Infrastructure
BUsiness models, valuation and
Innovation for
Local
Delivery

Economic evaluation of systems of infrastructure provision: concepts, approaches, methods

iBUILD/Leeds Report

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Preface and Acknowledgements

This report presents research on economic evaluation of systems of infrastructure provision by iBUILD researchers and collaborators (predominantly at the University of Leeds) in a form that is intended to inform policy makers and stakeholders of all kinds, as well as academics. It has arisen through two factors: firstly, the increasing recognition of the importance of sustainable and resilient infrastructure to economy and society by policy makers, businesses and wider civil society; secondly, the wealth of expertise on the economic evaluation of systems of infrastructure provision across the recently initiated 'iBUILD' Centre (introduced elsewhere in this report) and across the University of Leeds.

The report has been a collective effort. Presentations of preliminary versions of the chapters were made at an iBUILD workshop held in Leeds on July 2014 and the editors would like to thank Jo Cutter and Alistair Hay of the University of Leeds Professional Services Hub for organising the event, and the participants for making it such a success. The editors would also like to thank Tim Foxon and Phil Purnell for help on both the content of and organization behind the report as a whole. Thanks also to Andrew Smith for helping to initiate the contribution of the Institute for Transport Studies (chapter 2). Finally thanks to the wider iBUILD team at Leeds and Newcastle for help throughout the process, to the funders of iBUILD, namely the EPSRC and ESRC, and to David Penhallurick and John Appleton from Infrastructure UK for invaluable comments and discussion. (Acknowledgements on behalf of specific chapter authors can be found in each of the chapters concerned.)

Andrew Brown* and Mary Robertson, University of Leeds, October 2014.

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Executive Summary

Infrastructure is the system of systems that underpins our social, economic and environmental well-being. As such, it is a key target for public spending. As with any use of public money, this creates the need for tools of valuation and appraisal of infrastructure projects. However, as a complex system of systems, infrastructure possesses a number of characteristics that make valuation and appraisal difficult. This report, authored by iBUILD and University of Leeds researchers and their collaborators, is an attempt to grapple with those characteristics. It engages with a range of cutting edge theories and techniques, developing both standard and non-standard approaches to the economics of infrastructure in the UK.

Economics of infrastructure: the need for theory development

The economics of infrastructure tends to be subsumed within literature on market failure. Standard market failures in economics include externalities, public goods, and natural monopolies. These can justify state intervention but also present problems for valuation and appraisal. In the case of infrastructure, these problems are exacerbated by the presence of additional characteristics that feature less prominently in the market failure literature. These include infrastructure's systemic character, the possibility of non-marginal effects, the nature and degree of uncertainty surrounding those effects, and endogenous preferences. Non-standard techniques and theories in economics have the potential to extend our understanding of these features of infrastructure.

Valuing systemic transport resilience: the need for development of methods and evidence

Systemic resilience represents insurance against low probability events that can have severe consequences. The principle sources of lack of resilience in the transport sector are climate and extreme weather, and terrorism and theft. Standard methods for estimating the social value of systemic resilience, such as stated preference and revealed preference, can be used; however they require careful development in the context of systemic resilience. In particular, the severe consequences associated with extreme events include non-marginal effects. Consequently, results of existing studies, which tend to show high valuation of resilience (and high costs of disruption) but low benefit-cost ratios of intervention to improve tranport resilience, may be skewed by the application of marginal valuations to non-marginal changes. There is a need for further qualitative and quantitative research into the impact of non-marginal changes on valuations.

The need to consider decision-making under uncertainty

The valuation of most infrastructure is inherently uncertain with regard to the state of the infrastructure, project costs, and predictions of future economic, environmental and other conditions. Uncertainty is of particular salience for infrastructure because of the typically long duration of its usage. To be defensible in the face of uncertainty, a decision must be made on the basis of a range of possible valuations and their relative likelihoods. There is concern that uncertainty may not be properly accounted for in infrastructure evaluation and appraisal, leading to poor decisions being made. Methods to incorporate uncertainty range from standard approaches (including deterministic appraisal, sensitivity testing, Monte Carlo risk analysis), through more iterative approaches such as real options analysis to attempts to deal with deep uncertainty. The latter often has a more discursive aspect as the qualitative judgements of experts are elicited, though these may then be converted into probability distributions that lend themselves more readily to mathematical models.

Economic evaluation of passive provision in sustainable energy provision

Passive provision is defined as the facilitation of real options within an investment opportunity or action. This is appropriate as a way of dealing with uncertainty, particularly in relation to new technologies where there are significant benefits to flexibility and scope for investment in learning. Energy systems investment is an area in which there are significant levels of uncertainty, flexibility and scope for learning, and is therefore an important area for application of passive provision and the real options approach. Smart grids are one specific example in which the approaches have been usefully applied. However, there have also been many institutional and regulatory challenges to implementation. In particular, the pricing mechanism has tended to incentivise incremental gains over system innovation, and the allowable revenues structure prevents investment in networks ahead of capacity.

Valuation of passive provision for heat network investments

Several case studies show that heat networks are well-suited to passive provision and real options. However, both are difficult to incorporate into the financial models underpinning heat network investment given the existing regulatory framework. A particular problem is the absence of a local coordinating actor capable of aggregating the disparate interests and actions of multiple relevant agents. A number of institutional imperatives arise from a systems perspective; namely, the need for institutional actors to identify, consider and act on interdependencies, particularly across distinct phases of a growing system, and to coordinate disperate decision-makers. The local state is an actor with the potential to play such a role, though the use of iterative decision-making in infrastructure valuation requires enduring commitment from the actors involved.

Accounting for critical materials in sustainable energy provision: maintaining systemic resilience

The roll-out of low-carbon technology required by policy is often conditional on materials that are critical in the sense that: demand for them is high in other sectors; they are produced only as a by-product of other processes; they are sourced from a limited number of jurisdictions (making them prone to use as a geopolitical tool); their extraction is subject to rapidly changing legislation intended to reduce environmental impacts; and they are difficult to substitute. Dependence on such materials creates economic, geopolitical, and environmental risks, which should be factored in to infrastructure appraisal through a consideration of political as well as physical interdependencies. Dependence on critical materials is a particular example of a threat to systemic resilience. Technological diversification and the development of material recovery technologies are possible solutions, though material recovery in the case of infrastructure is likely to require significant state intervention owing to its scale, long timeframe, and significant levels of uncertainty.

Conclusion and next steps

The work on uncertainty and systemacity in this report needs to be continued. Additional future challenges for infrastructure evaluation include better identifying and measuring non-marginal effects; incorporating endogenous preferences into analysis and policy-making; better understanding the political economy of infrastructure evaluation and provision; and confronting the implementability problems that afflict some of the more sophisticated tools discussed in the rest of the report. Progress in these areas will require a more rigorous understanding of the social dimensions of infrastructure provision and how they interact with physical infrastructure systems. The systems of provision approach drawn from political economy has the potential to progress our understanding here. The systems of provision approach takes as its units of analysis the concrete and historically – and socially-specific chains of agents and activities that underpin the provision of particular commodities. Its outlook is therefore fundamentally systemic and social, well-equipped to address the political economy of infrastructure provision, endogenous preferences, and the multiple dimensions of value. However, the application of the systems of provision approach to infrastructure is still in its infancy, and it remains open to what extent it can be developed in to be an implementable method for project appraisal.

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Introduction

Andrew Brown and Mary Robertson
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For reasons that will be made plain in this report, the development of a range of approaches to the 'economic evaluation' of systems of infrastructure is a crucial task. It is ultimately economists who set the terms of debate regarding UK infrastructure and, indeed, it is often economists who are implicated by those who claim that there has been a deterioration in UK infrastructure over many decades. What is needed are new developments in standard and non-standard theories, methods and techniques of economic valuation, undertaken not in the splendid isolation of the mainstream economics discipline but in conjunction with the best minds of all relevant discipines, not only economics but also engineering and enviromental science. It is to meet this need, amongst others, that the iBUILD ['Infrastrucure BUsiness models, valuation and Innovation for Local Delivery'] research project was set up combining the expertise of all these disciplines. The iBuild project (introduced at the end of this report) seeks to address underinvestment in the UK's ageing infrastructure in the context of the growing pressures and challenges of a modern economy.

The project's working definition of infrastructure as "the system of systems that underpins our social, economic and environmental well-being" focuses on the kinds of goods and services provided by infrastructure, and on the structures and systems that underpin their provision. Infrastructure is identified as those systems or networks that provide goods and services that are in some sense basic or fundamental; that is, they are necessary for economic activity to take place and for people to participate in society.[1] Such a definition carries an awareness of the role that infrastructure plays in ensuring our social and environmental well-being, as well as in facilitating economic growth. The social, environmental, and economic importance of infrastructure makes it a key target for public investment. This, in combination with the need to demonstrate good value in the use of public money, creates the need for reliable tools and methods for the valuation and appraisal of infrastructure projects. However, infrastructure possesses a number of characteristics that can make such valuation and appraisal difficult. This report is an attempt to grapple with those characteristics. It is the first fruit of the ongoing research on the economics of infrastructure by iBUILD researchers and collaborating researchers predominantly at the University of Leeds.

Chapter one, on the economics of infrastructure, argues that economists have tended to subsume the peculiar characteristics of infrastructure into a more general literature on market failures. The first half of the chapter looks at standard market failures in economics, including externalities, public goods, and natural monopolies. It shows how such market failures apply to infrastructure – and therefore justify state intervention in infrastructure provision – but also points out problems for valuation and appraisal of this state-intervention. The second half of the chapter argues these problems are exacerbated in the case of infrastructure by the presence of additional characteristics that feature less prominently in the market failure literature but are important for understanding infrastructure. These include uncertainty, infrastructure's systemic character, the possibility of non-marginal effects, and endogenous preferences. It is suggested that non-standard techniques have the potential to extend our understanding of these features of infrastructure.

The remaining chapters differ in their level of generality and style of approach, ranging, for example, from the theoretical survey of techniques for dealing with uncertainty in chapter three to the use of case studies to investigate applications of the real options approach in chapter four. This variety notwithstanding, the chapters can be viewed holistically as a theoretical and empirical development of concepts, approaches and methods – both standard and non-standard – that engage with some of the more challenging characteristics of infrastructure from the point of view of valuation and appraisal, with a particular focus on systemacity and uncertainty.

Taking the specific and important example of transport infrastructure, chapter two surveys existing attempts to value systemic resilience, which is understood as insurance against low probability events that can have severe consequences. The chapter engages with a number of characteristics of infrastructure through the prism of systemic resilience. Transport is viewed systemically, with a focus on system-wide adjustment across different forms of transport. The severe consequences associated with extreme events are assumed to include non-marginal effects. Consequently, uncertainty is evident not only in the likelihood of the event occurring, but also with respect to estimates of valuations of such factors as travel time and safety. In the studies surveyed, these estimates tend to be taken from studies carried out under 'normal' conditions, owing, not least, to the paucity of data about rare, extreme events.

The chapter finds that, although consumers place a high value on resilience, interventions aimed at ensuring it are not necessarily value for money, given the low probability of extreme events occurring. However, they note that these results may be skewed by the application of marginal valuations to non-marginal changes and call for further qualitative and quantitative research into the impact of non-marginal changes on valuations.

Chapter three focuses on decision-making under uncertainty, providing an overview of the ways in which differing degrees of uncertainty can be dealt with within project appraisal. Uncertainty is recognised to be a particular problem in the valuation of infrastructure because infrastructure tends to have a long life span. One important claim of the chapter is that, where uncertainty and the potential for acquiring new information are both relatively high, a shift away from "one-shot" risk analyses towards more iterative approaches will often be beneficial. Iterative approaches reframe the decision by modelling risk and appraisal dynamically, staggering decision-making over time. Real options analysis is highlighted as one such example of iterative risk analysis, and the circumstances in which it is applicable considered. A second key claim of the chapter is that probabilistic techniques can be useful in the presence of uncertainty about data inputs. A range of such probabilistic techniques are considered, with examples of real-world applications given of Bayesian methods, fuzzy logic, and uncertainty tables, among others.

Chapters four and five develop the discussion of iterative decision-making within the realm of sustainable energy provision. They focus on passive provision and real options as two useful variants of iterative decision-making, drawing out their similarities and differences and stressing the role of active investment in knowledge acquisition in the latter. Specific applications of passive provision and real options to smart grids (chapter four) and heat networks (chapter five) are explored, with a number of specific case studies cited. These demonstrate the strengths of passive provision and the real options approach as ways of dealing with uncertainty, particularly in relation to new technologies where there are significant benefits to flexibility and scope for investment in learning. However, they also highlight the many institutional and regulatory challenges to implementation.

These institutional and regulatory barriers are shown to be intensified by the systemic quality of the infrastructure under consideration. For example, the chapters argue that beneficial shifts to new technologies may not occur because regulation has tended to incentivise incremental rather than systemic change. Another problem is the absence of a central coordinating actor capable of aggregating the disperate interests and actions of multiple relevant agents. The chapters thus highlight the institutional imperatives arising from a systems perspective; namely, the need for institutional actors to identify, consider and act on interdpendencies and to coordinate different decision-makers. The local state is suggested as an actor with the potential to play such a role, though it is recognised that the use of iterative decision-making in infrastructure valuation requires enduring political commitment from the actors involved.

The political economy of infrastructure is brought out even more strongly in the final chapter on critical materials and systemic resilience. This chapter is concerned with instances in which the roll-out of low-carbon technology required by policy is conditional on materials that are critical in the sense that: demand for them is high in other sectors; they are produced only as a by-product of other processes; they are sourced from a limited number of jurisdictions (making them prone to use as a geopolitical tool); their extraction is subject to rapidly changing legislation intended to reduce environmental impacts; and they are difficult to substitute. Dependence on such materials creates economic, geopolitical, and environmental risks, which, that chapter argues, should be factored in to infrastructure appraisal. In essence, it is advocating consideration of political as well as physical interdependencies, and that both be given a broader scope that they are currently. Dependence on critical materials is a particular example of a threat to systemic resilience, which was considered in more general terms in chapter two. The chapter advocates technological diversification and the development of material recovery technologies as possible solutions, noting that material recovery in the case of infrastructure is likely to require significant state intervention owing to its scale, long timeframe, and significant levels of uncertainty.

In combination, the chapters of this report contain important lessons from the frontier of research into systemacity and uncertainty in relation to infrastructure evaluation and appraisal. While the chapters derive much of their strength from their willingness to uncover the specificities of particular issues and examples, some general lessons can be drawn. These include:

- The potential for iterative methods to improve decision-making under uncertainty;
- The need to incorporate wide-reaching and multidimensional interdependencies into appraisal;
- That institutional and regulatory challenges are likely to confront any attempt to implement reformed methods of valuation and appraisal
- That seemingly simple technological decisions may be inextricably linked with political and environmental considerations

Notwithstanding these important insights, it is clear that significant challenges remain. The system-wide, long-run character of infrastructure signifies the importance of non-marginal changes, which remain difficult to address, particularly for standard economic theory (which is 'marginalist' in its essence). Another deep problem remains that of preference endogeneity. The probabilistic methods discussed in chapter three are not only sometimes complex to implement, they also generally represent an attempt at managing rather than addressing information that is characterised by fundamental uncertainty as opposed to calculable risk; an adequate way of dealing with more fundamental uncertainty, without collapse to spurious quantification, continues to be a pressing issue in decision theory. The last three chapters rightly introduce a range of political and institutional issues, and demonstrate that valuation and provision of infrastructure are in practice inseparable. But a deeper understanding of the institutional challenges to implementing improved valuation techniques will raise issues of vested interests, power etc. the analysis of which must be rooted in political economy.

Each of these challenges hint at important themes for future research. We use the concluding chapter of this report to suggest that the systems of provision approach promises to play an important role in progressing our understanding in a number of these areas. Endogenous preferences, in particular, were the original raison d'etre of the systems of provision approach, while its view of provision as the outcome of settlements among contesting agents brought together in a unique and integral chain of provision has the potential to shed significant light on the political economy of infrastructure provision and open the door to more rigorously grounded and multidimensional valuation techniques.

Footnotes

[1]What goods and services are considered 'essential' is subject to historical determination. For example, whereas broadband was a luxury good twenty years ago, it has arguably since become a necessary condition for participation in economy and society.

Chapter 1:

The Economics of Infrastructure

Chapter 1: The Economics of Infrastructure

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Introduction

Standard economics theorises the production and distribution of a good through profit-maximising firms and rational, utility-maximising consumers interacting in a perfectly competitive market.[1] A competitive market populated by optimising agents will allocate factors of production and consumption in such a way that their marginal utilities are equal, thus maximising total social welfare.[2] As economists interested in the peculiarities of infrastructure point out, however, the characteristics of infrastructure make it prone to violating one or more of the assumptions required to set this theoretical framework in motion (see, for example, Helm 2009; 2013). Indeed, infrastructure is archetypal of the literature on market failure, which is concerned with cases in which the price mechanism fails to fully capture the costs and/or benefits of economic activity. In such cases, distribution via the market will fail to achieve a socially optimal allocation of resources, providing grounds for state intervention to shift resource allocation to its socially optimal level. As clearly outlined in the Green Book, state intervention must be subject to a rigorous appraisal. However, the high incidence of market failure associated with infrastructure makes such appraisal particularly challenging.

This chapter begins, in the next section, with a critical discussion of three standard market failures that are commonly associated with infrastructure – externalities, public goods, and natural monopoly. In section three we expand the critique with a discussion of additional characteristics that, it is argued, are crucial features of infrastructure provision, but less frequently dealt with within the market failure literature. These include uncertainty, the systemic character of infrastructure, its potential to have non-marginal effects, and the possibility of endogenous preferences. The remaining chapters of this report consist of a range of attempts to grapple with these more challenging characteristics of infrastructure from different angles, at different levels of generality, developing both standard and non-standard economic theories and methods.

Market failures characteristic of infrastructure: standard examples

Following the first and second theorems of welfare economics, market provision is assumed to be socially optimal and taken as the default form of provision, unless specific reasons arise that may make provision by the market less than socially optimal. Only in this case is state intervention countenanced. These reasons are instances of market failures, of which externalities, public goods, and natural monopolies are the most standard examples. Infrastructure tends to display a high degree and frequency of the characteristics of all three.

Externalities

An externality occurs when production and/or consumption by an agent or group of agents has an impact on an unrelated third party. The presence of externalities implies that the price mechanism does not fully capture the costs and/or benefits of production and consumption and that the private and socially optimal levels of provision diverge. Hence externalities are an instance of market failure and often used as a theoretical justification for state intervention.

Reflecting the fact that the goods and services provided by infrastructure enter into the costs of every business and household, infrastructure is thought to be rife with externalities (Helm 2013). These may be both positive (for example, the public health benefits of sewerage and water provision; the productivity benefits of a good public transport system) and negative (for example, land/air/water/noise pollution), though for infrastructure positive externalities are generally thought to be the greater concern. This is especially so within literature on development, where infrastructure is often found to have positive spillover effects for the development of manufacturing and other industries (see, for example, Hulten et al 2006). But the citation of positive externalities as a reason for underinvestment in infrastructure also occurs well beyond matters of development (see, for example, Aghion et al 2014).[4]

The theory of externalities, combined with the attribution of net positive externalities to infrastructure suggests that, left to its own devices, the market will underinvest in infrastructure. It therefore creates scope for state intervention in infrastructure provision though there are problems of definition, identification and measurement.

Regarding definition, a major problem is whether to include pecuniary externalities (that is, cases in which the activities of an agent affect the prices and therefore budget constraint facing the third party) or to restrict the definition of an extenality to cases in which the activity of an agent affects the production or utility functions of the third party directly ('technological', 'direct', or 'non-pecuniary' externalities). It is often argued that only non-pecuniary externalities are genuine externalities because only non-pecuniary externalities lead the privately optimal provision to diverge from the socially optimal one. Pecuniary externalities, by changing prices, change the distribution of welfare but, because all costs and benefits are incorporated into prices, the final allocation continues to be pareto optimal.[5] However, a significant number of the externalities associated with infrastructure are pecuniary ones – the cheapening of transport, health, or energy costs, for example.[6] The importance of pecuniary externalities for infrastructure suggests a need to move beyond a partial equilibrium framework in valuing infrastructure (see section on 'non-marginal effects below').

Complications with the identification of externalities arise because infrastructure is often a derived demand (that is, demand for transport, electricity etc exists in virtue of existence of other markets). As Laird et al (2005) point out,[7] infrastructure's 'linkages back to the labour and land markets and forward to the goods and services markets are highly relevant to … pricing and investment policies' (Laird et al 2005 p538). In other words, a large number of diverse primary markets need to be considered when identifying the externalities associated with infrastructure and this greatly complicates the analysis directing pricing and investment policies.

There are two major problems concerning the measurement of externalities. One is knowing what is the baseline against which externalities are measured. The theory takes the 'pure' market case as the benchmark, and asks whether state intervention will improve aggregate welfare or not. But the reality will almost always be more messy, with some form of intervention having occurred already. This raises the question of whether one should take the counterfactual of no further intervention or of an alternative form of provision as the basis for comparison.

The other key measurement problem is that some externalities lend themselves more readily to monetisation than others. For example, plausible estimates can be made of the costs of time spent travelling to work using wage and productivity data. But it is much harder to estimate the monetary value of environmental or cultural preservation.[8] While consideration of the qualitative effects of investment are obligatory under current government guidance, it is hard to avoid the biases arising from the more ready monetisation of some effects compared to others, and these biases are likely to be transferred to levels of investment.

These issues of definition, identification, and measurement have to be thought through for each particular type of infrastructure in each particular context, which means that the seemingly simple concept of externalities can have a large burden of data and analysis and yet end up providing quite limited practical guidance.

Public goods

Items of infrastructure are often also thought to have the characteristics of a public good, another example of a market failure. Public goods are goods whose use is non-rival and non-excludable. Non-rival means that the marginal cost per additional user is very low so that it is socially and economically optimal for all firms and households that benefit from using the infrastructure to do so. Non-excludable means it is difficult to charge for use of the good, making the good prone to underprovision due to free-riding.[9] Together, these two properties mean that the private level of provision will tend to be below the socially optimal one, again in principle creating scope for state intervention.

In practice, however, state provision of public goods is complicated by the problem of valuation: how is the state to discern the optimal level of provision given the price mechanism's failure to do so? Hedonic pricing seeks to use data on prices of a marketed good to estimate the value of its non-marketable components. As such, it attempts to capture revealed preferences, though its results are dependent on model specification and data availability. An alternative, the stated preference or survey approach, asks consumers about their preferences directly, rather than relying on a surrogate. This approach has to confront problems of strategic bias or unreliability due to the hypothetical nature of the data (Brookshire et al 1982). As noted above, these valuation problems have to be thought through for each particular type of infrastructure in each particular context. The important case of transport infrastructure is explored in more depth in chapter two.

In a seminal article in 1965, Buchanan raised a further problem by arguing that pure public goods are rare (Buchanan 1965). This is because both non-rivalry and non-excludability are a matter of degree rather than of kind, with non-excludability depending on the level of transaction costs arising from charging for access to the good or service and non-rivalry depending on the point at which the infrastructure becomes congested. In other words, it is usually possible to think of ways to exclude people, the question is when transaction costs become prohibitively high. Similarly, goods, may be non-rival until they become congested, at which point marginal costs increase very rapidly with additional users. Public and private goods are therefore better thought of as lying on opposite ends of a spectrum, than as discrete types, with the goods and services provided by infrastructure lying somewhere in between, though closer to the 'public' end of the spectrum than other consumer goods. Buchanan termed those goods with a degree of excludability and congestibility club goods. By refocussing economists' attention on the optimal level of provision given a certain degree of excludability and congestibility, and by suggesting that there is an optimal level of excludability, the theory of club goods has helped to make the problem of public goods more tractable.

Natural Monopolies

Perhaps the theory most closely associated with infrastructure, and the closest that economics gets to having a distinct theory of infrastructure, is the theory of natural monopolies. Natural monopolies arise in industries with large sunk costs and increasing returns to scale, of which the most common examples given are public utilities or infrastructure such as water, electricity, or gas. Because entry under such production conditions requires the replication of sizeable fixed costs, it is both difficult and inefficient, hence the industry will tend towards a monopolistic industry structure. The theory of monopoly finds that monopoly prices are inefficient, which is in turn used to justify the regulation of the pricing practices of natural monopolies.

However, the regulatory solution to natural monopolies runs into a number of probems. First, how can the state/regulator discover the providers' costs and therefore determine the optimal level of provision? Second, assuming that information about costs can be obtained, regulators run into a time-inconsistency problem (see, for example, Helm 2009). The problem arises because in a natural monopoly industry with large sunk costs, average cost will exceed marginal cost. In order for an investor to recoup their (large, sunk) investment capital, they will need to set the price for usage of the item of infrastructure equal to their average costs; but once an item of infrastructure has been produced, it is more efficient to set price equal to marginal cost. The time-inconsistency problem refers to the incentive that the regulator has to promise to allow the provider to charge price equal to average cost before the investment occurs, but to force price down to marginal cost afterwards. The onus is on regulatory and contract design to reassure investors that costs will be recouped. Failure to do so will increase the discount rate used by investors and, with it, the cost of capital.

Finally, the theory of natural monopolies is, like the other market failures discussed so far, concerned with (deviations from) static, allocative efficiency – the efficient 'solution' to a natural monopoly requires that prices be set equal to average cost. But as a number of economists have pointed out, this pays no heed to the potential technological or productive inefficiencies that may also arise from a monopolistic industry structure.

Market failures that cause deeper theoretical difficulties in economics

The market failures discussed in the previous section all point to reasons why infrastructure provision may deviate from its social optimal, understood in the static, allocative sense characteristic of standard market theory. In this section, we look at additional characteristics of infrastructure, which also give rise to problems with investment in and valuation of infrastructure, but which are less readily incorporated into the static, allocative framework of standard market theory. These include uncertainty, its systemic character, the possibility of non-marginal effects, and endogenous preferences.

Uncertainty

Uncertainty is a feature of any economic situation, but is of particular salience for infrastructure because of the long duration of most infrastructure usage. This long life-span has repercussions for investment in infrastructure because it lengthens the period over which costs need to be recouped, thus intensifying the time-inconsistency problem. It also makes the valuation of the infrastructure asset fundamentally uncertain. One aspect of this is that variations in inflation and interest rates over the lifetime of the infrastructure mean that infrastructure's value 20 years into the future may not follow a well defined probability distribution. Another important aspect concerns maintenance costs, which are uncertain because under – or over-estimation of usage rates may lead to retarded or accelerated degradation respectively. This is exacerbated by a tendency for investors to prioritise recovery of short-term profit over long-term maintenance spend, enhancing short-term returns but further accelerating the degradation of the asset and thus limiting (or even negating) future returns (the whole-life cost problem).

The long duration of infrastructure usage also puts it at high risk of technological redundancy, that is, of becoming technologically out-dated or even obsolete as a result of technological developments made during the lifetime of its use. Less extreme but associated issues are those of technological lock-in and path-dependency, which both reflect the need to make decisions about technology now, when the future content and direction of technological progress is unknown.

Uncertainty is another example of market failure because it implies the failure of the assumption of perfect information in standard market theory. Economists have developed a number of techniques for dealing with uncertainty understood as calcuable risk or as costly information, however dealing with 'Knightian', 'deep' or 'fundamental' uncertainty, where it may be impossible to anticipate or quantify the likelihood of future events, has proved a more formidable challenge. Chapter three illustrates this with a discussion of a range of techniques for decision making in conditions of uncertainty, with an emphasis on the variety of forms taken by the latter. Chapters three and four suggest that the 'real options' approach can improve infrastruture valuation, by accounting for the value of creating real options that will increase flexibility and adapatability of a system in the face of future uncertainty. From a slightly different angle, evolutionary economics has developed a theory of knowledge as 'tacit and social' (Foss and Langlois 1997), being embodied in firm-specific routines and structures. This focuses attention on the way in which technology and knowledge develops through incremental learning processes within institutions in the context of wider systems.

System of systems

Another feature of infrastructure that is arguably more suited to non-standard techniques is the network or system-based character of infrastructure. For infrastructure is more accurately perceived as a set of (overlapping and interacting) systems than as a series of discrete projects or items. For example, an electricity generation or water provision extension should be assessed from the vantage point of its operation within the overall electricity or water network both of which will in turn interact with each other directly (e.g. electricity is required to pump water, and water is required to cool power stations) and indirectly with other infrastructure networks via the spread and location of population hubs. In short, infrastructure must be seen as a sub-system (or system of systems) that primarily serves the wider socioeconomic system as a whole, rather than any one private actor.

One implication is that infrastructure investment ideally requires system-level rather than project-based appraisal, which suggests the inadequacy, at least in some cases, of the kind of partial-equilibrium analysis in which both cost benefit analysis and the standard market failure literature is rooted. Where full system-level appraisal is impractible or too costly then the system-based character of infrastructure suggests that assessment should at least seek to account for interdependencies across different infrastructure sectors and actors, avoiding a 'silo-based' approach to valuation. Again, evolutionary economics, with its view of institutions as depositories of knowledge in the form of habits and routines may offer potential for grasping the systemic characteristics of infrastructure. Fruitful directions for research may also lie in the development of concepts such as systemic resilience and techniques of systems and complexity modelling, explaining the co-evolution of institutions within wider systems (see chapters two, four and five).

Non-marginal effects

Microeconomic partial equilibrium models assume that the economy's growth path is exogenous, but the systemic character of infrastructure means that it is often better thought of as a bridge between micro and macro. This in turn makes infrastructure liable to influence the level of growth of the economy as well as allocation within it. In other words, the economic impact of infrastructure may often be non-marginal. The presence and extent of such wider economic effects will vary across infrastructure projects and networks. One example is agglomeration effects, that is, when infrastructure permits the clustering of economic activities, which in turn gives rise to multiple efficiences.[10] Another example arises in the area of climate change mitigation, where growth paths may differ dramatically depending on the degree to which climate change is addressed. The possibility of wider economic effects suggests that our infrastructure appraisal should be guided by the pursuit of dynamic rather than – or, at least, as well as – static efficiency. Some of the challenges that non-marginal effects present for established valuation techniques are discussed in the next chapter and subsequent chapters address implicitly or explicitly this issue in different respective ways.

Endogenous preferences

A final characteristic of infrastructure, and one that presents a major challenge for standard tools, is the potential for preferences to be endogenous. Standard economic theory, as well as standard valuation techniques such as stated or revealed preferences, all assume that preferences are fixed and exogenous. But over the life-cycle of infrastructure it is likely that preferences, norms, and cultures of consumption are shaped and reshaped by what is provided. To give a (crude) example, good public transport provision may erode a culture of dependency on cars but eventually lead to congestion on train networks; expanding highway provision invariably attracts car traffic over and beyond that which it was design to carry.

The 'systems of provision' approach, originating in consumption studies, and rooted in non-standard economic theory, was designed inter alia to address endogenous preferences. The approach is also conducive to many of the other features of infrastructure described above but has only very recently begun to be explicitly developed for the purposes of infrastructure evaluation, for example featuring prominently within the iBuild research programme. In the concluding section of the report, after summarising and reflecting on the developments in the economics of infrastructure as represented in the preceding chapters, we introduce the salient features of the systems of provision approach as a useful basis for future discussion and debate, and look forward to exciting new developments in the economics of infrastructure.

Conclusion

The economics of infrastructure have tended to be subsumed within the economics of market failure. The system-based, long-run character of infrastructure, involving myriad interdependencies across the economy and over time, means that infrastructure provision displays a high degree of market failure, in both incidence and extent, so there is clear scope for state intervention in its provision. However, these same market failures create a number of challenges for the valuation of infrastructure and for the assessment of state intervention. Particularly important here are: identifying and estimating the costs and benefits of infrastructure investment especially where those costs and benefits are non-monetary, dynamic, non-marginal, or involve endogenous preferences; developing system-level assessment; and dealing with uncertainty. We have suggested that, in addition to the careful development of standard approaches and techniques, the introduction of non-standard approaches and techniques may be of use in dealing with these challenges.

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Footnotes

[1] What goods and services are considered 'essential' are subject to historical determination. For example, whereas broadband was a luxury good twenty years ago, it has arguably since become a necessary condition for participation in the economy and society.

[2] A perfectly competitive market is defined as one with many sellers and buyers such that all are price-takers; freedom of entry and exit (implying no sunk costs); perfect information; homogenous goods (i.e. goods are perfect substitutes); and perfectly mobile factors of production.

[3] The point at which the marginal utilities of all factors is equalised represents a stable, general equilibrium. Total social welfare is maximised because it is Pareto efficient, meaning that it is not possible to make anyone better off without making someone else worse off. A range of distributional outcomes satisfy this criterion of Pareto optimality; which is reached via the market will depend on the initial distribution of resources. These findings respectively constitute the 1st and 2nd fundamental theorems of welfare economics.

[4] http://www.lse.ac.uk/researchAndExpertise/units/growthCommission/documents/pdf/LSEGC-Report.pdf

[5] Consider the example of an influx of middle class homeowners into an area. This is a pecuniary externality because it drives up house prices in the area and lowers the welfare of hosueholds who want to move to the area. But the price change is welfare neutral in the aggregate because it merely distributes income away from buyers and towards sellers. Contrast this with a non-pecuniary externality, such as pollution. In this case, the loser – those harmed by pollution – have no reciprocal winner and the aggregate net welfare effect is negative.

[6] Which may occur via economies of scale, pooling of risks and homogenisation of markets through 'national grid' type networks.

[7] Laird et al are discussing transport in particular, but their point also applies to other types of infrastructure.

[8] See Laird et al on estimating heritage values. See also Brown and Veronese Passarella (2014).

[9] The seminal paper on this is Samuelson (1954).

[10] To give an interesting example of this, the 'Just In Time' doctrine developed mainly by Toyota in the 1950s onwards is facilitated by clustering of parts suppliers and manufacturers which in turn is enabled by infrastructure provision. The failure of many JIT implementations (especially in the UK) can at least partly be traced to a lack of clustering owing to path dependencies in infrastructure provision.

Chapter 2:

Valuing systemic transport resilience: methods and evidence

Chapter 2
Valuing systemic transport resilience: methods and evidence[1]

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Introduction

Resilience represents insurance for part or parts of the transport system which are vulnerable to external risks. These risks are generally of low probability but the key feature is that they can result in major consequences (Anderson et al, 2011; DfT et al, 2011; Mackie, 2010). The level of resilience will dictate the ability of the system to function following damage, withstand damage or the speed with which the pre-impact state can be restored (Anderson et al, 2011).

Given the above definition of resilience, the objectives of this document are to:

- Identify the principal sources of lack of resilience in the transport sector;
- Provide a selective review of the costs of infrastructure vulnerability and willingness to pay for improved resilience;
- Review research approaches for eliciting such values where they do not currently exist.

The challenges to transport sector resilience fall in the areas of climate and weather events, system security against terrorism and theft, scarce raw materials used in the supply of transport and industrial action.

Most transport modelling and appraisal work is focussed on the benefits of improving the system under normal operating conditions. It is quite reasonable to concentrate on the body of the distribution of performance and to look for marginal valuations of improving that performance. However, events such as the aftermath of the rail disaster at Hatfield which effectively doubled journey times on the East Coast Main Line for several months in 2001 suggest that attention also needs to be paid to the tail of the distribution of outcomes. Relevant to all work of this kind, both engineering and economic inputs are required. What is the reduction in risk of catastrophic flooding at Dawlish as a result of increasing the height of the sea wall? Then what is the social value of the reduction in the risk? This paper concentrates on the second while accepting that building the engineering model is very demanding.

Resilience measures have some special features. Typically they seek to prevent, or reduce the risk of non-marginal changes in accessibility to infrastructure users. This raises questions about whether marginal values, for example of travel time, are applicable directly to non-marginal changes. Secondly, disruptive events have a range of effects which need to be considered: the immediate term effects on people already in transit through to the medium term effects after the transport supply system has had a chance to adjust and temporary working arrangements are in place. Finally, there is the demanding question of the impact on regional and local economies of the direct impact of lack of resilience and the effects on confidence.

Our appreciation is that there is a gap here and this paper is an initial review with the aim of stimulating discussion concerning the economic benefits of resilience and particularly their estimation. That appreciation seems to be shared by the authors of the recent Transport Resilience Review who state:

> *"The true economic cost of disruption is not consistently captured and factored into spending decisions, so [we] recommend that the DfT reviews current economic appraisal guidance and develops robust systems to ensure that the full cost of disruption and recovery are captured in industry appraisals."*
>
> **(DfT 2014, Exec Summary para 49).**

It is useful to set out the scope of the paper and a framework to simplify the previous discussion and set out the values being sought out in a literature review of resilience. Categories of studies can be identified using the framework which includes impacts of transport resilience on transport costs, valuation and also cost-benefit analysis.

Following the framework, we discuss the economic parameters relevant to resilience. These are essentially the demand impacts, which have both financial and consumer wellbeing consequences and, independent of any behavioural change, the valuation element relating to individuals' willingness to pay to improve resilience or avoid the consequences of its failure.

Five methods have been identified as potentially being able to appraise resilience related issues. These are stated preference, revealed preference, hedonic pricing, the travel cost method and cost-effectiveness. Each method has advantages and disadvantages and is suitable in different circumstances. The literature review will then present the evidence that we have identified. The structure of the note is therefore as follows:

- Scope of analysis
- Framework of resilience
- The economic parameters
- Estimation methods
- Cost studies
- Valuation studies
- Cost-benefit analysis studies
- Summary

It is also worth providing a rationale behind undertaking the study before proceeding to the main body of analysis. Firstly, it is worthwhile examining whether disruption due to extreme events has a value to the individual, business community or to a transport provider. Is reducing the tail end of the distribution of consequences from disruption of a benefit to these parties? If there is some evidence of this then it offers the opportunity to explore the values under circumstances where it is not yet understood. It may be of great importance but not yet addressed adequately. If there is not any evidence or limited evidence then the opportunity arises from a different perspective as whether this value or cost exists can then be explored and pursued further. The better resilience and disruption is understood and with extreme events potentially becoming more severe due to climate change and evolving security threats, then with greater effectiveness can the transport system be delivered in terms of offering value for money and providing the requirements of a modern transport system which consumers, businesses and transport providers both require and desire.

Scope of Analysis

The scope of the paper covers two separate elements of focus. Methodological techniques to value resilience (Estimation Methods section) and evidence on the valuation of resilience (Cost Studies, Valuation Studies, Cost-benefit Analysis Studies) are examined. The methodological techniques section provides an overview of what the techniques entail, their relative merits, whether they have been identified in the literature review.

Evidence from the resilience literature is also examined in relation to the framework of resilience provided in the next section. A summary of the key valuations identified and the methodology used is offered. It is intended in the review to demonstrate a variety of both academic and industry literature which covers categories of risk discussed in the introduction. The focus is on studies which present monetary valuations or conversions into monetary impacts of resilience (e.g. converting time into monetary values using values of time). All values should be assumed to be in the prices of the associated year alongside the value or in the reference unless otherwise stated.

A summary will be offered which discusses the areas in which the literature appears rich in knowledge and where there is a scarcity of evidence. It is important to acknowledge that the identification of an area of resilience in the paper does not necessarily mean that literature on the valuation of this area is in existence. This in itself is of importance against the objectives.

Framework of Resilience

In defining resilience as insurance against external risks there is an implication that there are two sides to resilience. On the one side, there is an intervention to insure against disruption and on the other side a failure or choice not to insure against disruption. Therefore there is a trade-off between investing in resilience and tolerating disruption (Anderson et al, 2011; Koetse and Rietveld, 2009; Potoglou et al, 2009).

Studies reviewed highlight that there are some key impacts of resilience on which a value could be identified for. These impacts include the direct costs of replacing infrastructure, ongoing costs/revenues, travel time and reliability, productivity or economic output, safety and accidents, and civil liberties and privacy. These impacts are summarised in a framework to analyse the literature as presented in Table 1:

Table 1: Framework of evaluation for resilience literature

Impact	Resilience	Disruption
Strategy	Mitigation Willingness to pay	Adaptation Willingness to adapt
Duration	Short run Long run	Short run Long run
Time	Reduce delays	Acceptance of delays
Cost	Cost of prevention/ safeguarding revenue	Cost of recovery/ loss of revenue
Safety	Reduce risk of accidents	Acceptance of risk of accidents
Wider Economic Impacts	Reduce impact on output and productivity	Acceptance of impact on output and productivity
Privacy & Civil Liberties	Possible intrusion	No intrusion

This framework will be used to examine the resilience literature by providing a reference against which the evidence can be examined in content and coverage. It promotes a greater understanding of the areas in which the literature is vast and scarce in knowledge.

The Economic Parameters

There are two key economic parameters relevant to the consequences of a lack of resilience in the transport sector, taking the latter to involve non-marginal changes.

Firstly, there will be a demand impact. Those adversely impacted may decide not to travel, even if mitigation measures have been put in place. Or they made modify their behaviour by travelling less often or by different modes or to different destinations. The welfare effects can be established as the appropriate areas under demand curves, provide the full set of behavioural responses can be identified.

Secondly, there is a valuation element, represented in terms of individuals' willingness to pay (WTP). This has two components. One is a WTP to avoid an event occurring. This is made up of two components: the probability that an adverse event occurs and the consequences of that event. The valuation will represent possibly a myriad of different consequences, such as short term inconvenience, behavioural changes and disruptions to maintained travel patterns. Given that the probability of occurrence is low, this tends to make estimation more challenging. We term this valuation the 'expected total valuation'. The second is that, given an event occurs, a valuation can be obtained of the specific consequence, such as significantly longer travel times. This is little removed from the conventional world of transport appraisal, except that the consequences are of an order of magnitude larger. We term this the 'consequence valuation'.

We can also bring into play other factors, such as option values given the risk element involved here, and valuations based on other than purely personal preferences. These will tend to be second order effects and hence we restrict discussion to WTP values related directly to user benefits.

Estimation Methods

Five methods which have been used to value 'non-market' goods merit consideration here. These are:

- stated preference and its variants;
- revealed preference and its variants;
- hedonic pricing;
- travel cost;
- cost-effectiveness.

Each technique is discussed in turn with an overview of how the method captures valuations, the relative advantages and disadvantages of each, an examination of whether the method has been used to value transport resilience and a short examination of how it could be used.

The estimation methods cover to varying degrees the various economic parameters discussed above: behavioural response, the expected total valuation and the consequence valuation.

Stated Preference

Stated preference (SP) or stated choice (SC) methods investigate the decisions which respondents make to a set of hypothetical options based around products or services of interest (Pearce and Turner, 1990; Pearce et al, 1989; Potoglou et al, 2009; Robinson et al, 2010; Veisten et al, 2011). Typically, respondents are offered two, but sometimes more, options characterised by key explanatory variables, generally up to five but fewer might be sufficient and more have been attempted although then the increased cognitive effort might reduce the quality of data obtained. A series of choices are offered, with statistical criteria used in determining how the attributes vary across each choice. The choices made, or sometimes the rankings given, indicate the relative importance attached to each variable.

Thus, in a typical transport example, we might offer choices between car and train for a commuting journey. Car might be represented by fuel cost, parking charge and travel time, with train characterised by fare, access and egress time, service frequency and travel time. Such techniques have been extensively used in transport, both for forecasting behaviour and estimating valuations.

The choices which respondents provide enable their relative preferences for attributes to be determined and valued in terms of money or time for example (Potoglou et al, 2009; Robinson et al, 2010). Monetary values allow willingness to pay to be identified and time enables values of time to be calculated.

The technique can be summarised as a respondent (*n*) choosing the alternative (*j*) which maximises their utility (*U*) (Masiero and Maggi, 2012; Veisten et al, 2011):

$$U_{nj} = \beta' X_{nj} + \varepsilon_{nj}$$

$U_{nj} = \beta' X_{nj}$ reflects a systemic aspect of utility and ε_{nj} is an independent and identically distributed random term. The beta term (β) requires estimation, which is most commonly undertaken with a logit model.

Values can be obtained where evidence from actual markets is not possible, which is a key advantage of the technique (Louviere et al, 2000; Pearce and Turner, 1990; Pearce et al, 1989; Potoglou et al, 2009; Robinson et al, 2010). This is a particular strength where characteristics of alternative choices do not exist or are not within the range of consumer's experience. The technique also accounts for there not being an absolute, perfect choice for consumers but instead there are trade-offs influencing their decisions (Potoglou et al, 2009). The study conditions are also easier to control and adjust (Kroes and Sheldon, 1988), it is able to capture use and non-use values (Mayor et al, 2007) and enables multiple observations from a single respondent to be obtained (Kroes and Sheldon, 1988; Robinson et al, 2010).

However, there are also disadvantages including that hypothetical scenarios are used to collect data rather than actual decisions in the market (Adamowicz et al, 1994; Kroes and Sheldon, 1988; Louviere et al, 2000; Pearce and Turner, 1990; Pearce et al, 1989; Potoglou et al, 2009; Robinson et al, 2010; Wardman, 1988). A particular weakness of this is that it cannot be guaranteed that hypothetical choices would be consistent with actual choices a consumer makes in a working market. Bias can also occur or a respondent may misunderstand or find the survey difficult which can lead to unrealistic values. Furthermore, a respondent could choose to offer unrealistic choices or values to discourage or encourage an intervention if they feel strongly about its absence or presence.

A related technique is the direct WTP method, which simply asks respondents how much they would be prepared to pay for an improvement or to avoid a deterioration. SP tends to be preferred because it is easier to make choices than to express a direct WTP and because choices related more closely to real-world behaviour than do WTP questions.

Stated preference techniques have been a commonly used technique identified in the transport resilience literature examined. Studies examined in which the technique has been have focussed on airport security screening (Veisten et al, 2011), containerised maritime transport disruption (Figliozzi and Zhang, 2010), railway station security (Potoglou et al, 2009; Robinson et al, 2010) and road freight disruption (Masiero and Maggi, 2012).

Past studies have demonstrated how stated preference can be used in valuing resilience and therefore this technique is definitely a possibility for use. Experiments in the literature have tended to examine the level of disruption which may be avoided by a resilience intervention and included impacts on travel time or fare paid to determine how much respondents are willing to incur for this avoidance. A similar process could be undertaken for a future resilience study.

Considering the three economic parameters set out above, in principle SP methods can be used in each context.

In the case of behavioural response, the SP exercise can offer the sorts of choices that would confront an individual after some adverse event. The SP responses indicate the respondent's likely reaction to the specific events offered. The key issue though would be conveying in a realistic manner the consequences of the event, allowing the full set of relevant choice responses and in respondents being able to accurately anticipate what they would do in the light of a major upheaval.

In the case of 'expected total valuation', respondents can be offered choices between two options with different probabilities of occurrence and different consequences. To obtain valuations, a monetary numeraire needs to be included. In principle, this is little different to what are now routine SP exercises in the transport area that deal with issues of uncertainty. The challenge here though is that we are dealing with small probabilities of occurrence. Another challenge is in obtaining a suitable numeraire for inclusion in the SP exercise.

An example might be to consider the possibility of a railway line falling into the sea due to coastal erosion. One option might be to do nothing and then there is an associated chance that the railway line will fall into the sea with consequences such as extended journey times due to bus replacements for a given period of time. The other option might be to increase rail fare to provide a sea-wall or else to fund a new line further inland. This might have short term disruptions and costs for certain but the longer term large impact is avoided.

A similar sort of approach might be used in the security area. Respondents have to options regarding airport security. One might be the current position, with a given risk of a security threat and associated levels of time spent passing through security. The other option would involve a lower security risk but more time passing through security. A monetary instrument is only needed in evaluating the best approach insofar as there are different costs of delivery.

Given the challenges involved here, with small probability and appropriate numeraires, it would be essential to do detail exploratory qualitative research prior to design and conduct of the main SP exercise and for thorough piloting to be undertaken.

In the case of the ‘consequence valuation’, SP methods can be used to obtain valuations of the large consequence. Thus if the consequences of introducing tighter security controls at airports mean longer waiting times, an SP exercise can be based around variations in waiting times traded-off against money. There might in this context be a challenge of identifying an appropriate numeraire, although some kind of ‘speedy boarding’ option might be suitable. Similarly, we could estimate the inconvenience effects of a disrupted railway line in terms of the additional time involved. Once valuations are obtained, they can be used to appraise ‘engineering’ based estimates of the likelihood of an event occurring.

If the SP choice context were to be based around housing choice or destination choice, it would have elements of similarity with the hedonic pricing and travel cost methods discussed below.

Revealed Preference

Revealed Preference (RP) methods are based around the behaviours observed to occur in real market places. There are essentially three different RP approaches that could be pursued here:

- Discrete choice analysis
- Demand analysis
- ‘Ex-post’ surveys

The problem with RP is that there are often not the markets in which respondents can express their valuations. So, for example, there are no instances where travellers can trade-off, say, the risk of a security threat against the length of time in security (although the housing market might provide some examples as discussed below).

Revealed reference techniques rely on actual observations of the choices consumers make within working markets in order to identify valuations (Adamowicz et al, 1994; Louviere et al, 2000). Observing the choices consumers make in selecting certain products or services over others with varying attributes allow for preferences to be established (Houthakker, 1950; Kroes and Sheldon, 1988). Logit models are commonly used to extract the values which consumers place on the attributes (Adamowicz et al, 1994).

The basic principle of revealed preference can be illustrated through the consumption of a bundle of goods (x_1,x_2) and (y_1,y_2) at prices (p_1,p_2). It can be inferred that if consumption of a bundle of goods at the given prices is higher than for another bundle then there is greater utility from the more greatly consumed bundle, as presented below (Varian, 2010).

$$p_1x_1+p_2x_2>p_1y_1+p_2y_2$$

Revealed preference techniques have the inherent advantages that they reflect actual choices within a working market (Wardman, 1988). The methods thereby avoid criticisms of unreliability or lack of validity associated with techniques observing hypothetical behaviour (Adamowicz et al, 1994). On the face of it, reliability and validity is greater under revealed preference (Louviere et al, 2000).

However, developing models of behaviour based on actual data is not always possible (Adamowicz et al, 1994). The scenario being investigated may be out of the current range of experiences or possibilities for consumers. Separating the value of attributes may be difficult as well because collinearity may be present (Adamowicz et al, 1994; Kroes and Sheldon, 1988; Louviere et al, 2000). It may also be the case that there is insufficient variation in the data to examine all of the variables of interest and the data needs to be expressed in objective units which generally means the techniques are more suited to the primary variables of travel (i.e. time, cost) than secondary variables (i.e. design, comfort etc.) (Kroes and Sheldon, 1988).

Studies which have sought to examine resilience through revealed preference are rare but have been identified in the review with modelling of the value of adverse weather in the Netherlands drawing upon historical transport survey data (Sabir et al, 2010). It is not felt that the rarity is particularly controversial as the very definition of resilience as an insurance against low probability/ severe consequence external events raises the issue that obtaining data in rare situations will be a challenge.

This last point raises the issue of how a revealed preference study could be attempted in practice and the conditions for study set up and it is recognised it is very difficult. Perhaps the most appropriate method is to conduct interviews with individuals on their responses to historical disruption or use travel diaries. A value may be possible to elicit for attributes based on the modes or routes people choose during disruption owing to a perception of, or actual, greater resilience. However, data collection costs are significant given only one observation is obtained per person and markets are often imperfect. The insurance market might provide a suitable context, but then this relies on their being sufficient observations of individuals purchasing insurance or not in the context of resilience related risks.

An alternative approach to examining RP discrete choices is to analyse how demand changes in response to events. Whilst a drawback is that the analysis can only be done after the fact, its attractions are that it is based upon what people actually do and data collection costs are minor if secondary data exists. Take for example the Dawlish incident, which led to major disruptions to train services (although mitigated by good replacement bus services). It is possible to use routinely collected railway demand data to conduct econometric analysis of the consequences of the event.

A further alternative is, again after the event, to interview those affected to obtain a more detailed understanding of their behavioural response. Data collection costs would not though be trivial.

Hedonic Pricing

Hedonic pricing derives values of attributes through associated or related market transactions to the product or service of study (Johansson, 1991; Pearce and Turner, 1990; Pearce et al, 1989; Tyrväinen, 1997). Traditionally, the approach has been used to value aspects of the environment by using house prices as a proxy. However, the technique has also been drawn upon to value resilience of the human environment to natural events, including flooding, through house prices or insurance premiums (Bin and Landry, 2013; Hallstrom and Smith, 2005). Houses and insurance are not considered to be homogenous products and have a value that is dependent upon a variety of components. It follows that the risk of experiencing a natural event could be reflected in both house prices and insurance premiums and thereby offers a source of willingness to pay.

Regression analysis is required to determine the effect on value which various components have on house prices or insurance premiums (Boardman et al, 2006; Pearce and Turner, 1990; Pearce et al, 1989). A multiplicative functional form is commonly used and is illustrated as the value/price (P) consisting of the estimated coefficient (β) for each explanatory variable (X) and an error term (e^{ε}).

$$P=\beta_0+\beta_1X_i+\beta_2X_2+\beta_3X_3+\beta_4X_4+e^{\varepsilon}$$

The hedonic price r_{X1} of variable 1 is calculable as:

$$r_{X1}=\beta_1\frac{P}{X_1}>0$$

Considering that the method is a form of revealed pricing, the approach has the advantage of being based on market interactions rather than hypothetical data (Tyrväinen, 1997). It is also able to place a value on products or services which are otherwise difficult to value, for example if the price of consumption is zero (Pearce and Turner, 1990; Pearce et al, 1989). Furthermore, issues of omitted self-selection bias are considered to be reduced under hedonic pricing methods (Boardman et al, 2006).

However, the technique excludes the value of consumers not within the valuation proxy. Using a typical example of where hedonic pricing is used, national parks, it may be that consumers of the national park do not live nearby and are outside of the study area. Therefore some consumers are not included within the valuation (Tyrväinen, 1997). Problems of requiring large amounts of data and issues of collinearity and inseparability in the explanatory variables may arise (Pearce and Turner, 1990; Pearce et al, 1989). The analysis may also be complicated if the supply of the proxy adjusts to price changes, particularly when house prices are used (Johansson, 1991). It is also at risk of being biased if components of the price of the proxy are omitted (Pearce and Turner, 1990; Pearce et al, 1989).

Hedonic pricing studies specifically relating to transport resilience have not been identified in the examination of the literature. However, the impact on resilience to natural events more generally to the human environment have been identified (Bin and Landry, 2013; Hallstrom and Smith, 2005). Taking into account these studies and also that it would seem, hypothetically, reasonable for house prices to be reflective of the conditions of the transport network, hedonic pricing might seem an approach that would be possible. It may be feasible to examine the housing market to determine whether there is a value in property prices resulting from access to more resilient, or less disrupted transport networks. The approach though is restricted to the valuation of the expected total value, and insofar as the probabilities of occurrence are low it might well be difficult to isolate any effects. Moreover, house buyers might not be at all aware of resilience issues, even where they exist, and hence even if they had values it would not be possible to detect them. In the absence of identifying very clear contexts where resilience impacts on house prices, this approach does not seem to offer much potential in this context.

Note that this does not mean that discrete choice studies could not be based around the choice of house if that provided a realistic context in which to examine resilience, particularly in SP studies.

Travel Cost

Another form of revealed preference, travel cost methods examine how much a consumer is expending to travel to consume a certain amount of a product or service (Adamowicz et al, 1994; Brown Jr. and Mendelsohn, 1984; Johansson, 1991; Mayor et al, 2007; Pearce and Tuner, 1990; Pearce et al, 1989). Observing the level of travel expenditure which a consumer incurs to consume certain products or services with varying attributes over others enables a value to be established.

A conventional travel cost method can be illustrated using the number of trips to a site $(TRIPS)$ which are undertaken and are given to be a function of a set of travel cost variables $(COST)$, preferences $(PREF)$ and a set of socio-economic variables $(SOCECON)$ (Mayor et al, 2007).

$$TRIPS = f\,(COSTS, PREF, SOCECON)$$

Capturing the value using the travel cost method involves integrating the area under the demand curve with respect to travel costs (Carr and Mendelsohn, 2003; Mayor et al, 2007):

$$\int_{\mathrm{COSTS}_0}^{\infty} \mathrm{TRIPS}\,(\mathrm{COSTS}, \mathrm{PREF}, \mathrm{SOCECON})\ \partial\mathrm{COSTS}$$

The main advantage with the method is it can value products or services for which prices associated with marginal quantities are otherwise absent (Brown Jr. and Mendelsohn, 1984). It also draws upon actual behaviour of consumers within a market rather than using hypothetical scenarios (Carr and Mendelsohn, 2003).

However, as with other types of revealed preference studies, non-use values cannot be identified through the techniques (Johansson, 1991; Mayor et al, 2007). Furthermore, the wider costs which people incur to consumer the product or service are ignored. This includes specialised equipment, vehicle choice, lodging or choosing to buy a property to live nearer to the site (Randall, 1994). The method also fails to account for planned future use and also the data required to obtain values representative of different people's tastes, preferences and substitutes can be large and costly (Johansson, 1991).

Travel cost method studies valuing transport resilience have not been identified from the literature. It may be difficult to place a value on resilience through the travel cost method as there are not enough alternative travel choices for reliable values to be determined. However, it might be possible to identify whether people choose to incur greater travel costs during disruption by using a more resilient mode or route. It may be that the more resilient mode or route, despite greater travel costs, are less of a drawback to travellers than using a less resilient route which can result in addition travel time and worse reliability.

The travel cost method essentially relates to a specific trip, and hence is not well suited to issues of resilience more generally where there is a probabilistic element. Note that in discrete choice studies, this essentially becomes an issue of destination choice, but is it not clear that this context offers any attractions for valuing resilience.

Cost-effectiveness

The cost-effectiveness approach is similar to cost-benefit analysis but with a fundamental difference. Instead of comparing net benefits with net costs, total costs are divided by an appropriate unit to measure effectiveness. The preferred outcome is to maximise the unit of efficiency relative to costs in a decision-making process (Cellini and Kee, 2010; Johannesson, 1995; Kee, 1999).

$$CostEffectiveness = (Total\ Costs)/Unit\ of\ Effectiveness$$

It is noted that the technique is of most use when the desired outcome from the expenditure is known and can be compared for a given set of alternative options (Cellini and Kee, 2010). It is also considered to be useful when major outcomes are intangible, difficult to monetise or a monetary valuation is open to criticism, for example with using the value of life in an analysis (Cellini and Kee, 2010; Kee, 1999).

However, if a valuation is desired then it is required that an external valuation is obtained rather than obtaining one through the method (Cellini and Kee, 2010). Identifying the costs and the appropriate unit of effectiveness is a further issue (Kee, 1999). It is also possible that there may be multiple sources of benefit from the expenditure which may require weights on the benefits. Assigning and justifying the weights used can be open to criticism (Kee, 1999).

Numerous cost-effectiveness studies have been identified in the transport resilience literature for airline security (Stewart and Mueller, 2008a: 2008b: 2011: 2013), whilst wider cost-benefit analysis studies have examined natural disasters (Islam and Mechler, 2007; University of California, 2008) and tackling severe winter weather (DfT, 2010; DfT et al, 2011; Network Rail, 2014)

Augmenting the standard cost-effectiveness, it is possible to examine the choices which organisations make in enhancing infrastructure resilience and obtain valuations. Organisations are likely to trade-off the consequences of improving resilience against the consequences of not improving resilience. It is likely that this is a trade-off between revenue protection and preventative expenditure against revenue loss and recovery expenditure. Through considering the interventions which businesses make in actual markets, it may be possible to generate a value of improving resilience.

Cost Studies

The cost studies identified are discussed under the category of extreme event being investigated. This assists in determining the areas of the literature which have a wealth and which areas have a scarcity of coverage. In this section, studies of climate and weather, system security against terrorism and theft, and security of supply of raw materials used in the supply of transport have been identified.

Climate and Weather

Cost studies investigating the resilience of climate and weather (extending to climate change, severe weather and natural disasters) have covered a range of the elements presented in the framework of resilience in Table 1. Presented in this sub-section are studies on the costs of recovery and restoration, revenue losses, costs to the economy, travel time costs and safety costs. Studies on the cost of preventative measures have also been included.

In 2014, the DfT paid £183m to local highway authorities in order to assist in repairing the road network following damage due to severe weather conditions in England (DfT, 2014). Somerset, as one of the areas worst affected, which included flooding, received £10m alone. A wider range of the costs of severe winter weather disruption has been estimated regarding the economic (GDP) and social welfare loss per day, as presented in Table 2 (DfT et al, 2011).

Table 2: Daily cost of disruption due to severe winter weather in England (£m)

Impact	GDP			Welfare		
	Central	Low	High	Central	Low	High
Reduced economic output from lost business/commuting journey time delays	108	32	225	108	32	225
Lost output from working parents with dependent children not at school	9	5	14	9	5	14
Lost hospital appointments	3	1	6	3	1	6
Goods vehicles delays	2	1	4	2	1	4
wastage on food and perishables	2	1	3	2	1	3
Road vehicle collisions	0	-3	3	0	-9	9
Pedestrian accidents	3	2	5	24	12	37
Lost journeys – personal travel	0	0	0	49	12	110
Journey time delays – personal travel	0	0	0	34	20	40
Pedestrian delays	0	0	0	43	22	65
Lost education	0	0	0	6	4	7
Total	**127**	**39**	**260**	**280**	**101**	**520**

Unusually high levels of rainfall in England during summer 2007 also caused flooding, which led to the closures of multiple English motorways and further disruption to many local and trunk roads. The repair costs to both the Highways Agency and local road authorities were estimated to be £40-60m (DfT, 2014).

Extreme temperatures can also impact on the network with hot summers, as during 2003, causing disruption (Atkins, 2013). The temperatures and associated droughts resulted in Cambridgeshire County Council spending £3.5m in additional highway structural maintenance and £1.1m on emergency repairs through cracking and deformation. Wider local authority road subsidence costs resulting were estimated at £40.6m with the highest regional costs in the south-east (£18.7m) and the east (£13.2m).

Extreme storm damage in early 2014 caused disruption costs estimated to be between £40-45m for the railway between Exeter and Newton Abbot in the South-West of England (Network Rail, 2014). The costs cover cancellation and delay compensation payments to passenger and freight services and also repairs to the railway between Dawlish Warren and Teignmouth. Costs prior to the events of 2014 have typically been £0.8m per annum to maintain the sea wall and cliffs. Approximately £5m is spent in addition to this figure roughly every five years to recover from an incident such as cliff collapse. The costs of remedial works from 2014 alone were £24m to repair the seawall, restore the track and signalling, repair Dawlish station and stabilise the cliffs. Ongoing seawall strengthening along the rebuilt line at Dawlish will cost £8m and a further £5m is committed to be spent between 2019-24 on seawall maintenance, rock fall prevention and tunnel repairs.

A wider study of the costs of climate change impacting on the sea level and thereby disruption on the London-Penzance railway has been undertaken (Dawson, 2012). This does not consider severe, isolated events such as experienced earlier in 2014 but rather the long term trends of climate change. Tables 3 and 4 summarise the direct and indirect costs in 2010 prices to Network Rail resulting from the increase in propensity for sea-wall defence breaches. Three scenarios are considered against the recent historical position (1997-2009) and include low, medium and high emissions growth scenarios.

Table 3: Direct costs to Network Rail due to sea level rise affecting the London-Penzance railway line

Scenario & Time Period	Sea level Rise (cm)	Average DLRs*/Year	Increase in DLRs (%)	Delay Minutes/ Year	Delay Value (£m/Year)	Preventative Maintenance (£m/Year)
Current						
1997-2009	3.0	9.5	-	3,900	0.35	0.61
Low Emissions						
2020	4.7	16	69	6,510	0.59	1.04
2040	15.1	30	220	12,326	1.11	1.96
2060	26.8	46	389	18,836	1.70	3.00
2080	20.0	64	581	26,232	2.36	4.17
2100	54.5	84	792	34,360	3.09	5.47
Medium Emissions						
2020	5.7	17	83	7,049	0.63	1.12
2040	18.3	34	266	14,098	1.27	2.24
2060	32.6	54	474	22,110	1.99	3.52
2080	48.6	76	710	31,047	2.80	4.94
2100	66.4	100	964	40,985	3.69	6.52
High Emissions						
2020	6.8	19	99	7,665	0.69	1.22
2040	22.0	40	320	16,178	1.46	2.57
2060	39.3	63	571	25,847	2.33	4.11
2080	58.9	90	856	36,825	3.32	5.86
2100	80.6	120	1,170	48,920	4.41	7.78

*DLRs – Days with line restrictions

Table 4: Indirect costs to Network Rail due to sea level rise affecting the London-Penzance railway line

Scenario & Time Period	Sea Level Rise (cm)	Estimated ESR/Year*		ELC/Year**	Freight Time Losses (£/Year)			Passenger Time Losses (£/Year)			Total Time Loss Impacts (£/Year)
		Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	
Current											
1997-2009	3.0	5.4	3.8	0.3	86,122	303,021	38,276	1,490	2,098	6,026	437,033
Low Emissions											
2020	4.7	8.4	7.2	0.5	134,348	570,347	60,837	2,325	3,948	9,578	781,384
2040	15.1	16.0	13.6	0.9	254,351	1,079,794	115,178	4,402	7,475	18,134	1,479,333
2060	26.8	24.4	20.7	1.4	389,355	1,652,921	176,312	6,738	11,442	27,759	2,264,527
2080	40.0	34.0	28.8	1.9	541,666	2,299,527	245,283	9,374	15,918	38,618	3,150,387
2100	54.5	44.5	37.7	2.5	708,978	3,009,813	321,047	12,269	20,835	50,547	4,123,490
Medium Emissions											
2020	5.7	9.1	7.8	0.5	145,887	619,332	66,062	2,525	4,287	10,401	848,494
2040	18.3	18.3	15.5	1.0	291,275	1,236,546	131,898	5,041	8,560	20,767	1,694,087
2060	32.6	28.6	24.3	1.6	456,280	1,937,036	206,617	7,896	13,409	32,531	2,653,768
2080	48.6	40.2	34.1	2.3	640,900	2,720,800	290,219	11,091	18,834	45,693	3,727,537
2100	66.4	53.1	45.1	3.0	846,289	3,592,738	383,225	14,646	24,870	60,337	4,922,106
High Emissions											
2020	6.8	9.9	8.4	0.6	158,580	673,216	71,810	2,744	4,660	11,306	922,316
2040	22.0	20.9	17.8	1.2	333,969	1,417,792	151,231	5,780	9,814	23,811	1,942,396
2060	39.3	33.5	28.4	1.9	533,589	2,265,237	241,265	9,234	15,681	38,043	3,103,409
2080	58.9	47.6	40.4	2.7	759,749	3,225,349	344,037	13,148	22,327	54,167	4,418,776
2100	80.6	63.3	53.8	3.6	1,010,140	4,288,329	457,422	17,481	29,685	72,019	5,875,076

*ESR-Emergency speed restrictions

**ELC-Emergency line closures

Four further scenarios in the context of the global conditions which the railway exists in have been considered. The costs in 2010 prices due to a rise in sea level in the first scenario are presented in Table 5 for what is termed the World Scenario in which there is:

- Highest threat from sea level rise
- Highest growth, innovation and demand
- Unwillingness to plan ahead and adapt
- Government responsibility for climate change not well defined
- Low decision maker credibility

Table 5: Costs of climate change on London-Penzance railway – World Scenario

Year	Sea Level Rise (cm)	Restrictions (Days/Year)	Estimated Journeys (Millions/Year)	Socio-economic Costs (£m/Year)*	Future Costs (£m/Year)**	Cost of Climate Change (£m/Year)***
2010	0.0	9.5	3.96	1.05	1.05	-
2020	6.8	19	5.65	1.23	2.53	1.30
2040	22.0	40	8.97	1.59	6.93	5.34
2060	39.3	63	12.30	1.95	13.63	11.68
2080	58.9	90	12.30	1.95	19.41	17.46
2100	80.6	120	12.30	1.95	25.80	23.85

*Socio-economic costs arise regardless of any sea level rise
**Future costs are additional costs of delay and maintenance
***Total impact due to sea level rise resulting from climate change

Table 6 presents the costs in 2010 prices due to a rise in sea level for what is termed the Global Sustainability Scenario in which there is:

- Lowest sea-level threat
- Medium-high growth, high innovation and demand
- Coastal protection judged as most vulnerable by the nation
- Clearly defined roles and responsibility for climate change adaptation
- High decision maker credibility – value experts

Table 6: Costs of climate change on London-Penzance railway – Global Sustainability Scenario

Year	Sea Level Rise (cm)	Restrictions (Days/Year)	Estimated Journeys (Millions/Year)	Socio-economic Costs (£m/Year)	Future Costs (£m/Year)	Cost of Climate Change (£m/Year)
2010	0.0	9.5	3.96	1.05	1.05	-
2020	4.7	16	5.45	1.21	2.11	0.89
2040	15.1	30	8.54	1.54	5.09	3.94
2060	26.8	46	11.54	1.87	9.51	7.64
2080	40.0	64	11.54	1.87	13.24	11.37
2100	54.5	84	11.54	1.87	17.33	15.46

Table 7 presents the costs in 2010 prices due to a rise in sea level for what is termed the National Enterprise Scenario in which there is:

- Medium sea level threat
- Medium-low growth, innovation and demand
- Society has a lack of cooperation toward climate
- Clear responsibilities towards climate change but based on personal responsibility
- Medium-low decision maker responsibility

Table 7: Costs of climate change on London-Penzance railway – National Enterprise Scenario

Year	Sea Level Rise (cm)	Restrictions (Days/Year)	Estimated Journeys (Millions/Year)	Socio-economic Costs (£m/Year)	Future Costs (£m/Year)	Cost of Climate Change (£m/Year)
2010	0.0	9.5	3.96	1.05	1.05	-
2020	5.7	17	4.73	1.13	2.13	1.00
2040	18.3	34	6.44	1.32	4.98	3.66
2060	32.6	54	8.00	1.49	8.90	7.34
2080	48.6	76	8.00	1.49	12.40	10.91
2100	66.4	100	8.00	1.49	16.37	14.88

Table 8 presents the costs in 2010 prices due to a rise in sea level for what is termed the Local Stewardship Scenario

- Medium sea level threat
- Lowest growth, innovation and demand
- Threats of climate change clearly understood locally/regionally
- National responsibility less well defined
- Medium-high decision maker responsibility

Table 8: Costs of climate change on London-Penzance railway – Local Stewardship Scenario

Year	Sea Level Rise (cm)	Restrictions (Days/Year)	Estimated Journeys (Millions/Year)	Socio-economic Costs (£m/Year)	Future Costs (£m/Year)	Cost of Climate Change (£m/Year)
2010	0.0	9.5	3.96	1.05	1.05	-
2020	5.7	17	4.74	1.13	2.13	1.00
2040	18.3	34	6.20	1.29	4.88	3.59
2060	32.6	54	7.67	1.45	8.61	7.16
2080	48.6	76	7.67	1.45	12.09	10.64
2100	66.4	100	7.67	1.45	15.97	14.52

Disruption on a stretch of State Highway 1 (Desert Road) in New Zealand has been investigated for natural disasters and extreme weather events including snow/ice closures and volcanic activities (Dalziell and Nicholson, 2001). Costs were framed in terms of time, vehicle costs, accidents and implied loss of economic value due to suppressed or cancelled trips and are presented in Table 9:

Table 9: Cost per hour due to road closures through extreme natural activity – New Zealand (NZ$)

Closure Scenario	Operating & Time	Accidents	Lost User Benefit	Total Cost	Total Cost of Closure
All roads open	$180,590	$43,017	-	$223,607	-
Desert Road closed	$172,610	$40,858	$18,129	$231,597	$7,990
Desert Road & SH 4 closed	$164,412	$38,570	$43,498	$246,480	$22,870
Desert Road & SH 47 closed	$165,220	$38,846	$33,887	$237,953	$14,350
Desert Road & SH 49 closed	$169,944	$39,783	$26,058	$235,783	$12,180

Total annual costs of different types of event based on these costs per hour have been estimated at NZ$1.9m for snow/ice, NZ$1.5m for earthquakes, NZ$0.3m for traffic accidents and NZ$0.2m for volcanic events.

Similarly, disruption impacts resulting from the Northridge earthquake and associated highway closures of routes in Southern California have been estimated as in Table 10 (Wesemann et al, 1996). The disruption costs cover time delays and vehicle operating costs.

Table 10: Cost of delays due to Northridge earthquake highway closures (average weekday, US$)

Closure	Cost of Delay (Trucks)	Cost of Delay (Persons)	Excess Fuel Used	Total
I-5 & SR-14	$85,000	$310,000	$40,800	$436,000
I-10	$68,000	$811,000	$110,000	$990,000
SR-118	$23,710	$189,800	$24,600	$238,100
Total	**$176,710**	**$1,310,800**	**$175,400**	**$1,664,100**

A European study into a variety of disruption costs due to extreme weather in the continent has been undertaken recently (Nokkala et al, 2012). Included within these costs are total accident costs on the road.

- 2008 road fatalities: 4,900 costing €4,900.4m
- 2008 road severe injuries: 37,625 costing €15,824.6m
- 2009 rail fatalities: 75 costing €74.9m
- 2009 rail severe injuries: 68 costing €28.4m
- 2005 inland water fatalities: 1 costing €0.8m
- 2005 inland water severe injuries: 2 costing €1.6m
- 2009-10 marine/short sea fatalities: 3 costing €2.6m
- 2009-10 marine/short sea severe injuries 18 costing €7.7m

In the same study it is presented that annual accident costs due to extreme weather are estimated to be lower in the future due to improved safety in transport vehicles, infrastructure and education. Total road fatalities and severe injury costs reduce from €20,725m in 2010, to €6,630m by 2040 and €4,482m by 2070. Total rail fatalities and severe injury costs reduce from €103m in 2010 to €31m by 2040 and €20m by 2070. Inland-water transport costs remain stable at €1.5m and maritime costs fall from €10m in 2010 to €3m and €2m in 2040 and 2070, respectively. The figures are provided in 2010 prices.

Tables 11 and 12 present the cost of delays in 2010 prices determined using values of time for extreme weather in Helsinki for road and rail, respectively, from the same study on extreme weather in Europe.

Table 11: Daily Delay Costs to Road due to Extreme Weather (Helsinki)

Trips			Speed (km/h)			
Length	**Number**	**Total kms**	**Average**	**20% Reduction**	**30% Reduction**	**40% Reduction**
0-2km	112,000	112,000	10	€22,400	€33,600	€44,688
2-5km	112,000	392,000	20	€39,200	€58,800	€78,204
5-20km	313,600	3,920,000	40	€196,000	€294,000	€391,020
20-50km	16,800	588,000	60	€19,600	€29,400	€39,102
50-100km	2,800	210,000	80	€5,250	€7,875	€10,473
100-150km	2,800	350,000	100	€7,000	€10,500	€13,965
Total	**560,000**	**5,572,000**	-	**€289,450**	**€434,175**	**€577,452**

Table 12: Daily Delay Costs to Rail due to Extreme Weather (Helsinki)

Trips			Speed (km/h)			
Length	**Number**	**Total kms**	**Average**	**20% Reduction**	**30% Reduction**	**40% Reduction**
0-2km	5,600	5,600	10	€1,120	€1,680	€2,234
2-5km	5,600	19,600	20	€980	€1,470	€1,955
5-20km	15,680	196,000	40	€6,533	€9,800	€13,034
20-50km	840	29,400	60	€735	€1,102	€1,466
50-100km	140	10,500	80	€210	€315	€419
100-150km	140	17,500	100	€292	€438	€582
Total	**28,000**	**278,600**	-	**€9,870**	**€14,805**	**€19,690**

In the same study, the delay costs in 2010 prices due to extreme weather for freight shippers and hauliers are estimated to cost an annual €1,200m-5,900m for road, €4.8-24m for rail, €0.07-0.33m for inland water transport, €0.19-0.96m for sea and €0.45-2.3m for air.

The financial losses due to natural events have been estimated as for the disruption due to the Eyjafjallajokull volcanic ash cloud in Iceland in 2010, with calculated costs at £50m (DfT, 2010). Costs covered the care and accommodation paid for by airlines and tour operators to

UK nationals stranded abroad and for foreign nationals stranded in the UK. This was in addition to revenue which tour operators lost through refunds and lost demand.

Effects of climate change on cargo shipping operating costs on Canada's Great Lakes have been provided by Millerd (2005). The costs in 2001 prices are anticipated to increase due to lower water levels from an average annual total for all movements of CAD$254,951,845 in 1990 to CAD$275,196,120 in 2030, CAD$288,106,342 in 2050 and CAD$330,065,066 in 2100.

System Security against Terrorism and Theft

Cost studies investigating the resilience of system security against terrorism and theft (extending to terrorist attacks and cable theft) have few of the elements presented in the framework of resilience in Table 1. Presented in this sub-section are studies on the costs of recovery and restoration, revenue losses and losses to the economy.

Recovering from a terrorist event on the railways and the associated costs can be demonstrated with reference to the Madrid bombings in 2004 on the Spanish railways (Buesa et al, 2006: 2007). Table 13 provides a breakdown of the estimate:

Table 13: Cost of 2004 Madrid Bombings (€)

Item	Expenditure
Rescue, Response & Healthcare	
Initial Response & Rescue	€2,176,875
Healthcare for Victims	€5,156,878
Compensation to Victims	
National Government Compensation to Victims	€55,140,821
Damages Paid to Victims	€29,133,348
Region of Madrid Compensation to Victims	€4,176,979
Insurance Claims Department	€37,279,317
"In Itinere" Accidents (Spanish NHS)	€2,764,860
Private Insurance Payments to Victims	€5,625,000
Additional	
Wage Losses to Victims	€2,375,988
Damages in Infrastructure and Housing	€5,269,542
Cost of temporary use of IFEMA Facilities	€180,964
Psychological Attention to Victims	€4,938,740
Cost of Solidarity Demonstration	€57,365,450
Total	**€211,584,762**

Disruption costs due to a dirty bomb attack on the Long Beach and Los Angeles ports in USA were estimated with regards the length of shutdown required by various degrees of resulting radiation (Rosoff and Winterfeldt, 2007). Attacks leading to a 15 day shutdown could cost US$300m, 120 days could cost US$63bn and 1 year could cost US$252bn. High and medium severity scenarios were also presented in the study which provides a breakdown of what the costs could be if the attack was through theft of radioactive material from an industrial irradiator in a US facility (medium scenario) or the purchase of spent fuel assembly from a former Soviet nuclear power or reprocessing plant (high scenario).

Under the medium scenario, port shutdown and related business losses provide the most significant impacts of between US$0-200m, with decontamination costing US$10-100m and other impacts negligible. In the high scenario, port shutdown and related business losses are estimated at US$30-100bn, evacuation costs US$10-100m, business losses US$1-3bn, property value losses US$100-200m and decontamination costs US$10-100bn.

The costs of disruption to the railway due to train cancellations, delays and replacement resulting from cable theft have been presented in two House of Commons Transport Committee (2012a; 2012b) reports. A summary of the costs is provided in Table 14.

Table 14: Schedule 8 costs to Network Rail due to cable theft by year

Year	Incidents	Trains	Cancelled Trains	Part Cancelled	Delay Minutes	Schedule 8 Payments	Total Direct Costs
2004/05	17	1,846	44	90	38,648	£961,322	-
2005/06	49	2,387	82	138	34,900	£873,344	-
2006/07	538	19,042	691	624	241,035	£5,810,740	-
2007/08	687	24,237	1,457	1,125	244,074	£7,666,601	-
2008/09	742	27,709	885	1,022	283,167	£7,858,517	£12,264,682
2009/10	656	28,886	1,345	1,034	321,570	£10,931,352	£13,961,998
2010/11	995	35,629	1,430	1,440	365,430	£12,132,860	£16,510,663
2011/12	688	28,301	1,300	1,030	291,446	£10,279,665	-

It is also stated in the same reports that the costs of cable theft disruption to the economy may be in the region of £16-20m and if Passenger Demand Forecasting Handbook techniques and parameters were applied to cable theft delays, a loss of passengers of 0.5m with a total revenue loss of around £304m would result.

Certain regions provide some evidence of their costs incurred due to cable theft disruption with direct costs to London Underground estimated to be £1.9-4m in 2010/11 and Nexus, the Tyne & Wear Passenger Transport Executive incurring approximately £293,000 per annum. A breakdown of the Schedule 8 costs to West Yorkshire Passenger Transport Authority is offered:

- 2009/10: 43,166 delay minutes (106 incidents; 152 cancellations) – £980,849 per annum
- 2010/11: 51,984 delay minutes (161 incidents; 185 cancellations) – £954,294 per annum
- 2011/12: 130,121 delay minutes (364 incidents; 481 cancellations) – £2,689,775 per annum

Scarce Raw Materials used in the Supply of Transport

A single estimation of the costs of scarce raw materials used in the supply of transport has been identified. Marsden and Beecroft (2002) summarise that fuel supply disruption similar to the 2000 UK oil refinery blockades can lead to a loss to the economy of £1bn. This is on the basis of assuming a two to three week action which causes disruption to approximately 5% of the economy. In terms of GDP it is representative of 0.1% at market prices, or then £40 per person.

Summary

The literature would appear to be widespread for climate and weather costs due to disruption and there is a fair amount of evidence for system security against terrorism and theft. However, the review obtained little to no evidence on scarce raw materials used in the supply of transport or industrial action. The important message from the review is quite clear. Although the events may be of low probability, the consequences on costs are commonly estimated to be high regardless of the type of event.

Valuation Studies

Consistent with the cost studies review, the studies seeking a valuation on resilience are discussed under the category of extreme event being investigated and with reference to the framework of resilience in Table 1. In this section climate and weather, system security against terrorism and theft and multiple events studies have been identified.

Climate and Weather

A single climate and weather study attempting to value the delay effects of resilience from climate and weather has been identified. Using a public transport model based on observed data (revealed preference) covering bus, tram and metro as one mode and train as another, speed changes due to adverse weather have been captured for the Netherland. These speed changes have been converted into welfare effects per commuting passenger trip (Sabir et al, 2010) using values of time. The impacts calculated are:

- Strong wind: – €0.03 (bus, tram & metro); £0.00 (train)
- Temperature below 0°C: €0.00 (bus, tram & metro); 0.40 (train)
- Temperature above 25°C: €0.00 (bus, tram & metro); – €0.40 (train)
- Rain: €0.00 (bus, tram & metro); €0.00 (train)
- Rain and congestion: – €1.78 (bus, tram & metro); €N/A (train)
- Snow: – €0.76 (bus, tram & metro); – €0.5 (train)
- Visibility – €0.38 (bus, tram & metro); €0.00 (train)

The unusual value is the positive value for train commuters in temperatures below 0°C which was explained to be due to stations becoming less busy and crowded in low temperatures making access time lower. Furthermore, access is suggested to be by walking and cycling, which are modes less sensitive to extreme temperatures. Congestion is a highway rather than rail effect, explaining the N/A value for rain and congestion.

System Security against Terrorism and Theft

A couple of studies on system security against terrorism and theft have been identified seeking to identify the values which consumers place on safety due to improved rail and airline security measures. The study on airline security also covers privacy and civil liberties.

Willingness to pay for railway security measures aimed at tackling terrorism have been generated through stated preference techniques (Potoglou et al, 2009; Robinson et al, 2010). The results are presented against income group in Table 15:

Table 15: Willingness to pay for security interventions at railway stations by income group (addition to fare per trip, £)

		Income			
Base Security	**Intervention**	**<£20,000**	**>£20,000**	**N/A**	**Average**
No CCTV	Standard CCTV	£1.66	£2.46	£1.20	£2.03
No CCTV	Advanced CCTV	£2.55	£3.77	£1.84	£3.10
No bag checks	Pat down and bag search for 1 in 1000 travellers	£0.71	£1.04	£0.51	£0.86
No bag checks	Pat down and bag search for 2 in 1000 travellers	£0.71	£1.04	£0.51	£0.86
No bag checks	Pat down and bag search for 10 in 1000 travellers	£0.95	£1.40	£0.69	£1.15
No bag checks	Metal detectors and x-rays for all	£1.98	£2.93	£1.43	£2.41
Rail staff	Rail staff and British Transport Police	£0.59	£0.88	£0.43	£0.72
Rail staff	Rail staff, British Transport Police and Armed Police	£0.43	£0.64	£0.31	£0.52
Rail staff	Rail staff, British Transport Police, Armed Police and Uniformed Military	£0.23	£0.34	£0.17	£0.28
If an incident occurs there is lots of disruption and chaos	If an incident occurs then you are not aware of it	£1.96	£2.90	£1.42	£2.38
If an incident occurs there is lots of disruption and chaos	If an incident occurs then you are aware of it when you get back home	£1.96	£2.90	£1.42	£2.38
If an incident occurs there is lots of disruption and chaos	If an incident occurs then things are handled with minimum disruption	£0.89	£1.31	£0.64	£1.08
13 minutes	1 minute	£2.66	£3.73	£1.94	£3.13
13 minutes	2.5 minutes	£2.23	£3.47	£1.70	£2.82
13 minutes	5.5 minutes	£1.66	£2.48	£1.21	£2.04
13 minutes	9 minutes	£0.89	£1.32	£0.65	£1.08
1 plot every 10 years	20 plots every 10 years	£3.63	£5.41	£2.65	£4.44
1 plot every 10 years	10 plots every 10 years	£2.89	£4.30	£2.10	£3.54
1 plot every 10 years	5 plots every 10 years	£1.86	£2.77	£1.36	£2.28
1 plot every 10 years	2-3 plots every 10 years	£1.35	£2.01	£0.98	£1.65
1 plot every 10 years	1-2 plots every 10 years	£0.45	£0.67	£0.33	£0.55

A new type of security screening at Norwegian airports has been analysed in terms of willingness to pay for the measure based on stated choice techniques (Veisten et al, 2011). The technique involves more intensive screening based on passenger security risk level rather than using the current system of everyone being assumed to be of the same risk. It is determined that the value is on maintaining the uniform risk system at €13.50 per passenger trip despite the potential convenience of time saved at airport security resulting. It is explained that this is due to passengers placing a value on the protection of privacy and civil liberties.

Multiple Events

Three further studies which value resilience for transport have been identified which do not focus on a single, specific category of disruption. The studies have sought to value a reduction in time, reliability and damage.

The value of reducing disruption to containerised maritime transport has been examined in terms of willingness to pay based on stated preference methods for improvements in time, reliability and damage (Figliozzi and Zhang, 2010). Disruption appears to cover extreme events as it is stated that disruption could be due to natural disasters, accidents, terrorism, war, political and economic instability, supply unavailability, transportation delays and labour strikes or conflicts in the study. The willingness to pay values for the following reductions in disruption are as follows:

- One day reduction in transit time: US$33.10 (normal); US$180.66 (disruption)
- 1% increase in on-time deliveries: US$42.17 (normal); $42.81 (disruption)
- 1% reduction in damage: US$197.75 (normal); US$383.27 (disruption)

In a road freight study, the willingness to pay for a 1% improvement in punctuality has been estimated, as has the value of time (Masiero and Maggi, 2012). The values reflect a scenario of a rare but extreme two week closure on the A2 Transalpine highway pass with the results presented in Table 16. The four alternative scenarios are to use a different road (Road (A13)), a new road discussed to be the regulated A13, piggyback with road freight travelling on a rail freight vehicle (piggyback) or transfer between road and rail freight (combined).

Table 16: Transalpine freight study (Swiss Francs, CHF)

	Value of Time		Willingness to Pay	
Alternative	**Per Shipment**	**Per Ton**	**Per Shipment**	**Per Ton**
New Road	23.13	3.17	67.52	9.25
Piggyback	23.22	3.18	68.40	9.37
Combined	23.01	3.15	69.17	9.48
Road (A13)	15.98	2.19	54.07	7.41

A further study evaluating severe disruption was conducted by Cats and Jenelius (2013) for a resilience intervention involving a new cross-radial public transport line introduced to a largely radial network using Stockholm as a case study. Severe disruption included technical faults, vehicle failure, and terror incidents and was compared against a scenario of normal operations. It was estimated that the line could increase welfare by approximately SEK150,000 (£13,143), based on travel time savings, during a single rush hour period.

Summary

Valuations of resilience in the literature appear to be fairly rare but there are some valuations of adverse weather, system security against terrorism and theft and unspecified disruption. Evidence could not be obtained on valuations of scarce raw materials used in the supply of transport or industrial action. It would generally appear that there is a value which consumers place on a resilient network, but as one study demonstrates, it may be the case that some resilience measures should not be at the expense of privacy and civil liberties.

Cost-Benefit Analysis Studies

The same process is followed for the review of cost-benefit analysis and cost-effectiveness studies as has been followed for cost and valuation studies. Each study is presented under the category of event being investigated and with reference to Table 1. In this section climate and weather, and system security against terrorism and theft studies have been identified.

Climate and Weather

Cost-benefit analyses tend to cover a variety of benefit and cost impacts and across the climate and weather studies presented, a diverse range of items included in the framework in Table 1 are covered. In some studies alone, almost the entire spectrum. However, it should be noted that in some studies, the benefits and costs are not described in as much detail as in others, in some cases only a BCR value is provided.

Atkins (2013) investigated measures aimed at improving the resilience of the Highways Agency to a greater number of days in England where temperatures are higher than 32°C, 35°C and 40°C. This is as a consequence of climate change. The benefits included reflect reductions in user delays and maintenance costs and are compared against the cost of the resilience measures. A central and worse case is considered which reflects a lower and higher level of days with higher temperatures, respectively. The measures aimed at improving resilience are more heat-resistant pavements, bridge joints with better movement and expansion capabilities and bridges with better heat and drought resistance. The results of the cost-benefit analysis in 2010 discounted present values are provided in Table 17:

Table 17: Cost-benefit analysis of adaptation measures to hotter temperatures (000s)

Impact	Central Case	Worst Case
User Delay Savings	£2,253	£32,577
Maintenance Costs Savings	£4,728	£74,185
Adaptation Costs	£6,387	£41,628
PVB	£6,982	£106,761
PVC	£6,387	£41,628
BCR	1.1	2.6

A number of resilience measures aimed at tackling disruption during extreme winter weather in England have been evaluated (DfT et al, 2011). The benefits include reducing wastage for salt storage measures, reducing delay compensation (Schedule 8) loss and operating cost savings for rail measures, and reducing disruption to businesses (loss to the economy) for home working measures. The cost-benefit ratios (BCRs) are presented below against each of the possible measures:

- Building domes to cover all remaining uncovered salt storage capacity: 2.1 (low of 1.6; high of 3.6)
- Using sheet storage systems to cover all remaining uncovered salt storage: 2.5
- Gritter (salt) recalibration and staff training: 9.3
- Regional groups sharing salt storage facilities: 1.3 (low of 0.1; high of 37.2)
- Third rail heating: 6.9 (low of 3.2; high of 13.1)
- Fit de-icing equipment to 20 passenger trains: 3.7 (low of 1.7; high of 7.0)
- Fitting an additional 30 trains with de-icing equipment: 4.6 (low of 2.1; high of 8.8)
- Replace the third rail with a much higher voltage overhead electrification system: 1.2 (low of 0.8; high of 2.4)
- Home working with equipment provided by employer: 0.5 (low of 0.2; high of 0.9)
- Low-cost home working: 3.1 (low of 1.4; high of 5.8)

The DfT (2010) also estimated the benefits of an £80m increase in highway authority expenditure to tackle severe winter weather. The benefits were estimated at £100m to the economy and £100m to welfare (time etc.), which means a BCR of 2.4. A low of £15m benefits to the economy and £35m to welfare and a high of £225 and £200m, respectively, were estimated. Therefore the low BCR is 0.6 and the high is 5.3.

A number of diversionary routes for the West of Exeter railway line to mitigate disruption due to damage at Dawlish have been proposed for the future and appraised (Network Rail, 2014). Table 18 presents the results of the cost-benefit analysis (2014 prices):

Table 18: Cost-benefit analysis of Dawlish diversionary rail routes (£m)

Benefit/Cost	Value (£m)						
	Option 1*	Option 2**	Option 3A***	Option 3B***	Option 3C***	Option 3D***	Option 3E***
UK Rail Revenue Impact	£28	£30	£66	£74	£74	£66	£56
User Time Savings	£134	£138	£235	£265	£265	£234	£203
Road Decongestion	£2	£3	£6	£6	£6	£6	£5
Infrastructure	£0	£0	£0	£0	£0	£0	£0
Accident	£1	£1	£2	£2	£2	£2	£1
Local Air Quality	£0	£0	£0	£0	£0	£0	£0
Noise	£0	£0	£0	£0	£0	£0	£0
Greenhouse Gases	£0	£1	£1	£1	£1	£1	£1
Indirect Taxation	-£3	-£3	-£7	-£8	-£8	-£7	-£6
Operating Costs	-£162	-£79	£7	£2	-£1	-£12	-£9
Capital Costs	-£814	-£436	-£2,883	£2,338	£2,096	£1,448	£1,387
NPV	-£813	-£346	-£2,572	-£1,995	-£1,755	-£1,157	-£1,134
BCR	0.14	0.29	0.08	0.12	0.13	0.17	0.15

*Reinstated railway via Tavistock and Okehampton **New railway via the Teign Valley alignment ***New inland railway alignments between Exeter and Newton Abbot

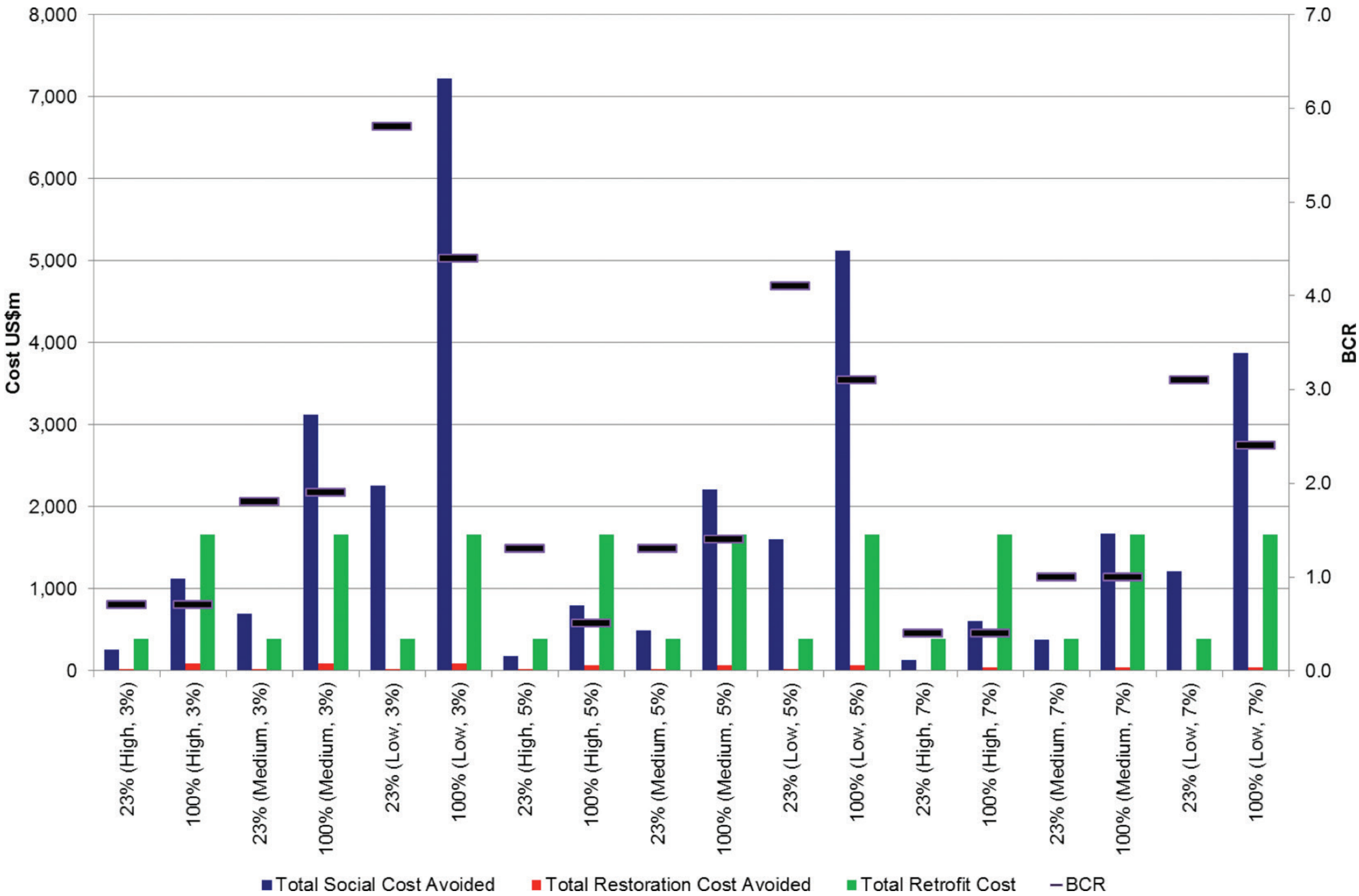
Dawson (2012) offers a cost-benefit analysis of a potential new inland railway route to replace the existing London-Penzance line which is susceptible to breaches of sea-defences. The benefits include reductions in delay and maintenance compared with initial capital expenditure and ongoing operating and maintenance costs incurred. Table 19 presents the results of the appraisal in 2010 discounted present values:

Table 19: Cost-benefit analysis of new inland railway line to replace London-Penzance

Impact	Value (£)
Scheme Benefits	£61,061,721
Scheme Costs	£344,500,000
PVB	£34,203,844
PVC	£327,553,511
BCR	0.10

A cost-benefit analysis of the seismic retrofitting of bridges in Los Angeles to protect against earthquake damage has been conducted (University of California, 2008). Traffic modelling software and Monte Carlo simulation has been used to estimate the impact on travel time and vehicle operating costs which values of time and cost parameters can be applied to. These figures can be added to the estimated cost avoided through having less damage to repair and compared against the costs of retrofitting to produce BCRs. A series of discounting scenarios (3%, 5% and 7%) for 23% and 100% of bridges being retrofitted have been compared under scenarios of there being high, medium and low levels of residual capacity available on the bridge after an earthquake event. Figure 1 presents the comparison in 2008 discounted present values.

Figure 1: BCRs of Seismic Retrofitting of Los Angeles Bridges



Islam and Mechler (2007) provided a cost-benefit analysis of raising highways in Bangladesh to the highest recorded flood levels and implementing cross-drainage facilities. The benefits reflect reduced recovery costs and are compared against the costs of the intervention.

Over an appraisal period of 2007 to 2031, the benefits were estimated at 4,998 million Taka (approximately £39m) against 3,090 million Taka (approximately £24m) in 2007 discounted recent values. The BCR is therefore 1.6.

System Security against Terrorism and Theft

The studies of system security against terrorism and theft have focussed on cost-effectiveness analysis for the airline industry. The intention has been to demonstrate the level of risk required for the costs to meet a required threshold measured as either the cost per life saved or against the economic loss from an incident.

Stewart and Mueller (2008a) illustrate how cost-effectiveness analysis can be used in resilience by comparing against a threshold for a given level of risk reduction and the cost of the intervention using an analysis of the presence of US Federal Air Marshalls onboard planes and hardened plane cockpit doors for US airlines. Examining the hardened cockpit door intervention, it is expected that the risk reduction is 16.67% at a cost of US$40m per year and it is assumed there are 300 fatalities per year before the intervention. Therefore the cost per life saved is £800,000 (40m/(300*0.1667)). This is below the US regulatory goal of US$1-10m per life saved and demonstrates cost effectiveness.

However, in the case of the Federal Air Marshall Service, the risk reduction is just 1.67% at a cost of US$900m and an assumed 300 fatalities per year before the intervention. Hence, the cost per life saved is approximately US$180m, which is well above the US regulatory goal and demonstrates a lack of cost effectiveness.

The same principles were applied by Stewart and Mueller (2008b) for the Australian airline industry for effectively the same interventions of hardened cockpit doors and the presence of Australian Air Security Officers onboard the plane. In the case of hardened cockpit doors, the cost is AU$2.5m, with annual lives lost of 21 prior to the intervention. In this case the intervention only needs to reduce the risk by 1.2% in order to be within the regulatory range of an intervention being considered cost effective of AU$1m-10m per life saved (2.5m/(21*0.012)). The Australian Air Security Officers onboard the plane intervention is estimated to cost around AU$55m per year with 21 lives lost annually prior to the intervention. Even with a best case scenario of a 10% reduction in risk, the cost per life saved is AU26m (55m/(21*0.1)), which is above the threshold of AU$10m.

A similar technique by the same authors examines advanced imaging technology full body scanners for passenger security screening (Stewart and Mueller, 2011). It is estimated that in order for the intervention to be cost-effective then the US$1.2bn cost of the technology will need to be in an environment where there is a minimum of a 61.5% terrorist attack probability. This is in the scenario where the loss of an aircraft and passengers in terms of disruption to the economy would be approximately US$26bn and the intervention reduces risk by 7.5% (1.2bn/(26bn*0.075)).

The techniques have been used by the same authors again for four airline security measures which are Installed Physical Secondary Barriers (IPSB), Federal Air Marshall Service onboard (FAMS), Federal Flight Deck Officers with flight crews able to carry firearms onboard (FFDO) and a combination of the three with IPSD, 25% of the FAMS scenario and 200% of the FFDOs scenario together (Stewart and Mueller, 2013). Table 20 offers the minimum cost-effectiveness attack probability required for the intervention to be cost-effective if the economic loss due to an attack is US$50bn. To offer an illustration of how the figures are calculated, for FAMS the probability is (1.2bn/(50bn*0.01)).

Table 20: Minimum Annual Attack Probability for Intervention to be Cost-Effective

Security Measure	Additional Risk Reduction	Cost ($USm)	Minimum Cost-Effectiveness Attack Probability
IPSB	5%	$13.5	0.50%
FAMS	1%	$1,200.0	240%*
FFDO	2%	$22.0	2%
IPSB, FAMS & FFDO	6%	$357.5	12%

*There would have to be an increase in attacks by a factor of 2.4 essentially, assuming 1 attack is the expected level.

Summary

Cost-benefit analysis and cost-effectiveness studies of resilience measures are fairly widespread across climate and weather and system security against terrorism and theft. However, evidence was not found for scarce raw materials used in the supply of transport or industrial action. The studies are of particular interest as they demonstrate that despite the two previous sections of the review identifying that consumers place a value on resilience and that disruption can impose high costs, interventions are not necessarily value for money. This is likely to be a feature of the low probability of events occurring. It should also be noted that the cost-benefit analysis/cost-effectiveness studies have a tendency to take existing valuations of time, safety etc. from previous transport appraisal literature rather than estimating specific valuations for resilience measures.

Summary

The objectives of this paper were to define resilience and the principal sources of lack of resilience in the transport sector; to provide a selective review of the costs of infrastructure vulnerability and willingness to pay for improved resilience; and to review research approaches for eliciting such values where they do not currently exist.

A definition has been offered which underpinned the findings of the paper. This definition encapsulated that resilience implies insurance against low probability events which can have severe consequences. On the other hand, failure to enhance resilience implies a tolerance to disruption.

A framework of analysis developed from the above definition of resilience, which enabled the review of literature to be examined with reference to, and brought a greater focus to meeting the objectives of the paper. Cost, valuation and cost-benefit analysis studies were examined due to consideration of the framework.

There are many studies on the costs of disruption due to a lack of resilience, particularly with regards to climate and weather, a few studies on the cost of system security against terrorism and theft but with particular weakness in the areas of scarce raw materials used in the supply of transport and industrial action.

Overall, there appears to be a lack of evidence on the valuation of reducing disruption through resilience as explicit studies, although some have addressed climate and weather and system security against terrorism and theft. Instead the focus appears to be on using existing values and estimated costs in order to produce cost-benefit analysis/cost-effectiveness studies of resilience measures. These studies have focussed on climate and weather and system security against terrorism and theft.

In the studies which have been identified there appears to be a clear picture with regards costs of disruption, valuation of resilience and the relative costs against benefits. Disruption can cause high impacts on costs and from the studies available it appears consumers place a value on resilience measures, although care must be taken to avoid intruding on civil liberties.

However, it must be recognised that there is a trade-off between disruption and resilience. Owing to the nature of the low probability of severe consequence events which resilience is understood to tackle, it can be the case that the benefits from avoiding disruption are not high enough to cover the high costs required to implement them.

In terms of estimation methods, we make the following recommendations:

- SP methods appear promising for estimating the ‘consequence valuation’ of an event. Indeed, this context only real differs from conventional transport SP applications insofar as the consequence, such as a journey time loss, is an order of magnitude larger here;
- SP methods might be used to estimate the ‘expected total valuation’ but care would be needed in this challenging context. It would be prudent to couch any such exercise in rigorous qualitative research and extensive piloting given the small probabilities set against large consequences. However, given past application of SP methods to a wide range of challenging issues, such as the value of life and environmental factors, this area would seem to be a logical next step. Indeed, some studies have already been conducted;
- SP methods can provide a means of exploring behavioural consequences of events, but the same caveats apply as in the previous case;
- We do not see a role for RP discrete choice methods given the absence of relevant markets and the inherently larger costs of data collection;
- RP methods based around the econometric analysis of demand responses to events would seem to have value, albeit not providing evidence until after the event;
- Survey based RP methods, enquiring as to what travellers do after some event, can supplement RP demand based analysis by providing more detail on behavioural response. However, identifying those affected is not straightforward and data collection costs might be significant;
- Hedonic pricing based around surrogate markets (such as the housing market) do not seem appropriate here;
- Travel cost methods in their conventional format do not seem appropriate here;
- Cost effectiveness methods do have a role to play but by their very nature do not cover the valuation, behavioural and benefits aspects.

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Footnotes

[1]With thanks to Andrew Smith for helping to coordinate this work.

Chapter 3:

Decision making under uncertainty: methods to value systemic resilience and passive provision

Chapter 3:
Decision making under uncertainty: methods to value systemic resilience and passive provision

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Scope

It is clear that the valuation of most infrastructures is inherently uncertain. The typically system-wide and long-run character of infrastructure can be seen to directly cause or exacerbate multiple sources and kinds of uncertainty. Judgements not only need to be made about the state of the infrastructure and project costs, but in many cases long-run predictions of future conditions (including economic and environmental) need to be taken into account. This chapter is concerned with ways to evaluate infrastructure projects in contexts where the relevance of uncertainty is sufficiently high that failure to recognise it might lead to sub-optimal choices being made. Of course, in most substantial practical applications, it is not reasonable to expect that all uncertainties can be formally characterised, but many can. It is against the background of the availability of a very wide range of general advice about project appraisal and uncertainty, for example, the Green Book, that the chapter is written. It does not seek to repeat already well-established core principles.

A range of procedures exist for undertaking project appraisals. For example: Cost effectiveness; Cost benefit analysis (CBA) / Net present value (NPV); CBA 'Spackman approach'; Real options analysis; Modified real options analysis; Multi-criteria analysis. Different methods exist at least in part because the circumstances of different project appraisals vary and a method that suits one exercise may well be difficult, even impossible, to implement in other circumstances. In this chapter, we discuss a number of different ways of incorporating, specifically, uncertainty into appraisal processes with the differences in large part driven by differences in the circumstances of the appraisal.

The next section of the chapter is theoretical, considering types of uncertainty and methods to deal with these. In the following section a particular method termed real options analysis is focused upon in some detail. Finally, we consider a range of illustrative empirical applications to infrastructure of these methods and touch upon more innovative approaches, some of which have been conceived to allow analysis of long term and "deep" uncertainties of a type that mainstream methods are not well suited to address. There is, of course, a degree of overlap between mainstream and non-mainstream approaches, where many of the most interesting and challenging issues regarding uncertainty and project appraisal lie.

Characterisations of uncertainty

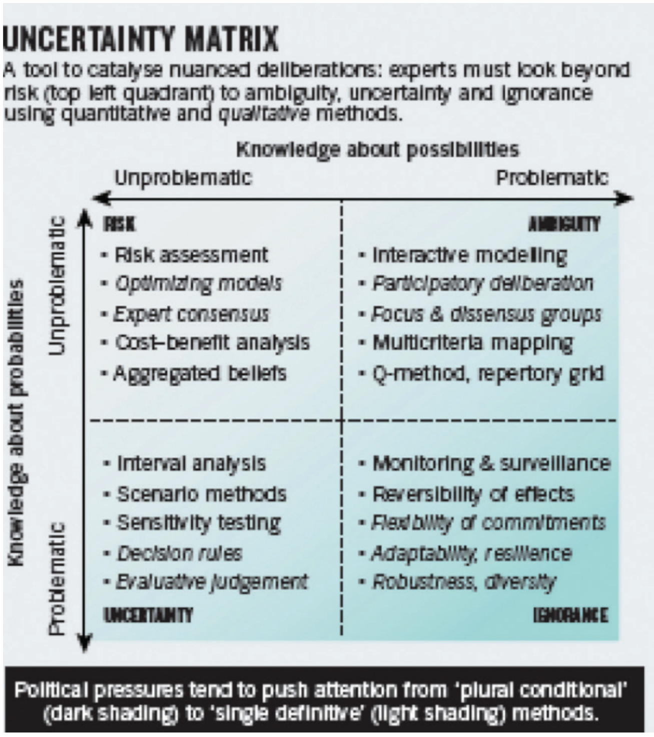
There are many types and sources of uncertainty including:

- sampling uncertainty,
- other study quality and design issues including ambiguity and inadequate reporting,
- inconsistency of results across multiple cost studies or evaluating reports,
- relevance of the data to valuation scenario, and the use of surrogate data,
- uncertainty of expert judgements, including differences between experts,
- applicability of default assumptions,
- uncertainty about which factors to include in the valuation,
- uncertainty about the structure of conceptual or quantitative models,
- dependencies between different elements of an assessment or model.

Within these uncertainties, the potential for unexpected events or changes in the overall environment also needs to be included. This is especially relevant for the valuation of infrastructure where a long-term view is often necessary.

How such uncertainties are characterised and their influence explored in the context of decision making in general (including project appraisal) varies a great deal and has been considered by many people interested in decision making. In practical terms, there is no single "correct" way to take account of uncertainty: how it is done will depend on context. The diagram included in Stirling (2010, p.1030) gives a helpful frame of reference.

Figure 1



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At one extreme, it is not uncommon to ignore uncertainty altogether in appraisal. This may be for many reasons:

- Level of uncertainty is perceived as low;
- Choice is too insignificant to merit the extra analysis time;
- Political context will not allow explicit recognition of uncertainty;
- Difficulty in characterising and/or bounding the range of the uncertainty.

At the other extreme, some issues may by so suffused with deep uncertainty, that it is not clear how to comprehend or represent that uncertainty.

It is typical for experts to describe uncertainty in qualitative terms; for example, high confidence or low probability. These types of expression do not give the range or likelihood of alternative outcomes. It is well known that qualitative expressions are ambiguous. A verbal expression of uncertainty can be interpreted in vastly different ways by different people.

Therefore, decision-makers could under – or over-interpret the uncertainty in the valuations, which could lead to incorrect decisions. It is not sufficient to identify and describe uncertainties associated with a valuation: it is essential to evaluate their potential impacts on the valuation. If this is not done explicitly as part of the analysis, then it will be done implicitly by the decision maker. Decision makers using any valuation should take account of the quality of the analysis that has been presented to them. When there have been resource constraints that could have a negative impact on the quality of the analysis, the decision-maker needs to decide whether this implies additional uncertainty about the valuations beyond what is indicated by the analysis.

There are many techniques for quantifying uncertainty. Uncertainty can be characterised and analysed with methods of increasing time requirements, resources and specialist expertise. The sophistication of the uncertainty analysis should match the requirements of the decision problem and the costs should be realistic given the circumstances. If there are uncertainties for which nothing can be said about its impact on the valuation (often called deep uncertainties), the value of the system under consideration could be anything. The presence of deep uncertainties has great implications for decision-making. In this situation, decision makers are likely to use strategies that are precautionary that can be implemented alongside the monitoring of the system being valued.

Stirling suggests that issues of resilience and adaptability (issues germane to infrastructure) rightly belong in the bottom right (Ignorance) quadrant and that government decision making methods typically inhabit the top left (Risk) quadrant of the diagram above. He argues for more nuanced deliberation, moving from the top left into the other quadrants. In terms of securing deeper understanding of the issues involved, this is hard to argue against, but, for many types of public investment decision, moving into those other three quadrants is effectively saying in terms of process and governance that the decision will either (a) be reached through essentially discursive, political means or (b) that following deeper consideration, the detailed process of choice will be returned to the top left quadrant.

Against this background, it may be worthwhile, while not excluding other ways of exploring and characterising the uncertainty faced in certain types of investment choice, nonetheless to review how some procedures closer to the top left quadrant might be implemented in a way that is sympathetic to reflecting characteristics of infrastructure investment, where this seems that it could make a material difference to the types of investment options that are considered and ultimately pursued.

Two typical characteristics germane to infrastructure that we will bear in mind in our review are 'systemic resilience', the ability of a system to recover or adapt to extreme events or long-term changes (introduced in chapter two, above) and 'passive provision', where an investment makes possible (but does not necessitate) adoption of future new investments (explained further below – both in this chapter, and in subsequent chapters).

Standard approaches to incorporating uncertainty in project appraisal

The outcome of a project appraisal is typically a decision to incur cost in order to undertake an action in the expectation that the action will generate a (uncertain) future flow of benefits. Exactly what action is taken will depend upon many factors, but is typically primarily influenced by:

A One or more alternatives to be appraised

U A view about what uncertainties are to be considered, and how.

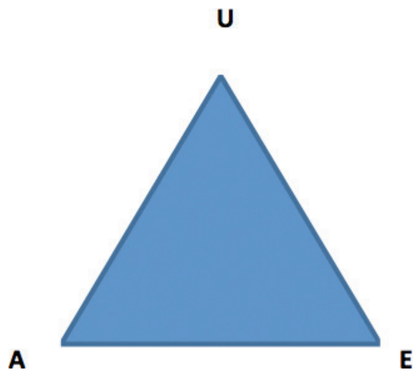
E An evaluation model which is likely to involve modelling of impacts (I) and a valuation process which might typically be cost-benefit analysis (CBA), multi-criteria analysis (MCA) or a combination of the two.

While other factors, such as budget and time available for making the choice, may well be relevant to the outcome, the above three are arguably the fundamental components.

In practice, there is a good deal of interdependence between these three. For example:

- The degree of uncertainty and the time frame over which it may be resolved may influence the range and number of alternatives that can be considered.
- The number of alternatives considered may influence the evaluation procedure adopted for each one, because of modelling or data gathering requirements.
- The evaluation procedure used may need to reflect the uncertainty faced, since some evaluation methods are difficult to combine into formal decision guidance with some ways of characterising uncertainty.

Figure 2



Specifically in the context of evaluation responding to systemic resilience and passive provision and concerns that failure to recognise these two factors may distort choice of projects, arguably it is the U and then the A dimensions that need to be the prime focus. This is because the main policy concerns are that uncertainty and its consequences may not have been properly accounted for and that the range of alternatives considered may have been either biased or too narrow. The E procedure applied to any individual alternative may have to respond to how U and A are addressed, and may have to respond in terms of the framework of impacts to be captured and evaluated, but will not be a primary driver of shaping an approach that duly acknowledges the potential importance of resilience and passive provision.

A deterministic appraisal

In a very simple case, there might be just one alternative to appraise (perhaps against some external performance benchmark like npv), uncertainty may be considered to be negligible relative to the scale of the investment, and a single impact and cba model would be applied. Modelled npv would be compared with the benchmark and a choice made accordingly.

Sensitivity testing

If the appraisal requires a slightly more thorough analysis (perhaps the scale of investment is larger or there are doubts about the accuracy of the modelled impacts) then sensitivity analysis offers a simple extension. Critical input parameters to the overall appraisal are identified by some combination of domain expertise and experimentation. For example, the critical inputs might be investment cost and forecast demand. The full appraisal process is repeated but with, one by one, each of the critical inputs adjusted to a new value. So cost and demand might be subject, say, to +/ – 20% adjustments and four additional appraisal calculations performed. Out of such a process may come reassurance (the decision suggested by the original analysis holds good even if the inputs are amended), so the original choice appears robust to these changes, or some doubt (changing the inputs significantly changes the appraisal recommendation). In the latter case, there is no fully specified way forward. The sensitivity testing process has simply served to sensitise the decision maker to the fact that the choice has some clear dependence on certain of the input assumptions. Typical responses might be to do further work to assure the accuracy of the inputs or to look for a re-designed alternative that is less sensitive in its performance to the uncertainties just explored. Nonetheless, for relatively simple appraisals, sensitivity testing in this form offers valuable insights at limited extra cost and effort. It can also be a useful first step in focusing more sophisticated analysis.

Monte Carlo risk analysis

Sensitivity testing is typically performed one variable at a time and considering only a small number of fairly arbitrary adjustments to the initial appraisal inputs. Ready availability of powerful spreadsheet packages, plus specialised commercial packages (@Risk and Crystal Ball are two well-known examples) now make it quite straightforward in principle to undertake a more sophisticated sensitivity testing in which:

- The consequences for chosen key performance indicators of varying several input variables simultaneously is modelled
- Uncertainty in input values is represented by statistical distributions of possible values for those inputs rather than individual discrete adjustments

This process, Monte Carlo risk analysis is performed straightforwardly, using an add-in capability for a standard spreadsheet, so that any appraisal that might typically run in deterministic form in a spreadsheet can readily be subject to risk analysis. The outcome is that, instead of a set of single-number, deterministic performance indicators for each alternative, a probability distribution of possible values for each indicator is made available.

An analysis of this kind generates extra insights for relatively low cost and effort. However:

- It does not rank alternatives or directly determine whether benchmark levels will be met;
- Extra analytical effort is needed to generate the probability distributions of inputs and the accuracy of these distributions may be difficult to guarantee;
- It is important to consider correlations between the input values, for which data or more general understanding may be hard to come across.

A non-standard approach to valuation under uncertainty: real option analysis

A standard risk analysis is individual and static. It is applied to a single, fixed (investment) proposal with no opportunity for reaction or amendment in the light of better knowledge or understanding gained over time or the possibility of new technology. For this, an explicitly dynamic modelling and appraisal process needs to be put in place. Flexibility, it is argued, is undervalued in conventional appraisal. One possibility that in principle meets these requirements is appraisal from the perspective of option value or real options analysis. (For a useful clear introduction to real options, see OFGEM (2012) chapter 2).

Real options

Financial options have been traded and the process analysed academically for a long time, back at least as far as the Black-Scholes work of the 1970's. Work on real options is often linked to Dixit and Pindyck (1994) and reflects the fact that, analogously with traded financial options, the opportunity to exercise an option at some time in the future has value to the owner of that option. In that sense, in the face of uncertainty, an investment with some available optionality is more valuable than an equivalent with no optionality. More concretely, an investment that for example may be implemented in a time-staged fashion such that later stages need not be undertaken if unfolding circumstances do not merit it, is more valuable than an equivalent that has to be completed in a single stage, provided that the cost of the staging does not outweigh the potential benefits of the element of 'wait-and-see'. The key considerations here are uncertainty, learning about the future (possibly including even just basic 'wait-and-see'), and the possibility to adjust behaviour in the light of how the uncertainty unfolds. Investments that are resilient or offer an element of passive provision have potential benefits in these regards that will not normally be captured by conventional static appraisal. As a result, such investments (which might well involve limiting physical investment commitment in favour of more flexible regulatory or market-based mechanisms) will be systematically under-valued by conventional appraisal.

Awareness of the possible systematic undervaluation of flexible investments can be traced back to the 1980s and the elements of at least one way to respond to this, using decision trees, have been well understood within the decision science literature since at least the 1960s. However, this and related approaches that directly address uncertainty have not to any great extent fed through into appraisal practice, for a number of reasons. However, society now is arguably much more sensitised to risk/uncertainty and to responses to it, than in the past. Important elements of the external environment, notably climate, appear to be changing rapidly and, to a degree, unpredictably.

All this, combined with the realisation that flexibility has a value that can be formalised and incorporated in analytical decision making, suggests that a look at the practicality of real options analysis could be worthwhile. There are some potentially demanding issues of principle and practice that have to be addressed in moving from an acceptance of the general idea of option value to its use in infrastructure appraisal practice, but understanding and reflecting on what these are in itself could be a useful exercise. Even if not all these issues can be fully turned aside, it might, for example, be possible to identify typical circumstances in which even an imperfect real options analysis may add value to the broader appraisal process.

Real Options Analysis as a move from static to dynamic evaluation and appraisal

The publication of the Green Book supplement, Accounting for the Effects of Climate Change, in 2009 and subsequent work by OFGEM (2012) has raised the profile of real options analysis in UK infrastructure project appraisal in the last five years. Both these pieces of work present the use of real options analysis (ROA) in terms of decision tree assessments of choosing a (partially) deferred investment in preference to an immediate, 'all-or-nothing' one with that preference being driven by the fact that the passing of time allows greater clarity about the future state of the world in which the investment will have to function.

Moving to a ROA framework essentially changes the frame of reference from making a once-and-for-all decision to choosing the first step along a path. In doing so, it provides a framework for valuing flexibility (and differences in flexibility between options) along the path that conventional project appraisal does not. It allows for the potential to learn more about matters relevant to the appraisal that are not currently well understood. It puts an emphasis on identifying different future sets of circumstances and on design/development opportunities that might respond to the unexpected or the merely possible. Not making the decision now but choosing to postpone by keeping at least some aspects of the choice open is sensible if it opens up a way of acting that, with the benefit of hindsight, may be better than the one you would choose if you were to make a commitment straight away. Essentially, the choice is being re-framed, away from being a static one to one which is dynamic and whose details will unfold over time. A static framing systematically undervalues opportunities that provide future options.

More specifically and building on the OFGEM and Green Book thinking, this move from static to dynamic can make particular sense when:

- The project is significant in terms of financial scale or other indictors of importance – ROA typically involves more analytical effort and so is not justified if the projects of limited significance
- Has performance elements that will be significantly affected by an uncertain external environment
- May involve important irreversible impacts

However, postponement of aspects of the choice only makes sense if, again drawing on the references cited earlier, if:

- There is a significant degree of uncertainty
- The future options being considered can indeed be implemented
- There is sufficient time for meaningful learning to take place
- The cost of information and extra analysis are not disproportionate to the scale of the decision

To establish this information, some type of prior risk assessment, quite possibly qualitative in the first instance, is advisable.

Suppose the circumstances of the investment "pass" in terms of the criteria just outlined. What issues now have to be addressed? It is possible to set out some general guidelines in this respect, although much of the implementation detail can turn out to be domain-specific, or even application-specific.

Having said that, many researchers favour seeing real options as a component of an extended net present value, rather than as something separate or competitive:

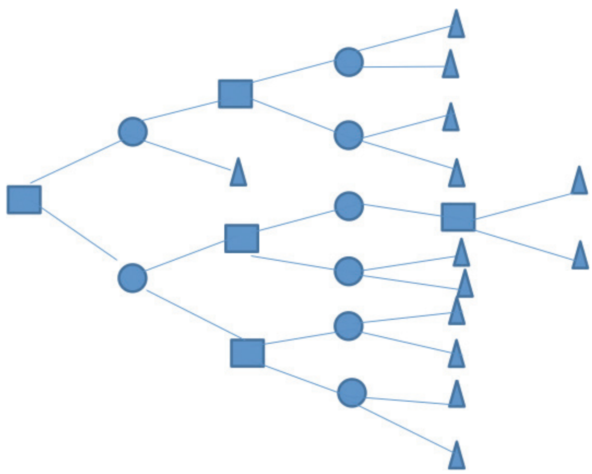
Total value = Standard npv + real option value

Thus in cases of high uncertainty but also a large amount of flexibility, standard npv may particularly undervalue an investment. Standard npv's are likely to be at their highest in the early years of a project (because of discounting) with the real option component more valuable later, when uncertainty is higher and flexibility more valuable. A contingent approach to ROA application, involving growing degrees of sophistication only where merited, is recommended by Eschenbach et al. (2007), for example.

Decision tree representation

Although not the only way of representing the problem faced in a real options appraisal, it is helpful initially to consider a decision tree diagram such as the following:

Figure 3



Squares nodes are termed decision nodes; where the "decision maker" has to make a choice. The square node on the far left is called the root node and marks the beginning of the decision process. Circular nodes are termed chance nodes and mark a time when an uncertainty will be resolved. Triangular nodes are payoff nodes, the final evaluated consequence of a particular pathway of decisions and resolutions of uncertainty. The diagram serves to highlight a number of issues.

Alternatives (at decision nodes). At the start of the process it may be very difficult to envisage the full set of alternatives that will be available and when.

Uncertainties (chance nodes). Similarly, what eventualities will present themselves over the life of the project may be far from clear. Additionally, even if the structure of uncertainty is understood, the probabilities associated with different possible outcomes may well not. Moreover, these probabilities may well change with time as other information becomes available.

(Payoff) **Evaluation** (outcome nodes). Forecasting the potential impacts of each sequence of decisions is a potentially demanding task.

In a nutshell, the abstract representation provided by the decision tree is useful, but the practicalities need to be addressed and are not always straightforward. An informal review of the academic literature suggests that use of real options on real problems is still quite limited. Block (2007) asked: Are "real options" actually used in the real world? His survey revealed that only 40 out of 279 responding companies were using the approach in capital budgeting. Bennouna et al. (2010) found a figure of 8%.

However, it is worth bearing in mind that decision tree analysis is regularly used to underpin choice of action in the real world and also that many of the problems mentioned above also impact conventional appraisal. Arguably, conventional appraisal sweeps them under the carpet and thinking in real option/decision tree terms is just doing some overdue domestic chores.

The decision tree can be used qualitatively to help understand the structure of the range of future choices available as well as in the more familiar quantitative way. Indeed, it is a good idea to reflect on the nature of the decision first in a qualitative way. But to replace the functionality of standard quantitative appraisal, the ROA needs be quantitative as well. In making this jump, a key question, of course, is how to do it? What practical issues need to be addressed? What evidence is there to date of successful application to infrastructure projects? What types of project?

Difficulties of implementation

Implementing ROA within the decision tree format described thus far is potentially useful and feasible, but with caveats:

- Using the decision tree format to think more or less qualitatively about the structure of the choice faced, the options, the uncertainties and their timing and possible resolution is likely to be valuable in itself. This need only be slightly more sophisticated than 'back of envelope'.
- If the qualitative analysis suggests that flexibility may be valuable (and hence some version of an ROA should be performed) then a choice of how to implement must be made. A full implementation of the (discrete event) decision analysis described earlier may involve a very large amount of computation, difficulty in fully identifying options and complexities such as Bayesian up-dating of (subjective) probability estimates as progress of the project is monitored. It is likely to be appropriate for important and relatively well structured problems.
- It may be worthwhile initially to extend the qualitative analysis just one stage to a simplified version of how the full problem could be represented. For example, a limited time horizon for detailed modelling; only representative investment options considered; broad brush estimates of probabilities. This may be enough to provide the insights required. As with many appraisal procedures, sensitivity testing is an important adjunct to ROA.
- If a more thorough analysis appears necessary, then substantial modelling, forecasting resources will be needed and/or it may be worthwhile to move to a way of applying the decision tree/ROA logic that moves away from the discrete modelling framework used so far and closer to the type of recognition of uncertainty and potential decisions used in financial options modelling.

Examples of this latter type of approach applied within an infrastructure investment appraisal framework include de Reyck et al. (2008), Pendharkar (2010), Guj (2011) and Lara Galera and Solino (2010). A thread running through many of these applications is alternative ways of characterising and estimating risk and developments in risk over time, a topic which will be explored in the next section of this chapter.

An alternative approach which in the right circumstances can have merit is to move to an explicitly multi-criteria analysis with uncertainty, volatility or some similar measure included as one of the evaluation criteria (see Dodgson et al. (2000), pp. 69/70. An application of multi-criteria analysis to address dependent infrastructure evaluation is presented by Haigh (2014).

Other approaches that seek to implement ROA in a way that responds to some of the practical difficulties identified above include the use of simpler decision criteria (e.g., maximin and minimax regret, see Colombo and Byer (2012), and use of scenario-based cost benefit analysis to characterise the range of future uncertainties, combined with some qualitative assessment of outcomes (e.g., Frontier Economics, 2013).

Although ROA is arguably a good way to broaden the scope and increase the realism and accuracy of what may be thought of as standard project appraisals, not all issues are readily modelled and assessed in this way. Especially as time horizons lengthen, scientific understanding becomes less confident and uncertainties become "deep" (see below), alternative ways of supporting public decision making are needed.

Case study examples of techniques for dealing with uncertainty applied to infrastructure

In this section, we give a range of examples of where advanced techniques for dealing with uncertainty in decision-making have been used for valuing infrastructure.

Uncertainties in the inputs of the analysis can sometimes be characterised through probability distributions. This approach gives rise to probabilistic modelling. Probability distributions that encode beliefs about the uncertainties can be derived using statistical analysis techniques and through the formal capture of expert judgements. In both cases, care must be taken to record the assumptions underpinning the chosen probability distributions. Uncertainty encoded in probability distributions may be propagated through the valuation model by repeating the calculation after sampling different values from the distributions. This can be done by Monte Carlo simulation (see Example 1).

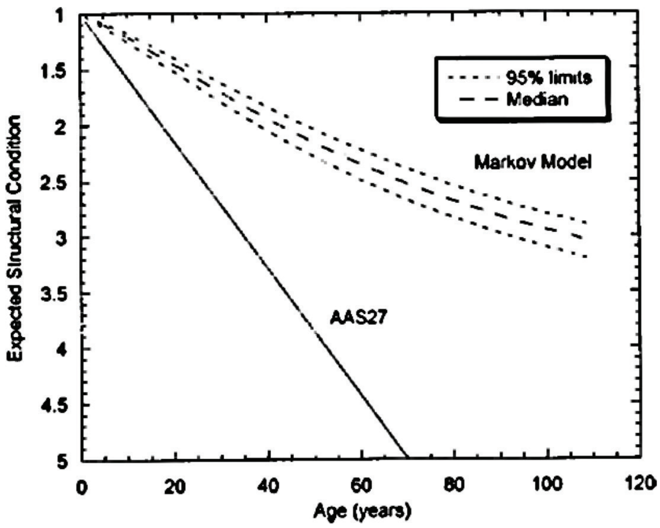
Example 1: storm pipe deterioration.

Micevski et al. (2002) model the deterioration of storm pipes in Newcastle, Australia using a simple probability model that aims to replicate the transition between several stages of deterioration.

Structural condition	Physical description
1	Near perfect condition
2	Some superficial deterioration
3	Serious deterioration, requiring substantial maintenance
4	Deterioration affects the fabric of the asset, requiring major reconstruction or refurbishment
5	Deterioration is such to render the asset unserviceable

In order to run the model, parameters need to be specified. The probabilities of transition from one stage to the next are key parameters and can be estimated from data. Given probability distributions on the parameters of the model, it is possible to propagate the uncertainty to an end-point of interest. For instance, the expected structural condition of a storm pipe over time can be compared with Australian accounting standards (AAS27) and credible intervals can be produced for each time point using Monte Carlo simulation.[1] Here, we repeatedly select input values at random and rum them through the model to get a distribution of possible outcomes for each pipe age.

Figure 4



In the context of probabilistic modelling, elicitation is the process of translating experts' beliefs about some uncertain quantities into a probability distribution. Elicitation can help us to take stock of the uncertainty about quantities of interest without the cost of data collection. Elicitation is far from being a precise science. It can be difficult for the experts to articulate their beliefs, and there are other complications due to the biases of experts and the biases created by the questioning process. Feedback of the results is important to confirm the fitted distributions are representative of the experts' beliefs. Ideally, all fitted distributions that are used in the subsequent valuation model should be reviewed with the experts. Due to the subjective nature of elicitation, it is important to make the process as transparent as possible. A written record should be kept of any interviews or workshops. These should include details of experts present at the meeting, a summary of each expert's relevant expertise and declarations of interest obtained from them at the start of the elicitation process. The declarations of interest are recorded for the purposes of transparency only and are not used as grounds for exclusion from the elicitation. Example 2 highlights elicitation being used in the design of nuclear waste storage.

Example 2: evaluation of underground repository for nuclear waste.

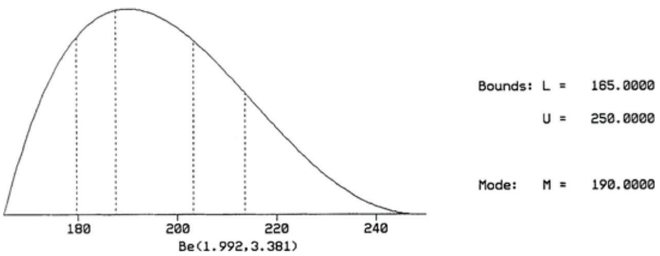
O'Hagan (1998) describes an expert elicitation exercise that aimed at evaluating a deep underground repository for nuclear waste work in work commissioned by Her Majesty's Inspectorate of Pollution.[2]

In a two day elicitation exercise, several experts in hydrology were asked to make judgements about the average log-conductivity over the whole site amongst other quantities of interest. The expert was asked to make judgements about the most likely value and the probability of the true value lying on defined intervals. This led to judgements of the type:

Modal value = 190,
Probability between 165.0 and 177.5 = 0.175,
Probability between 177.5 and 190.0 = 0.325,
Probability between 190.0 and 205.0 = 0.250,
Probability between 205.0 and 250.0 = 0.250.

Given the judgements, it is possible to find "best" fitting probability distributions that the experts' are willing to accept as their own. In this case, a beta distribution was found to appropriate.

Figure 5



After propagating uncertainty in the model inputs through to the valuation, sensitivity analyses can be formed to help judge the relative contributions of the modelled uncertainties to the overall uncertainty. These methods can be valuable if further resources are available to reduce the most important uncertainties. One particular measure of interest is the proportion of overall variance that is attributable to each uncertain model input.

Instead of simply selecting probability distributions to encode uncertainty about model parameters, we can use formal approaches to synthesising information that result in probability distributions. Bayesian statistical methods provide a framework for synthesising data with expert judgements. Bayesian methods are a form of probabilistic modelling and, as such, lead to probability distributions on the quantities of interest.

The basic idea of these methods is to start with some appreciation of uncertainty for the quantities of interest and update them in the light of new data. The starting point (or prior) is usually modelled within this framework using probability distribution and it is updated in the light of data using the likelihood. The likelihood is the distribution for the data that is familiar from classical statistics. The result is the posterior that encodes uncertainty about the parameters of interest given the information from the data. Although Bayesian methods are based upon coherent and rigorous principles, there can be substantial overheads in the computation of the posterior and in the initial set-up of the prior and likelihood. In most reasonably complicated situations, a high level of statistical expertise is needed to perform this type of analysis (see Example 3).

Example 3: water industry asset valuation

In order to value the assets as part of the investment plans, newly-formed water companies in the 1990s needed to estimate the condition of the existing infrastructure and future costs. Because most of a water company's assets were underground, the condition of the assets was not known in any detail and the determination of their condition by field studies was too costly.

O'Hagan et al. (1992) used Bayesian methods to estimate the amount of capital investment that would be required to maintain, improve and extend water industry assets over a twenty year period. Bayesian methods were used because they provide a framework for combining experts' judgements on the future costs with the (limited) data on the condition of existing infrastructure.

Experts' opinions were elicited on the costs of maintenance and expansion of the infrastructure in different areas. For example, for two of the areas, the following was elicited for the prior:

Area	Prior mean	Prior standard deviation
6	£16,084k	£7,475k
12	£10,661k	£4,117k

The expert judgements were updated with cost information recorded from several study areas. This updating gives rise to the following posteriors (it should be noted that area 6 was a study area and area 12 was not):

Area	Posterior mean	Posterior standard deviation
6	£7,000k	£1,894k
12	£8,397k	£3,676k

There is an appreciable reduction in the standard deviation for both areas (which means that there is a reduction in uncertainty). The reduction is greater for area 6 because there was data available for that area. The Bayesian model here not only modelled the experts' uncertainty about the costs, but also allowed for judgements to be made on the uncertainty in the recorded information.

As mentioned earlier, there will be some situations where quantification is not practical due to cost or lack of knowledge. In such cases, a decision maker may apply the precautionary principle or turn to sensitivity analyses. Methods such as scenario modelling and robustness analysis can be helpful to decision makers in this situation.

When the uncertainties seem to be too complex to model quantitatively, experts often use scenario modelling so that quantitative judgements can be made based on a number of plausible future scenarios. The danger with this approach is that the decision maker may put too much faith in a particular scenario that seems to match their beliefs about the future. This could lead to overconfidence in certain outcomes. Therefore, it is important for the expert to give an appreciation of the likelihood of each scenario and to state that the chosen scenarios are just an infinitesimal part of the overall space of possible scenarios. However, if the expert produces information on a wide range of scenarios and the outcomes are similar, this may build confidence in the outcome.

Robustness analysis offers a more comprehensive version of scenario modelling where all of the possible values for the model inputs are used to value the system. Using this method, there is no information on what value is most likely, but we can find the range of possible values. In some cases, this range could be enough to make a decision if the range is far away from the point of concern. Of course, our ability to do this depends on the computational burden of the valuation model and the ability to define the space of all possibilities.

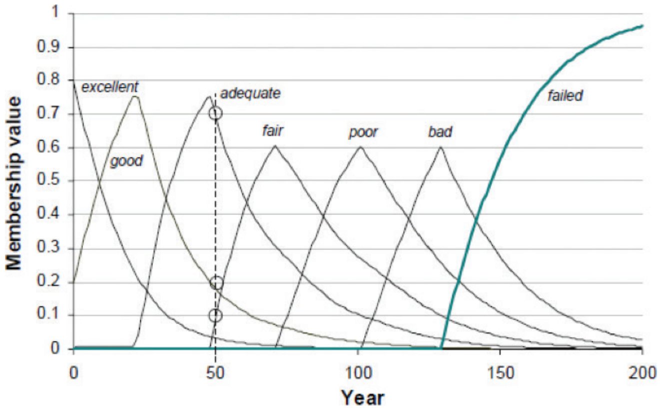
In addition to these approaches, minimax strategies, fuzzy logic (see Example 4) and possibility analysis are other structured ways of performing this type of analysis. Each has its own demands on information needed to set up the model and the resource required to complete computations.

Example 4: deterioration of buried infrastructure

Kleiner et al. (2006) presented a model of the deterioration of buried infrastructure that was applied to pre-stressed concrete cylinder pipes in Arizona, US. To characterise the uncertainty, they used fuzzy sets to model uncertainty in the age and condition of the pipes.

The basic idea when using fuzzy sets and fuzzy logic is to assign membership values to different sets. In Kleiner et al. (2006), the sets of interest were derived from the condition of the pipes giving rise to seven sets from excellent condition to failed. For each pipe, a membership value between 0 and 1 is assigned. In the following graph, the modelled membership value for a pipe is plotted over time.[3]

Figure 6



The membership value is not a probability: it is a measure of how much a pipe is in each defined set rather than being a probability of being in any set. For instance, the modelled pipe at year fifty could be classified as adequate, fair or excellent or it could be something outside. This allows us to accommodate uncertainty in the set definitions that need to be fixed in a probabilistic analysis.

We will rarely be able to formally quantify all uncertainties that could potentially affect the valuation. These unquantified uncertainties must also be made transparent and qualitatively evaluated because it is the overall appreciation of uncertainty that is important for decision-making. In these situations, methods like uncertainty tables, multi-criteria mapping and participatory processes amongst others have been used to highlight and judge the potential impact of the unquantified uncertainties (as mentioned above, with reference to the work by Stirling, 2010).

Evaluating uncertainties outside the quantitative analysis can be done following the same basic principles of quantitative analysis. First, the individual sources of uncertainty are evaluated, and, afterwards, the combined effect of the individual uncertainties are considered. This approach to capturing and evaluating unquantified uncertainties is implemented in the uncertainty table approach (see Example 5).

Example 5: assessing the impact of contaminated land

Gosling et al. (2010) describes a probabilistic modelling exercise that was commissioned by Defra to perform uncertainty and sensitivity analyses on risk characterisations of contaminated land. The output of interest was the level of exposure for users of the sites.

Although there were measurements taken at sites and data available, there were many uncertainties that could not be modelled quantitatively due to incomplete knowledge and time constraints. As part of the work, uncertainty tables were produced (as described in Hart et al., 2010) to capture the unquantified uncertainties. The following is an example uncertainty table for unquantified uncertainties stemming from modelling assumptions.

Source of uncertainty	Magnitude & direction
The equations in the model are not a perfect representation of reality.	– – /++
Average values are often used in site-specific assessments. This could lead to variability in the actual values being underplayed.	– /+
The chemical concentration in the soil does not degrade over time.	– –/–
Overall assessment of uncertainty: it is a logical approach to modelling exposure from contaminated land. However, there are many choices that could have an impact on the exposure estimate.	– –/++

The +/ – symbols indicate whether each source of uncertainty has the potential to increase (+) or decrease (-) the assessment outcome. The number of symbols provides a subjective relative evaluation of the magnitude of the effect (e.g. +++ indicates an uncertainty that could make the reported risk much higher). A • is used to represent an unquantified uncertainty that is thought to have no appreciable effect on the estimated risk. If the effect is uncertain, or could vary over a range, lower and upper evaluations are given (e.g. – / ++ or • / ++). Finally, the combined impact of all the uncertainties is evaluated subjectively by considering all of the row-wise judgements.

Whatever technique is used to characterise the uncertainties in the valuation process, there should be a guiding principle of transparency and effort should be spent in communicating the implications to the decision maker. It is clear that the additional effort required will put the decision maker to make full use of any infrastructure valuation.

Ways ahead?

In those areas where systems modelling, risk assessment and option identification are relatively straightforward, ROA throws a light on the appraisal of infrastructure projects in the presence of flexibility and uncertainty which is potentially different from conventional appraisal and can lead to arguably superior investment choices. It is conceptually straightforward and, indeed, the framework for the basic modelling and evaluation has been present through the decision tree modelling employed in decision analysis for many decades. But it is still not in routine use as an appraisal technique, largely because (a) the modelling and associated analytical requirements can be very demanding in practical terms once the issue to be decided gets at all complex; (b) some of the procedures used to simplify the analysis lie outside the mathematical and statistical understanding of many potential users and/or decision makers. In the latter case, lack of understanding of the methods can breed lack of confidence in the recommendations. However, implementation can be facilitated by exploiting some of the growing range of ways of quantifying uncertainty that are set out in the previous section which are increasingly finding their way into practice.

Granted that ROA is typically more time-consuming and expensive to implement than standard appraisal procedures, nonetheless, for certain decisions, the benefits in terms of better decision process (and hopefully decision outcome) can be substantial. Work to develop application guidelines that are well focused on a range of typical infrastructure investment decisions, backed up by case studies, could be very valuable.

In those areas where the nature of the policy dilemma being faced involves long-term, strategic decision making in the face of deep uncertainty, some of the scenario based and similar approaches to strategic thinking are potentially valuable. Inevitably, the specificity of the information input to, and drawn from, such exercises is less, but as the previous section has illustrated, there are also formal ways to represent uncertainty in these circumstances that can bring a degree of rigour to the overall evaluation process.

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Footnotes

[1] The structural rating and graph in this example are reproduced from Micevski et al. (2002).

[2] The elicited judgements and graph in this example are reproduced from O'Hagan (1998), and the judgements were part of a training exercise rather than the actual, confidential judgements.

[3] The graph is reproduced from Kleiner et al. (2006).

Chapter 4:

Economic evaluation of passive provision in sustainable energy provision

Chapter 4
Economic evaluation of passive provision in sustainable energy provision

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Introduction

Investment in energy infrastructure systems is a key part of UK's National Infrastructure Plan. This aims to deliver energy policy objectives of reducing carbon emissions, ensuring energy security and delivering affordable energy, whilst contributing to UK's economic development. Under the 2008 Climate Change Act, the UK has a goal of reducing its carbon emissions by 80% by 2050, from 1990 levels. This will require deployment of significant amounts of low carbon electricity generation and heat provision technologies, as well as radical improvements in the efficiency of delivery of energy services. This and the next chapter draw on our work on the values and business models associated with local low carbon energy systems, particularly for electricity distribution smart grids and district heat networks.

Passive provision is defined as the facilitation of real options within an investment opportunity or action. Here, a "Real Option" is an alternative or choice that becomes available through an investment opportunity or action. This approach is incorporated in existing Treasury guidance on accounting for the effects of climate change[1], by for example, designing an activity with the flexibility to upgrade in the future provides an option to deal with more (or less) severe climate change. The real options approach has been identified as appropriate for policies, programmes and projects showing: *uncertainty, flexibility, learning potential*, (see Chapter 3), where

- Uncertainty: outcomes are difficult to project;
- Flexibility: benefits of information acquired by early investment;
- Learning potential: technological and/or institutional learning generated by early investment.

This is important in the case of energy systems investment, which is susceptible to the dynamic, systemic and partial public good characteristics of infrastructure identified in Chapter 1. Investment needs to contribute to delivering the public good goals of decarbonisation, energy security and affordability, whilst being subject to high levels of uncertainty in relation to:

- the role of any particular investment in relation to wider infrastructure systems;
- the costs and benefits of social and environment impacts of these investments;
- the future dynamics of infrastructure systems change;
- the impact of external changes, such as global energy prices;
- cultural changes to the importance assigned to different social, environmental and economic outcomes.

Flexibility is required, due to the uncertainties in the mix of demand side and supply side options needed to meet low carbon targets. Early investment can provide information on the technical performance, fit with systems and public acceptability of different low carbon options. In addition, early investment can generate learning both in the development of low carbon technologies and in the market and regulatory systems designed to support low carbon systems change.

It has been argued that including real options valuation is particularly relevant for investment in early stage low carbon energy technologies, such as solar PV and other distributed generation technologies, as these investments show uncertainty, flexibility and learning potential. This argument was made in a 2003 report commissioned by the UK Department of Trade and Industry (as was), co-written by one of the present authors (Foxon et al., 2003). This report argues that investment in early stage renewable energy technologies provides a case in which:

> *"Actions that create options, which we may later choose to exercise or not, have an additional value – the 'option value' – if the future is uncertain and decisions are wholly or largely irreversible. The additional cost of investing now to create or keep open the option may well be outweighed by the additional benefit that would accrue if the option is needed, given that we may choose not to exercise the option if further information tells us that it is not needed."*
>
> **(Foxon et al., 2003, p.10).**

Further, it argues that "This option value is complemented, in the case of early stage technology development, *by the positive benefits of learning*, leading to cost reductions – 'moving down the learning curve (IEA, 2000)' – *that accrue if investment is made in experiments to gain experience*."

The point here is the initial investment, in the early stages of low carbon technology innovation, creates a future option through enabling learning to take place *and in doing so leads to increased future information. It is not a case of waiting to see if new information* arises, rather the option to be valued is precisely one which *will* (amongst other things) increase future information. Thus the initial investment increases the resilience of the system, through *inter alia* increasing the knowledge-base. This is not quite 'passive' provision, given the *active* information increasing role of the initial investment. It is (in appropriate conditions) captured through real options valuation.

It may be helpful to quote the report a bit more to further illustrate the point:

> *"Previously in energy policy, 'keeping an option open' has usually referred to a mature technology, such as nuclear power or deep mined coal, which is currently economically unattractive, but which would be lost if investment is not made to maintain current capability.*
>
> *Here, we are referring to technologies in the earlier stages of development. In this case, there are typically long lead times and large amounts of investment needed for such technologies to advance to commercialisation. Thus, for such a technology to form an 'option' capable of making a significant contribution to renewable energy and carbon reduction targets in the medium term … it is likely to need to at least move into the pre-commercial stage of large scale demonstration in the short term. The technology would then have the opportunity to demonstrate its technical and economic feasibility, and to find and develop niche markets for its commercialisation.*
>
> *As further experience is gathered, [enabled by the initial investment in advancing an early stage technology to the pre-commercial stage] it may become clear that, for some technologies, the UK does not need to maintain a capability at each point in the supply chain, but should instead concentrate at high value-added at key points in the chain."*
>
> **(Foxon et al., 2003, p.11).**

This and the next chapter of the report go on to discuss the valuation of passive provision in the context of sustainable energy investments relating to 'smart grids' and 'heat networks'.

Valuation of passive provision for smart grid investments

Introducing smart grids as key infrastructures

Due to the privatisation of the UK energy system, electricity distribution infrastructure has not featured heavily in public procurement over the past two decades (Hall et al, 2012). However, new challenges for the energy system to deal with increasing amounts of distributed renewable energies and new demands on the system from the electrification of transport, heating and other sectors/uses means electricity distribution infrastructure is back on the agenda at both national and local level. Because of the relative absence of electricity distribution infrastructure in public infrastructure procurement, many actors are unfamiliar with the issues and challenges electricity distribution infrastructure faces over the short to medium term; yet the challenges of security of supply, decarbonisation and energy affordability demand new business models and infrastructure investments that will include new stakeholders in the smart grid.

The UK's electricity distribution infrastructure is increasingly under strain as it is being asked to transition from a system of simply distributing electricity from the transmission network to users, to one where small scale generators feed more and more electricity into the system, renewable energy needs balancing with flexible conventional plant, and smart meters open up new opportunities for energy efficiency and network management. Distribution Network Operators (DNOs) are increasingly using new technology and ICT to develop 'smart grids', in order to manage these changes and avoid expensive grid reinforcement. If the existing network can be used smartly, then new developments such as housing, business, new renewable energy sources, vehicle chargers and electricity storage can be connected without prohibitive cost which can slow down or stop economic development opportunities (Ofgem, 2013). However, the way electricity distribution regulation currently works in the UK means that some smart grid investments are harder to achieve than others, even when they could lead to significant gains in other parts of the economy and faster decarbonisation of the energy system.

The liberalisation and privatisation of the UK energy system led to competitive markets being created for generation and supply whilst transmission and distribution functions were moved to a regulated approach (Bolton and Foxon, 2013). As electricity generation and supply are competitive markets, the business models of generators and suppliers have relied on generating or selling more units of electricity at lower unit prices, with prices being defined by market conditions. The infrastructure that connects generators and consumers however, is not subject to competitive markets, as electricity transmission and distribution networks constitute natural monopolies.

As such the revenues derived by the operators of these infrastructures operate on a 'regulated asset base approach' where the system regulator (Ofgem) sets the allowable revenues structure, within which DNOs must cover expenditures as well as realise profit. This section summarises research aiming to discern whether the allowable revenues structure in the UK could sufficiently incentivise smart grid developments, and whether there are opportunities outside the allowable revenues structure to deliver passive provisioning of smart grids in order to realise the full potential of new smart infrastructures. Our full findings from phase 1 of this research are reported in Hall and Foxon (2014), based on interviews and focus groups with industry and municipal stakeholders.

4.2.2 Investing in smart grid innovation

Smart grids form a key part of the transition to low-carbon energy systems. The UK's energy regulator has estimated that meeting electricity system decarbonisation targets compatible with the UK's Climate Change Act 2008 (CCC, 2008) would require up to £32bn of investment in distribution assets by 2020 (Ofgem, 2010a).

Whilst there is no universal definition of what makes an electricity distribution grid 'smart', Xenias et al. (2014) define the main features of a smart grid as an energy network that can: *manage embedded suppliers; communicate between the producers and users of electricity; utilise ICT to respond to and manage demand; and ensure safe* and *secure electricity distribution*. The current electricity distribution system in the UK does not incorporate these features and, save some demonstration projects, is still a 'dumb' grid that is maintained to accommodate one-way power flow and ensure security of supply (Balta-Ozkan et al., 2014).

The allowable revenues structure that has hitherto been used to ensure delivery of distribution grid services since system privatisation has been based on the 'RPI-X formula'. RPI-X was used under the distribution price control reviews (DPCRs) to set allowable revenues for the seven Distribution Network Operators (DNOs). The DPCRs ran for five years each, at the time of writing the network remains under the DPCR 5 period (2010-2015), the last to use 'RPI-X' mechanism (Ofgem, 2010b). 'RPI-X' caps price increases to the distribution use of system charge (DUoS), the predominant revenue stream of DNOs levied on consumer bills. The DUoS charge cap is based on the rate of inflation defined by the Retail Prices Index minus a factor 'X' (hence, 'RPI – X'). 'X' is a function of the capital and operational expenditure (CAPEX and OPEX respectively) of the DNO. For the OPEX element, DNOs are incentivised by benchmarking against the best practice DNOs in the sector. The allowed OPEX recovery increases with incremental efficiency gains during the pricing period. For CAPEX, the asset value is the assessed value of the asset base, plus investment, minus depreciation. DNOs earn an allowed rate of return on these assets based on a weighted average cost of capital (WACC). Together with separately calculated service incentives, this represents the allowable revenue structure of the UK's regulated distribution business model, i.e. the charges a DNO can pass onto the users via DUoS. Any expenditure outside of this calculation is likely to be avoided as the DNO has no allowed revenue to recoup the expense.

There are two problems with this structure when discussing smart grid infrastructure and passive provision. Firstly the RPI-X mechanism has been described as unfit for incentivising smart grid investments on the grounds that it incentivises incremental efficiency gains over system innovation, thus failing to deliver environmental and social benefits (Müller, 2011). We call this the 'innovation incentive problem'. Secondly the allowable revenues structure does not allow DNOs to invest in their networks ahead of capacity, because predicted capacity may not materialise and the DNO can be left with the costs of a 'stranded asset'. This expenditure could not be recouped through the DUoS charge and therefore DNOs tend to avoid strategic investments ahead of need. We call this the 'strategic investment problem'. These two issues frustrate the development of smart grid infrastructures in the UK and in turn often increase the electricity network costs of wider innovations such as renewable energy proliferation, transport electrification and storage technologies.

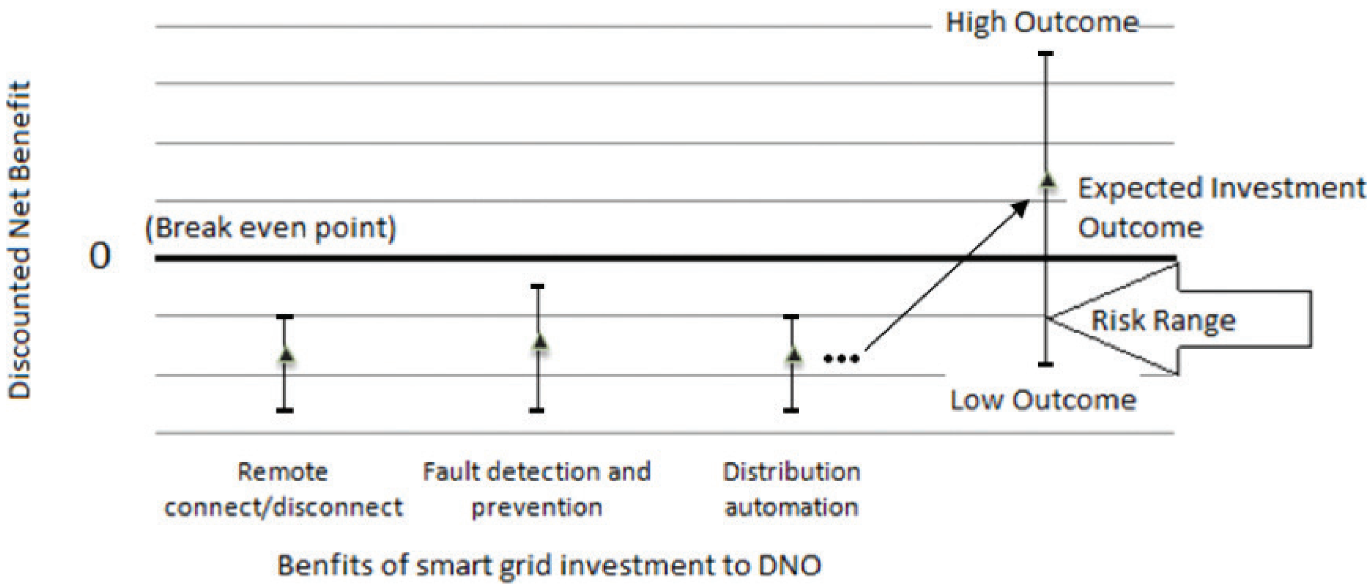
4.2.3 The innovation incentive and strategic investment problems.

There have been several incremental institutional changes to address the innovation incentive problem (see Xenias et al, 2014) chief amongst which has been the creation of grant funding for smart grid innovations, which DNOs can bid into for 'innovative' solutions, where 'innovation' here can be read as smart grid investments. As part of DPCR 5, Ofgem established the latest of these funds, the Low Carbon Networks (LCN) Fund. The LCN Fund allows up to £500m to support projects sponsored by the Distribution Network Operators (DNOs) to try out new technology, operating and commercial arrangements. The aim of LCN Fund is to embed smart grid solutions as business as usual for DNOs and to share information on projects delivered under LCN Funding (Ofgem, 2014). The LCN Fund has delivered a step change in the understanding of smart grid services (SPEN, 2013; SSE, 2012) and has contributed to the UK being considered a lead investor and innovator in smart grid applications in Europe (Giordano et al 2013; IET, 2013). However, in the face of a £32bn investment need over the next price control period, the current levels of innovation funding sources are likely to be insufficient for wide scale system change, and indeed were never intended to be so.

What is intended to be a step change in the investment opportunity is a move to an allowable revenues structure that can deal with the innovation investment problem. RPI-X is being replaced in order to move to an allowable revenues structure that better incentivises a 'timely delivery of a sustainable energy sector' (Ofgem, 2010b P.4). RPI-X is being replaced by the 'RIIO' framework (Ofgem, 2010b; Müller 2011). The RIIO (Revenue = Incentives + Innovation + Outputs) framework is a significant shift towards an allowable revenues structure that better incentivises smart grid solutions. This allows network constraints to be addressed through innovative applications of smart technologies which can then be routinely recouped through the DUoS charge. The difference between RPI-X and RIIO is the way network problems can be addressed. Where DNOs have problem areas, they may continue to fix them traditionally but can also routinely offer smart grid solutions. RIIO does not specify that DNOs have to install so many cables, so many overhead lines or so many transformers – it just mandates DNOs to fix problems in the most cost effective way (see Xenias et al, 2014; Müller, 2011; Ofgem, 2013).

RIIO allows smart grid technologies to be assessed alongside conventional reinforcement solutions, which is more in line with a commercial logic of technology deployment for best cost as opposed to constraining activities to those that meet regulatory standards. The RIIO approach brings the investment decision closer to a traditional cost benefit analysis where innovation and traditional solutions can compete on the basis of fiscal opportunity. This brings smart grid investment decisions in the UK closer to what Jackson (2011) describes as the 'smart grid investment problem' (Fig. 1) where the aggregated benefits of smart grid technology deployment define the likelihood of smart investments. Yet whereas Jackson (2011) includes remote meter reading and demand side management (DSR), these are un-captured values for DNOs due to the structure of the UK energy market (see below).

Figure 1: The smart grid investment problem.[2] Source: Adapted for the UK from Jackson (2011 p.77)



(Source: Hall and Foxon 2014)

The 'risk' element of figure 1 in a UK context is notionally complicated by the strength of the regulatory incentive and LCN funding; yet figure 1 still holds as a sufficient description of the problem.

The move to RIIO, coupled with an innovation funding source was regarded by respondents to the research as a step change in the ability of DNOs to address the innovation incentive problem. What was not clear to any of the stakeholders in the research was whether these changes would be sufficient to incentivise transformational change. Equally, RIIO does not substantially alter the second identified issue of the strategic investment problem (Ofgem, 2013 p24-26). As such DNOs are still not incentivised to undertake strategic investment in the electricity distribution network; this is an issue where:

- significant renewable resources could be exploited if compatible network infrastructure existed;
- where economic development opportunities exist, but are constrained by the availability of electricity infrastructures;
- where new business models for transport and heat could exist if compatible distribution infrastructures were 'smart' enough; and
- where new generator, supplier, customer business models could be enabled by innovative network investment.

Clearly, if new economic development opportunities, new business models in the energy sector and new opportunities to decarbonise transport and heat can be unlocked by strategic smart grid investments. This implies that new ways of valuing and enabling this infrastructure spend are needed to break the strategic investment problem.

Much recent work has focussed on defining the value chain in the smart grid and how new actors may benefit from new technologies and distribution infrastructures (see Bialek and Taylor, 2010; Xenias et al 2014, Agrell et al, 2013; Giordano and Fulli, 2012). Our work framed this issue within the strategic investment problem and interrogated this as a passive provisioning issue, where "Real Options" can become available through strategic investment in grid infrastructure.

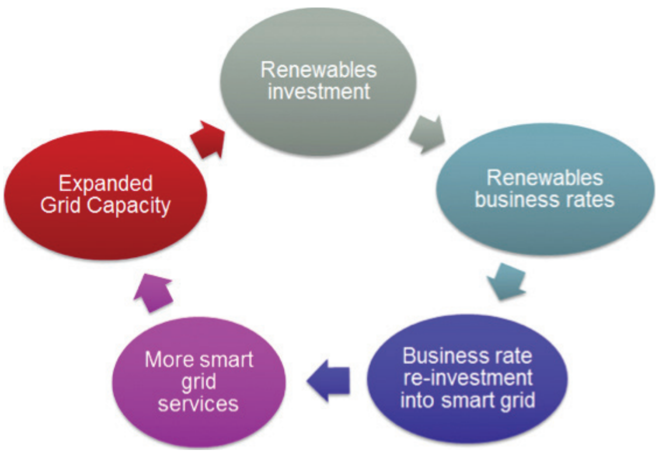
Due to the focus on local infrastructure business models within the iBuild research project, we focussed on the city and municipal scale and how the local state (predominantly municipalities but also combined authorities and local enterprise partnerships (LEPs)) could define, quantify and capture values in the smart grid and offer new ways of providing strategic investment in electricity distribution infrastructure.

The value of strategic investment; passive provisioning in the smart grid.

Cities are no strangers to speculative infrastructure spending to secure inward investment. Acting to secure inward investment utilising infrastructural incentives is a primary activity of the local state, and has most recently been focussed on transport infrastructures. In many cases this leads cities to make infrastructure investments ahead of need (strategic infrastructure investment), to reduce relocation costs for firms and secure mobile investment (Hildreth and Bailey, 2013). There is a growing body of evidence on the values smart grid infrastructures can provide to the wider economy, how municipalities in several countries are recognising this and thus paying more attention to smart grids as enablers of economic development (Heinbach et al 2014; Core Cities, 2013; Fei and Rinehart, 2014). Below we analyse three direct economic values identified by our research that accrue to city-regions through smart grid deployment. Our empirical analysis and findings are detailed in Hall and Foxon (2014) but can be summarised into three relevant categories for this analysis. These categories are: (1) Renewable energy connection co-ordination; (2) Inward investment stimulus; and (3) Municipal supplier load control, each of which is described below.

Firstly, DNOs currently offer connection agreements to renewable energy generators based on a first come first served basis. When there is capacity within existing infrastructure to accommodate the electrical load that a renewable scheme will place on the network, connection charges are relatively inexpensive as a proportion of the capital cost of the project. In other cases, a developer may wish to connect to the network where there is constraint on the amount of new load the network can take. In this case, developers must either find another site, or bear the cost of conventional reinforcement to the network, which is often prohibitive. When several developers are looking to connect capacity within a specific geographic area (e.g. somewhere with high wind resource) the cost of reinforcement falls on the developer unlucky enough apply for connection once the local network is at capacity. Innovative connection agreements with multiple developers and associated technical solutions to this problem are emerging (Anaya and Pollitt 2013), but DNOs find it difficult to co-ordinate developers due to issues of commercial data sensitivity and regulatory structures. Our interviewees identified a need for a scheme aggregator who could play this role in order to increase connections in high demand areas. We identified municipalities, with their spatial planning function as a natural home for this role. Further, if as for fracking operations, business rates from new renewables installations can be recycled to the municipality, a sensible economic solution could be reached for developer co-ordination that could benefit all parties. In this case a virtuous circle could be achieved where an element of the tax take from a new renewable energy development could be recycled through the municipality for strategic grid investment as in Fig 2:

Figure 2: possible revenue recirculation for smart grid investment:



Using this model a new revenue stream for smart grid investments can be identified that is not beholden to the regulated payment and can thus be invested strategically in consultation with spatial development plans and priorities.

Secondly, in several cases, municipalities had designated economic development zones where new commercial activity was planned, but where electricity grid constraints meant infrastructure costs would be prohibitive for relocating firms. In these cases, respondents were investigating the possibility of using economic development funds and innovative tax structures to subsidise smart grid solutions that would reduce the need for conventional reinforcement. This would make firm relocation far more likely and unlock land for development that was hitherto constrained by electricity distribution infrastructure. The use of economic development funding for critical infrastructure is becoming more common as evidenced by the recent wave 1 and wave 2 city deals agreed with government (see also Box 1 below). The majority of City Deals and subsequent Growth Deals have specific provision for strategic infrastructure investment to unlock growth (Office of the Prime Minister et al, 2014). As this economic development funding is unrelated to the regulated asset base of the DNO, it can be applied to areas of constraint to unlock investment, further addressing the strategic investment problem for smart grids.

Box 1: Passive provisioning for economic development

In our review of evidence for this study we discovered several examples of passive provisioning of distribution grid infrastructure for economic development purposes. The most clear example was at the Liverpool Innovation Park* where the site developers Liverpool Vision, supported by economic development funds, instructed Energetics UK** to provide network upgrades which would accommodate electrical load for developments already under construction, and would provide infrastructure with enough capacity and flexibility to accommodate planned developments on the entire footprint of the economic development site. Examples such as these demonstrate the ability of the economic development community, both municipal and private, to contribute to smart grid infrastructure development in the UK.

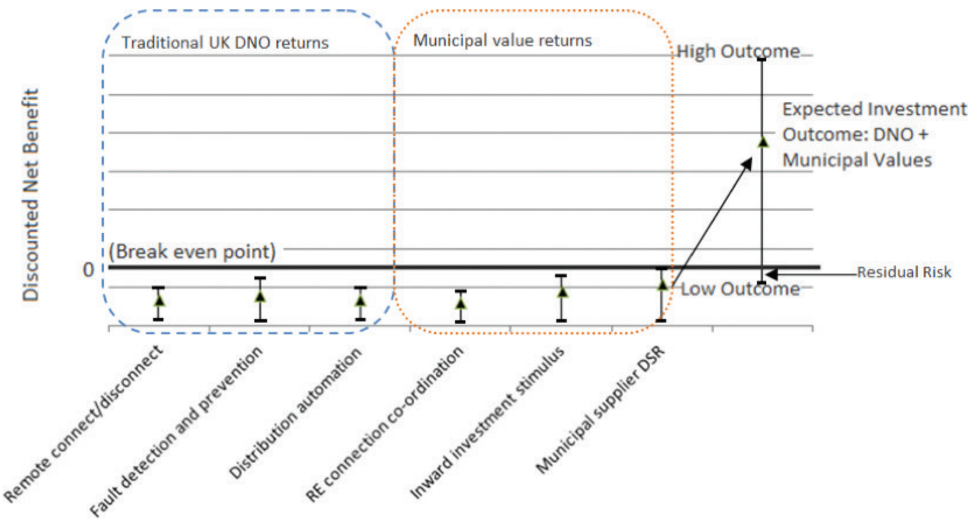
*http://www.liverpoolvision.co.uk/invest/property-investment/liverpool-innovation-park/

**http://www.energetics-uk.com/_downloads/LiverpoolInnovationPark.pdf

Thirdly, the way in which the smart meter rollout in the UK has been undertaken is arguably hindering demand side response (DSR) functions, a key component of the smart grid. When DNOs have direct access to smart meters in homes or businesses they can offer financial incentives for consumers to allow them to remotely control non-essential load (such as freezers, chillers and storage heating) at periods when demand peaks threaten system integrity. Demand response is a recognised option for prudent infrastructure spending (HM Treasury, 2013), but as electricity suppliers are responsible for smart meter control in the UK, and grid operators are not able to directly access meter controls, beneficial demand response is foreclosed. If, however, municipal supply companies were to sign up bundles of geographically concentrated load, they could act as an aggregator, offering load control to DNOs who can then offer contracts to aggregators that allow them to avoid network reinforcement.

This research has characterised just three clear fiscal and economic values which can overcome the strategic investment problem if new approaches to smart grid value capture are adopted. Infrastructural constraints on renewable energy developers can be reduced by co-ordinating developer connections and using recycled business rates for smart grid investments. Sites for development can be subsidised by inward investment stimulus funds which can be channelled to 'hard' technology investments in partnership with DNOs. On the demand side, municipal energy supply companies deploying smart meters would enable meaningful demand response contracts to be negotiated with DNOs. This would both realise the technical benefits of load control and strengthen the economic case for municipal supply companies. This may also facilitate value streams 1 and 2 as demand side response can release capacity on the network for renewable energy schemes or for land use intensification. We can thus amend the smart grid investment problem (figure 1) by paying attention to these values, and the business models that might capture them in figure 3.

Figure 3: The smart grid investment problem taking account of municipal value returns.[3]



By including municipal fiscal and economic development value streams in the smart grid investment problem, the size of the residual risk is reduced. Each of the values in the box on the right of Figure 3 can be deployed strategically, surmounting the strategic investment problem to augment the resources available to DNOs for smart grid infrastructure investment, thus accelerating smart grid deployment in the UK.

Here we have used the terms ‘passive provisioning’ and ‘strategic investment’ interchangeably. Whilst there are some distinctions between the two, they are both linked to justifying investment ahead or in anticipation of future need. This leads to a search for the contractual structures that can underpin this investment, to enable ‘Real Options’ to be realised in future uses of electricity distribution infrastructure.

Capturing and redeploying values for strategic grid investments

From the above analysis we identify three specific value streams that accrue to municipal actors for Smart Grids that have previously been unrecognised in the UK’s smart grid investment calculus. Mechanisms for value capture here are already being explored. Business rate retention in the UK’s new enterprise zones in particular represents a demonstrable fiscal value stream which accrues to host municipalities. Investing in infrastructure ahead of these values is a recognised feature of economic development activity. Other, wider fiscal mechanisms are also being used for infrastructure investment in cities. Recently Greater Manchester, has agreed a ‘revolving infrastructure fund’ with £150m retained business rate revenues (GMCA, 2012). Sheffield, Newcastle and Gateshead, and Nottingham have secured powers to raise a combined total of £133m for speculative infrastructure investment to secure growth (Sandford, 2013). Much of these revenues are often directed towards transport investment as transport networks are the responsibility of the municipalities, whilst energy networks are not. From our research, we find no functional reason why municipal infrastructure funds cannot be deployed for smart grid infrastructure.

Whilst rate retention is a demonstrable fiscal value stream, the employment benefits identified in the smart grid are more diffuse, but can equally be paid for by economic development funds. Leeds City Region for example is aiming to raise almost £1.5bn over the next ten years to fund transport and economic infrastructure with no prospect of recouping the cost directly. This is because the promoters of the new transport fund believe the combined schemes will lead to 20,000+ jobs in their geographic area (LCRP, 2013). These calculations are underpinned by land use intensification models which could be adapted for other types of infrastructure investment such as electricity networks.

One further enabling business model for each of the values identified above would be a municipal (i.e. city scale) supply company. Members of the Core Cities group, an organisation of England’s 8 largest cities outside London, is investigating the opportunities presented by new configurations of energy supplier business models, generating assets and distribution networks (Core Cities, 2013). A municipal supply company can further co-ordinate and incentivise renewable energy development by offering attractive power purchase agreements (PPAs) to RE developers and can achieve the aforementioned geographic DSR. By combining these benefits, a municipal supplier can build a strong case for new investment into smart grid infrastructures. Indeed this combined structure is the very aspiration of one of our local growth actors in the municipal energy space:

> *“…what we are looking to do here in [city name] is to use our purchasing power to enter into PPA agreements with community groups who want to install small scale generation, turbines, tidal, wind, stuff like that. We would be able to do some deals with our energy from waste plant, we would be able to get into that whole area where we can sort of drive sustainable and local low carbon energy zones to drive economic growth in that area.”*
>
> **(Local growth actor interview,2014)**

Phase 2 and future research

Phase 2 of this research will develop real world cases where city and municipal actors can partner with DNOs and network stakeholders to deliver novel business cases for smart grid investment. This work will specifically investigate the valuation of passive provisioning in electricity distribution infrastructure and aim to quantify the values defined in Figure 3 on at least two case study sites where traditional approaches to distribution grid infrastructure are prohibiting new low carbon growth.

These findings will be reported in the academic literature and through relevant stakeholder publications and fora. Most importantly, in each of these cases the iBuild research aims to solve currently existing problems using the cross disciplinary approach inherent to the project. Whilst Phase 2 of this project will deliver new knowledge on smart grid business models, there still remain several important questions for smart grid investment trends more generally. From our research, our top four questions are:

1. Whilst risk sharing is an important consideration in tackling the strategic investment problem, the accrual of gain is equally important. How can risks and rewards be balanced when municipalities take a stake in smart grid infrastructure and what contractual arrangements can facilitate this?

2. Given the electrification of transport, can the new transport infrastructure funds at city regional level contribute to charging infrastructure 'beyond the charge point' i.e. by investing in smart grid services to accommodate the load of new charge points?
3. How can new energy supplier business models at the city scale interact with the regulated assets of the DNOs, maximise renewable energy installations and deliver demand response services whilst protecting consumer bills?
4. How are state aid regulations implicated in cross subsidy of smart grid infrastructures with different public funds?

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Footnotes

[1] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/191501/Accounting_for_the_effects_of_climate_change.pdf

[2] These values are illustrative only and define the problem, they do not relate to the relative value of each benefit.

[3] These values are illustrative only and define the problem, they do not relate to the relative value of each benefit.

Chapter 5:

Valuation of passive provision for heat network investments

Chapter 5
Valuation of passive provision for heat network investments[1]

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In this chapter we apply ideas about real options value and passive provision to case studies related to the development of heat networks by local authorities in the UK.

Introduction

Heat networks consist of highly insulated pipes that transport heat to multiple buildings using hot water or steam. They provide an alternative to individual building-level gas or electric heating. Heat networks are "source agnostic" and can be tailored to make use of local resources, such as residual heat from industrial processes, energy-from-waste plants, or upgraded heat pumped from various sources including data centres and rivers. Alternatively, the network can be linked up to a purpose built heat source, such as a gas or biomass boiler or efficient combined heat and power (CHP) plant. Large systems in Europe typically use multiple different heat sources. Heat networks, therefore, enable carbon emissions reductions, cost savings, and enhanced energy security through diversity and flexibility. The UK Heat Strategy *'The future of heating: Meeting the challenge'* (DECC, 2013) highlights heat networks as having a crucial role to play in a future low carbon energy system, particularly in urban areas with high heat demand density.

Heat networks are long lived (40–50 year) capital intensive infrastructures that traditionally move heat from places where it is of relatively low value (such as residual industrial energy) to where its value is high (space heating demand). High capital costs (highly insulated pipework that require wider trenches for installation than gas or electricity networks) are consistent with affordable consumer prices due to this difference in the economic value of heat. The broad structure of heat network financial models, then, in comparison with other energy networks, is relatively low variable costs (low value heat) but high upfront costs. This means the challenges for infrastructure outlined in other sections of this report (such as time inconsistency) are particularly acute for heat networks.

Investment in heat networks can be seen as high-risk, since large sunk investment must be made before customers are connected, and returns depend on customers' long-term use of the network. This is challenging in the context of a highly centralised and market-driven energy system which emphasises consumer choice, and with users and intermediaries (such as facilities managers) most familiar with building-level heating systems such as gas boilers and electric heating. Most investors want assurance of at least some guaranteed sales of heat to offset the investment costs and long-term contracts, with large heat demands often required in advance of a scheme being installed. Networks are therefore often developed in phases structured as self-contained financial packages so as to reduce the financial risk to developers in terms of upfront capital investment and establishing a customer base. This contrasts with historic municipal development of heat networks in Europe, where large upfront investment could be justified by the planned ongoing expansion of the network to new users.

New actors, different values

Many local authorities are taking on a new role in the UK energy system to facilitate heat network development and try to coordinate multiple actors with different priorities and interests. They take a range of approaches to this role, either acting as a facilitator to attract private investment in a scheme or leading the development themselves. Since nationalisation, local authorities have had weak statutory powers to engage with energy systems. With relaxation of some restrictions, some are now seeing multiple opportunities to achieve a range of outcomes by acting as energy generators and suppliers. Recent work has highlighted that local authorities often seek to develop heat networks as a means to meet social, environmental and economic objectives (Bush et al., 2014, Hawkey et al., 2014). In this way, in developing local energy infrastructure, local authorities are seeking to create complex value, beyond the traditional economic drivers of market actors.

Social value: Local authorities are seeking to develop heat networks as a means to improve the living conditions of residents in social housing and tackle fuel poverty. Heat networks are also developed in response to regulatory requirements for the quality of social housing and, more broadly, to improve deprived areas.

Environmental value: Carbon reduction is an important driver. Many local authorities have voluntary climate strategies and ambitions around green growth.

Economic value: Local authorities are using investment in infrastructure as a means to increase the competitiveness of their local region, using heat networks to attract industrial and commercial activity to the area and thus creating more local jobs. Lower heating costs, low carbon energy and resilient energy supplies are the main forms of value local authorities see heat networks creating for these users.

The case for real options in heat networks

The social, economic and environmental benefits of heat networks are most significant in larger schemes (BRE et al., 2013). Large networks create options for flexible exploitation of different heat sources (with different temporal characteristics, scale economies and uncertainties in future costs/benefits) and can balance different heat use profiles leading to higher load factors which in turn imply greater economic and environmental efficiency (Woods et al., 2005). However, development of heat networks is a complex and multi-stage process which, under current UK market structures often prevents the development of larger schemes. The host of actors that need to be involved, often with differing objectives, means that development of each scheme can be time sensitive, dependent on key individuals, and not necessarily linked in with the wider opportunities that exist across the area (Hawkey et al., 2013). The Department of Energy and Climate Change and the Scottish Government currently support work on heat mapping which can feed into local strategic plans for heat networks. However, to take these maps from the stage of individual stand-alone projects to larger-scale schemes that link up the strategic areas for a network will require careful facilitation to encourage the phased expansion of schemes necessary to achieve local strategies. Decisions at the early stages of smaller-scale heat network projects or new developments must consider how to create real options for large heat networks in the future. However, decision-makers (housing services, or perhaps urban design and engineering services) are not usually in a position to deliver an area-based, or regional, integrated energy and spatial strategic plan; this is where local authorities can provide a facilitating strategic role.

Passive provision in heat networks

Incorporating passive provision into heat network schemes can create real options and bring benefits as outlined in the previous section. There are several ways in which passive provision can be incorporated into financial models underpinning heat network investment:

1. Heat networks tend naturally to incorporate a degree of passive provision in the sense that once established they can switch to heat from a variety of different sources. Larger networks with multiple heat sources create operational flexibility (with heat dispatch responsive to changes in relative prices) and resilience supporting connection of innovative heat sources.
2. Flexibility can be incorporated in the design of heat networks to accommodate future expansion and ease of source switching/diversification. Energy centres and pipe diameters can both be over-sized to ensure phase-1 projects do not "lock out" more significant networks. Modular approaches can facilitate changing heat sources, and systems can be designed to ensure small networks can technically be integrated into larger systems.
3. Potential heat sources and users can be "future proofed" to allow connection to networks in future. Large energy developments (such as energy-from-waste plants) can be designed to easily supply heat in future, and design decisions in buildings can support future market creation. Local authority planning policies can also support connection of new developments to networks.

These are, however, difficult aspects to incorporate into financial models. Although the benefits of passive provision and the creation of real options for heat networks is clear, it is challenging to deliver these measures in the current context of the energy market and regulatory framework. For many projects, sourcing finance to cover the large upfront capital costs of schemes is challenging in many situations. Adding extra costs for aspects such as over-sized pipes for future potential schemes is therefore even more difficult. Schemes can be developed by a range of actors, from private sector actors (such as heat network development companies), to public sector (universities, health service bodies or local authorities). Objectives of projects are not always aligned with city-wide strategic plans and this makes the inclusion of passive provision hard to incentivise. The lack of experience of heat network development in the UK also means that local authorities have sometimes found it difficult to include effective provisions within tender documents or planning permissions to make new developments such as energy-from-waste plants fully "heat network ready". Despite the numerous challenges of including passive provision there are examples in the UK where it has been achieved.

Case studies

In this section we introduce three case studies as a means to highlight aspects of certain schemes where passive provision has been incorporated for facilitation of real options in heat networks.

Islington — provision of heat network opens opportunities for new heat sources to be used

Bunhill Heat and Power, a company owned by Islington Borough Council, run a heat network on the Bunhill housing estate. The network has 1km of pipes, connecting 850 homes and 2 leisure centres to a gas-fired combined heat and power plant. The scheme was retrofitted to the site and was completed in winter 2012. The project resulted in a reduction in carbon emissions of 60% on the previous heating systems that were in use. Energy cost reductions and fuel poverty alleviation were key drivers of the scheme. Since the initial phase of the scheme, a second phase of expansion is being planned that will connect a second council-owned housing estate as well as additional nearby heat sources of scavenged heat: the London Underground and a nearby electricity substation (Islington Borough Council). Without the stability of the first phase, exploitation of these innovative heat sources would be unlikely. Information for this case study was sourced from a Bunhill Heat and Power Case Study report (Islington Borough Council, 2013).

Leeds — local strategic vision for heat underpins "network ready" energy-from-waste plant design

This project is still in the development stages. An energy-from – waste plant is currently under construction 2km from Leeds City Centre, commissioned by Leeds City Council and run by Veolia. The plant was initially designed to generate electricity with no planned heat network connection. Though the original tender specified that the plant should be "CHP enabled", this did not allow for a heat network connection.

Leeds City Council has strategic aims to develop heat networks in the city within its fuel poverty action plan and sustainability strategy, as well as within the Local Enterprise Partnership low carbon economy work programme of the wider Leeds City Region. Leeds City Council is planning to deliver the initial pipe infrastructure between the Veolia plant and the city centre (2km), connecting to 2,500 council-owned homes along the route. This connection is intended to open up investment opportunities for a commercial heat network provider in the city centre. Information for this case study was sourced from 2 semi-structured interviews and personal communication with Leeds City Council.

Aberdeen — early system oversizing enables expansion of local heat market

Aberdeen Heat and Power Ltd (AHP) is an independent not-for-profit company limited by guarantee; it was established in 2002 under a fifty-year framework agreement with Aberdeen City Council. Beginning with one energy centre and heat network in Stockethill, the company now own and operate three energy centres; the total network length is 14km. Multi-storey housing blocks have been retrofitted with new central heating and hot water systems, replacing old electric storage heaters. Information for this case study was sourced from RC UK Energy Programme Heat and the City project at the University of Edinburgh.

Table 1 details the forms of passive provision that have been included within each case study scheme.

Table 1

	Islington – existing project	Leeds – project in development	Aberdeen – existing project extended since initial development
Scheme (size, type, consumers...)	**Bunhill Heat and Power, Islington** ■ The heat is sourced by a gas-fired CHP plant. ■ The network was initially connected to 850 council homes and two leisure centres. ■ Bunhill energy centre houses a 1.9MWe gas CHP engine and 115m^3 thermal store, and the network comprises of 1km of trenching which holds 2km of insulated district heating pipework.	**Veolia Waste Treatment Site, Leeds** ■ Project in the planning stages. ■ Heat will be sourced from an energy-from-waste plant. ■ Council aims to install initial 2km pipe infrastructure and connect to social housing estate near to the city centre and range of commercial high heat demands. ■ Longer term aim to expand network and connect the scheme to range of commercial customers.	**Aberdeen Heat and Power Ltd (AHP), Aberdeen** ■ Heat sourced from three gas-fired CHP engines. ■ Stockethill energy centre houses a 210 kWe CHP engine and two back up gas boilers; Hazlehead energy centre houses a 300kWe CHP engine; Seaton energy centre houses two 1MWe CHP engines. ■ A fourth energy centre, using gas CHP, is under development at Tillydrone.
Motivation	■ Housing quality improvements, cost saving for council. ■ Demand driven: This scheme was initially built to meet the housing regeneration and heating needs of the Bunhill estate.	■ Fuel poverty reduction, carbon reduction, local job creation. ■ Supply driven: After construction of a waste incinerator to meet waste disposal needs of the city, this scheme is planned to make use of the waste heat generated from the plant.	■ Provision of affordable warmth to housing tenants. ■ Improvements in National Home Energy Rating (NHER) of council-owned multi-storey housing. ■ Reduction in home energy use, and associated CO_2 emissions, by 30% to meet UK Home Energy Conservation Act (1995) requirements. ■ Improved Council revenues from regeneration of social housing. ■ Retention of revenues in local economy. ■ Sustainable and affordable energy for Aberdeen City Council buildings.
Business model	■ Islington council owns and manages the scheme through its Bunhill Heat and Power company; gaining revenue from electricity sales. ■ Council ownership and revenue enables heat costs to be kept low for residents.	■ Options are currently being explored. The intention is to set up a special purpose vehicle with Leeds City Council having a significant financial stake in it and one or two commercial partners doing the generation and the heat sales to the customers.	■ AHP is an independent not-for-profit company Ltd by guarantee. It was set up by the City Council in 2002. ■ Revenues are from heat and electricity sales. ■ Cost-based, rather than market-based heat tariff is regarded as enabling affordable warmth targets to be met. ■ AHP works for City Council under a fifty year framework agreement and Teckal exemption. ■ A low rate of return was acceptable, given the primary return sought was in well-being and local economic benefit, combined with carbon saving. ■ AHP has established a wholly-owned for-profit subsidiary, District Energy Aberdeen Ltd (DEAL), to enable heat supply to be offered to private sector users.

	Islington – existing project	Leeds – project in development	Aberdeen – existing project extended since initial development
Source of finance	■ Grant funding was used for the initial phase of the scheme (£3.8 million energy centre and heat network) from the Greater London Authority and the Homes and Community Agency. ■ The second phase of the scheme will utilise funding from Islington Borough Council, Bunhill ward and the EU CELSIUS research project (managed by the GLA in London).	■ Leeds City Council intends to invest directly in the project, although specific financing of the project has not been finalised.	■ The £1.8 million Stockethill energy centre and heat network were funded by a 40% grant contribution from the UK Community Energy Programme (CEP)[2] , combined with a 7% grant from the energy utility Energy Efficiency Commitment (EEC, now ECO), with 53% from the City Council housing capital budget. ■ A £1million loan from the Cooperative Bank to AH&P, repayable over 10 years, was raised to finance initial construction. A favourable interest rate was secured through provision of a loan guarantee from the Council, hence minimising costs. ■ The £1.6 million Hazlehead energy centre and heat network were funded by a 40% grant from the UK CEP, combined with a 7% grant from the energy utility EEC, with 53% from the City Council housing capital budget. ■ Seaton Energy Centre and heat network were developed in two phases, at a total cost of £3.3M. Phase one was funded by a 40% grant from the UK CEP, combined with 60% from the City Council housing capital budget. Phase two was funded by 40% finance from the energy utility Community Energy Saving Programme (CESP) and 60% housing capital. In both cases, prudential borrowing was used to cover a time gap between construction and receipt of grant and to capitalise future avoided costs. ■ In 2013 the Seaton network was extended to City Centre with funding from a £1M Scottish Government grant.

	Islington – existing project	Leeds – project in development	Aberdeen – existing project extended since initial development
Passive provision planned or installed	■ Network pipes have been sized to be larger than current needs allowing future additional capacity. ■ Flexible design of the modular CHP system to allow future supply from other heat sources. ■ Local planning policies to ensure future connections where possible.	■ Tender document specified that the energy-from-waste plant must be "CHP enabled". However, this did not allow connection of a heat network; the significant costs of this connection are falling to Leeds City Council rather than Veolia. ■ 2km pipe infrastructure to connect heat source to area of high heat demand (to be installed). ■ The arena development in the city centre has a heat network connection, in advance of there being a network.	■ At the technical feasibility stage of each project, AHP is required by Council to size, and cost, pipework and CHP engine housing specifically for the planned project, but not for future growth in demand and network expansion. However, AHP invests any surplus income to enable oversizing of main sections of the pipe network and energy centre for future load growth. The Seaton energy centre was built to accommodate 3 generators and associated plant, when initially only 1 generator was to be installed; the distribution pipe network at Seaton Phase One was oversized to enable later extension into the City Centre. This was subsequently achieved with a £1M grant form Scottish Government ■ Strategic plan for development of city centre heat main includes intention to connect other sources of heat, such as Aberdeen energy from hydrogen project and new energy-from-waste facility incorporated into current Local Development Plan.
Benefits of passive provision envisaged or accrued	■ Heat sales to commercial demand can provide income to local authority. ■ A further 160 new build homes have already been added to the network.	■ Lower cost, low carbon heat provision for connected social housing. ■ Leeds City Centre as an attractive location for location of commercial businesses.	■ Doubling of initial CHP capacity has taken place at Seaton. Initially built to supply heat to six multi storey blocks (503 flats), the scheme was first extended to provide heat to five public buildings (Beach Ballroom, Leisure Centre, Linx Ice Arena, Aulton Sports Pavilion and Aberdeen Sports Village); it was subsequently extended to a further 8 multi storey blocks (740 flats). ■ Initial over-sizing of pipework has enabled extension to city centre with a further 5 public buildings connected ■ City centre extension enables AHP/DEAL to supply private sector heat loads, offering carbon saving at a competitive price. Any profit will be returned to AH&P for use in maintaining affordable tariffs for social housing and to build reserves for capital replacement and further developments.

	Islington – existing project	Leeds – project in development	Aberdeen – existing project extended since initial development
Real options (for future developments)	■ Flexible heat source allows future connection to lower carbon heat sources such as waste heat from the London Underground. ■ Existence of the initial network serves as a basis for easier future expansion to new developments and commercial customers.	■ Provision of initial connection to waste network to city centre creates an attractive business case for future commercial expansions in the city centre.	■ Network extension allows future connection to low carbon and renewable heat sources, as these become viable through liaison with academic and other partners. Current aim is to investigate use of biomass, bio-gasification, anaerobic digestion and geo-thermal sources. ■ Current projects in the Cairncry, Tillydrone and Torry areas of the city are connecting a further 11 multi storey blocks to DH; target completion date April 2015. ■ There are plans to link the multiple CHP stations around the City into one city-wide heat network. ■ Successive phases of expansion provide potential commercial, and further public sector, customers with evidence of business performance standards and costs.

Benefits of real options

The approaches to passive provision in these case studies show the range of possible benefits that real options offer. Islington and Aberdeen clearly saw the investment in a heat network as a first phase that would later be expanded, in both cases, to support other social housing estates in nearby areas, and in Aberdeen as having strategic potential for interconnection to form a city centre heat network with diverse heat loads. Flexible design of the CHP plants and oversizing of the pipes were used with the initial aim of creating wider social benefits with the technology through housing improvements and fuel poverty alleviation, as well as energy and carbon savings. In the case of Leeds the energy-from-waste plant would have gone ahead regardless of planned development of a heat network. There was a missed opportunity in that the tender document failed to mention supply to heat network, and only required the plant to be CHP-ready. The modular design of Islington's CHP plant, and AHP heat networks, also offer the potential to switch in the future to lower carbon sources of heat more easily to gain greater environmental benefits. Economic benefits are clear from all case studies as well. Leeds are planning to provide the initial pipeline between the energy-from-waste plant and the city centre to connect tower blocks of social housing flats to the network whilst simultaneously 'bridging the gap' between what the private sector will provide on its own. By bringing the network to the city centre the City Council envisages an attractive business case will be created for investment into a commercial city centre network. Islington is generating income from its scheme as new developments in the area connect to the scheme. In Aberdeen, provision of the heat network has led to improved council revenues from housing, alongside reduced turnover, reduced levels of tenant complaints and informal evidence of improvements in tenant health. Higher housing standards have the added benefit of elimination of dampness; the average National Home Energy Rating (NHER) in multi-storey housing increased from 3.3/10 in 1999 to 7.19/10 by 2009. Network extension to the city centre has resulted in AHP establishing of a for-profit business subsidiary (DEAL) to secure supply contracts with private sector businesses. Incorporating passive provision into projects creates new opportunities, but depends on local actors (particularly local authorities), taking a long-term strategic view on heat network development.

Valuing passive provision

The adoption of whole life costing by public bodies has been important in justifying heat networks whose upfront costs are typically higher than alternatives, but whose value lies in the long term exploitation of energy sources that would otherwise be unavailable. However, incorporating the value of passive provision within this approach is difficult given uncertainties in factors influencing the evolution of the network (its scale, users and heat sources) and the value of different outcomes (in turn influenced by future market prices and technological innovation). These factors tend to relate to locally specific issues and thus resist formulation as generic values that can be applied across different heat networks.

- The flexibility to incorporate different heat sources in future is valuable in mitigating uncertainties, but difficult to translate into quantified economic value because those uncertainties are difficult to quantify as risks. For example, the economic and carbon balance between biomass combustion and large heat pumps depends on how biomass and electricity markets evolve (both in terms of prices and the technologies and inputs underpinning each market). Heat network business models tend to focus on viability of a system assuming no change in heat input source, to ensure investment returns can be secured. The future flexibility of heat provision with heat networks is in effect treated as an externality.
- The costs and benefits of making buildings and potential heat sources "heat network ready" are similarly difficult to quantify, particularly where they depend on the development of a heat network (or networks) by third party actors.
- Investing in oversized systems adds upfront cost, though these additional costs are significantly lower than the alternative option of retrospectively replacing components sized for an initial phase with components sufficient for a later expanded phase. Where the financial viability of initial phases is seen as marginal, there may be pressure to minimise upfront expenditure whose value is perceived to be speculative. The capacity and willingness of local actors to progressively build a heat market is, therefore, an important component of the value of this form of passive provision.

As the case studies illustrate, passive provision has been incorporated into heat network initiatives in the UK, though often through tacit and precarious routes reflecting these uncertainties. For example, Aberdeen Heat and Power itself undertook to oversize its systems beyond the scale represented in technical feasibility studies which were bounded by specified heat loads and which formed the basis of financial agreements with the council. The additional investment, in part financed through commercial loans, has proven justified through the expansion of the system and plans to diversify the user base. However, that this expansion to new users was possible rests on a combination of factors including the initial oversizing, the state of the energy market (and consequent favourable structure of costs and revenues for AHP), but also ongoing commitment of local and Scottish government to facilitate both further investment and recruitment of new heat loads to the system. That is, one important factor influencing the value created by oversizing is the capacity and commitment of local actors to ensure the targeted heat market is eventually created.

This is a key tension with including passive provision for future phases of scheme. Given heat networks have high CAPEX/OPEX ratio compared with other infrastructure, investment in passive provision can be quite expensive and difficult to justify in a project-oriented (as opposed to a growth-oriented) business model.

Conclusions and future research areas

As we have discussed the current market-based system does not facilitate expansion of heat networks (which are often, instead developed on an ad hoc basis and driven by key individuals or organisations). However, new non-traditional actors are becoming involved in developing and operating energy infrastructure (mainly local authorities), who are aiming to capture social and environmental value, in addition to economic value. Passive provision needs to be incorporated at the early stages of heat network development in order to deliver larger schemes and the associated cost saving and environmental benefits they bring.

Finding a way to value passive provision in heat networks is critical to enabling the introduction of the level of heat networks envisaged in the low carbon heat strategy and realising their full benefits. Without it, extending existing networks could require digging up pipe routes again, causing extra costs and hassle for the surrounding area.

To date, some projects in the UK have managed to include passive provision to open up real options for heat networks via tacit and precarious routes (as we have reflected in the case studies presented). However, linking in passive provision to local heat plans could help bring about more strategic area-wide schemes.

We intend to explore further:

- existing schemes that have managed to include passive provision; in particular, to investigate how the planning and development of the business case was achieved to incorporate passive provision.
- guidance on governance and methods of financing schemes that enables passive provision.

A key challenge is in finding new ways of valuing energy infrastructure that is needed to transition to a low-carbon, affordable and secure energy system.

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Footnotes

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[2] The UK Community Energy Programme (CEP) ran from 2002-2007, and consisted of a £50M budget from UK Treasury Capital Modernisation Funds for a Community Energy Programme (CEP) to support DH developments led by public bodies. Applicants for capital grants had to demonstrate additionality, and show that community heating was the most viable solution for cost and carbon saving compared to alternative options, and that a range of finance options (such as existing capital funds or bank loans) had been explored.

Chapter 6:

Accounting for critical materials in sustainable energy provision: maintaining systemic resilience

Chapter 6
Accounting for critical materials in sustainable energy provision: maintaining systemic resilience

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Critical materials and sustainable energy provision

We have seen that planning, installation, operation and disruption of infrastructure often have system-wide economic impacts, not accounted for in partial equilibrium approaches. The case of the demand for critical materials in sustainable energy provision illustrates these general points, and their specific ramifications for valuation of systemic resilience in energy provision, as follows.

As we introduce new, more efficient and/or low carbon technologies into infrastructure (wind turbines, PV panels, electric vehicles etc.) we change the materials mix to include relatively exotic materials that previously were not present in significant amounts in the infrastructure, such as lithium for electric vehicle batteries, or rare earth metals for wind turbines (US Department of Energy 2011; IEA-RETD 2012). Many of these materials are:

- in great demand from other high-value industries (and thus prices are rising);
- not mined in their own right but are co-products of other primary refining processes (and thus lead times for new facilities are very long – up to 10 years – negating normal market responses);
- characterised by primary supply chains based in a limited number of jurisdictions (leading to the use of supply restrictions as a geopolitical tool e.g. China's cessation of rare earth metal exports to Japan);
- difficult to substitute.

Such materials are classed as 'critical materials' (European Commission 2010).

Many roll-out scenarios for low-carbon technologies take little account of this, ignoring induced material demand and the associated systemic scarcities; i.e. they implicitly take a partial equilibrium approach). For example, the DECC projections for uptake of plug-in hybrid and other related electric vehicles in the UK needed to achieve carbon emission reduction targets would require that the UK's imports of lithium for batteries (either primary for local manufacture or secondary within imported batteries) would have to increase to a level of comparable magnitude to the current global supply of lithium within a few years (Busch et al. 2014). Without proper consideration of the necessary aggressive and pro-active preparation of the relevant supply chains, this roll-out will not be achieved and carbon targets will be missed.

A proper cost-benefit analysis of such new technology-led infrastructure proposals should take this scarcity into account so that we better understand the risks associated with material dependence and the value of reducing this dependence. This kind of analysis requires an understanding of the scale of induced material dependence, the implications of this dependence and the potential for reducing dependence without creating other, new dependencies. Approaches have been developed to address these dimensions of critical material risk.

Induced material dependence

Analysing the material dependence of infrastructure needs to take account of the physical scales, time-dependencies and technological complexity involved. The physical scale of infrastructure often induces a requirement for quantities of material that outweigh any other industrial demand. Infrastructure is expected to function for time periods counted in decades if not centuries. Infrastructure often requires many different potentially critical materials for a single technology (e.g. electric vehicles require neodymium, lithium, cobalt, and high-performance polymers), and a single material is often required for multiple disparate technologies (e.g. the rare earth neodymium is used in wind turbines, electric/hybrid vehicle motors and computer hard drives).

However, once this is understood, it affords opportunities to understand and reduce the risk to infrastructure deployment from material supply disruptions. The physical and temporal scale of infrastructure makes it possible to forecast when technologies and materials will reach end-of-life and thus be ready for recycling or reuse in sufficient quantities and with sufficient lead time that the development end-of-life recovery supply chains should be responsive to economies of scale. In other words, we should be able to predict that there will be enough material in the right place at the right time to make it 'worth our while' investing in recovery infrastructure.

The lifetimes of many of the infrastructure-related technologies that will eventually implement part of the UK Governments low carbon transport and electricity generation plans are, like most infrastructure components, much longer than those of most consumer products. Electric vehicles will most likely have lifetimes similar to that of the current vehicle fleet (an average of 13 years, although the lithium-ion batteries may only last 8 years). Wind turbines and solar panels are designed to last at least 25 years. This means the technologies, components and materials contained in this new infrastructure will not immediately become available for recycling. However, they will come out of service and on to the recycling 'market' in far greater quantities than is typical for current technologies.

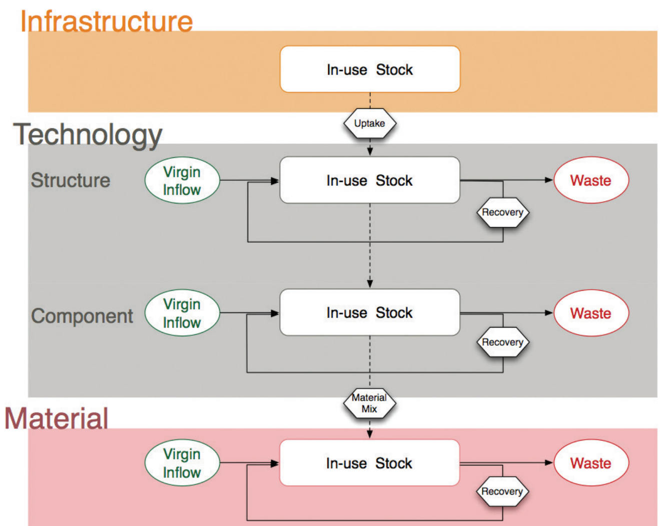
If we wait until such secondary resources start appearing on the market, it will be too late to develop facilities to recover them; economically viable facilities typically take many years to develop and are currently only at the laboratory stage (see e.g. http://www.colabats.eu/). This is not an issue that the market can deal with efficiently because the magnitude, timescale and uncertainty surrounding prices and supply are all too large. Understanding, quantifying and predicting both inflows and future outflows from the infrastructure system provides more potential for an integrated energy and waste infrastructure policy response.

It is important to recognise that simple mass/volume of material is only part of the picture: for maximum material efficiency and minimal environmental impact, material must not be allowed to enter the system if it cannot be recovered. For example, a tonne of copper entering the system as refurbishable and reusable components is worth more than a tonne of copper that has to be collected, melted down and recycled (with associated greater energy use and carbon emissions); which in turn is worth more than a tonne of copper mixed with other metals or plastics in components that are difficult or costly to dismantle; which in turn is worth more than a tonne of copper dispersed as e.g. oxides, chlorides or particulates throughout many tonnes of waste requiring complex reprocessing. Careful technology design embracing modularity can ensure that such dissipation of value is minimised; the policy challenge is to encourage the resultant (often minor) depredation of performance or increase in design cost to be tolerated.

A recent paper (Busch et al 2014) proposes stocks and flows modelling of technology and materials as the basis of a planning tool that can address issues of material dependence and risk mitigation through targeted reuse and recycling.

This approach uses "roll-out" scenarios – i.e. projections for the adoption of low-carbon technologies – issued by policy makers as the basis for calculating the in-use stocks of infrastructure and technologies required to meet service demands (e.g. for low carbon transportation or electricity generation). The material intensity of these technologies (the 'recipe' of materials used in each per unit of output) determines the amounts of materials that will be in-use at any given time over the roll-out period. Estimates of the lifetimes of infrastructure technologies and components are then used to forecast the demand for materials (inputs) and the availability of end-of-life technologies and materials for recovery and reuse (outputs) over the roll-out period. The model is based on a hierarchical representation of infrastructure, technologies and materials (see Figure 1).

Figure 1: Hierarchical representation of infrastructre, technology and materials used in the material demand model.



At the top, infrastructure stocks provide a required level of service. This infrastructure is physically constituted of technologies (such as electric vehicles or wind turbines) which in turn contain many components (batteries, motors, generators, magnets, etc…). The technologies and components in turn contain materials (lithium, cobalt, neodymium, copper, etc…).

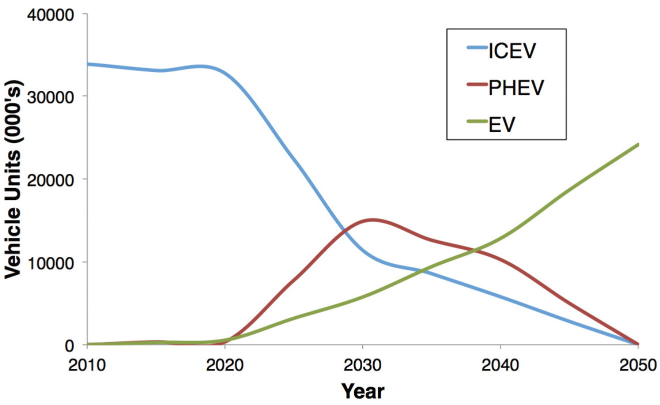
The hierarchical representation allows us to analyse the effects of recovery and reuse/refurbishment at different levels of the system, and across different systems.
Not only can we analyse the possibility of for example extracting and recycling neodymium from end-of-life wind turbine generators, we can also analyse the potential for designing the permanent magnets in such a way that they could be re-used or refurbished as components. We could then balance the economic or technical penalties associated with such modular design against the cost and environmental impact of extracting the neodymium in a complex metallurgical process. This quantification of the potential benefits of different end-of-life treatments is crucial to valuing modular design and design for

reuse in the planning stages of infrastructure projects. The dynamic basis of this analysis makes it possible to identify points in the system at which interventions might be most effectively made to both preserve the technical and economic value of critical materials and minimise depletion of primary materials.

Material demand for Low Carbon Vehicles

A prominent example of where critical material dependence in infrastructure could potentially disrupt roll-out scenarios is in the transition to low carbon personal transportation. The decarbonisation of transport plays a major role in the low carbon pathways published by the Department for Energy and Climate Change (HM Government 2010). The 'Renewables' scenario from this report forecasts a rapid transition away from internal combustion engine vehicles (ICEVs) first towards plug-in hybrid vehicles (PHEVs) and then to fully electric vehicles (EVs), as shown in Figure 2.

Figure 2: Total in-use stock of vehicles in the UK deployment of low-carbon vehicles under the 'Renewables' scenario of the DECC pathway analysis.



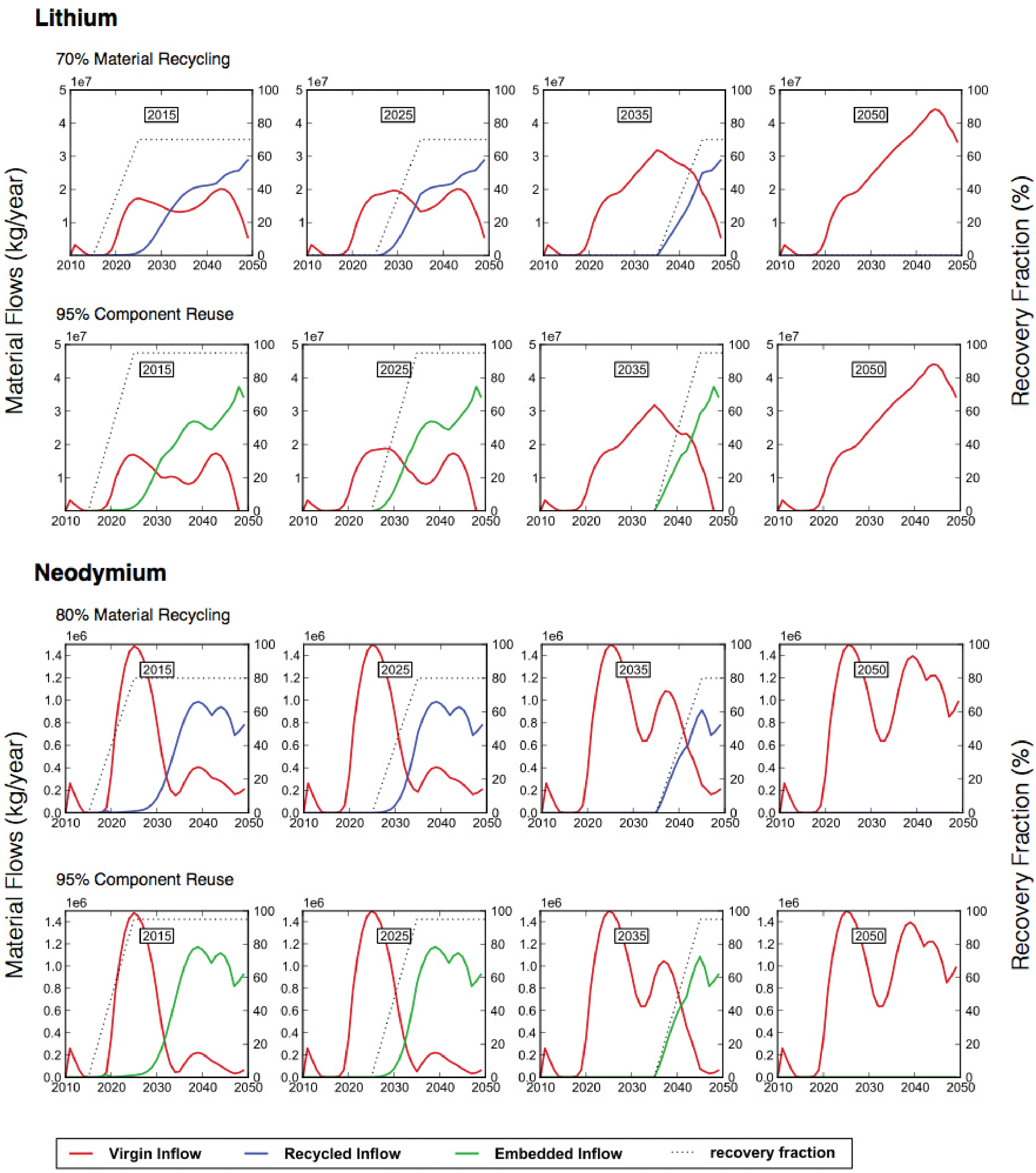
The low-carbon technologies involved in this transition are the adoption of electrical storage and drivetrain systems for the vehicles. For both PHEVs and EVs this requires lithium-ion batteries and motors that use permanent magnets; the batteries contain lithium and cobalt, and the magnets contain neodymium. All three of these materials have been considered as potentially critical by UK, EU and US criticality assessments (British Geological Survey 2012, European Commission 2010, United States Department of Energy 2010). The amounts of these materials contained in the components is summarised in Table 1. The large range in material intensities, particularly in the lithium-ion batteries is due to uncertainty over which battery chemistry is likely to become dominant in the coming years. This type of uncertainty is much lower in technologies that are at a more mature stage of development, such as permanent magnets.

Table 1: Material intensities of components.

Component	Material	Intensity (kg/unit)
NdFeB motor	Neodymium	0.31 – 0.60
Li-ion battery EV	Lithium	3.38 – 12.68
	Cobalt	0 – 9.41
Li-ion battery PHEV	Lithium	1.35 – 5.07
	Cobalt	0 – 3.77

The material demand profiles for the technologies described above for the DECC Renewables scenario are shown in Figure 3 below.

Figure 3: variety of material recovery scenarios. Recycling rates are technically feasible whereas reuse rates are more speculative. The varying recovery scenario curves show the effect of differing supply chain readiness.



For both materials shown there are steep increases in demand starting in 2020. By 2030, the UK would require over 30 kilotons of cobalt, between 10 and 45 kilotons of lithium and between 0.7 and 1.5 kilotons of neodymium, equivalent to 0.03%, 160% and 7% of 2010 world production respectively. The short timescale of this step change in demand, together with the lack of availability of end-of-life materials for recycling or reuse makes some of this demand shock – and associated unpredictable increase in price and decrease in availability – inevitable. However, the results show significant potential for longer term demand reductions if the supply chains for material recycling, technology reuse and remanufacturing are put in place quickly. This highlights the significant potential benefits of planning for the possibility of this kind of recycling and reuse in the development stages of technology and infrastructure.

Implications of critical material dependence

Induced critical material demand does not constrain technology roll-out per se; it is the relationship between supply and demand that results in constraints. In early studies of critical material constraints, supply was addressed in aggregate as the remaining reserves of a material and a constraint was created by scarcity, when these reserves were nearly depleted (Andersson 2001; Kleijn & van der Voet 2010). The growth potential of low carbon technologies was assessed by comparing the reserves of a particular material to the demand for that material from a pre-determined roll-out of low carbon technologies over a particular period of time. The maximum potential growth rate was deemed to have been constrained if reserves were less than forecasted demand.

However, this tells us little about when this constraint might occur. This is important for low-carbon transition, because the timing of technology roll-out is as important as the final number of technologies deployed, since the timescales for achieving carbon targets are fixed and relatively short. Secondly, disruptions are more likely to happen in the short-term because mine production cannot adapt quickly to meet structural changes in demand patterns (Morley & Eatherley 2008). The endemic and increasing volatility in commodity prices, especially among technology metals, does not provide sufficient motivation for investment in new mines (Cashin & McDermott 2002; Morley & Eatherley 2008); furthermore, even when investment decisions are taken, it can take between 9 to 25 years to get the necessary permissions and infrastructure to increase production (Moriguchi 2010). Although an equilibrium between supply and demand may be achieved in the long-term, the metals market in the short-term is more characterised by disequilibrium than equilibrium (Morley & Eatherley 2008).

The approach to analysis used must be able to identify potential constraints in the short – and medium-terms rather than on aggregate over the period of analysis. Comparison of availability and demand over a period of time is not sufficiently detailed to achieve this aim. Furthermore, short-term disruption is a function of more than just the reserves. There is increasing recognition that short term constraints in access to critical materials could be affected by a series of political, geographical and environmental factors as well as geological availability (Graedel et al. 2012; Morley & Eatherley 2008; US Department of Energy 2011; European Commission 2010). The assessment of the potential for critical material supply disruption needs to take all these factors into account.

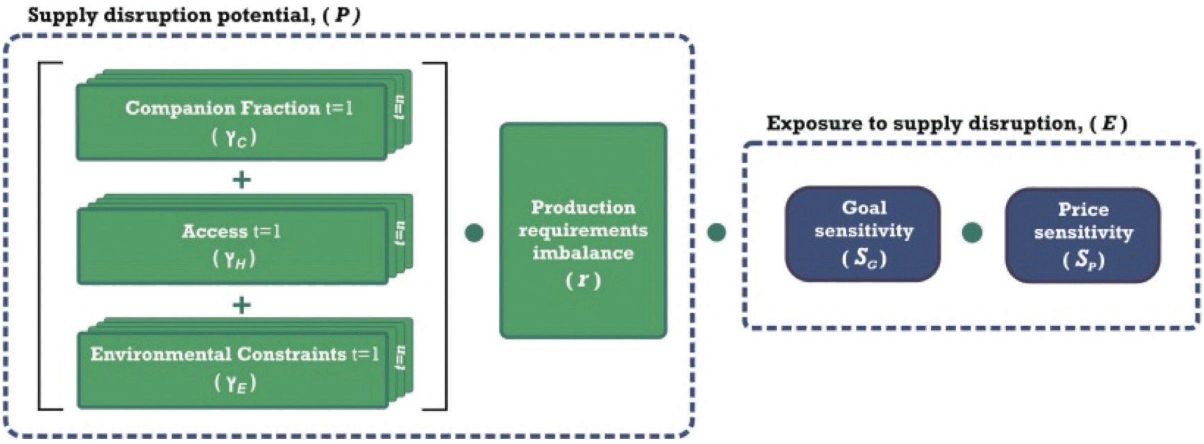
Complex, risk-based approach to analysis of material criticality constraints

The risk to low carbon technology roll out of disruption caused by induced critical material demand, or criticality as we call it, is a function of the potential for supply disruption and the exposure of low carbon transitions to this disruption. A recent paper by Roelich et al (2014) has demonstrated the value of a complex, risk-based approach to analysis of the material criticality of infrastructure transitions. The approach conceptualises criticality as analogous to risk; that is, defined as the product of the probability of an event and the severity of harm resulting from that event. Two principal indices are created to represent these dimensions of risk:

- Supply disruption potential *(P)*, which quantifies the likelihood that access to a particular material could be restricted;
- Exposure to disruption *(E)*, which quantifies the severity of the likely effect of the resultant disruption on the goal in question.

When multiplied, the two indices provide an assessment of the risk that material criticality poses to a low carbon electricity system transition. Importantly, both indices are produced as a forecasted time-series, which allows us to estimate criticality over time and identify trends of increasing (or decreasing) criticality. Each index is composed of a series of metrics, the trends in which can be tracked individually. This is essential to provide more detailed insights into the drivers of criticality for particular materials or technologies and the associated policy interventions that might reduce criticality. The combination of metrics contributing to indices is summarized in Figure 4 and the metrics themselves are described briefly below and in detail in Roelich et al (2014).

Figure 4: Indicators (P and E) and metrics for assessing the criticality of infrastructure transitions



Using this method it is possible to analyse the criticality of a range of transition pathways, such as those outlined by DECC in the Carbon Plan (HM Government 2011), to compare the risks associated with critical materials of different pathways to the same goal.

Supply disruption potential

The Supply Disruption Potential index represents the likelihood that access to a particular material could be restricted as a result of an imbalance between production and requirements, which could be exacerbated by a range of factors that could constrain future increases in production. Therefore we produce a metric 'r' which represents the potential scale and frequency of imbalance over the period of analysis, and a series of exacerbating factors γ_x. Comprehensive analysis of the entire range of potential exacerbating factors would be complex and require advanced modelling. Therefore, we have selected three factors that are considered to have the most significant and direct influences on production-requirements imbalance, have widely recognised metrics associated with them, and are readily quantifiably. These three factors are:

- co-production (γ_C) – many of critical materials are not produced as primary products but as co-products of other materials);
- geographic distribution of production (γ_H) – geographic monopolies in production may tempt policymakers to impose supply restrictions for geopolitical purposes);
- environmental constraints (γ_E) – the environmental sensitivity of land surrounding mines may give rise to restrictive legislation.

It is recognised that commodity price is an important determinant of future production and supply disruption; however, predicting the dynamics of this relationship with any certainty is extremely complicated and unreliable and so this excluded from the approach at this stage.

For a given material, we assume that the exacerbating factors tempering the production-requirement imbalance r (namely $\gamma_{C,H,E}$) are independent and equally weighted. The sum of the exacerbating factors is multiplied by the production-requirements imbalance to provide an overall assessment of the potential for supply disruption.

In order to compare criticalities of materials we normalise with respect to the values for some well-characterized element (e.g. iron), denoted by the subscript 0. This allows us to express relative criticality: we will be able to analyze the magnitude of the increase in criticality (e.g. "delivering the goal using the new technology which is dependent on a given critical material will increase the risk of probability of disruption by a factor of p/p_0").

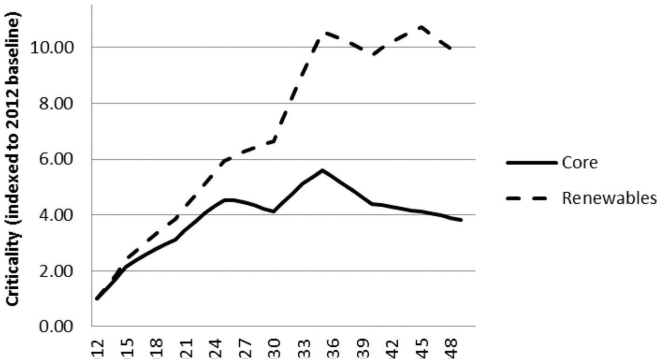
Exposure to supply disruption

The exposure index represents the potential degree of severity of the effect of supply disruption on the transition to a low carbon infrastructure system. Unlike the supply disruption potential, which is a material property, exposure is a property of the technical system under consideration; therefore, it must be assessed at the level of the goal we are analysing i.e. in this case decarbonisation of the infrastructure system. Exposure is operationalized as the product of the proportion of the goal affected by any disruption (the goal sensitivity S_G), and the likely effect of increasing price resulting from disruption (the price sensitivity S_P).

Criticality of wind turbine deployment to neodymium disruption

When applied to the case of the effect of neodymium disruption on the deployment of wind turbines in the UK[1] we see that criticality in DECC's Core Pathway increases four-fold over the period from 2012 to 2050, with a step-change occurring in 2030, as shown in Figure 5 with reference to 2012 values. This trend is even more dramatic in the Renewables Pathway with an almost ten-fold increase. Analysis of the contribution of individual indices shows that exposure is the principal cause of the increase in criticality over the period under investigation, as wind turbines that rely on neodymium become more prevalent in the energy mix (i.e. a greater proportion of the delivery of the goal is reliant on this technology, so disruption thereof has a greater impact).

Figure 5: Criticality of two scenarios of wind turbine roll-out in the UK 2012-2050 (source: Roelich et al 2014).



This demonstrates the importance of considering the temporally dynamic analysis of criticality. In the case of low-carbon electricity from wind turbines in the UK, the likely decrease in P for the key critical material is outweighed by the increase in the exposure E of the goal to that material as the electricity system becomes increasingly reliant on wind turbines; thus the overall criticality C increases over the analysis period. The dynamic approach described in this chapter allows analysis of the nature of the change in criticality over time. Furthermore, the analysis of the relative risk to different pathways to achieving the goal of low-carbon transition provides more specific and relevant information to support decision making under uncertainty and may prevent reliance on pathways and technologies that could become highly critical in the future (creating 'lock-in').

Technology diversity

One of the best responses to material criticality is technology diversity. Diversity in technology – retaining a number of different technologies that contribute to the same goal – reduces exposure and hence risk. The value of technology diversity has been explored extensively in what is called the portfolio effect, whereby a portfolio of technologies achieves the best balance between risk and cost and can reduce the long-term costs of energy system transformation (Awerbuch, Janssen et al 2005).

Diversity can also mitigate future lock-in, hedges ignorance (with regard to both future demand and supply) and also offers a means to promote innovation (Stirling 2007). As an example of this; electric motors and generators that use rare-earth permanent magnets are increasingly favoured in low carbon transport and renewable generation technologies, leaving us exposed to supply disruption in neodymium. Technology diversity would require a move away from a sole focus on rare-earth permanent magnets in these applications to the development of alternatives such as superconducting motors and generators which may soon be feasible for, e.g. wind turbine generators and large motors for ship propulsion, or indeed retention and further development of 'old' electromagnet technology using less critical materials with established recovery and recycling infrastructure (copper, iron) where the technical performance penalty is outweighed by the reduction in exposure to critical materials supply (see section 4 below).

However, diversity, and the ensuing resilience under shock and robustness under stress, is more than just the presence of many technologies: *"diversity is generally a state under which an observed system is seen to display: (1)* ***even balance*** *across (2) a* ***variety*** *of (3)* ***mutually disparate*** *categories"* (Stirling 2011). In the example given above; balance would mean that shares between motors and generators based on electromagnet, permanent magnet and super-conducting technologies would have to be similar; variety and mutual disparity would mean that the various electromotive and generating technologies would not rely on the same critical material.

Technologies with multiple critical materials: criticality vs. performance.

It is very challenging to achieve this diversity in a system where single technologies include a number of critical materials and where multiple technologies rely on the same critical material. Therefore we need analytical tools to see whether substituting technologies increases or decreases criticality, while providing the same or different system function.

A methodology has recently been developed that allows comparison of technologies reliant on multiple critical materials in terms of technical performance vs. criticality, using a comparison of various types of wind turbine and one of their key components (i.e. magnet technologies) as a case study (Dawson et al, 2014 in press: note that the remainder of this section draws heavily on this paper). In general, technological progress tends to be driven by a quest for techno-economic efficiency; a greater output of a service (e.g. electricity, fuel economy, water cleanliness) for the same input of financial and material resources.

Thus, interventions in infrastructure systems are made at a particular level, largely driven by engineering and economic considerations. Wider impacts on the system caused by such interventions – upstream carbon emissions, pollution from refining of new materials, effects on functionally or physically interlinked processes, treatment of waste at end-of-life etc. – are often considered either peripherally or not at all.

For example, the recent push to use gas and biomass as alternatives to coal for electricity generation, in pursuit of carbon targets, has led to a reduction in production of the key by-product, fly ash. Fly ash is a major ingredient in modern concrete, increasing its technical performance and reducing its cost and carbon footprint. Many construction industry analysts are now reporting actual or impending shortages of concrete, increasing build costs and causing disruption to major projects as a direct result of reduced fly ash availability (Mann, W: New Civ Eng 7-14/8/14 p8). An engineering-level intervention has led to unintended, system-level impacts in a different industry with the potential to reduce short-term resilience (i.e. disruption of projects) and long-term resilience (owing to forced substitution of lower-grade materials that may increase carbon footprint and/or reduce durability).

Materials criticality is a case in point, as outlined in several cases above where the rapid adoption or development of a technology may lead to increased exposure to supply of critical materials. We can analyse changes in criticality caused by technological interventions using a "global – translational – local" properties conceptual framework.

Local, translational and global properties

This can be illustrated by considering road infrastructure provision as a very simple example. A policy priority for road infrastructure is user safety: this is a global property of the system. User safety is a function of a number of properties nested under this, such as stopping distance, lighting, roadside information; these are translational properties, in that they relate to the global property but are not under the direct control of those making interventions in the system (in this case, highways design engineers).

These translational properties can be sequentially 'unpacked' into further, more technical translational properties (e.g. vehicle braking, driver reaction times and coefficient of friction of the road surface all contribute to stopping distance) until we reach local properties over which engineers have direct control (e.g. the materials used for the road surface). Interventions at any of these levels will influence user safety. When we have defined the global-translational-local property set, we can then apply mathematical analysis to quantify the influence of changing local properties, identify the most sensitive parameters and so on.

Wind turbines: a case study

Roll-out of new wind turbine capacity is a key tenet of the UK's strategy for achieving low-carbon policy goals, and provides a useful example of how the approach might be applied.

There are a number of competing technologies for wind turbines, differentiated by varying combinations of gearbox type and whether permanent magnets (PM) or electromagnets (EM) are used in the generator of the turbine. Polinder (2006) defined five key types; in order of technological maturity (and perceived techno-economic efficiency):

1. An EM generator with a 3-stage gearbox
2. An EM generator with a single-stage gearbox
3. A direct-drive (i.e., without a gearbox) EM generator
4. A direct-drive PM generator
5. A PM generator with a single-stage gearbox

The switch from EM (1 – 3) to PM (4, 5) technologies is associated with significant concern over the criticality of the materials used to make the permanent magnets; in particular, the rare earth metals neodymium (which provides the magnetic performance) and dysprosium (which prevents loss of magnetism under higher-temperature operation). The US Department of Energy (2011) has expressed concerns that roll-out of wind turbines (along with other low-carbon technologies) could *"face considerable risks of [rare earth metal] supply-demand imbalances that could lead to increased price volatility and supply chain disruption".*

Other commentators have noted that it is not possible to quantitatively analyse supply chains for rare earths used in wind turbines, export quotas are decreasing and may be used for geopolitical purposes, and that prices are highly volatile, fluctuating by orders of magnitude (Shih et al 2012). Allied to this is the fact that all turbines, both EM and PM, use considerable amounts of copper, itself considered a critical material in many contexts (though generally less so than the rare earths, see EC 2010) and iron; the PM technology also uses boron.

Clearly, making a **local** technology decision (choice of turbine type based on a given performance criteria) could affect the ability to deliver the **global** system goal (provision of low-carbon energy via wind turbines) and the two are linked by a **transitional** property: the criticality of the turbines. Thus it is appropriate to examine criticality as a function of the performance criteria of the turbine types in order to provide information on how the resilience of the system against materials supply changes according to its technical configuration.

Performance criteria

This poses two challenges. First, we must define performance criteria for the turbines (NB it is important that these are normalised in terms of an equivalent unit of output; clearly, a 10 MW turbine will require more material and be 'more critical' than a 1 MW turbine and we must adjust accordingly if our data comes from multiple sources). There are many parameters that may be considered in the choice of a particular turbine – not least of course price – but here we wish to illustrate the response of criticality to technical decisions. Dawson et al (2014) considered two key engineering parameters:

1. For a given unit of output, it is useful to minimise the total mass of the generator, as this will minimise the static and dynamic structural loads on the tower, the size of the foundations and the installation cost of the turbine. The total mass of the generator is largely accounted for by: the mass of the 'active material' that contributes directly to electricity generation such as coils, magnets and electrical stators/rotors; and the mass of the gearbox. PM generators are often lighter than the equivalent EM technologies, both intrinsically and because the gearbox may be reduced or omitted.
2. It is also useful to minimise the 'downtime' of the generator i.e. the number of days per year in which the generator is not working owing to failure, repair and/or maintenance. Using a simpler gearbox or a direct drive system without a gearbox reduces the incidence of mechanical failure but may increase the risk of electrical component failure.

If we assume (for a first approximation) that these are equally important, then the product of these two factors could be used as our performance parameter that we would seek to minimise.

Criticality of multiple combined materials

Secondly, we must calculate the relative criticality of the generators. Criticality indices are normally only defined for a single material, yet each of our generators combines rare earth metals, copper, iron and boron in various proportions. Dawson et al (2014) showed that, for the purposes of comparing technologies contributing the same output in the context of the same policy goal, the relative criticality C_T of a technology T containing multiple elements $X, Y, Z\ldots$ can be calculated thus:

$$C_T = P_X E_{XT} + P_Y E_{YT} + P_Z E_{ZT} + \ldots$$

Where:

P_X, P_Y, P_Z etc. are parameters related to the probability of the occurrence of a material supply disruption for elements X, Y, Z etc. calculated according to Roelich et al (2014). They can best be thought of as relative probabilities of disruption relative to iron, the reference element; an element with P = 12 is twelve times more likely to experience supply disruption than iron; a process solely reliant on an element with P = 200 is fifty times more likely to be disrupted than one reliant on an element with P = 4; and so on. P values for the materials considered here are given in Table 2.

E_{XT}, E_{YT}, E_{ZT} etc. are the fraction of the price of technology T attributable to elements X, Y, Z etc. For example, if the cost of the copper (Cu) required to make a £1M generator is £100k, then E_{CuT} = £100k ÷ £1M = 0.1.

Table 2: P values and approximate prices for selected elements (after Dawson et al, 2014)

Element	(P)	$/kg
Iron (Fe)	1.00	0.099
Boron (b)	1.23	0.866
Copper (Cu)	1.96	6.86
Dysprosium (Dy)	6.90	1600
Neodymium (Nd)	11.58	270

Performance vs. criticality

Figure 6: Performance vs. criticality for various wind turbine technologies

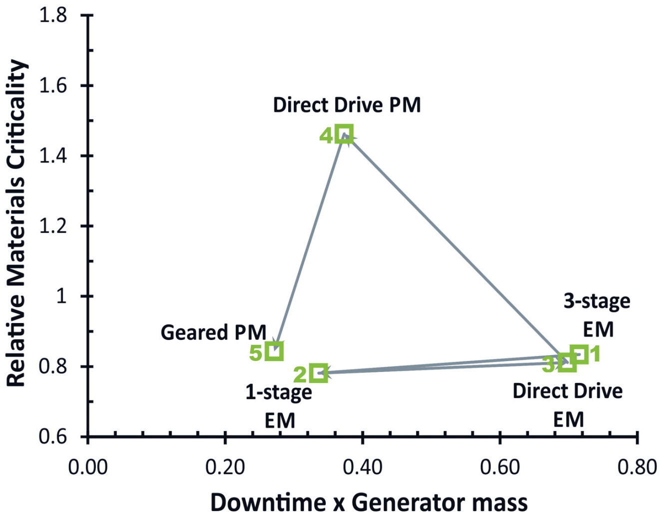


Figure 6 plots the performance parameter against criticality for the generator choices available (derived for 3 MW turbines in each case, see Dawson et al 2014 for full details of the calculations). The path traced (1 – 2 – 3 – 4 – 5) approximates the chronological maturity of the various technologies, but of course any path is valid. By analysing the transitions between the various technology choices, we can examine the trade-offs between criticality and performance, and identify potential strategies to mitigate against lock-in to technologies with the potential to become disrupted owing to restricted materials supply.

Making a technology decision to replace a three-stage EM system with a single-stage EM system (1 – 2) yields a net reduction in total mass and reduced downtime; this is associated with a small decrease in criticality. The local and translational properties are both improved and so this appears to be a good design choice. Switching to a direct-drive EM system (2 – 3) yields net increases in mass, downtime and criticality and thus does not appear to be a good design choice. However, in both cases, the transitional variable is not significantly affected by the local variable, and thus the system goal is not sensitive to these choices.

The next transition however (3 – 4) introduces the PM technology. An improvement in local performance (because of the greatly reduced mass of active material permitted by the use of PM over EM) is accompanied by an 80% increase in criticality. In this case, the trade-off between technical performance and the exposure of the system to potential disruption in rare earth metal supply would need to be analysed more closely. The final transition (4 – 5) reintroduces a single-stage gearbox. This increases rotor speed and allows the size of the PM to be reduced by more than the mass of the gearbox; it also reduces downtime as the increased maintenance requirement of the gearbox is surpassed by the increased reliability of the electronic components. Both the local and transitional variables are improved and so this appears a good design choice.

Interestingly, this appears to reflect current industrial trends, in that some turbine manufacturers are seeking to adopt such systems to reduce exposure to rare earth metal supply despite such 'hybrid' systems being seen as somewhat radical and untested (Vestas 2011; Vries & Bruist, 2012).

With regard to resilience, of most interest is the comparison between the optimal EM (2) and PM (5) technologies. To all intents and purposes, these have the same performance and criticality. Thus retaining a suite of both technologies (or at least manufacturing and supply capabilities thereof) – retaining technodiversity – would provide a hedge against sudden changes in the criticality of rare earth metals or indeed more traditional materials such as copper, without a significant degradation of supply capability. This technological substitution is by far a more realistic engineering option than the 'elemental' substitution (e.g. of one rare earth for another) that is often advocated by criticality scholars who do not consider the engineering properties of the systems in which these materials are employed.

Of course, the analysis presented above does not consider all the parameters that must be considered when choosing a wind turbine technology (for example, the ability for a turbine to operate in synchronous mode and effectively store kinetic energy that can be used to help with load balancing across an electricity supply grid, or the interaction of the technical performance with political aspects that must be considered when designing on – or off-shore installations). Nonetheless, it presents a useful basic framework to analyse how local design interventions can impact on global system properties through translational variables. This moves beyond a simple cost-benefit analysis, which so often will drive systems towards technological lock-in by concentration on techno-economic performance alone without considering wider system impacts.

Conclusions

This chapter has discussed and illustrated the risks to systemic resilience of sustainable energy provision posed by potential supply disruptions to critical materials. This is a particularly thorny problem due to the complexity of these kinds of infrastructure systems: many technologies may contain the same critical material and any one technology may contain multiple critical materials.

The determination of criticality is far more complex than geological scarcity; supply chain readiness, environmental legislation and geo-political factors must be considered over the lifetime of the infrastructure system.

Planning and design of infrastructure should consider dependence on materials and the potential for criticality to lead to supply disruption, and employ a framework for determining the trade-offs between the functional properties of the systems and criticality.

Methodologies exist to tackle these problems, and these have been illustrated on a number of case studies above. Stocks and flows modelling is a proven methodology for determining the future material dependence of infrastructure roll-out, and where there is potential to reduce this by recycling and reuse of technology components.

The criticality of an infrastructure transition can be analysed in a risk based framework where criticality is conceptualised as the combination of the supply disruption potential (likelihood of disruption) and the exposure (severity of impact of disruption) of the system to this.

This criticality metric can be used to analyse the impact of different technology choices and design decisions where the technology choices involve multiple potentially critical materials and impact on multiple functional properties of the system.

An implicit finding of the analysis is that diversity in technological systems is as important as it is in natural systems. Moving wholesale to a nominally 'most efficient' technology may lead to unintended consequences, locking systems into modes of operation that are vulnerable to disruptions in material supply (and indeed other sources of volatility in the operating environment). Retaining a suite of technologies to deliver a given infrastructure goal will pay dividends in the long run.

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Footnotes

[1] Using wind turbine roll-out scenarios defined in DECC's Carbon Plan (HM Government 2011).

Conclusion

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Introduction

Infrastructure possesses a number of peculiar characteristics, which both create a need for state investment in infrastructure and make difficult the kind of valuation and appraisal that such investment requires. With a view to advancing our tools and understanding of infrastructure valuation and appraisal, this report has brought together a range of cutting edge work, with a leading role for economics but also including a number of other disciplines, including engineering, environmental science, and mathematics. While the contributions varied in their scope and focus, we argued in the introduction that they contained a number of general lessons, including:

- The potential for iterative methods to improve decision-making under uncertainty;
- The need to incorporate wide-reaching and multidimensional interdependencies into appraisal;
- That institutional and regulatory challenges are likely to confront any attempt to implement reformed methods of valuation and appraisal;
- That seemingly simple technological decisions may be inextricably linked with political and environmental considerations.

Beyond these particular points, we suggested that systemacity and uncertainty emerged as central and recurrent themes, being present, in different forms, in the dilemmas considered in every chapter. Thus, chapter one highlighted both as areas neglected in the standard market failure literature. Chapter two was concerned with how much to invest on securing the resilience of transport infrastructure, understood as a system, in the face of uncertainty about the likelihood of extreme events occurring and lack of knowledge about consumers' preferences. Chapter three focused on the problem of uncertainty, but it is notable that the sources of uncertainty lay in properties of the physical infrastructure system and the social and eocnomic context in which it operates. Chapters four and five focused on the opportunities and barriers created by the systemic nature of infrastructure for the employment of methods such as real options and passive provision to manage uncertainty. Finally, chapter six highlighted the way in which uncertainties characterising the social and economic context of infrastructure provision may interfere with the operation of physical systems.

It is clear that systemacity and uncertainty are major issues confronting infrastructure valuation and provision, and one of the functions of this report has been to assemble a number of promising avenues for their future investigation. Much of the research contained in the chapters of the report is, like the iBuild project itself, still in its relative infancy. In this sense the report should be seen as providing a starting point for further work on systemacity and uncertainty in infrastructure provision to build upon. A number of further challenges also emerge from the report. These include:

- Developing a better understanding of, and means of measuring, non-marginal or wider economic effects;
- Incorporating endogenous preferences into our modelling and analysis;
- Achieving a better balance between quantitative and qualitative appraisal, in order to enable a balanced, multidimensional assessment of value;
- Better acknowledging and addressing the role of power, institutions, and politics in infrastructure assessment and delivery;
- Confronting challenges of implementability, particularly with regard to methods for dealing with uncertainty.

These are all important issues in infrastructure valuation and appraisal and that future research, including that carried out under the iBuild project, should seek to address. Without wanting to pre-empt this research, we wish to conclude with some further consideration of the interdisciplinary nature of research on infrastructure valuation and to report on the some of the current and planned future work in iBUILD on systems of infrastructure provision.

One way of thinking about all of these issues is in terms of the complex interaction of physical and socioeconomic systems. Infrastructure provision can be thought of as a two-stage interaction between the socioeconomic and the physical. First, policy design and implementation, which occurs within a socioeconomic system, creates a physical infrastructure system. Second, this physical infrastructure system interacts with, shapes, and serves a broader socioeconomic system, encompassing economic, environmental and other components. Of course, this way of thinking about infrastructure provision is a crude and rather abstract simplification, but it is a useful heuristic for organising the challenges that arise in trying to value and appraise infrastructure.

For some of these challenges arise at the first stage and concern the way in which infrastructure is designed and delivered, while others arise at the second stage and concern the ways in which infrastructure serves, shapes, and is shaped by the broader socioeconomic system in which it operates.

What is needed, then, is a better understanding of both the physical and the socioeconomic systems that are combined in infrastructure provision, and of the relationship between the two. This means complementing technical knowledge drawn from engineering and environmental science with theories, concepts, and methods drawn from economics and the social sciences, with a view to improving our (socioeconomic and technical) policy-making systems in order to design, deliver, and maintain improved physical infrastructure systems that will in turn better serve the broader socioeconomic systems in which they operate. This report demonstrates the first fruits of attempts to do that as initiated by iBUILD and University of Leeds economists and their collaborators. Much work, of course remains to be done but we can see in this report some distinctive aspects that are likely to continue to mark the iBUILD/Leeds approach to interdisciplinary infrastructure research involving economists.

Traditionally, it has been standard economic theory that has furnished infrastructure policy with social scientific tools and theories. Chapter two demonstrates the ongoing and highly fruitful development of the best of this tradition. However, chapter one identified several limitations of standard economic theory for understanding infrastructure, and these were compounded by chapters four, five, and six, which demonstrated the relevance of institutions, politics, power, and ideology, most of which lie beyond the domain of standard economics. Thus it is apparent that there is a diversity of approaches to economics represented in this report and that non-standard approaches have a role to play. It can also be mentioned that the very distinction between standard and non-standard economics is itself developing and blurring in places, given well-known new developments in economics such as behavioural and happiness economics, and the criticism of the old orthodoxy in wake of the global economic crisis.[1] The remainder of this conclusion is given over to introducing a specific alternative approach being developed in iBUILD (also developed in the FESSUD project) the systems of provision, or sop, approach, drawn from the non-standard tradition of political economy.[2]

The Systems of Provision Approach

The system of provision approach takes as its units of analyses commodity-specific chains of provision, which are called 'systems of provision' or 'sops'. Though it is recognised that the boundaries of a sop are porous and will frequently overlap, these sops are defined "vertically" to encompass the entire chain of activities and agents involved in the provision of a good, including financing, production, distribution, marketing and consumption.[3] It is assumed that these different components of provisioning are combined within a sop as an integral whole, and thus demand a systemic approach to theorising. The structure, form and content that define the sop as an integral whole are said to derive 'from the material and cultural properties of the commodity or service in question as well as the wider context' (Bayliss 2014 p8), all of which are grappled with in their concrete and historically-specific form.

Three features of the sop approach are particularly relevant for our current purposes. First, the approach integrates the study of physical and social systems, by looking at how a sop is shaped by the physical properties of a commodity and the physical processes involved in its provision alongside the commodity's cultural properties and the social institutions, beliefs and practices within which provisioning takes place. Thus, the physical aspects of a system (materials, procurement, construction method, method of service delivery) are investigated alongside its social or organisational aspects (ownership, control, conditions of access, legal and regulatory framework), with an emphasis on the ways in which each aspect both constrains and is shaped by the other.

Second, the material and cultural properties of the commodity or service in question, and the wider context in which the sop exists, are all understood to be historically evolved and consequently time – and place-specific. In other words, sops are investigated concretely, with the historically – and socially-specific way that the institutions and structures underpinning provision have evolved in a particular context recognised and incorporated into the analysis. Even where the physical properties of a commodity impose some necessary features on the sop, these features will take socially-specific forms. As Bayliss (2014) says in her investigation of water provision in the UK:

> *'each sop is different and depends on the commodity or service in question and the context in which provision is located. Water has specific material properties which affect its delivery and which also impact on the way in which consumers engage with producers. When the wider historical, political, geographical and socio-economic context is added to the mix, this creates a sop that is unique to the delivery of water in England and Wales.'*
>
> **(Bayliss 2014 p2).**

This is a long way from the universalising and ahistorical theories of standard economics, which tend to homogenise across goods, institutions, and societies.

Third, notwithstanding this emphasis on concrete specificity, sops are recognised to coexist within a shared social context and consequently have some generalizable features. Most notably, within a capitalist economy '[s] ystemic tendencies [are] explained on the basis of the imperatives of profitability and capital accumulation' (Fine 2002 p197).[4] This focuses analysis of sops within a capitalist system on the ways in which value is created and appropriated within the sop, and on its distributional consequences: 'This sector-wide approach is intended to provide an overview of the flow of funds with a view to understanding the distributional outcomes from the sop' (Bayliss 2014 p7). It is primarily because of the pursuit of value that relations between agents are contested, if not conflictual. Outcomes, then, are analysed not in terms of equilibria of greater or lesser efficiency, but as the result of settlements among agents within the sop. These settlements reflect a complex and diverge range of factors within the sop:

> *'Contestation among agents leads to continually evolving outcomes which result from the interplay of various factors including vested interests, bargaining positions and government policy, all of which are embedded in a specific context. Contestation may take the form of formal negotiation … However, much of the contested space lies outside the realms of the formal regulatory framework. For the sop approach, what is not regulated is as important as what is'*
>
> **(Bayliss 2014 p5).**

The virtue of these three features is that they root our understanding and appraisal of infrastructure as a physical system in a rigorous understanding of the socioeconomic processes through which infrastructure policy is made and of the social systems which it is intended to serve. The study of both aspects of a sop in light of each other promises to enhance our understanding of infrastructure and provide a reliable basis for policy. It is important to note at this stage that the approach was developed as a tool or framework for theoretical investigation; its usefulness as a policy tool in general, and for valuation and appraisal in particular, remains to be determined. Nonetheless, we now briefly outline three areas in which we think the sop approach has the potential to advance our understanding of infrastructure provision.

The political economy of infrastructure provision

First, as should by now be clear, the sop approach incorporates into its analysis a number of aspects of provision that are important determinants of the level and quality of infrastructure investment but frequently neglected by standard valuation techniques, including institutions, power, culture and ideology. In doing so it promises to enhance our understanding of the political economy of policy-making (stage one above) and of the broader social, economic, and political context within which infrastructure systems operate. Furthermore, the approach's stress on investigating sops concretely, that is, as they actually exist, means that the understanding of political economy attained through sop analysis is rigorous, reliable, and relevant.

The strength of the sop approach as a means to investigate the political economy of infrastructure provision can be illustrated through a discussion of the sop approach's conception of the state. Current thinking about infrastructure policy is organised around a discourse of market versus state. Since the late 1970s, if not before, this has been accompanied by a presumption in favour of the market on the grounds that it leads to a more efficient allocation of resources. This way of thinking about economic policy is based on highly idealised conceptions of both state and market, which bear little relationship to the form that states and markets take in the real economy. As Bayliss says of water provision in England and Wales,

> *'[s]ector policy is largely oriented around making the structure as market-like as possible. The regulatory framework is intended to mimic the incentives and constraints that monopolistic companies would face if they were under competitive pressure. The sector is seen as deviating from an idealised state'.*
>
> **(Bayliss 2014 p5).**

The sop approach, by contrast, sees that the role of the state, even within a single system of provision, can seldom be reduced to a single dimension or point of intervention. Rather, states intervene in multiple and complex ways throughout the chain of provision. For example, in addition to good or service-specific types of intervention, the state is involved in creating and enforcing the legal and regulatory framework within which financing, production, employment, and consumption occur. This implies a recognition that markets are, to a significant extent, created and maintained by states. Thus the neoclassical market-state dichotomy is supplanted by an investigation of the multifaceted ways in which states shape particular, concrete sops.

By doing away with crude state-market dichotomies the sop approach roots our thinking about policy in the real, concrete forms taken by, and roles played by, state and market institutions in particular contexts:

The sop approach … interprets the sector in terms of the way in which agents relate to each other and, as such, is based in the real world. Rather than seeing the delivery of water as a market that needs to be corrected, the sop approach starts from the premise that outcomes emerge from settlements between agents which are themselves embedded in historically evolved social and economic structures and processes' (Bayliss 2014 p5).

Grounding policy-making in an understanding these structures and processes is more likely to lead to policy that is effective, realistic, and pragmatic: '[t]he implications of organising provision around either the state or markets cannot be known without the kind of detailed analysis advocated by the sop approach' (Robertson 2014 p73).

However, and in part related to the multifarious role of the state, the sop approach also recognises that states are not homogenous entities. On the contrary, states encompass many different bodies and branches, including different branches of government (legislature, executive, judiciary), different tiers of government (national, regional, local), and a range of government departments, to name but a few dimensions of difference.[5] This internal diversity creates the possibility that different wings of the state will at times conflict with each other, though whether and how this occurs can only be determined in particular, concrete circumstances. The sop approach's conceptualisation of the state thus provides a strong starting point for thinking about the political economy of infrastructure provision, in particular how joined up policy making can be achieved in the face of barriers such as power imbalances and conflicting interests or goals across different branches of government. Crucially, it is also admitted that the role that the state plays in a sop is shaped by political and ideological agendas. As the content and influence of political and ideological agendas will be context specific and change over time, they too must be subject to investigation.

Endogenous preferences

Standard economists' long-standing wariness of making interpersonal comparisons of utility has created a steadfast commitment to the notion of consumer sovereignty, which places a tautology at the heart of neoclassical consumer theory: individuals prefer what they choose and choose what they prefer. The requirements for model tractability have added to this commitment to consumer sovereignty the idea that agents are rational, selfish optimisers.[6] As a result, consumption is dealt with in terms of an optimisation problem, while the black box of utility functions have remained firmly closed, its determinants assumed to be fixed and exogenous and, for the purposes of theory, wholly subjective.

The sop approach breaks with this by reversing the reduction of consumer behaviour to preferences, and instead viewing consumption behaviour in terms of the consumption cultures that they arise from. Like consumer behaviour itself, these consumption cultures are good – and context-specific, with variation likely, not only across sops but also across different social strata within a given sop. The second strength of the sop approach for evaluating infrastructure is therefore that its theory of consumption treats preferences as legitimate subjects of theoretical and empirical analysis. Here, the sop approach is distinctive not only for endogenising preferences, but also for how it goes about doing so.

Consumption cultures are said to result from the material conditions of provision: 'consumption [is] linked to production as part of a vertically integrated process.' (Bayliss 2014 p2). This gives them a strong objective component, opening the door to their scientific investigation. However, a central role is also given to cultural beliefs and perceptions in shaping how material provision is perceived. Again, we see the sop approach subtly integrating the material and the social, though in the case of consumption the integration is achieved through a reconceptualisation of individual agents as embedded and socially-constituted, with limited (but nonetheless estimable) cognitive capacities. The sociability of agents and their cognitive limitations (by which is meant a fundamental inability to have perfect knowledge and foresight, rather than a condition of costly information and calculable risk) mean that agents rely in part on cultural discourses to form their beliefs and desires about their consumption. This reliance is not dependence – individuals also have critical faculties, which they use to interpret cultural information, in light of both other cultural information and their material experiences: 'individuals are social and not omniscient and so use public images and representations in making decisions, interpreting material and cultural factors reflexively in light of each other' (Robertson 2014 p66). Nonetheless, it does imply a theoretical privileging of social factors, both material and cultural, in shaping consumption cultures and associated behaviours.

Multiple dimensions of value

Standard economics defines outcomes in terms of equilibria, which privileges efficiency as an assessment criterion. The sop approach, by contrast, views outcomes as settlements among agents, which may be appraised in terms of a range of criteria, including their environmental impact, their distributional consequences, or their technological efficiency, reliability and sustainability. The third strength of the sop approach is therefore that it paves the way for a multidimensional assessment of outcomes and can incorporate a broad range of policy goals. Sop analyses provide for a rich investigation of the different dimensions of value realised in any particular outcome, instead of reducing the multiple dimensions of value to a single monetary dimension, as occurs in cost-benefit and similar analyses (e.g. Brown and Veronese Passarella 2014). Take distribution as an example. Under the sop approach, distributional results are not just a matter of the allocation of initial resources as in neoclassical welfare economics, but of the way in which value is competed over and distributed along the chain of provision. One implication is that employment practices as well as consumption levels have distributional implications. Furthermore, the sop approach permits a more substantive assessment of distributional outcomes because it looks at the way in which consumption norms shape well-being in good-specific ways: '[o]ne of the purposes of the sop approach is to look at the range of different consumption norms that exist in relation to a good as a result of social and economic stratification' (Robertson 2014 p10).

Conclusion

This concluding chapter began by summing up the findings of this report and outlining the challenges for future work in infrastructure valuation and appraisal. Uncertainty and systemacity are now recognised as key challenges in valuing and appraising infrastructure, and most of the report was geared towards developing new ways to address them. Work on uncertainty and systemacity remains pressing, but, in addition, a need for a deeper understanding of the political economy of infrastructure provision emerged from the report. This requires a rigorous economic, socioeconomic and political economic analysis, of both the processes of infrastructure policy-making and the broader socioeconomic context in which infrastructure operates, as well as of how both interact with the physical components of infrastructure systems.

We have argued that the sop approach has the potential to deepen our understanding of the socioeconomic dimensions of infrastructure provision, and should be given a prominent role in such future work. In its conceptualisation of agents and the economy, and its methodological commitment to starting with concrete conditions rather than abstract theory, the sop approach differs radically from standard economics and this puts it in a unique position to shed light on certain key aspects of infrastructure provision. Particularly notable here are the political economy of infrastructure provision, endogenous preferences, and the multidimensional evaluation of outcomes.

Of course, challenges will remain. The sop approach does not directly address problems of uncertainty, for example, and implementing the methods outlined in chapter three will continue to test policy-makers. An important future direction of research will be to integrate the sop approach with sophisticated analysis of uncertainty. The development of the sop approach in relation to complex systems theory, co-evolutionary perspectives (e.g. chapter five) and agent-based modelling approaches represent further crucial areas for infrastructure research, given the nature of infrastructure as a system of systems. Nonetheless, the outline given in this conclusion suggests that developing the sop approach in these directions may bring rich fruits. The future for the economics of infrastructure promises to be exciting indeed.

References

Bayliss, Kate (2014) 'Case Study: The Financialisation of Water in England and Wales', FESSUD Working Paper Series No 52

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Footnotes

[1]For a broad demonstration of non-standard economics approaches and of developments in economics more generally see the copious material on the FESSUD [Financialisation, Economy, Society and Sustainable Development, EU FP7] website (http://fessud.eu/).

[2]See Bayliss (2014) for an application of the sop approach to water provision and Robertson (2014) for an application to housing.

[3]It is worth emphasising that in stressing the 'vertical' character of a sop, we do not mean to deny that sops often have wide reach; on the contrary, they will frequently overlap and interact in a network-like way. Rather, the 'vertical' imagery is employed to distinguish the sop approach from neoclassical economics, which consigns most activities involved in provision to the black boxes of production and utility functions, themselves reduced to assumptions about optimising behaviour, in order to model the "horizontal" allocation of resources. In contrast to such an approach, the sop approach abandons methodological individualism in favour of a systemic analysis that takes social and economic structures and relations, and not the individuals that inhabit them, as its starting point.

[4]Fine is actually referring to political economy more broadly here, but it provides an accurate description of the sop approach.

[5]It is worth noting that this structural and operational diversity is also true of markets: 'the term market encompasses numerous sets of arrangements for distributing goods, which vary significantly by content, form and outcome' (Robertson 2014 p73).

[6]Technically, consumers are only assumed to be selfish in a narrow sense that their behaviour is shaped by optimisation over their utility function. Theoretically its conceded that utility function may contain other-regarding arguments, in practice this complicates the modelling process and is rarely considered.

Introduction to iBUILD:

Vision and core objectives

Introduction to iBUILD: **Vision and core objectives**

The iBUILD Centre brings together a multi-disciplinary team from Newcastle, Birmingham and Leeds Universities that includes internationally leading researchers in systems analysis, civil and infrastructure engineering, business modelling, economic analysis, geography and social science, alongside an extensive stakeholder group.

iBUILD will develop and demonstrate potential reforms to existing, as well as, a suite of alternative infrastructure business models that enable more effective delivery of local and urban infrastructure via a number of core objectives:

1) Establish a hub of expertise to provide thought leadership and innovation in the development of infrastructure business models – with a distinctive focus on local and regional scales. One element of our mission is to grow the stakeholder involvement in the consortium, we welcome new members to engage in a variety of ways, for example, through joint case studies, secondments or participation in workshops.
2) Develop new infrastructure business models that:
   a) Exploit the technical and market opportunities, whilst managing the associated risks that emerge from the increased interdependence of modern infrastructure systems.
   b) Challenge and enhance theories of infrastructure value to enable leveraging of economic, social, environmental, aesthetic and other dimensions of value.
   c) Reconcile the local scale at which infrastructure services are provided with regional, national and global scale priorities around strategic planning, financing, procurement and operation.
3) Bench test our novel infrastructure business models on a series of case studies to integrate activity across the Centre and provide evidence for policy-makers, investors, operators and other stakeholders.
4) Identify pathways to infrastructure sustainability and resilience that exploit new business models and valuation methods and consider wider issues around governance, regulation and public perception.

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