CONNECTING RESEARCH WITH CITIES

mapping the UK's research landscape on urban systems and technologies

Compiled by
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FOREWORD

The UK is home to some of the world's leading universities and research institutions. Within them, across the country, cutting edge research is underway that could impact our lives in cities today and in the future. To ensure cities, businesses and governments are connected to this leading research and to new technologies, it is important to understand what is happening on urban systems and technology development inside UK universities.

In early 2014, the Future Cities Catapult, the UK's government-backed urban innovation centre commissioned the Urban Systems Laboratory at Imperial College London to outline this. The objective of this work was to list promising city-relevant technologies and research areas within universities across the UK, and to provide insights into academic innovation systems around integrated city systems and services. The objective was to identify key players on various urban issues and highlight the innovation process in UK universities that will help connect priority research and technologies with cities.

We see this paper as a valiant first effort to map the UK university landscape related to future city solutions, from the perspective of its research and innovation activity. Whilst the focus of this study was principally on relevant developments in engineering and physical sciences, environmental and social sciences are also recognized as being key to help us create thriving future cities.

In this rapidly evolving field, we recognise that the report is not fully comprehensive and might quickly become dated. It was also carried out as a piece of market research for the Future Cities Catapult. However, we believe that the information is helpful for those involved in city-related research and innovation, so in the interest of sharing insights we publish it here. The study complements our wider programme of research on UK Future Cities capabilities which outlines the UK business and industry expertise in future city solutions (report available in July 2014).

We welcome discussion with you if you're interested in adding to our understanding of this area, or in knowing more about our work. Please visit our website, follow us on twitter, or email **Caroline Twigg** ctwigg@futurecities.catapult.org.uk and **Karl Baker** kbaker@futurecities.catapult.org.uk.

- Caroline Twigg, Head of Partnerships

About Future Cities Catapult
The Future Cities Catapult is one of a network of elite technology and innovation centres established by the Technology Strategy Board, as a long-term investment in the UK's economic capability. Applying business-led research, Catapults help businesses transform great ideas into valuable products and services to compete in the global markets of tomorrow.

The Future Cities Catapult focuses on the challenge of urban integration: helping cities take a more joined-up approach to the way they plan and operate. Its central London Innovation Centre and Cities Lab provide cutting-edge facilities for cross-cutting disciplinary innovation.

About Urban Systems Laboratory:
Imperial College has more than 200 researches activity engaged in various aspect of cities research. The newly created Imperial College Urban Systems Laboratory brings together under a single banner Imperial's world leading research capabilities in key underlying areas of engineering, science, medicine and business.

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AIMS AND OBJECTIVES OF THE RESEARCH

The aim of this research is to provide the Future Cities Catapult with an overview of the activity of the UK academic sector in technology areas relevant to the development of integrated city systems.

The specific objectives are:

- Identifying emerging technologies and research areas that relate to integrated city systems and which are likely to have an impact over a 5-10 year time horizon.
- Documenting the nature of the research funding streams available and the funding requirements associated with different technologies and research areas.
- Describing how innovation and translation processes operate within the UK academic sector including the strengths and weaknesses of these arrangements.

These results provide insights into potential collaboration opportunities with UK academia, in particular, by highlighting key innovation opportunities and means of reducing existing barriers to the successful commercialisation of relevant academic research.

OVERVIEW OF RESEARCH CONTEXT AND APPROACH

Research context

Central to this research is the Future Cities Catapult concept of integrated city systems and services – the idea that by considering the functioning of cities more systemically we will be better able to address the many challenges confronting cities now and in the future. The notion that there is benefit in considering how different city systems might interact and be coordinated is not new and indeed there are some notable practical examples of successful integration such as the Swedish experience with district heating systems fuelled in part by the incineration of household. However, these and other examples of the successful integration have remained largely isolated, niche operations – technological curiosities rather than mainstream practice or successful business.

The implicit goal of much of the recent work in city systems is to enable the concept of integration to break out of its existing niches so that it can be applied more extensively both across different functional domains of the city and across a wider range of city types, scales and contexts. Yet the field of urban systems integration is still relatively immature and both commercially and academically fragmented and it has not yet succeeded in creating specific products and services or wider technology supply chains that adequately address the needs of the market.

Research approach

Against this backdrop, the research objectives posed a number of specific methodological challenges:

- The relevant technologies and research directions are spread across many different academic disciplines and sub-disciplines and many of the relevant researchers will not naturally identify their work as relating to integrated city systems.
- This same disciplinary diversity and scale also means that a 'bottom up' treatment of individual research outputs (papers, projects, patents etc.), of the sort that would be typically undertaken in a conventional academic literature review, is impractical.
- Different academic disciplines vary significantly in their treatment of technology maturity.

> Whilst some disciplines, such as aerospace and materials science, have a strong culture of the explicit assessment of 'technology readiness levels', for a variety of reasons, this approach is much less common in many of the most relevant sectors for integrated city systems such as ICT, energy, transport and the built environment. Information on the structure and operation of the wider innovation and translation eco-system is generally not publicly exposed. It must be pieced together on the basis of the knowledge and experience that resides in senior academics and University based translation specialists.

In the light of these challenges, the approach we adopted relied heavily on consultation with leading UK researchers and innovation experts in relevant technology areas. These discussions were augmented, where relevant and useful with desk-based research to collect information on e.g., past funding flows and future funding opportunities.

In order to make most effective of the resources available, we created a two-level project structure comprising a small core team responsible for the execution of the work and the production of the Deliverables and a wider Reference Group of senior academics and administrators to provide input to the work through discussions and brainstorming and by means of critical review and feedback on Deliverables[1]. This structure enabled us to retain simplicity in working arrangements whilst at the same time being able to benefit from a wide range of specialist technical input.

The work was organised into three main phases:

I. Initial workshop
A half day workshop for the core team, members of Reference Group and representatives of the Future Cities Catapult with the aim of producing an initial map of relevant technology opportunities and research directions.

II. Synthesis
This work package was concerned with synthesising and extending the results of the initial workshop and, using the strategic directions and priorities so established, producing an updated technology mapping document. A number of elements of work were undertaken in this phase.

- Follow up discussion with member of the Reference Group and others with a particular focus on gaining insight into those technology and application areas that were not strongly represented in the initial workshop. These discussions have focused on (i) identifying the most promising technologies, (ii) the structure of translation and innovation activities in these domains and (iii) examples of successful and unsuccessful translation including 'stranded assets'.

- Discussion with University administrators and support staff involved in promoting and supporting the translation of academic research to practice using the formal innovation pipelines mechanisms available within UK Universities. The objective was to understand the range of the different mechanisms used within UK universities to identify and exploit research including the approach to IP management, policies for rewarding innovators and the influence of national legislation and practice.

- Collection of information on RCUK and EU grant activity in the relevant domains and themes highlighted in the workshop.

III. Final workshop
A second half day workshop for the core team, members of Reference Group and representatives of the Future Cities Catapult with the aim of obtaining feedback on the synthesis document and (especially) its conclusions.

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1. Members of the Reference Group are listed in Appendix B.

2. THE STRUCTURE OF UNIVERSITY RESEARCH IN URBAN SYSTEMS AND TECHNOLOGIES

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TRADITIONAL DISCIPLINARY STRUCTURES

University research has traditionally been structured around the notion of academic disciplines. Disciplines are defined by distinct and coherent bodies of knowledge and are often (though not always) directly linked to professions (e.g., medicine, law, engineering). This emphasis on disciplines is reflected in the organisational structure of most Universities where disciplinary-oriented Departments, Faculties and Schools typically constitute the basic operating units of the institution.

Although at any given point in time, the structure of disciplines appears fixed, in fact disciplinary boundaries are always evolving, albeit usually rather slowly. This is evident in the gradual separation of engineering from the natural sciences during the 18th century and development of independent identities for civil, mechanical and electrical engineering during the 19th century, the development of transport as a distinct academic area during the 20th century and the more recent emergence of cross cutting fields such as bioengineering, bioinformatics and data science.

A strong disciplinary structure creates a culture in which researchers can be encouraged to pursue depth and rigour in their work and, at least to some degree, insulated from pressures that might compromise their independence. However, at the same time, it is often argued that it has the side effect of fragmenting knowledge with respect to challenge areas that inherently cut across existing disciplinary boundaries. Areas in which this phenomenon has been noted include environment, energy, climate change and aging.

In recent years, Universities have seen it as attractive to develop new mechanisms to address cross cutting challenges, driven in part by a shift in national and international research funding away from purely curiosity-driven, disciplinary focused research towards an emphasis on programmatic funding addressing so-called societal grand challenges (most of which are cross cutting in nature). The standard approach is to create new institutional entities – variously termed Institutes, Centres, Laboratories etc. – that generally sit outside the traditional disciplinary and Departmental structures and which are tasked to work with disciplinary-oriented researchers across the institution to connect, aggregate and unify the work undertaken in a particular cross cutting area. The aim is to preserve the rigour and depth associated with the traditional disciplines whilst at the same time improving the institution's capability to respond to cross cutting challenges.

These entities typically do not attempt to duplicate the functions of traditional academic departments (e.g., they do not directly employ significant numbers of academic staff nor run undergraduate courses) but are usually active in postgraduate education at Masters and PhD level offering multidisciplinary courses and research opportunities drawing on academic input from several Departments (e.g., the Energy Futures Lab at Imperial). Funding for these entities varies significantly from case to case but usually involves some element of institutional investment at start up, with an ongoing income stream based on a share of the generated teaching and research income and, in some cases, corporate and or philanthropic donations (e.g., Grantham Institute at LSE). Many also have a strong emphasis on translation activities, including formal links with local authorities (e.g., Institute for Research on Sustainability at Newcastle) and national and international agencies (e.g., Environmental Change Institute at Oxford).

Table 1. lists some examples of such entities in the areas of environment, energy, climate change, aging and manufacturing from a number of universities. In each case, we provide a web link and quote a short paragraph of self-description from the web site. It is important to appreciate that the specific activities cited in Table 1. are offered merely as examples of kind and do not constitute a complete coverage of relevant activities in the specific challenge areas identified nor of wider activity of this nature within the UK higher education sector as a whole.

Table 1. Examples of existing university initiatives in cross cutting challenge areas

Challenge area: **Energy**

Institution	Name	Description
Imperial College London	Energy Futures Lab www3.imperial.ac.uk/energyfutureslab	"The Energy Futures Lab builds on the high-quality research across Imperial in areas including energy efficiency, nuclear power, renewable energy, transport, electrical networks, economics and policy development. By providing a focus for energy research at the College and developing research programmes, the Energy Futures Lab is developing the sustainable future energy supply for society."
University College London	Energy Institute www.bartlett.ucl.ac.uk/energy	"The UCL Energy Institute delivers world-leading learning, research and policy support on the challenges of climate change and energy security. Our approach blends expertise from across UCL, to make a truly interdisciplinary contribution to the development of a globally sustainable energy system. We are part of The Bartlett: UCL's global faculty of the built environment."
Durham University	Energy Institute www.dur.ac.uk/dei	"From Anthropology to Physics, Durham Energy Institute covers the spectrum of energy research but the areas in which we excel are those which lie at the boundaries between the traditional technical disciplines and the social sciences and humanities. We encourage such interdisciplinary work as we feel these areas will yield major breakthroughs. The small size and compact nature of the university is to our advantage as it naturally stimulates interactions between departments and disciplines. Thus, we are agile and responsive and we can quickly assemble bespoke-research teams."

Challenge area: **Manufacturing**

Institution	Name	Description
University of Cambridge	Institute for Manufacturing www.ifm.eng.cam.ac.uk	"Part of the university's Department of Engineering, it takes a distinctive, cross-disciplinary approach, bringing together expertise in management, technology and policy to address the full spectrum of industrial issues. The IfM integrates research and education with practical application in industry. It disseminates its research findings via a university-owned knowledge transfer company, IfM Education and Consultancy Services Ltd."

Challenge area: **Climate/Environment**

Institution	Name	Description
London School Economics	Grantham Research Institute on Climate Change and the Environment www.lse.ac.uk/GranthamInstitute	"The Grantham Research Institute on Climate Change and the Environment is a research centre at the London School of Economics and Political Science (LSE). Its research looks at the economics of climate change, and aims to inform policy and academic debate."
University of Oxford	Environmental Change Institute www.eci.ox.ac.uk/	"The Environmental Change Institute was founded in 1987 'to organize and promote interdisciplinary research on the nature, causes and impact of environmental change and to contribute to the development of management strategies for coping with future environmental change'. This statement still embodies the ECI's ethos of purposeful environmental research and knowledge exchange."
Newcastle University	Institute for Research on Sustainability www.ncl.ac.uk/sustainability	"In the field of sustainability, the Newcastle Institute for Research on Sustainability (NIReS) coordinates research across traditional discipline boundaries to deliver practical, engaged solutions to real-world issues, under the banner of Enough, For All, Forever. Sustainability is one of three societal challenge themes on which the University marshals a significant proportion of its research power, as part

Challenge area: **Aging**

Institution	Name	Description
University of Manchester	Institute for Collaborative Research on Ageing www.micra.manchester.ac.uk	"The Manchester Institute for Collaborative Research on Ageing (MICRA) promotes interdisciplinary research on all aspects of ageing. Based at the University of Manchester, we have access to a network of over 1,200 academics, practitioners, policy makers and older people. This greatly enriches our research environment and helps bridge the gap between academic research and policy and practice."

THE EMERGENCE OF CITIES AS A RESEARCH DOMAIN

Work in the area of city systems and technology has not yet matured to a point where there is a clearly defined unitary disciplinary identity. As such, for most academics, it is seen as an application area for work undertaken in their more mature parent disciplines and as a result, a wide variety of different interpretations and perspectives contend. Indeed, for many years, research into urban systems and technologies was a classic example of academic fragmentation, with many Universities having largely disconnected pockets of research activity, typically embedded in conventional (disciplinary oriented) Departments such as Civil, Electrical and Mechanical Engineering, Planning, Architecture, Economics, Geography, Sociology, Political Science, Epidemiology, Business and several others. This situation was relatively stable, with each disciplinary group broadly content to pursue its own perspective on urban systems, technologies, problems and issues largely independently of the activities of the others.

However, over the past decade or so, the situation has begun to change as gradually a new identity has started to emerge for the cities research domain (variously referred to as "Smart Cities", or "Future Cities"). Although this new identity is in many respects still rather nebulous, two key features are clear and are of particular importance in the current context. First, this new perspective takes a more holistic view of cities as systems of systems, emphasising the intellectual challenge and practical importance of understanding the inter-relationship between different component city systems. And second, it has involved the introduction into the disciplinary mix of a new set of perspectives, largely drawn from the ICT sector.

A number of factors have contributed to the emergence of this new perspective:

- The growing political and economic influence of cities, based on changes in the balance of political power as between cities, nation states and international institutions and the recognition of the critical role of cities as engines of economic growth and innovation.
- Cities becoming perceived as a critical focus area for other major policy issues, such as sustainable development and climate change and for emerging technology trends such as Big Data and the Internet of Things.
- The unprecedented pace of urbanisation, especially in the emerging economies of Asia and Latin America is creating a large market for rapid centralised solutions to urban development challenges, distinct from the more organic and decentralised patterns of change associated with cities in mature economies. This market opportunity has had the effect of energising engaging a new set of industrial players.

National and international public sector funding agencies are now increasingly supporting Smart/Future Cities themed research activities and Universities are likewise increasingly seeing Cities research as a cross cutting area where some degree of coordination and integration is desirable.

THE CURRENT ACADEMIC ECO-SYSTEM

As a result of this pattern of development, the structure of the UK academic eco-system in the area of city systems and technology is rather complex, with a number of different types of players:

- There are a relatively small number of research groups that explicitly self-identify as urban/city related and which pursue research that reflects their distinct disciplinary perspectives and priorities (e.g., engineering, planning and social policy). Table 2. lists a number of examples of groups of this type. As with Table 1., this list is not exhaustive either with respect to the relevant groups within the specific institutions mentioned (we have chosen to list no more than 3 from a given institution) nor with respect to the coverage of institutions across the country.

- There is a second somewhat larger set of more broadly based research groups, which have a long standing interest in the Cities research domain through work in relevant functional or technology areas (e.g., building physics, geotechnics, water systems, transport systems). Table 3. lists a number of these groups. The same caveats apply as with Table 2.; the list is partial and (inevitably) subjective. We have organised the information according to broad disciplinary groupings (buildings, transport, energy etc.) and for each group given two or three examples of relevant groups and activities.

- There is a third much larger set of groups and individuals that do not explicitly identify an interest in the Cities research domain per se but who are nevertheless doing work that is relevant, either at the level of individual component technologies or at the level of broader system integration. A good example of the former are research groups working in medical sensor systems for remote patient monitoring and diagnosis, whereas a good example of the latter are groups working in sensor network technologies. Since these groups and individuals are very numerous, we have not attempted to compile an indicative list.

Notwithstanding the recent higher profile of cities as a research domain, the fragmentation of the field along traditional disciplinary demarcations, both within individual institutions and across institutions as a whole, is still very evident from Tables 2. and 3. Some Universities are in the process of creating new organisational entities to achieve better internal connectively amongst their different strands of Cities related research, In effect, (Smart/Future) Cities research has started to follow the well-established template previously deployed in the development of other cross cutting challenge areas such as energy and climate change.

We are aware of initiatives of this type underway in a number of institutions, including:

- University of Cambridge
- Imperial College London
- University of Manchester
- University of Reading
- University of Warwick
- University of Strathclyde

Most of these initiatives are however, still at an early stage of development.

Table 2. Examples of specialist urban research groups in a selection of UK universities

Institution: **University of Birmingham**

Group	Description
Centre for Urban and Regional Studies www.birmingham.ac.uk/schools/gees/departments/curs/	Focus on spatial and social planning studies including economic development and regeneration, and urban resilience.
Livable Cities liveablecities.org.uk/	Collaboration between 4 Universities (Birmingham, Lancaster, Southampton and UCL) lead by Birmingham with the aim of creating an integrated, multi-disciplinary city analysis methodology.

Institution: **University of Cambridge**

Group	Description
Martin Centre www.martincentre.arct.cam.ac.uk/ http://www.urbanconflicts.arct.cam.ac.uk/	Architectural group with substantial activity in urban design and urban land use modelling.
Centre for Sustainable Development www-csd.eng.cam.ac.uk/	Engineering group focusing on the social and environmental aspects of urban infrastructure and services including energy and water.
Energy, Transport and Urban Infrastructure www.eng.cam.ac.uk/research/strategic-themes/energy-transport-and-urban-infrastructure	Research theme within the Department of Engineering focusing on energy, transport, information, buildings, water and waste treatment in the context of the urban environment

Institution: **University of Glasgow**

Group	Description
Urban Big Data Centre urbanbigdatacenter.wordpress.com/8-2/	Focus on methods and technologies to manage, link and analyse massive amounts of multi-sectoral urban data, both historic and real time.
Urban Studies www.gla.ac.uk/schools/socialpolitical/research/urbanstudies/	Research theme of the School of Social and Political Sciences focusing on governance, urban economics and neighbourhood wellbeing.

Institution: **Goldsmiths, University of London**

Group	Description
Centre for Urban and Community Research www.gold.ac.uk/cucr/	Research group within the Department of Sociology focusing on work concerned with community, ecology, governance, and citizenship.

Institution: **Heriot Watt University**

Group	Description
Institute for Housing, Urban and Real Estate Research www.sbe.hw.ac.uk/research/ihurer.htm	Social policy emphasis with research themes including housing design and housing policy, residential and commercial property markets and social exclusion.

Institution: **Imperial College London**

Group	Description
Urban Water Group www.imperial.ac.uk/ewre/research/currentresearch/urbanwater	Engineering group with focus on sustainable water management, urban flooding, integrated catchment management, smart technologies for asset management and performance measurement.

Urban Energy Systems www.imperial.ac.uk/urbanenergysystems	Engineering group with focus on integrated modelling for the design and operation of urban energy systems to improve energy efficiency and environmental impact.
Digital City Exchange www.imperial.ac.uk/digital-economy-lab/partnernetworks/dce	Collaboration between Engineering and Business School focusing on model-based digital innovation in cities.
Intel Collaborative Research Institute in Sustainable Connected Cities www.cities.io/	Collaboration between Imperial, UCL and Intel focused on use of computer science and human centred design techniques to creating new urban systems and services.

Institution: **King's College London**

Group	Description
Cities@King's www.kcl.ac.uk/sspp/departments/geography/research/cities	Based in the Department of Geography, research focuses on aspects of social, economic, political, historical and cultural change in cities.

Institution: **London Metropolitan University**

Group	Description
Cities Institute www.citiesinstitute.org/	Based in the Faculty of Social Sciences and Humanities, it undertakes research into urban economic development, housing, transport and culture.

Institution: **London School of Economics**

Group	Description
LSE Cities www.lse.ac.uk/LSECities/home.aspx	Focus on how the design of cities impacts society, culture and the environment and also on city governance.
Cities@geography www.lse.ac.uk/geographyAndEnvironment/research/cities/	Based in the Department of Geography and Environment focusing on urban regeneration, governance and sustainable development; megaprojects.

Institution: **University of Leeds**

Group	Description
Centre for Spatial Analysis and Policy www.geog.leeds.ac.uk/research/centre-for-spatial-analysis-and-policy/	Group based in geography focusing on applications of GIS to urban systems modelling.

Institution: **University of Manchester**

Group	Description
Centre for Urban Policy Studies www.sed.manchester.ac.uk/research/cups/	Research focusing on urban and regional policy. Themes include evaluation of area-based urban policy initiatives, spatial planning, spatial analysis and public participation.
Centre for Urban Resilience and Energy www.seed.manchester.ac.uk/research/centres/cure	Research focuses on urban aspects of energy, climate change and spatial systems from a social science perspective.
Global Urban Research Centre www.seed.manchester.ac.uk/gurc/	Focuses on urban development and globalisation and undertakes research on poverty, inequality, conflict, housing and climate change.

Institution: **University of Oxford**

Group	Description
Programme for the Future of Cities www.futureofcities.ox.ac.uk	Based in the Institute for Science, Innovation and Society and with an anthropological focus, research focuses.
Infrastructure Transitions Research Consortium www.itrc.org.uk/	A consortium of 9 universities lead by Oxford working on the development of new decision support tools for national infrastructure planning. Scope is national not urban but many projects have urban focus.

Institution: **University of Salford**

Group	Description
Centre for Sustainable Urban and Regional Futures www.salford.ac.uk/built-environment/research/research-centres/sustainable-urban-and-regional-futures	Based in the School of Build Environment, this group works in three areas; urban futures, cultural intermediation and urban retrofit.

Institution: **University of Warwick**

Group	Description
Warwick Institute for the Science of Cities www.wisc.warwick.ac.uk/research/	Focuses on the means to gather city-scale data, and the apparatus to transform this data into knowledge, capitalising on emerging developments in big data and in interdisciplinary solutions to urban challenges.

Institution: **University College London**

Group	Description
Centre for Applied Spatial Analysis www.casa.ucl.ac.uk	Originally established as a GIS centre with strong urban focus, now orientated towards simulation, spatial data and visualization.
Urban Laboratory www.ucl.ac.uk/urbanlab/	Group with a strong geography/planning focus working in the areas of urban housing, ecology, design and data.
International Centre for Infrastructure Futures www.icif.ac.uk/	A consortium of 6 universities led by UCL, focusing on the development of innovative business models for infrastructure investment, with a strong focus on cities.

Table 3. Examples of research groups with strong urban interests in a selection of UK universities

Discipline: **Buildings and construction**

Institution	Name	Description
Loughborough University	Department of Civil and Building Engineering www.casa.ucl.ac.uk	Particular strengths in the area of construction technology and organisation and building.
University of Reading	School of Construction Management and Engineering www.reading.ac.uk/cme/	Particular strengths in digital technologies in construction (including BIM), healthcare infrastructure and sustainable building technologies.
University College London	The Bartlett School of Architecture www.bartlett.ucl.ac.uk/	Particular strengths in urban and building design (as well as urban informatics and energy).

Discipline: **Transport**

Institution	Name	Description
Imperial College London	Centre for Transport Studies www.impierial.ac.uk/cts	Particular strengths in transport modelling and economics, intelligent transport systems and urban public transport.
University of Leeds	Institute for Transport Studies www.its.leeds.ac.uk	Particular strengths in transport modelling and economics, transport policy and safety.
University of Southampton	Transport Research Group www.southampton.ac.uk/engineering/research/groups/transportation_group.page	Particular strengths in rail transport, intelligent transport systems and human factors in transport.

Discipline: **Energy**

Institution	Name	Description
Imperial College London	Control and Power Research Group www.imperial.ac.uk/controlandpower	Particular strengths in design and operation of smart grids and advanced energy markets and the integration of electric mobility with grid operations (includes Smart Energy Lab).

Loughborough University	Centre for Renewable Energy Systems Technology www.lboro.ac.uk/research/crest/research/	Includes work on decentralised energy systems in urban areas.
Strathclyde University	Advanced Electrical Systems and Power Systems Group www.strath.ac.uk/ eee/research/iee/researchgroups/advancedelectricalsystemsandpowersystems/	Particular strengths in fundamental technologies underlying smart power grids.

Discipline: **Environment**

Institution	Name	Description
King's College London	Environmental Research Group www.kcl.ac.uk/biohealth/research/divisions/aes/research/ERG/index.aspx	Particular strengths in urban air quality measurement, modelling and analysis.
Imperial College London and King's College London	MRC-PHE Centre for Environment & Health www.environment-health.ac.uk/	Research includes analysis of exposure to air pollution, noise and environmental toxins, impacts on health and development of policy response. Strong emphasis on urban areas.
University of Southampton	Institute of Sound and Vibration Research www.southampton.ac.uk/engineering/research/centres/isvr.page	Research interest includes traffic, railway and aircraft noise impacts in urban areas.

Discipline: **Waste and recycling**

Institution	Name	Description
University of Southampton	Waste Management Research Group www.southampton.ac.uk/engineering/research/groups/waste_management.page?#overview	Particular strengths in urban air quality measurement, modelling and analysis.
Imperial College London	Centre for Environmental Control & Waste Management www.imperial.ac.uk/ewre/research/currentresearch/environmentalcontrolandwastemanagement	Particular strength in research on re-cycling and waste management.

Discipline: **Water**

Institution	Name	Description
Cranfield University	Water Science Institute http://www.cranfield.ac.uk/	Research and education in the science, engineering and management of water in the municipal, industrial and natural environments.
University of Exeter	Centre for Water Systems emps.exeter.ac.uk/engineering/research/cws/	Major focus on urban water distribution and drainage system management and flood risk management in urban areas.
University of Sheffield	Pennine Water Group www.sheffield.ac.uk/penninewatergroup/	Particular expertise in potable water, storm water and waste water service provision in urban areas.

Discipline: **Ground and Structures**

Institution	Name	Description
University of Cambridge	Geotechnical and Environmental Research Group www-geo.eng.cam.ac.uk/	Particular expertise in underground construction including tunnelling and smart infrastructure
Imperial College London	Department of Civil and Environmental Engineering (Geotechnics Section and Structures Section) www.imperial.ac.uk/geotechnics www.imperial.ac.uk/structuralengineering	Relevant geotechnical research focuses on soil-structure interaction, geothermal energy recovery, seismic hazards and tunnelling, especially in urban areas (e.g., JLE, Crossrail). Relevant structural research focuses on structural materials, reliability, resilience and extreme loading (including fire and blast).
University of Southampton	Infrastructure Group www.southampton.ac.uk/engineering/research/groups/infrastructure_group.page?	Relevant expertise includes work in smart infrastructure monitoring and geothermal energy via building foundations.

Discipline: **Climate**

Institution	Name	Description
University of Bristol	Cabot Institute www.bristol.ac.uk/cabot	Carries out research on environmental uncertainty and risk. One of its eight research themes is future cities.
Tyndall Centre for Climate Change Research	Cities and coasts www.tyndall.ac.uk/research/cities-and-coasts	Cities and coats is one of the Tyndall Centre's 4 principal research themes. Work focuses on the development of modelling tools to quantify and reduce infrastructure and service vulnerabilities.

Imperial College London	Grantham Institute for Climate Change Climate KIC www3.imperial.ac.uk/climatechange www.climate-kic.org	The Climate KIC is a public-private partnership in the field of climate innovation, established by the European Institute of Innovation. Two of its themes are directly relevant – sustainable city systems and the built environment.

Discipline: **Security**

Institution	Name	Description
Imperial College London	Institute for Security Science and Technology www.imperial.ac.uk/securityscience	Relevant expertise in video analytics for infrastructure protection and security in crowded places and applications of sensing and real time control for CBRNE threat detection and response.
University College London	Department of Security and Crime Science www.ucl.ac.uk/scs	Relevant expertise includes work in crime mapping and prevention-by-design and counter-terrorism.

Discipline: **Economy and Community**

Institution	Name	Description
London School of Economics	Spatial Economics Research Centre www.spatialeconomics.ac.uk	Research centre involving 6 universities, focusing on the analysis of spatial disparities in economic prosperity. Significant streams of work concerned with urban issues and areas.
University of Oxford	Centre on Migration, Policy and Society www.compas.ox.ac.uk	Research centre focusing on migration with major research theme on urban change and settlement.

Discipline: **Healthcare**

Institution	Name	Description
University of Manchester	Manchester Urban Collaboration on Health www.population-health.manchester.ac.uk/epidemiology/MUCH/	Particular strength in the application of epidemiological methods to healthcare challenges in urban areas.

Discipline: **ICT**

Institution	Name	Description
Imperial College London	Data Science Institute www.imperial.ac.uk/data-science ICT Labs KIC www.eitictlabs.eu	Imperial's new data science institute includes cities as one of its focus areas.. The ICT Labs KIC is a public-private partnership in the field of ICT-based innovation, established by the European Institute of Innovation. Three of its themes are directly relevant – smart energy, health and wellbeing and urban life and mobility.
University of Oxford	Oxford Internet Institute www.oii.ox.ac.uk	Focus on exploring the socially networked World with a significant urban focus on information geographies.

3.

KEY TECHNOLOGIES

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CONCEPTUAL APPROACH TO MAPPING

In this research, the definition of 'technologies' is very broad and includes relevant developments in hardware, software, physical processes, materials, methods, models, protocols and related knowhow. Whilst the focus of this study is principally on relevant developments in engineering and science, the interface with human systems and behaviour is also important.

On the basis of discussions with a number of members of the Reference Group, it was decided to structure the discussion of technologies along two dimensions. The first dimension distinguishes between technologies according to whether they principally impact at the component or integration level.

- **Component-level technologies:** Those concerned with improving or extending function principally within a particular functional or sectoral domain e.g., improved materials for energy storage, new sensing capability for urban water networks, improved predictive traffic management.
- **Integration-level technologies:** Those concerned principally with enabling integration between existing domains or sectors e.g., platforms for data sharing, cross sectoral modelling and visualisation capability, sensor network systems.

It is of course recognised that this simple categorisation involves a substantial degree of abstraction and simplification. For example, even the most narrowly defined component level technology will inevitably involve the integration of more elemental sub-components as part of its design (e.g., piezoelectric based systems for energy harvesting involve the integration of a range of electronic and mechanical components) and some technologies (e.g., building information modelling) are not necessarily easily classified as exclusively either component or integration level. However, despite these limitations, the distinction between component-level and integration-level proved, we believe, to a useful mechanism to structure our discussions.

The second structuring dimension identified six broad areas of research activity that relate to urban systems and technologies:

- **Resource efficiency:** Developments in materials, physical processes, design concepts and operating procedures that can improve efficiency in the use of resources such as energy, water and raw materials and reduce or eliminate waste.
- **Networked infrastructures:** Developments in design, management and operating procedures associated with the networked infrastructures for water, energy, communications and transport systems.
- **Construction:** Developments in materials, processes and design concepts associated with the construction of urban infrastructure including both surface and sub-surface structures.
- **Sustainability and environment:** Developments in processes, systems and designs aimed at reducing the environmental impacts associated with all aspects of city systems and services.
- **Citizen services:** Developments in the concepts, design and methods of delivery for the services used by urban populations including healthcare, education, social services and policing.
- **Markets, making and manufacturing:** Developments in technologies, institutions and business models associated with the production and consumption of physical and digital artefacts of all types.

Once again these categories are clearly not completely orthogonal but they do provide a useful simplifying structure that relates well to distinct clusters of technological innovation and which proved useful in organising the execution of the work. Moreover, we believe that this structure will prove useful as a basis for on-going technology mapping work in this area.

COMPONENT LEVEL TECHNOLOGIES

Table 4. provides a summary of the key component level technologies identified during the research. A total of approximately 40 different technology areas emerged from the research, some very closely linked to particular functional areas (e.g., vehicle power trains) while others, (e.g., citizen sensing) are more generic in nature. Table A.1 (Appendix A) provides a non-technical explanation of these component level technologies.

INTEGRATION LEVEL TECHNOLOGIES

Table 5. provides a summary of the key integration level technologies identified during the research. We have divided the set between on the one hand those technologies that are highly generic (mainly but not exclusively associated with data, system modelling and analysis), and on the other, specific examples of near term integration level challenges/opportunities. Table A.2 (Appendix A) provides a non-technical explanation of these integration level technologies.

OTHER RELEVANT TECHNOLOGY SCANNING EXERCISES

In recent years, a number of initiatives have sought to identify key future technologies. In this section, we briefly discuss two of these; the UK Government's eight great technologies and the European Commission's key enabling technologies.

UK Government's Eight Great Technologies

From 2010 onwards, a number of UK Government reports including the Chief Scientific Advisor's "Technology and Innovation Futures Reports"[2] and the TSB's "Emerging Technologies and Industries Strategy"[3] together with input from the UK Research Council's capability shaping exercise established momentum behind the idea of a need for increased but targeted investment in the UK's science base. In the UK Government's 2012 autumn financial statement, £600m was allocated to new investments in the UK science base, covering both capital equipment and research programmes.

In January 2013, David Willetts, the Minister for Universities and Science in the UK's Department of Business and Innovation announced that the Government intended to direct approximately £460m of this sum towards research and innovation in eight key areas of technology – the so called 'eight great technologies' (EGTs). These areas are[4]:

- The big data revolution and energy-efficient computing
- Satellites and commercial applications of space
- Robotics and autonomous systems
- Life sciences, genomics and synthetic biology
- Regenerative medicine
- Agri-science
- Advanced materials and nano-technology
- Energy and its storage

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2. https://www.gov.uk/government/publications/technology-and-innovation-futures-uk-growth-opportunities-for-the-2020s 3. https://www.innovateuk.org/documents/1524978/2139688/Emerging+Technologies+and+Industries+-+Strategy+2010-2013/c589c4b9-2634-4884-9b44-c3454b5ad3d9

Consideration of these technologies is likely to figure prominently in the investment priorities of the Research Councils and the Technology Strategy Board during the current planning cycle.

European Commission's Key Enabling Technologies

In 2009, the European Commission published a communication entitled "Preparing for our Future: Developing a Common Strategy for Key Enabling Technologies in the EU"[5], which identified a number of key enabling technologies for growth and discussed potential mechanisms to support their development. Key Enabling Technologies (KETs) were defined by the Commission as technologies that "...enable the development of new goods and services and the restructuring of industrial processes needed to modernise EU industry and make the transition to a knowledge-based and low carbon resource-efficient economy"[6]. In 2009, five KETs were identified:

- Advanced materials
- Nanotechnology
- Micro- and nano-electronics
- Biotechnology
- Photonics

In June 2012, the Commission published a strategy document entitled "A European Strategy for Key Enabling Technologies – A Bridge to Growth and Jobs"[7], with the aim both to help focus EU investment in research and innovation activities through e.g., Horizon 2020, the use of structural funds and European Investment Bank's activity and to provide a wider context for the development of national and European innovation and industrial policy.

In the same document the Commission also announced its intention to form an EU-wide monitoring mechanism on KETs[8] (a "KETs observatory"[9]), to enable it to track relevant developments and update plans over time. In addition, it also announced its intention to form a new high-level expert group on KETs to provide it with ongoing advice and overview on the evolution of its KET strategy[10]. The KETs observatory is a novel development and although it is still in an early stage of development it already includes some interesting content, including summaries of technology and innovation policy approaches in the 27 member states[11].

The most up to date statement of the Commission's thinking on KETs appears to have been presented at a conference in Brussels in April this year[12]. This presentation, which was delivered by the Head of the unit on Key Enabling Technologies and Digital Economy within DG Enterprise and Industry, identified six KETs (in essence the earlier list of five with the addition of advanced manufacturing systems) and also introduced the Commission's H2020- Leadership in Enabling and Industrial Technologies work programme. This work programme focuses on supporting pilot projects involving multiple KETs. The initial round of H2020-LEIT projects (funded during 2015-15) will be focused on four areas:

- Smart structures
- High-performance production
- Embedded energy (batteries)
- Industrial bio-processes using renewable resources

The KETs are strongly represented in the H2020 work programme.

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4. A copy of the Minister's speech is available here: https://www.gov.uk/government/speeches/eight-great-technologies. Further elaboration on the technologies and their expected impact can be found here: https://www.gov.uk/government/publications/eight-great-technologies-infographics and here http://www.policyexchange.org.uk/images/publications/eight%20great%20technologies.pdf **5.** http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0512&from=EN **6.** This quotation together with a history of the development of the Commission's activities in this area can be found at http://ec.europa.eu/enterprise/sectors/ict/key_technologies/index_en.htm **7.** http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52012DC0341&from=EN **8.** http://ec.europa.eu/enterprise/sectors/ict/files/kets/final_report_kets_observatory_en.pdf **9.** https://webgate.ec.europa.eu/ketsobservatory/ **10.** http://ec.europa.eu/enterprise/sectors/ict/key_technologies/kets_high_level_group_en.htm **11.** https://webgate.ec.europa.eu/ketsobservatory/policy **12.** http://www.mkpl.eu/fileadmin/site/bestanden/presentations/Conference%20KETs%202%20April%20Michel%20Catinat_final.pdf

Table 4. Summary of component level technologies based on workshop session (full descriptions in Appendix A.1)

	Research areas related to urban systems and technologies					
Component level technologies	Resource efficiency	Networked infrastructures	Construction	Sustainability & environment	Citizen services	Markets, making & manufacturing
Additive manufacture						
Autonomous vehicles						
Behaviour change technologies						
Blue-green technologies						
Building information systems						
Citizen sensing technologies						
Combined heat and power systems						
Demand aggregation and demand management (inc. via dynamic pricing)						
District heating and heat networks (inc. energy from waste)						
Environmental monitoring						
Green roofs						
Grey water reuse						
Ground source heat pumps						
Innovative vehicle design (inc. lightweighting and new form factors)						
Intelligent transport systems						
Low carbon construction materials						
Low carbon powertrains (inc. electric and hydrogen fuel cell)						
Low friction pipelinings						
Low power operation and energy harvesting for sensors and other devices						

Component level technologies	Resource efficiency	Networked infrastructures	Construction	Sustainability & environment	Citizen services	Markets, making & manufacturing
	Research areas related to urban systems and technologies					
Microbial treatment of wastes						
Microclimate sensing and control						
Opportunistic networking						
Patient / citizen monitoring and diagnosis						
Pervasive (indoor-outdoor) positioning and localisation						
Photovoltaics						
Power electronics and smart grid						
Predictive analytics						
Real time and distributed control						
Robotic construction						
Smart facilities management						
Smart infrastructure (inc. embedded sensing)						
Smart water networks						
Specialised nano materials (inc. self-cleaning, self-repairing)						
System modelling						
Thermal storage materials (heat and coolth)						
Underground construction						
Upcycling of waste products for construction						
Virtual citizen services (e.g. healthcare, social care, education)						

Table 5. Summary of integration level technologies based on workshop session (full descriptions available in Appendix A.2)

Intergration level technologies	Research areas related to urban systems and technologies: Resource efficiency	Networked infrastructures	Construction	Sustainability & environment	Citizen services	Markets, making & manufacturing
Big data methods						
Cross sector visualisation - incl. urban dashboards etc.						
Data brokerage services – management of privacy, reputation and trust						
Data platforms for sharing/integrating data across different sectors						
Generic and cross sectoral wireless sensor networks						
Identification, estimation and valorisation of co-benefits						
Identification, prediction and control in cross sectoral systems						
Large scale real time data fusion and data assimilation						
Modelling the vulnerability and resilience of highly inter-connected urban systems						
Multi-sector, multi-scale system modelling at an urban scale						
New business models and governance structures						
Standards for urban system ontologies (inc. semantic web)						
Treatment of uncertainty propagation in integrated urban systems						

	Research areas related to urban systems and technologies					
Examples of integration level technologies	Resource efficiency	Networked infrastructures	Construction	Sustainability & environment	Citizen services	Markets, making & manufacturing
Blue Green Systems – integration of urban water systems with urban vegetation						
District heating based on geothermal and/or waste to heat						
Recovery of geothermal energy from underground assets (e.g. via foundation piles or extracted from the LU network)						
Vehicle to Grid and vehicle to home integration for electric vehicle operation in the context of smart grids						

4.

RESEARCH ACTIVITY IN URBAN SYSTEMS AND TECHNOLOGIES

Catapult Future Cities

INTRODUCTION

In the UK, university research is funded through a very wide range of different channels (e.g., scientific research councils, EU, national and local government, NGOs, corporates, charities, foundations). Moreover, especially in research lead universities, a significant amount of Masters and PhD research is in fact funded by the students themselves, via parents or other overseas sources. There is no publicly available central record of this activity covering individual universities or the university sector as a whole at a level of subject/domain specificity or technical granularity that would be useful to this study. Therefore, it is simply not possible within the constraints of the current study for us to perform a comprehensive assessment of all research activity/grant income in this area.

It is however, possible to map some elements of these research funding flows, and such an exercise has indicative value.

SUMMARY OF RECENT RCUK GRANT ACTIVITY

Information on research funded by RCUK and TSB can be obtained through two mechanisms:

1) The grants portals provided by the individual Research Councils and TSB:

- gow.epsrc.ac.uk
- gotw.nerc.ac.uk
- www.esrc.ac.uk/research/research-catalogue/
- www.mrc.ac.uk/Ourresearch/Successrates/index.htm
- www.innovateuk.org/innovation-in-action

These portals provide access to a catalogue of information on current and past research projects funded by each council. The precise format of the information varies across the different research councils but generally includes information on the title of the research, institution and principal investigator, industrial and academic collaborators and grant value as well as a non-technical summary of the objectives and content of the research.

RCUK's Gateway to Research portal (gtr.rcuk.ac.uk) which provides summary information on research funded by RCUK (and TSB) since 2006, together with information on research outputs.

Whilst it is important to appreciate that funds from UK Government sources such as RCUK and TSB typically constitute only between a third and a half of the research income of most research led universities, these portals are nevertheless a potentially very useful resource that can help the Future Cities Catapult understand the academic research landscape, and do so on an on-going basis.

The number of projects reported in these sources is very large. For example, EPSRC's Grants on the Web portal reports a current portfolio comprising over 4,000 active grants spanning 22 industrial sectors, 112 research areas and 219 research topics and contains information on a total of more than 40,000 grants in all, dating back to 1985. Similarly, the ESRC's portal contains information on over 11,000 grants dating back to 1979. Gateway to Research currently returns details on 1,612 projects containing the keywords "urban" or "cities" or "city".

Via Grants on the Web, an extract from EPSRC's current research portfolio (i.e., currently running projects) covering 14 of its 112 research areas that we believe are most relevant to urban systems and technologies. The research areas included are:

- Built Environment
- Complexity
- Energy Efficiency
- Energy Networks
- Energy Storage
- Graphics and Visualisation
- Ground Engineering
- Mobile Computing
- Sensors and Instrumentation
- Structural Engineering
- Sustainable Land Management
- Transport Operations and Management
- Water Engineering
- Whole Energy Systems

Via Gateway to Research, an extract from RCUK's research portfolio dating back to 2006, covering two categories of projects. The first category comprises projects that appear to have an explicit urban focus and which relate to one or more of the key functional domains identified by the Future Cities Catapult. The second category comprises projects that relate to generic technologies (e.g., in the field of distributed energy generation and storage, sensor networks).

2) One particular aspect of EPSRC's portfolio that merits separate mention is their programme of Centres for Doctoral Training (CDT). CDTs are now ESPRC's principal method of funding and delivering PhD training. A CDT typically comprises a 4-5 year grant which provides funding for between 30 and 50 PhD students to work on projects within the broad subject area of the CDT. CDTs typically involve significant industrial collaboration.

The first round of CDTs were awarded in 2009 and a further round in 2013. There are now over 100 CDTs in operation, in various stages of maturity, including some that are nearing the end of their funding cycle and are no longer recruiting new students. Table 6. lists 25 of the current CDTs that appear to be most relevant to the Future Cities Catapult interests. It is however, important to appreciate that CDTs are not research projects in the conventional sense. Their fundamental remit is training and their key deliverable is human capital rather than specific research outputs. A detailed work programme is not defined ab initio but rather emerges over time, as the portfolio of PhD activity accumulates.

Table 6. **EPSRC Centres in Doctoral Training relevant for cities**

Institution	Name of Centre for Doctoral Training
Cranfield University	Centre for Doctoral Training in Engineering for the Water Sector
Durham University	Multidisciplinary Centre for Doctoral Training in Energy
University of Exeter	Centre for Doctoral Training in Water Informatics: Science and Engineering
Imperial College London	Centre for Doctoral Training in Sustainable Civil Engineering Energy Futures Doctoral Training Centre
University of Cambridge	Centre for Doctoral Training in Sensor Technologies and Application Centre for Doctoral Training in Future Infrastructure and Built Environment
University of Liverpool	Centre for Doctoral Training in Quantification and Management of Risk & Uncertainty in Complex Systems & Environments Centre for Doctoral Training in New and Sustainable PV
University of Manchester	Centre for Doctoral Training in Power Networks
Newcastle University	Centre for Doctoral Training in Cloud Computing for Big Data
University College London	Industrial Doctorate Centre in Urban Sustainability and Resilience Centre for Doctoral Training in Energy Demand
University of Leeds	Centre in Technologies for a Low Carbon Future
Loughborough University	Industrial Doctorate Centre for Innovative and Collaborative Construction Engineering
Newcastle University	Centre for Doctoral Training in Digital Civics
University of Nottingham	Horizon Doctoral Training Centre for the Digital Society
University of Oxford	Centre for Doctoral Training in Autonomous Intelligent Machines and Systems
University of Reading	Centre in Technologies for Sustainable Built Environments
University of Sheffield	Centre for Doctoral Training in Energy Storage and its applications
University of Southampton	Centre for Doctoral Training in Sustainable Infrastructure Systems Doctorate Centre in Transport and the Environment

University of Strathclyde	Centre for Doctoral Training in Future Power Networks and Smart Grids - a partnership between the University of Strathclyde and Imperial College London
University of Surrey	Industrial Doctorate Centre in Sustainability for Engineering and Energy Systems
University of Warwick	Centre for Doctoral Training in Urban Science and Progress

SUMMARY OF RECENT EU GRANT ACTIVITY

Research funded by the European Commission via mechanisms including framework research programmes, the European Research Council and the European Institute of Innovation and Technology currently constitutes approximately 10-15% of the research income of most research led universities but is of growing importance.

The CORDIS (cordis.europa.eu) and EUROPA (europa.eu) web sites provide information on research projects funded by the Commission under its framework programmes and related mechanisms dating back as far as the 1980s, and the ERC provides information on its research projects and results via its own portal (erc.europa.eu/projects-and-results).

As with the UK national sources, the volume of research activity is large; CORDIS currently returns details on 2,564 Framework projects containing the keywords “urban” or “cities” or “city”, in which there was a UK academic or industrial participant.

RESEARCH FUNDING OPPORTUNITIES

There are a number of current research funding opportunities that are relevant to the area of integrated city systems and services.

Horizon 2020

The most significant opportunity is probably within the European Commission’s Horizon 2020 research programme[13] (the latest incarnation of its Framework funding mechanism). The organisation of H2020 is complex with several different types of mechanism. However, the most important mechanisms in the current context are those associated with research in the six key societal challenge areas defined under H2020:

- Health, Demographic Change and Wellbeing
- Food Security, Sustainable Agriculture and Forestry, Marine, Maritime and Inland Water Research and the Bioeconomy
- Secure, Clean and Efficient Energy
- Smart, Green and Integrated Transport
- Climate Action, Environment, Resource Efficiency and Raw Materials
- Europe in a changing world - Inclusive, innovative and reflective societies
- Secure societies – Protecting freedom and security of Europe and its citizens

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13. See http://ec.europa.eu/programmes/horizon2020/ for general information and http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/master_calls.html for more detailed information about the content of specific calls during the period 2014-15.

In each of these challenge areas, a work programme is defined that sets out tasks that are released as call for proposals. Across these six areas, there is ample opportunity to defined and undertake research in relevant component technologies in the areas of transport, energy, water, health, security and several others. In addition, there is a specific focus on projects addressing Smart Cities and Communities within the Secure, Clean and Efficient Energy work programme.

European Institute of Innovation and Technology – Knowledge Innovation Communities

A second set of relevant mechanisms are the Knowledge Innovation Communities, established by the European Institute of Innovation and Technology[14] (EIT). The EIT was established in 2008 by the European Commission to promote more effective innovation in Europe (it is, in a sense, a European scale TSB). Its principal mechanism for doing so has been to establish and fund a number of Knowledge Innovation Communities (KICs)[15].

A KIC consists of a pan-European network of academic institutions, businesses and local and regional government agencies that collaborate in a variety of activities including innovation projects, human capital development and entrepreneur support. There are currently three KICs, operating in the areas of climate change, ICT and energy systems[16]:

- Climate KIC
- ICT Labs KIC
- KIC InnoEnergy

All three KICs have strong interests in urban systems innovation and both the Climate KIC and the ICT Labs KIC have strong UK representation. Imperial is a core partner in the Climate KIC and hosts the UK Climate KIC node (as well as providing the current CEO). Imperial and UCL are both core partners in the ICT Labs KIC and jointly host the UK ICT Labs node (which is physically based at Imperial West).

KICs have access to substantial funding[17] but are subject to EU State Aid rules so operate a matched funding model, requiring at least 3:1 leverage on their contribution. Moreover, the KICs are fundamentally partnerships rather than open funding mechanisms – access to funding is conditional on joining the partnership and participating in its activities.

Research Councils UK

Between 2004 and 2012, the Engineering and Physical Sciences Research Council supported a number of projects under its Sustainable Urban Environment[18] programme. We understand that it currently has no plans for further programmatic investments in this area, although it continues to welcome high quality responsive mode applications.

We understand that later this year, the Economic and Social Research Council is planning to launch a call for proposals under the general title of Urban Transformations. This call is likely to identify a number of themes, which at the time of writing include:

- Resilience and urban environmental change
- Technology and automation
- Vulnerability, exclusion and inequality
- Urban economies
- Politics, governance and institutions

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14. http://eit.europa.eu/ **15.** http://eit.europa.eu/kics/ **16.** http://www.climate-kic.org/; http://www.eitictlabs.eu/; http://www.kic-innoenergy.com/ **17.** http://eit.europa.eu/kics/key-features/funding/ **18.** http://www.epsrc.ac.uk/research/ourportfolio/themes/engineering/activities/sue/Pages/environment.aspx

5.
MECHANISMS FOR TRANSLATION AND EXPLOITATION

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OVERVIEW OF TRANSLATION MECHANISMS USED IN UK UNIVERSITIES

Academics in the UK and elsewhere are under increasing pressure to demonstrate the benefit to society and economy of their research through the translation of the research to practice and its commercial exploitation.

An important part of the context of translation activities is that in general, UK Universities adopt the stance that IP generated by their employees (academics and researchers) is owned by the University[19]. This means that translation and exploitation involves the academic working, at least initially, with the formal translation mechanisms provided by the University. There are a variety of different translation mechanisms available and although there are some differences in terminology and organisation between different institutions, the basic model is essentially the same across the UK university sector.

- Collaborative research or consultancy: Involving direct collaboration between an academic and an industrial or public sector partner which funds the research and implements the results. This model works especially well in those industrial sectors (e.g., the oil industry) where there are a small number of large players, who can propagate the work effectively.

- Licensing arrangements: In which an industrial partner wishing to use some element of existing IP licenses it from the University, typically for a fixed period and within a defined geography.

- Spinouts: In this mode, the University supports the academic in setting up a spin out company. The support available takes the form of relevant legal advice (e.g., in relation to patenting) and negotiations regarding venture funding, which may come either from external venture capital sources or from the institution's own venture funding.

In addition many universities offer physical incubation facilities for university spinouts and an increasing number are opening up these facilities to external SMEs who wish to benefit from interaction with university researchers and the industrial eco-systems present in a university environment. Indeed, several institutions have active programmes of SME recruitment, often linked to other incentives such as the TSB's Knowledge Transfer Partnership/Secondment and Innovation voucher schemes.

These translation mechanisms offer a number of advantages for universities looking to commercialise their work. For individual academics, an effective in-house technology transfer system can reduce the risks of commercialisation by providing access to relevant legal and financial expertise and accelerate the process by facilitating networking with potential investors and customers. This includes in particular, access to sources of venture capital funding (both internal and external) which it would oth   erwise be difficult for an individual academic to engage (a number of the examples described in $5.3 have benefited from this mechanism). For universities themselves, these activities can provide both revenue and reputational benefits. However the exclusive technology transfer arrangements operated by some Universities may restrict the commercialisation of a new innovation and its target investors, particularly in cases where the IP is not easily commodified (as with licensed IP). Indeed, it has been argued that the commercialisation of university research happens more effectively through problem-oriented collaborations with existing firms or training of future employees, rather than spin-outs on science parks[20]. These arguments are however, difficult to quantify.

19. Slightly different arrangements sometimes exist for PhD students (who in general are not employees)

CASE STUDIES

In this section we present a number of case studies that illustrate the translation mechanisms discussed above. These case studies focus on spinouts since information on licensing and consulting activity is not so widely available.

Acoustic Sensing Technology Ltd. (www.acousticsensing.co.uk) was founded in 2013 to commercialise new acoustic technology to locate very quickly blockages and structural defects in water distribution networks, developed by academics at the University of Sheffield and the University of Bradford. Initial funding was provided by the North West Fund.

Adept Management Ltd. (www.adeptmanagement.com) was formed by academics from Loughborough University to commercialise software tools to improve the efficiency of design process associated with the development of new products, services or assets. The initial focus was on the construction sector, which still forms an important part of the business. It now has a staff of 10 and a £6.2 million turnover and an international client base.

Encos Ltd. (www.encosltd.com) was formed in 2007 by academics at the University of Leeds and the University of Nottingham to commercialise new materials for construction industry made from recycled and waste materials, offering potential improvements in sustainability. The company exhibited at EcoBuild 2012 and is currently undertaking development trials.

EVO Electric (www.evo-electric.com) was formed by academics from Imperial College London to commercialise a new form of electric motor that opens up the possibility of substantially lighter and cheaper hybrid and electric vehicles. Imperial Innovations (Imperial's technology transfer arm) assisted with patenting the technology and assembling a syndicate of investors to raise seed funding in order to develop the next generation motor, and brought in a management team to help take the product to market, and retains a shareholding. A joint venture has recently been established between EVO Electric and GKN Driveline to exploit EVO Electric's technology for the automotive sector.

Smarter Grid Solutions (www.smartergridsolutions.com) was formed to commercialise technologies for energy network management and control developed at the University of Strathclyde. These technologies enable the integration into the grid of distributed generation resources, without compromising safety and security. The company was formed in 2008 with investment of Strathclyde's own venture fund. It now has offices in Glasgow, London and New York.

Space Syntax (www.spacesyntax.com) provides consulting services in economics, planning, design, transport and property development with a strong focus on urban design and development. It was formed over 25 years ago by a group of academics from The Bartlett at UCL with an initial emphasis on the commercialisation of a then newly developed set of theories of how individuals interact with the built environment, for the purpose of improving architectural and design practice. UCL Business (UCL's technology transfer arm) advised Space Syntax on the establishment of the company and remains a shareholder and has a nominee on the board.

20. Nightingale P. and Coad A. (2014) 'The Myth of the Science Park Economy' Demos Quarterly No.2. http://quarterly.demos.co.uk/article/issue-2/innovation-and-growth/

APPENDIX A

Table A.1 Non-technical summary of key component-level technologies

Additive manufacture	Additive manufacturing refers to technologies that create three-dimensional objects by building them up layer by layer from digital models. They differ from conventional manufacturing techniques that rely on removal of material through cutting or drilling (i.e., subtractive processes). Additive manufacturing gives design freedom, minimizes waste, and makes the best use of available raw material hence reduce costs. They open up the possibility of smaller scale and personally customised production, potentially enabling some of this activity to be located in smaller facilities, closer to consumers, including in urban areas.
Autonomous vehicles	An autonomous vehicle is a vehicle with the capability to take over some, or in the limit, all of the conventional driving tasks from the driver. These vehicles sense and navigate through their environments with reduced or no human intervention. Autonomous vehicles have the potential to reduce number of collisions, make better use of existing roadway space hence reduce congestion, enable vehicle occupants to make better use of the time spent in traffic, improve accessibility by allowing everyone to use cars (e.g. the elderly, children, and disabled persons), and provide smother rides. Furthermore, these vehicles reduce the need for parking and open up increased vehicle sharing opportunities.
Behaviour change technologies	Behaviour change is an extension of demand management which aims not only to shift demand temporarily in space and time but rather to bring about more fundamental changes in behaviour by changing the tastes, attitudes and beliefs that underlie overt behaviour. The example that is often used by proponents of this approach is the reduction in the incidence of smoking that they argue was brought about by health awareness campaigns and the banning of advertising and sponsorship. Methods such as targeted information provision, real time feedback and reinforcement learning etc. are used. Increasingly, are harvested, processed and delivered using ICT platforms often via mobile devices.
Blue-green technologies	Blue-green technologies is concerned with combining the management of 'blue infrastructure' of urban water system and services (e.g., water collection, storage, distribution and drainage networks and associated treatment facilities) and the 'green infrastructure' of urban areas including parks, recreation grounds, gardens and green roofs. It can be seen as a systemic extension of narrower technologies such as green roofs and grey water reuse at the urban scale. A key example is the use of green infrastructure to retard potentially problematic storm water runoff thus allowing existing drainage and sewer infrastructure to better cope with extremes rainfall with reduced risk of flooding. Important elements of the technology include sophisticated modelling to predict local rainfall and runoff patterns and knowledge of the absorption properties of different types of land cover, soil and vegetation.
Building information systems	Building information models are digital representation of physical and functional characteristics of buildings. The models not only cover geometrical information on buildings, but also spatial relationships, details of building components, geographic information, and also real time sensor measurements (e.g. energy and water use) from the building systems. Such complete representation of buildings will help with construction management and facility operations, and support decision making throughout the buildings' lifecycle. These systems can be used by businesses and government agencies who manage a diverse range of buildings, facilities, and infrastructure.

Citizen sensing	Users of smart phones and networked devices are increasingly capable in engaging with data collection for monitoring purposes through the use of wireless sensors. Such capability enables development of an interconnected network of people who actively observe, measure, report, collect and analyse data. Citizen sensing applications might include air and water pollution monitoring, health care monitoring, and a range of other topics. Citizen sensing intend to crowd-source the collection and use of sensor data in order to facilitate expanded citizen engagement. This will not only provide rich data sets but also give rise to new means of awareness on topics such as pollution, health care, climate change, and biodiversity.
Combined heat and power systems	Combined heat and power (CHP) is the simultaneous generation of usable heat and power in a single process. CHP systems are efficient and they save fuel by making use of the heat already being generated during the process of generating power, which is wasted in conventional heating systems.
Demand management and demand aggregation (inc. via dynamic pricing)	The objective of demand management is to incentivise individuals to adjust their behaviour in space and time in such a way as to enable the underlying infrastructure and service networks in cities to accommodate it more easily. Demand management is already widely used in urban transport system management to address issues of congestion and air quality (using a combination of regulation and pricing) and is increasingly being considered in energy and water systems. A particular aspect of demand management that is especially important in energy supply networks is the reduction in demand uncertainty through the aggregation and coordination of individual demands. An important opportunity for improved demand management in the future is dynamic pricing (e.g., of transport services, energy services).
District heating and heat networks (inc. energy from waste)	District heating schemes or heat networks supply heat from a central source to geographically dispersed residential and commercial buildings for space heating and water heating. Hence, individual buildings or flats do not need to generate their own heat. Heat can be generated in such centralised systems which also enable the easier use of renewable energy sources (e.g., biomass, geothermal, solar and CHP systems). A number of district heating systems are also fuelled in part by domestic and commercial wastes, further improving efficiency.
Environmental monitoring	Increasing concerns over human impacts on the environmental resulted in the increased demand for the monitoring, analysis, and modelling of environmental systems. Environmental monitoring involves collection of data on a various range of environment-related areas including air and water pollution, climate change, erosion, soil quality etc. Environmental data is valuable for governments and industry to guide their decision-making. Systems of sensors to gather the data, and tools for processing and analysing will be increasingly important given increasing environmental concerns.

Green roofs	Green roofs are layers covered with vegetation that sit on top of the conventional roof surfaces of a building. Green roofs have many different forms and types, mainly distinguished by the amount and type of plants grown. The plants that cover the roofs provide insulation reducing building energy consumption for cooling and heating, and absorb rainwater reducing drainage. They are also attractive due to creation of additional green spaces especially in cities. Green roofs are seen as one of the effective ways of combating the urban heat island effect (i.e. the temperature disparity between urbanised areas and surrounding rural areas) and might be part of the solutions to help cities with climate change adaptation. The disadvantages of green roofs include higher initial costs and potentially higher maintenance costs compared to traditional roofing, the additional strain on the buildings' structural support, and the potential for attracting pest insects.
Grey water reuse	Grey water is the wastewater generated from bathroom and kitchen sinks, showers, baths, washing machines, and dishwashers. Domestic wastewater is often combined at the sewer; hence grey water and sewage are removed together. Yet, if collected separately from sewage, grey water can be recycled on-site and re-used for end uses such as toilet flushing, landscape irrigation, and constructed wetlands. Greywater reuse reduces demand on conventional water supplies, reduces energy use and chemical pollution from sewage treatment, and saves energy.
Ground source heat pumps	Ground source heat pump is a type of heating system that uses heat extracted from the ground instead of burning fuel for generating heat. A mixture of water and antifreeze circulated through pipes absorbs the heat in the ground. The heat pump extracts the heat from the fluid and transfers it to the heating system. The ground stays at a fairly constant temperature under the surface throughout the year, making heat pumps a viable option for heating homes. The pumps use electricity for power yet they generate more heat than the electricity they consume. Heat pumps could lower fuel bills, reduce carbon emissions, and need little maintenance. The installation costs, however, are typically higher than conventional boilers and installation requires suitable space for digging trenches.
Innovative vehicle design (inc. lightweighting and new form factors)	Innovation in vehicle design has the potential to reduce emissions from vehicles, reduce costs and emissions associated with vehicle manufacturing, improve performance and safety, enable enhanced recycling capabilities, and utilise new technologies in vehicles. For instance, lightweight vehicles have the potential to improve fuel efficiency reducing emissions without compromising safety and performance. Furthermore, innovative design of individual vehicle components (batteries, tyres, supercapacitors, etc.) will have impact on vehicle emissions and performance of future vehicles.
Intelligent transport systems	Intelligent transport systems represent the convergence of traditional transport engineering and planning with the ICT sector. The UK DfT has defined ITS as "...the application of advanced sensor, computer, electronics, and communication technologies and management strategies - in an integrated manner - to increase the safety and efficiency of the surface transportation system". In urban areas ITS applications include both those aimed at improved network management (e.g,. bus fleet management, coordinated traffic signal control) and those aimed at providing better user services (automatic payment systems, travel information and trip planning services) as well as important applications oriented towards safety and security (e.g. collision avoidance,

Low carbon construction materials	A large part of greenhouse gas emissions associated with buildings arises from the manufacture of construction materials, particularly the production of cement and steel. Technologies that will reduce carbon footprint of construction materials will therefore be crucial to reduce emissions from the construction sector in the future.
Low carbon powertrains (inc. electric and hydrogen fuel cell)	The powertrain is the mechanical system in a vehicle that provides the energy required to move the vehicle, and includes the engine, transmission, and driveshaft. Low carbon powertrains are being developed either through improved efficiency or use of low-carbon fuels, or both (e.g. more efficient combustion, conventional hybrids, biofuels, hydrogen fuel cells, plug-in hybrids, battery electric vehicles etc.). Low carbon powertrains are expected to reduce transport related emissions and reduce dependency on conventional fuels.
Low friction pipelinings	Large amounts of energy are required to pump large volumes of water through pipelines from source to destination. Developing new materials that would reduce the friction between the pipe walls and the flowing water have the potential to reduce the energy required to transport water through the pipeline network. Energy requirement for this process is especially significant in countries where water is scarce and water needs to be transported longer distances. As water scarcity is expected to rise due to climate change in the future, energy intensity of water transport will become increasingly material for many regions. Existing research on new materials that could be used in water pipelines together with other chemicals is promising for reducing the energy intensity of water transport.
Microbial treatment of wastes	Urban areas generate large amount of organic waste in the form of waste water (industrial and domestic – sewerage and grey water) and solid waste materials (industrial, medical, commercial and domestic). In its raw state, much of this waste is potentially harmful but also potentially value as an input to digestion and re-cycling processes that can reduce the health hazard of these wastes and recover useful products such as nitrogen fertilizers. Examples include improved technologies for home composting of biodegradable domestic wastes and improved technologies for industrial biowaste screening and digestion. In the longer term, technologies are emerging that may enable the direct generation of electricity through the digestion of biowastes (the “microbial fuel cell”).
Microclimate sensing and control	Microclimates are local atmospheric zones where the climate is different from surrounding areas. These exist, for instance, around heavily urban areas where heat island effects are observed due to human activity. Other microclimatic differences observed in urban areas include differences in rain days, sunshine duration, precipitation, winds, and smog. Microclimates may affect health, water and air quality, and agricultural practices. It is therefore important to monitor microclimates and take necessary actions to minimize their impacts. For example, it is possible to reduce urban heat island effects by using green roofs, or reflective/white materials for building roofs and roads reducing absorbed heat in the city.

Opportunistic networking	In opportunistic networks, mobile nodes are enabled to communicate with each other even if a route connecting them never exists and nodes are not required to possess or acquire any knowledge about the network topology. These new networks will relax some of the restrictions currently exist on data transmission. They may enable the integration of a diverse range of communication, computation, sensing, storage devices surrounding us and their use for transmitting information. These diverse ranges of devices are currently under-leveraged due to barriers limiting communications between them. Their applications, for instance, will be valuable in emergencies where forwarding critical information is crucial and existing network infrastructure might either be destroyed by a disaster or overloaded due to heavy use. They also have the potential to make the networks more efficient by utilising a diverse range of devices. However, there are still outstanding issues regarding secure and efficient transfer of information, privacy, and performance.
Patient (citizen) monitoring and diagnosis	ICT can play an important role in patient monitoring, clinical decision support, and treatment planning. First of all, monitoring devices equipped with medical sensors can be used to track patients more closely at the comfort of their homes. Days spent in the hospital can be reduced by the use of these monitoring devices to detect anything unusual, w which will cut costs for hospitals and increase the quality of patient care. Secondly, ICT can be used to process and analyse medical history data of patients and suggest treatments or issue warnings based on data analysis for practitioners. Such automation might be helpful for early detection of particular diseases and minimize individual and organisations errors.
Power electronics and smart grid	Smart grids are electricity networks that enable the delivery of power from generation of sources to end-users to be monitored and managed in real time. They allow for real-time data collection (e.g. on supply and demand behaviour) and control (e.g. adjusting supply levels) of the network. One of the key characteristics of smart grids is that they will enable the mass adoption of distributed renewable power sources and ensure a stable supply at the same time. Power electronic devices are required for use in smart grids to accommodate fluctuations in frequency and voltage, which will result from the use of renewable sources of energy where the output power is difficult to control.
Predictive analytics	Increased use of sensors and monitoring should be coupled with tools and methods to make the best use of collected data. Predictive analytics refers to statistical methods that can be used to make predictions about the future state of the system by analysing real time and historical data. Predictive analytics are the basis for improved methods of control.
Real time and distributed control	Real-time distributed control systems consist of sensors, actuators, controllers, and communication devices that are physically dispersed but are connected to each other through a network. The controller elements are not located centrally, rather are distributed throughout the system. It is made possible by the development of small smart devices allowing for controllers to be implemented at the local level with limited power requirements. These systems will become increasingly important with the increasing use of wireless embedded sensors and move towards smart devices and structures.

Robotic construction	In construction, people work through a detailed execution plan for a given building/infrastructure design. This requires close oversight from an operator throughout the construction process. It is however possible to automate the construction process which might reduce costs and errors, while accelerating the process. Robot construction teams may be used for building complex large scale structures, where each robot acts independently in light of the common rules specified by computers based on the initial design.
Smart facilities management	Smart facilities management systems aim to make the best use of collected data from facilities to make buildings work more efficiently. Buildings today are increasingly equipped with connected sensors and systems that constantly generate data about the buildings. Smart facilities management systems aim to leverage this data to better manage facilities, and improve financial and environmental performance.
Smart facilities management	A smart infrastructure system is the one that uses a feedback loop of data that is used for informed decision making. The smart system is capable of monitoring, measuring, analysing, communicating and acting based on gathered information. Smart infrastructure systems therefore should have embedding sensing networks for collecting data (e.g. demand data for utilities, leakage or tearing warnings, traffic count data). Furthermore, systems should be in place for processing the data being collected and present information in a format that can guide decision making (e.g. traffic count data should be processed and used to detect congestion that can be used to inform drivers). Smart systems make use of historical data for predictions to guide planning of operations. Smart systems are capable of taking action without human intervention and are adaptive (e.g. smart grids controlling themselves to maximise efficiency in operations). As infrastructure gets smarter, the efficiency will improve.
Smart water networks	A smart water network links multiple systems within a network for sharing data across platforms, which is helpful for efficiently operating the physical layer of pipes, pumps, reservoirs and valves in a water network. Smart water networks have sensing and control layers on top of the physical layer, which are responsible for data collection and distributed control. These layers are supported by collection and communication, data management and display, data fusion and analysis layers. IT and technological systems are being developed separately for each of these layers and their integration. These include, for instance, smart meters, pump optimisation, network monitoring, active pressure management. Smart water networks will enable water utilities to remotely monitor and diagnose problems, prioritise and manage maintenance in advance, remotely control and optimize the network using data-driven insights, and provide customers with the information and tools they need to make informed choice about their behaviour and water usage patterns.

Specialised nano materials (inc. self-cleaning, self-repairing)	Nano-materials are materials having particles of nano-scale dimension or are produced by nanotechnology. Nano-materials can be engineered with specific properties related to shape and size, surface properties, and chemistry for specific functions. Hence, they allow for design of materials and surfaces that can fundamentally improve the design and use of buildings, infrastructures, and products. For instance, self-cleaning materials keep themselves free of dirt using nano-materials with special hydrophobic, hydrophilic or photo-catalytic properties. Applications include self-cleaning glasses, self-cleaning paint, and self-cleaning textiles. Self-healing or self-repairing materials have the inherent ability to repair damage due to normal usage, thus expend material's lifetime.
System modelling	Systems modelling helps conceptualize and model complex systems, where different components within the system can interact with each other in various ways. Systems modelling can make use of different modelling techniques, and quantitatively model large inter-related systems. These models can then be used for predicting future behaviour, understanding impacts of various policies and measures which would otherwise be difficult to understand given the complexities involved. Such approach is especially relevant for cities research given the complexity of inter-relationships between different city system components.
Thermal storage materials (heat and coolth)	Thermal storage materials enable collection of excess thermal energy for later use. Stored energy can be used for heating or cooling applications, and power generation. Thermal energy storage is attractive for balancing energy demand and supply on a daily/weekly/seasonal basis, reducing peak demand, reducing consumption, and helping to increase the share of renewables in the energy mix. Thermal energy can either be stored by heating/cooling a storage medium such as water, or by using phase change materials since melting/solidification can store larger amounts of heat. Alternatively, chemical reactions could be used to store and release thermal energy. Research efforts continue for developing materials that are suitable and economically viable for different thermal energy storage applications.
Underground construction	Underground construction is becoming popular as a design strategy for sustainable buildings. They have the advantage of maximising space in small areas by making use of the space below the ground, reduce material use for construction and maintenance costs, save energy, and allow for designs with a minimum impact on the surrounding environment.
Upcycling of waste products for construction	Upcycling is the process of converting waste materials/products into new materials/products of better quality or better environmental value. It is different from down-cycling (or recycling), which involves converting waste into new materials of less quality. Upcycling of waste products for construction have the potential to reduce emissions and waste to landfills, preservation of natural resources, and reduce costs for manufacturers.
Virtual citizen services (e.g., healthcare, social care, education)	ICT technologies can be utilised to allow citizens to remotely carry out various administrative processes without needing to physically visit offices. This might involve development of systems where citizens can take care of administrative work without human interaction, or might involve face-to-face interactions through video conferencing with public servants. Virtual citizen services can be utilised in many areas including healthcare, social care, and education. They will be more efficient, reduce costs, save time, reduce travel, and improve public services.

Table A.2 Non-technical summary of key integration-level technologies

Big data methods	Big data comes from sensors, devices, social media, networks etc, and is generated in real-time in very large quantities and at very fast rates and of very diverse types. The volumes and rate of such data can pose problems for traditional methods of analysis and require specialised methods that are designed to find meaningful patterns and structure in streams of diverse data.
Cross sector visualisation – urban dashboards etc.	Visualisation of data becomes increasingly important for making sense of the increasingly large sets of digital data. Live views of city data can be presented, for instance, on real-time by pulling data from a variety of feeds. This could be useful for systems management, city governments, and citizens.
Data brokerage services – management of privacy, reputation and trust	As more data gets collected and tools are developed to monetise gathered data, data brokerage services will become increasingly important. These services will intermediate between different data creators and data users in order to create effective markets. The companies offering these services will need to overcome the challenges regarding privacy issues for securing long-term sustainability of their businesses.
Data platforms for sharing/ integrating data across different sectors	Massive amounts of digital data are being collected from all sorts of sources and such collection of data is expected to grow. These data are often very large and unstructured. Data platforms provide means to integrate data from different sources and share them effectively with different categories of user.
Generic and cross sectoral wireless sensor networks	In an urban wireless sensor network, autonomous sensors are distributed throughout the city. They cooperatively pass their data through a wireless network, and smart networks also allow for real-time distributed control of the sensor activities. Generic and cross-sector network designs should be developed that would suit different purposes for organising integration and forwarding of relevant data.
Identification, estimation and valorisation of co-benefits	Investments or improvements in one urban sub-system can have effects in other sub-systems. For example, investments in better transport infrastructure can improve the efficiency of labour markets and hence economic performance. It is important to understand the nature and magnitude of these co-benefits (and dis-benefits), since they potentially form a significant part of the overall value of such investments.
Large scale real time data fusion and data assimilation	Big data comes from diverse range of sources and mostly in an unstructured format. Real-time data fusion techniques will enable to reduce the amount of the data without losing information, which will make data more useful and reduce data processing times. This might also involve integration of data from multiple sources. Data assimilation is a process in which observations are incorporated into an existing computer model in real time, and are used to improve the predictions of the model.

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Modelling the vulnerability and resilience of highly inter-connected urban systems	Urban systems are susceptible to a wide range of natural and man-made hazards that could cause disruption and loss of service. As different urban sub-systems become ever more closely integrated, the scope for impact arising in one sub-system to cascade into consequences for other sub-systems potentially increases. Models are required that help us understand the nature of these cascading vulnerabilities and how most effectively plan and operate systems to maximise resilience and enable effective recovery.
Multi-sector, multi-scale system modelling at an urban scale	The development of integrated urban systems that can capitalise on the opportunities for synergy and cooperation between different urban sub-systems will require modelling tools that can represent fully the key features of these different urban sub-systems and the relationships between them. These models will need to be able to operate at a variety of different temporal and geographical scales.
New business models and governance structures	By creating the capability to design, plan and operate urban systems in new ways, we potentially create new sources of value and new opportunities for business. However, these opportunities may require not just technological innovation in systems and services but also innovation in the business models used to capture and distribute these benefits. A closely relate set of questions concerns governance structures for the funding, financing, design, planning and operation of integrated city systems.
Standards for urban system ontologies (inc. semantic web)	Standards are required for urban systems at a number of different levels, from the physical interoperability of devices to the conceptual description of multiple interacting urban sub-systems. A critical step is the development of ontologies that enable different urban sub-systems to be described, modelled and analysed in a consistent and manner.
Treatment of uncertainty propagation in integrated urban systems	The complex models used for the planning and management of integrated city systems will entail a large number of modelling assumptions and require a large amount of data. Both modelling assumptions and input data are subject to a range of errors. These errors can accumulate as the output of one model is used as the input to another. In this way errors can be propagated and potentially magnified. Understanding how this process of propagation operates and is important, in order to avoid erroneous conclusions being drawn from such model systems.

APPENDIX B

CATAPULT Future Cities

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CONNECTING RESEARCH WITH CITIES: mapping the UK's research landscape on urban systems and technologies

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