analysis did not examine this question specifically, though the Committee on Climate Change has done extensive analysis of this question (Committee on Climate Change, 2015). The question is however cast rather narrowly in that it exclusively talks about the 'power system'…..if we assume that heat is not electrified, we then have a system that has similar demands (possibly lower

through demand side management/efficiency) than today. This would be an ideal situation when attempting to get to a near 'zero carbon power system', but would not be sufficient to achieve a near zero/low carbon 'Energy' system.

21. What are the implications of low carbon vehicles for energy production, transmission, distribution, storage and new infrastructure requirements?

From a supply perspective this 'might' lead to a large increase in electrical demand on the system. In some of our scenarios electric vehicles were projected to represent 10-12% of electricity demand by 2050 (Hall et al., 2017b, Baruah et al., 2014). This increase in demand was included in our analysis of production and transmission infrastructure requirements, but not distribution.

The implications of charging electric vehicles depend on when they are charged. In the ITRC project we did not explicitly explore the possibility of optimising charging times during the day/night. This will be addressed in the MISTRAL project, alongside explicit consideration of intermittency in renewable supplies (wind, solar, tidal) and hence the probability of insufficient supply.

Water and wastewater (drainage and sewerage)

22. What are most effective interventions to ensure the difference between supply and demand for water is addressed, particularly in those parts of the country where the difference will become most acute?

The interventions that can be used to improve security of water supply are all well-known:

- technologies and behavioural options for demand reduction;
- reduction of leakage, the cost of which will be assisted by technological innovation;
- abstraction reform to allocate water more efficiently and safeguard the aquatic environment
- new and enhanced supplies from surface and groundwater, including groundwater recharge, surface storage and inter-basin transfers; wastewater reuse; desalination

In our analysis for ITRC (Simpson et al., 2016) and in other research studies (Borgomeo et al., 2016), we have explored the full range of options, as have Water UK (Water UK, 2016). The more challenging issue is how to:

1. sequence interventions so that they cost-effectively and adaptably provide security of supply; and
2. ensure that the interaction between a growing number of actors in water supply and use does not lead to systemic risks at times of stress across the whole system.

We are proposing the reform of Water Resource Management Planning so that it more explicitly deals with the trade-off between affordability and security of supply (Hall et al., 2017a). We are also beginning to develop national synthetic drought event sets that can be used to stress test the nation's water resource systems, including interdependencies and interactions.

In related research we have analysed the demand for cooling water by the power sector in order to analyse the risks of cooling water shortage (Byers et al., 2014, Byers et al., 2016, Byers et al., 2015). Ongoing research funded by EDF is exploring the possibilities for optimising the interplay between intermittent energy supplies and energy use in the water sector, including possible energy storage and load-shedding.

Over the coming year we will include agricultural abstractions (Rey et al., 2016) alongside public water supply and industrial/energy abstractors, to understand better the interplay between different abstractors during times of drought.

23. What are the most effective interventions to ensure that drainage and sewerage capacity is sufficient to meet future demand?

Demand for sewage transfer and disposal is a simple function of population and per capita water use. However, most sewers are also used for storm water drainage so are sensitive to intense rain storms. Because of the complexity of rainfall patterns and runoff in urban areas, analysing sewer capacity and the conditions under which that capacity will be exceeded requires high resolution modelling. In the MISTRAL programme we are combining synthetic rainfall generation with high resolution modelling of sewer and surface flows (Glenis et al., 2013). We have developed broad scale methods based on the Drain London datasets to simulate the changing risk of surface water flooding for all of London (Jenkins et al., 2017). This analysis also explored the potential for reducing flood risk through retrofitting of Sustainable Drainage Systems (SuDS). In our assessment of waste water systems (Manning et al., 2016) we estimated the costs of different rates of sewer replacement.

24. How can we most effectively manage our water supply, wastewater and flood risk management systems using a whole catchment approach?

In a previous submission (ITRC, 2016) we have argued for a more integrated approach to the natural environment. Many of the services that infrastructure networks deliver rely upon the natural environment: rivers and groundwater for water supplies; uplands and floodplains for the regulation of flooding; water bodies for the assimilation of treated sewage effluent; the land for the provision of biofuels and spreading of sewage sludge etc. The natural environment cuts across infrastructure sectors, notably water and flood risk management, but also energy and solid waste. 'Blue-green infrastructure' can potentially substitute for 'grey infrastructure' in several respects: recharging groundwater avoids the need for storage reservoirs or desalination; natural flood management can reduce some of the risk of flooding; sustainable drainage systems (SuDS) can reduce the need for piped drainage infrastructure; restoring uplands can reduce discolouration of water supplies and avoiding diffuse pollution from agricultural land can improve the quality of rivers, both of which avoid costly water treatment costs for public water supplies.

Flood risk management

25. What level of flood resilience should the UK aim to achieve, balancing costs, development pressure and the long-term risks posed by climate change?

The concept and terminology of "resilience" is helpful in that it emphasises the importance of a system's capacity to cope with and recover from extreme events like floods. However, the term "level of flood resilience" is not generally understood. The concepts and quantification of risk is much more prevalent in decision making regarding flooding. If properly conducted, risk analysis evaluates not only a systems capacity to resist flooding, but also the effectiveness of coping strategies and the full costs of recover (see for example (Beven and Hall, 2014, Hall, 2011, Crawford- Brown et al., 2013). The amount invested (in the broadest sense) in flood risk reduction should be determined by the cost-effectiveness of risk reduction (Hall et al., 2012a), taking into account projected future changes and associated uncertainties. A given design standard (e.g. 1:200 years for urban areas) provides a very rough guideline but it would be unwise to rigidly adopt any such target because (i) the costs and benefits of flood risk reduction can vary significantly, so a prescribed design standard will not result in efficient allocation of resources and (ii) focussing upon the standard of protection neglects alternative cost-effective steps that might be taken to reduce flood risk, for example though land use planning, property level protection or flood forecasting and warning (Hall et al., 2003).

26. What are the merits and limitations of natural flood management schemes and innovative technologies and practices in reducing flood risk?

The merits and limitations are reviewed in the following, soon to be published paper: Dadson et al. (2017)

Solid waste

27. Are financial and regulatory incentives correctly aligned to provide sufficient long- term treatment capacity, to finance innovation, to meet landfill and recycling objectives and to assign responsibility for waste?

Long term treatment capacity: It is not clear whether or not the UK has sufficient long term treatment capacity. Eunomia predict that there is sufficient capacity (Goulding, 2016b), though this view is not universally held in the industry. In 2016, 3 million tonnes of RDF were exported to incinerators in Northern European (primarily, Netherlands, Germany, Sweden and Denmark) where there is overcapacity (Goulding, 2017). It is likely that this overcapacity will reduce over time as old plant comes off line. It is not clear when this will happen or if new capacity will be built or if the post-Brexit UK will have access to this market hence leading, potentially, to a major shortfall in thermal treatment capacity. However this may be offset by continuing reductions in waste arisings (Watson and Powrie, 2014).

Regulatory incentives: Removal of ROCs for AD under 5MW in 2013 may well have acted as a brake on further investment in small AD and the planned cap on FiTs for AD > 500kW may make large AD less attractive (Moore, 2017). Holder (2015) was told that the government incentives - RHI, ROCS (for gasifier) and FiTs (for AD) - are the third most important revenue stream (for a plant taking black bag waste and treating by sorting to remove recyclates, digesting the organics using AD and gasifying the remainder), behind gate fees and power sales, but ahead of recyclate sales. This position may be changed if the planned reduction in FiTs for large AD is introduced.

Financing innovation: There has been a great deal of investment in gasification despite the contrary recommendations in the Defra New Technologies Demonstrator Projects (NTDP) (Powrie, 2011, Pugh et al., 2011). Despite this, there have been multiple failures of companies and difficulties with the technology (e.g. (Goulding, 2016c, Goulding, 2016a, Date, 2016). Eunomia (2016) suggest that despite these difficulties, the take up of gasification is likely to increase.

Landfill objectives: The objectives for landfill come primarily from the Landfill Directive, and are to reduce the amount of biodegradable waste going to landfill in order to reduce methane emissions. The main mechanism for achieving this in the UK has been the landfill tax and the landfill tax escalator. The objective has been achieved with amounts of waste being landfilled having fallen faster than required by the Directive (e.g. (Date, 2016)). The unintended consequence of this has been to reduce the revenue obtained from landfill (due to reduction in both amount of waste being received and gas generation per tonne of waste decreasing) and hence the landfill business is becoming unsustainable. This has led to some of the major players leaving the industry and to a funding shortfall for the long term management of landfill (Beaven et al., 2014). It seems likely that there is a long-term requirement for landfill in the UK and that an alternative funding mechanism will need to be developed (Watson et al., 2016, Watson and Powrie, 2014). Other issues arising from landfills include the redevelopment of land (e.g. housing & HS2) and pollution risks.

Recycling objectives: The increase in UK recycling has slowed and in some areas, stopped. Wales is the only nation on target to meet the 50% 2020 recycling target. It seems likely that this is due to a variety of reasons (e.g. (Morton and Read, 2017) some of which e.g. LA price cutting leading to reduced communication budget contributing to confusion/disinterest amongst consumers). It is possible this will need to be incentivised more effectively, possibly by increasing producer responsibility.

28. What are the barriers to achieving a more circular economy? What would the costs and benefits (private and social) be?

Principal barriers:

1. Design which fails to incorporate the principles of the waste hierarchy (Curran and Williams, 2012) for:
    i) Reduction,
    ii) Reuse,
    iii) Repair,
    iv) Refurbishment,
    v) Remanufacturing,
    vi) Recycling,

2. Accessibility and availability of facilities to undertake and perform the 6 “R’s”.

3. Recoverability and separation of materials (recovery rate and quality of recycled materials).

4. A market and demand for products and materials recovered using the 6 “R’s”.

5. Foreign markets for recyclates are becoming increasingly selective so quality needs to increase (Morton and Read, 2017). Better design and improved education/communication would help. Domestic industries could create more sustainable markets for recyclates.

The benefits would be:

1. Less reliance on imported raw materials
2. Less waste (with associated disposal costs)
3. Significant economic savings (e.g. (Ellen MacArthur Foundation, 2017))

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