

Research Councils UK Energy Programme Strategy Fellowship

ENERGY RESEARCH AND TRAINING PROSPECTUS: REPORT NO 4

Transport Energy

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Research Councils Energy Programme

The Research Councils UK (RCUK) Energy Programme aims to position the UK to meet its energy and environmental targets and policy goals through world-class research and training. The Energy Programme is investing more than £625 million in research and skills to pioneer a low carbon future. This builds on an investment of £839 million over the period 2004-11.

Led by the Engineering and Physical Sciences Research Council (EPSRC), the Energy Programme brings together the work of EPSRC and that of the Biotechnology and Biological Sciences Research Council (BBSRC), the Economic and Social Research Council (ESRC), the Natural Environment Research Council (NERC), and the Science and Technology Facilities Council (STFC).

In 2010, the EPSRC organised a Review of Energy on behalf of RCUK in conjunction with the learned societies. The aim of the review, which was carried out by a panel of international experts, was to provide an independent assessment of the quality and impact of the UK programme. The Review Panel concluded that interesting, leading edge and world class research was being conducted in almost all areas while suggesting mechanisms for strengthening impact in terms of economic benefit, industry development and quality of life.

Energy Strategy Fellowship

The RCUK Energy Strategy Fellowship was established by EPSRC on behalf of RCUK in April 2012 in response to the international Review Panel's recommendation that a fully integrated 'roadmap' for UK research targets should be completed and maintained. The position is held by Jim Skea, Professor of Sustainable Energy in the Centre for Environmental Policy at Imperial College London. The main initial task is to synthesise an Energy Research and Training Prospectus to explore research, skills and training needs across the energy landscape. Professor Skea leads a small team at Imperial College London tasked with developing the Prospectus.

The Prospectus contributes to the evidence base upon which the RCUK Energy Programme can plan activities alongside Government, RD&D funding bodies, the private sector and other stakeholders. The Prospectus highlights links along the innovation chain from basic science through to commercialisation. It is intended to be a flexible and adaptable tool that takes explicit account of uncertainties so that it can remain robust against emerging evidence about research achievements and policy priorities.

One of the main inputs to the Prospectus has been a series of four high-level strategic workshops and six in-depth expert workshops which took place between October 2012 and July 2013. The main report, *Investing in a brighter energy future: energy research and training prospectus*, was published in November 2013. This is one of nine topic-specific documents supporting the main report. All reports can be downloaded from: www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents/reports. This first version of the Prospectus will be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This report is the product of work conducted independently under EPSRC Grant EP/K00154X/1, Research Councils UK Energy Programme: Energy Strategy Fellowship. The draft report was reviewed by David Bannister of the Transport Studies Unit at Oxford University, Brian Robinson of the Transport Research Laboratory and Jonathan Köhler of Fraunhofer ISI. While the report draws on extensive consultations, the views expressed are those of the Fellowship team alone.

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Executive Summary

This report examines transport energy research covering both vehicle-systems (i.e. vehicle design, technology and fuels) and the wider transport system (i.e. transport infrastructure, planning, governance and business models). The conclusions from a two-day, facilitated expert workshop attended by academics along with representatives from private and public sector organisations have been some of the most important inputs to this report. The report sets these conclusions within the context of the UK's scientific and industrial capabilities, policy ambitions, global and UK developments and outputs from existing roadmaps and needs assessments. The main findings are:

- Priority research areas span technology-focused, engineering-based research through to behaviour-focused, social science-based research. Relevant spatial scales range from the micro- (e.g. vehicle component) to macro-level (e.g. transport system infrastructure). Eight categories of research have been identified: **automotive transport; aviation; transport fuels; freight and logistics; transport energy behaviour; transport energy governance and business; transport planning and infrastructure;** and **understanding, measuring and modelling transport system change**. Whilst rail and shipping research were not highlighted specifically during the workshop, many of the other categories, such as **freight and logistics**, have direct relevance to these modes of transport.
- An interdisciplinary approach is needed for high quality transport energy research. The research councils could take the following steps to foster greater inter-disciplinary coordination and collaboration across the UK transport energy research community:
 - issuing calls for systems-level transport energy research that demands input from multiple disciplines;
 - introducing cross-council research calls;
 - introducing cross-disciplinary peer-review panels for funding proposals; and
 - supporting longer and larger research projects to provide the necessary resources and time to adequately address the interdisciplinary, whole-systems nature of the research challenges.
- Some workshop participants proposed establishing a central interdisciplinary national transport energy research institute with associated research networks. We note this suggestion without necessarily endorsing it. Universities could help by forming cross-campus university transport energy research centres. Other steps to promote interdisciplinarity include cross-disciplinary peer-review panels for journals and the Research Excellence Framework (REF).
- There is a need to centralise, curate and disseminate transport energy consumption data generated by a broad range of actors, in order to open up research opportunities. However, special attention should be paid to confidentiality and intellectual property issues associated with this data. Some of these issues may be addressed via working agreements with private sector organisations.
- Whilst various testing facilities exist to test technological transport innovations, there is a need for test beds or 'living labs' capable of examining the effectiveness of innovations in 'real world' places with 'real' people. However, issues are likely to emerge as to how these might impact upon public safety and privacy.
- There is a need for additional PhD training in transport energy research via both Centres for Doctoral Training and project funding models. PhDs supported jointly by the research councils and either industry or government would provide PhD students with a rich learning experience, as well as helping to foster academic and non-academic research collaboration.

- Industrial collaboration is essential if priority research challenges are to be addressed, particularly given the innovation track record of the UK's transport sector (e.g. motorsport, aviation). This can be supported by better integration of the energy innovation landscape, particularly through relationships between the research councils and R&D funders such as the Technology Strategy Board and the Energy Technologies Institute. Solutions include: jointly-funded research projects; multi-directional secondment schemes; and knowledge exchange programmes that engage end-users and tailor information to their needs.
- Researchers should be encouraged to collaborate with international research partners via networks such as the European Energy Research Alliance in order to access non-UK research funding. Such support systems should address the significant 'up-front' time and effort needed to cultivate and execute such research projects. Additionally, the Knowledge Transfer Networks are well positioned to coordinate such international engagement and could become more involved in facilitation.

Acronyms

2DS	two degrees scenario
4DS	four degrees scenario
ACARE	Advisory Council for Aeronautics Research in Europe
BBSRC	Biotechnology and Biological Sciences Research Council
BIS	Department for Business, Innovation and Skills
CCS	carbon capture and storage
CDT	Centre for Doctoral Training (also referred to as DTC)
CNG	compressed natural gas
DECC	Department of Energy and Climate Change
DETRA	Developing a European Transport Research Alliance
DoE	Department of Energy (US)
EARPA	European Automotive Research Partners Association
ECTP	European Construction Technology Platform
EERA	European Energy Research Alliance
ETS	Emission Trading Scheme (EU)
EPSRC	Engineering and Physical Sciences Research Council
ERRAC	European Rail Research Advisory Council
ERTRAC	European Road Transport Research Advisory Council
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
ETP	Energy Technology Perspectives
ETPC	European Technology and Production Concept
EUED	End Use Energy Demand
EV	electric vehicle
GHG	greenhouse gas
HEV	hybrid electric vehicle
HGV	heavy goods vehicle
IATS	Integrated Active Transportation System
ICE	internal combustion engine
ICT	information and communications technologies
IEA	International Energy Agency
IP	intellectual property
KTN	Knowledge Transfer Network
LCA	life cycle assessment
LCICG	Low Carbon Innovation Carbon Group
LDV	light-duty vehicles
LNG	liquefied natural gas
MARKAL	Market Allocation (Model)
NAIGT	New Automotive Innovation and Growth Team
NERC	Natural Environment Research Council
OECD	Organisation for Economic Co-operation and Development
PHEV	plug-in hybrid electric vehicle
R&D	research and development
RCUK	Research Councils UK

RD&D	research, development and demonstration
STFC	Science and Technology Facilities Council
toe	tonnes of oil equivalent
TRL	Transport Research Laboratory
TSB	Technology Strategy Board
UKERC	UK Energy Research Centre
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

This document is one of a series of reports that sets out conclusions about UK research and training needs in the energy area. The focus of this report is **transport energy**. The primary audience for the report is Research Councils UK (RCUK), which supports energy research in UK higher education institutions through the RCUK Energy Programme.¹ However, other bodies involved in funding energy research and innovation, notably those involved in the UK's Low Carbon Innovation Carbon Group (LCICG),² may also find the content useful. The report is also being disseminated widely throughout the UK energy research and innovation community to encourage debate and raise awareness of the work conducted under the Fellowship.

The most important input to this report has been a two-day, facilitated expert workshop held at Coventry Transport Museum on 11-12 June 2013. Excluding the Fellowship and facilitation team, 32 participants attended the workshop, most of whom were academics and researchers falling within the communities supported by the Engineering and Physical Sciences Research Council (EPSRC) and Economic and Social Research Council (ESRC). In addition, a number of attendees were from private sector and government organisations.

A full report of the workshop has previously been published as a working paper.³ The working paper constitutes a document of record of the workshop outputs and represents an intermediate step in the production of this report, which focuses on key messages and recommendations. The workshop also drew on the outcomes of a series of 'strategy' workshops titled: **energy Strategies and energy research needs; the role of the environmental and social sciences; and the research councils and the energy innovation landscape**. Reports of these workshops are also available on the Fellowship's website.⁴

The conclusions respond to a recommendation of the **2010 International Panel for the RCUK Review of Energy**⁵ that the research supported by the RCs should be more aligned with the UK's long-term energy policy goals. The key criteria used in developing this report have been the three pillars of energy policy – environment, affordability and security – coupled with potential contributions to UK growth and competitiveness.

The Fellowship team is using the EU/International Energy Agency (IEA) energy research and development (R&D) nomenclature⁶ to map out the energy research landscape. This report primarily covers **Area I, Sector 3 Energy Efficiency – Transport**, encompassing the various aspects of the transport sector that characterise transport energy demand. It should be noted that some transport related research areas are covered by other reports, for instance fuel cells and batteries are examined in **Prospectus Report No 6: Electrochemical Energy Technologies and Energy Storage** and biofuels are covered by **Prospectus Report No 8: Bioenergy**. In this report the research challenges and needs identified in Section 5 of this report falls into eight broad areas: 1) automotive transport; 2) aviation; 3) transport fuels; 4) freight and logistics; 5) transport energy behaviour; 6) transport energy

¹ <http://www.rcuk.ac.uk/research/xrcprogrammes/energy/Pages/home.aspx>

² <http://www.lowcarboninnovation.co.uk/>

³

<https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Expert%20Workshop%20Reports/Tra%20transport%20Energy%20Working%20Document%20Final.pdf>

⁴ <http://www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents/reports>

⁵

<http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/reports/ReviewOfEnergy2010PanelReportFinal.pdf>

⁶ http://ec.europa.eu/research/energy/pdf/statistics_en.pdf

governance and business; 7) transport planning and infrastructure; and 8) understanding, measuring and modelling transport system change.

This report is structured as follows. **Sections 2-4** provide the wider context within which research and training challenges are identified. Section 2 focuses on the potential importance of transport energy consumption in future energy systems both globally and in the UK. Section 3 describes the current UK research landscape and capability levels. Section 4 reviews existing roadmaps and assessments of research and innovation needs. **Sections 5-8** draw heavily on the Coventry workshop. Section 5 sets out high-level research challenges across the eight different categories. Section 6 focuses on the ways in which the research councils operate, how the research they support is conducted and underlying needs for research infrastructure and data collection/curation. Many of the conclusions are generic in the sense that they may be applicable beyond the area of transport energy, across the energy domain or even more widely. Section 7 addresses training provision. Section 8 addresses generic issues about the role of the research councils within the wider UK energy innovation system and EU/international engagement. **Section 9** outlines the key conclusions and recommendations from the report.

2 Current and future status of transport energy

This section addresses the future role of transport energy. Section 2.1 situates the importance of this field of research in the global context, whilst Section 2.2 situates it within the UK context. Section 2.3 presents some key findings from the Fellowship's strategic workshops to highlight experts' aspirations and expectations as to how transport energy consumption and supply may change in the future.

2.1 Global perspectives on transport energy consumption

Globally, transport energy demand has increased dramatically over the past century and this demand growth is expected to continue for the foreseeable future, particularly outside the Organisation for Economic Co-operation and Development (OECD) countries. The majority of this demand is currently satisfied by liquid hydrocarbons, raising concerns not only about the future security and affordability of these fuels given their finite nature but also the impact their combustion will have on the environment, particularly in relation to climate change. This debate is of critical importance considering how integral transport is to the fabric of our society in terms of economic activity, wellbeing and leisure. To illustrate the scale of this challenge we begin by exploring how transport energy demand has grown in recent years and how different types of energy have helped satisfy this demand.

In 2010, transport energy demand accounted for approximately 27% of total global final energy consumption. Between 1975 and 2010 global transport energy demand steadily increased, growing by 115% (Figure 1). The World Energy Council's report *Global Transport Scenarios 2050*⁷ identifies the two main drivers as being economic growth and population growth. This helps to explain why transport energy demand has grown much more quickly across emerging economies located in non-OECD countries, where demand increased by a factor of 3.5 between 1975 and 2010, double that for OECD countries. However, OECD countries typically consume much more transport energy per head than non-OECD countries.

⁷ http://www.worldenergy.org/documents/wec_transport_scenarios_2050.pdf

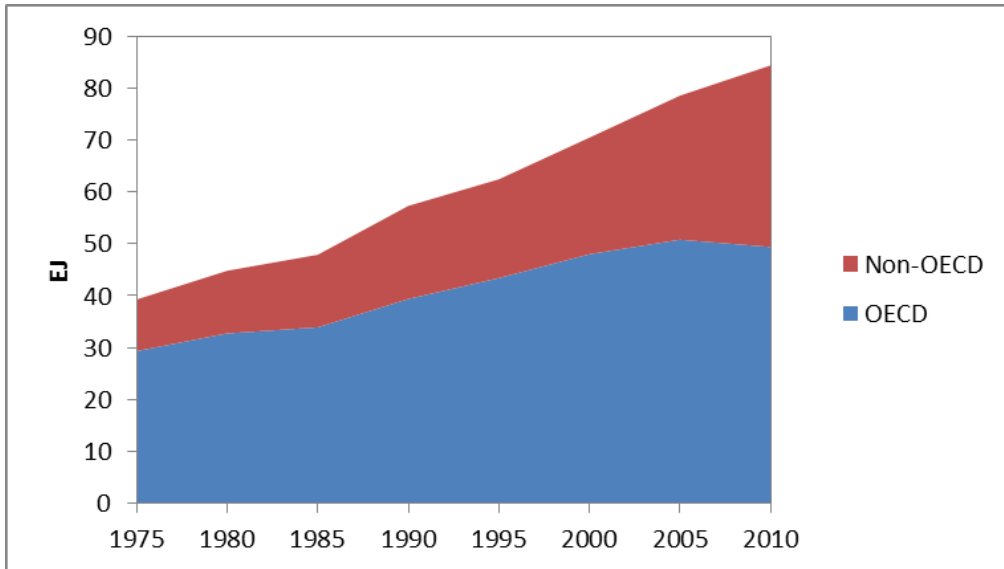


Figure 1: OECD and Non-OECD Transport Energy Consumption 1975 – 2010⁸

Source: IEA⁹

Historically the majority of transport energy demand can be attributed to road transportation. For example, in 2009 the energy consumed by road transportation was three times greater than that consumed by all the other transport modes (e.g. rail, shipping, aviation) combined (Figure 2). Road transport has also experienced the highest rate of growth with demand from two-, three- and four-wheelers and light-duty vehicles (LDVs), e.g. cars, light trucks, and heavy vehicles,¹⁰ e.g. trucks, buses etc., almost tripling between 1971 and 2009. Aviation energy demand has more than doubled, with shipping experiencing a more modest increase of 64%. In contrast, rail energy demand has fallen by 40%. International shipping and aviation have grown at a much faster rate than their domestic counterparts.

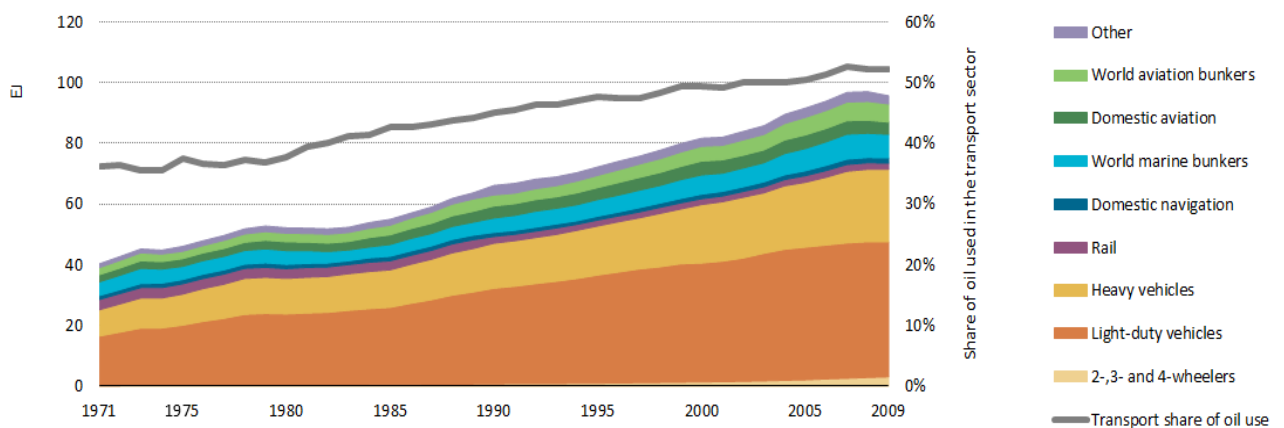


Figure 2: World transport energy consumption by mode 1971 – 2009

Source: IEA Energy Technology Perspectives (ETP)¹¹

⁸ This excludes international shipping and aviation, which is outlined in Figure 2. It therefore only focuses on domestic transport energy consumption

⁹ http://esds80.mcc.ac.uk/wds_iea/TableView/tableView.aspx?ReportId=790

¹⁰ Light-duty vehicles refer to cars and light trucks up to 3.5 tonnes in weight, whilst heavy vehicles refer to trucks and buses

¹¹ <http://www.iea.org/w/bookshop/add.aspx?id=425>

The transport energy supply mix has changed relatively little over the past few decades, with oil products continuing to satisfy the majority (currently 93%) of transportation needs (Figure 3). Whilst fossil fuels continue to dominate the transport sector, the market share of some non-fossil fuels has grown significantly.¹² For example, bioenergy's share of total transport energy supply grew from 0.01% to 2.4% in the period 1975 to 2010.

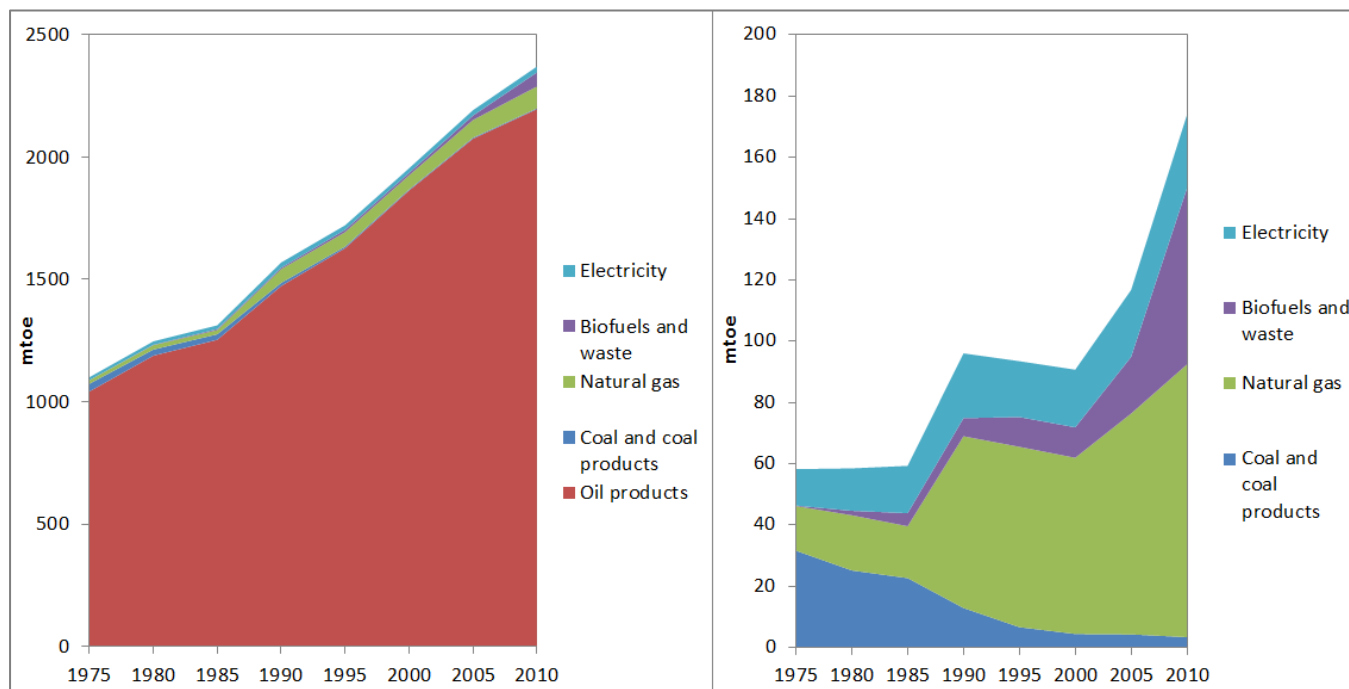


Figure 3: Global transport energy supply mix 1975 – 2010 including and excluding oil products

Source: IEA

Future global transport energy demand is uncertain, as evidenced by a range of energy scenarios. Two broad types of energy scenario are currently common: **normative** scenarios tend to be climate-driven and identify combinations of technologies that have the potential to meet the United Nations Framework Convention on Climate Change (UNFCCC) goal of keeping global temperature increases to no more than 2°C above pre-industrial levels; **exploratory** scenarios or **projections** tend to assume lower levels of deployment of 'new' energy technologies and extend current trends in the use of fossil fuels into the future. We examine two contrasting scenarios, the IEA's **Two Degree Scenario (2DS)**,¹³ which is a normative scenario, and Shell's **Mountains** scenario.¹⁴

In IEA's **2DS** scenario, the transport sector evolves significantly by 2050 (Figure 4). Whilst total transport energy demand remains broadly similar to that at present, increasing by only 12%, demand increases by 66% in non-OECD nations due to a combination of economic development and population growth. In contrast, demand falls by 30% across the OECD nations largely due to tightening fuel economy standards, an expansion of the EU Emissions Trading Scheme (ETS) across the international airline industry, and the shipping industry's move to more energy efficient, low-sulphur fuels.

In Shell's **Mountains** scenario, transport energy demand grows by 53% between 2010 and 2050 (Figure 4). Whilst the scenario does not provide a detailed breakdown of transport energy demand, it

¹² To help illustrate these changes we have displayed the transport energy supply mix both with and without oil, given that its dominance of total consumption makes trends across the other fuels difficult to visualise

¹³ <http://www.iea.org/w/bookshop/add.aspx?id=425>

¹⁴ http://s01.static-shell.com/content/dam/shell-new/local/corporate/Scenarios/Downloads/Scenarios_newdoc.pdf

provides broader qualitative indications as to how it is likely to develop. Whilst transport energy demand is expected to increase, growth in demand will be constrained by improving vehicle efficiency due to policies such as vehicle fuel economy standards, tailpipe emissions standards, anti-pollution measures, fuel taxes and embedded CO₂ footprint taxes on imports. Demand is also constrained to some extent by increasing urbanisation, largely because urbanisation is conducive to shorter average journeys and may encourage the use of more energy efficient, 'urban' modes of transport, such as public transport and two-wheelers.

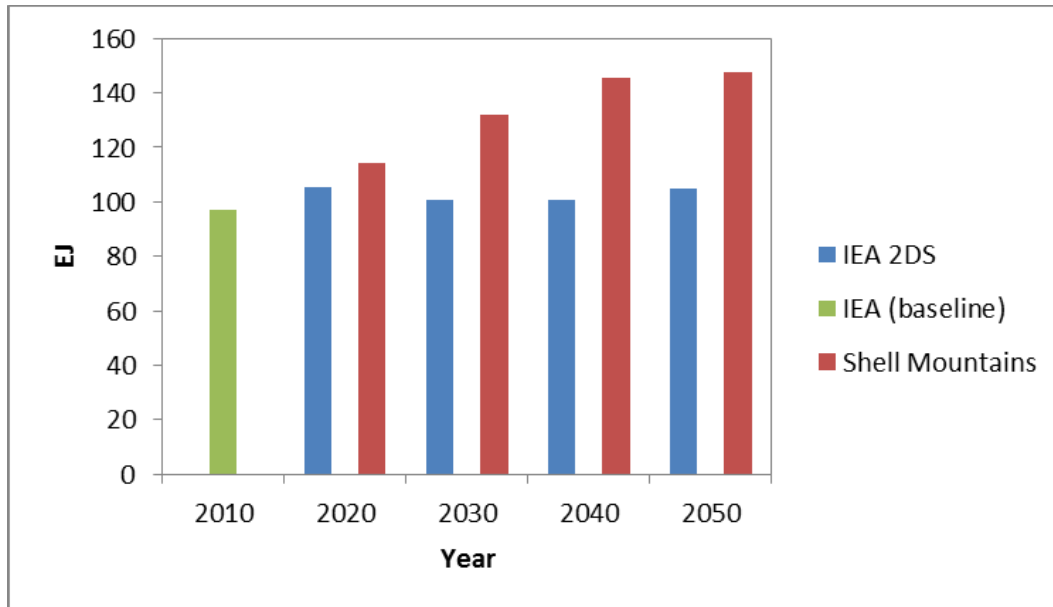


Figure 4: Projected Transport Energy Consumption

Source: Shell New Lens Scenarios – Mountains; IEA ETP

Under Shell's **Mountains** scenario, total transport energy demand increases substantially whilst the balance of transport modes remains broadly similar to that at present (Figure 5)¹⁵. Energy demand from freight transportation increases at a much faster rate than does passenger transportation up to 2050. Energy demand from aviation, road freight, and both rail and marine passenger transportation account for a larger share of total transport energy demand by 2050 than at present. In contrast, rail and shipping freight account for a smaller share. Passenger road transport continues to represent the largest share of energy demand but peaks around 2040.

¹⁵ IEA has not have any transport mode specific data available as part of its 2DS scenario

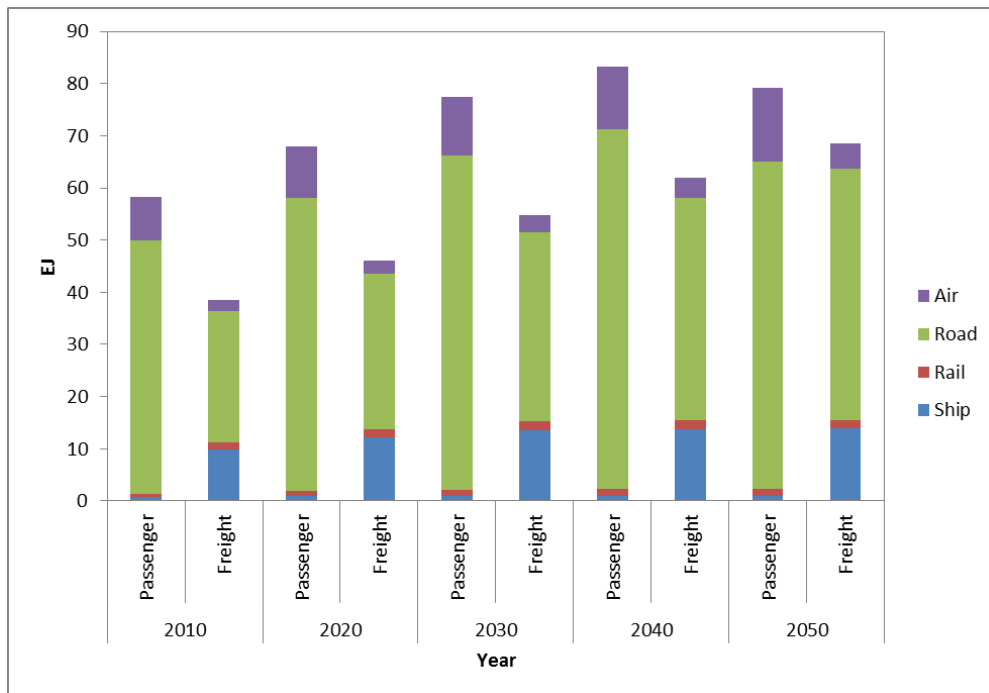


Figure 5: Projected Transport Energy Consumption by Transport Mode¹⁶

Source: Shell New Lens Scenarios – Mountains

In terms of the energy supply mix, oil consumption declines after a global peak in 2035 in the Shell **Mountains** scenario, leading to the possibility of ‘oil-free’ road transportation by 2070. This is attributed to an expected reduction in travel demand, improvements in vehicle efficiency and a significant growth in the number of natural gas, electricity and hydrogen vehicles. The latter is highly dependent on infrastructure that supports the use of these alternative fuel vehicles being rolled-out towards the end of century.

In IEA’s **2DS** scenario, oil consumption also falls dramatically by 2050, with the share of oil based transport fuels falling by around 45%. The majority of oil’s share is displaced by alternative transport fuels. For instance, biomass and waste account for 26% of transport energy supply by 2050, with electricity accounting for 13%, gas 6% and hydrogen 4%. Even though the scenario envisages a step-change towards alternative transport fuels by the middle of the 21st century, oil products continue to account for nearly half of global transport energy supply by 2050. The scenario is displayed in Figure 6 alongside IEA’s **Four Degree Scenario (4DS)** to provide some perspective as to how developments may differ if there is little coordinated action against climate change.

¹⁶ IEA scenarios are not compared here because they do not provide a detailed breakdown of the future mix of transport modes

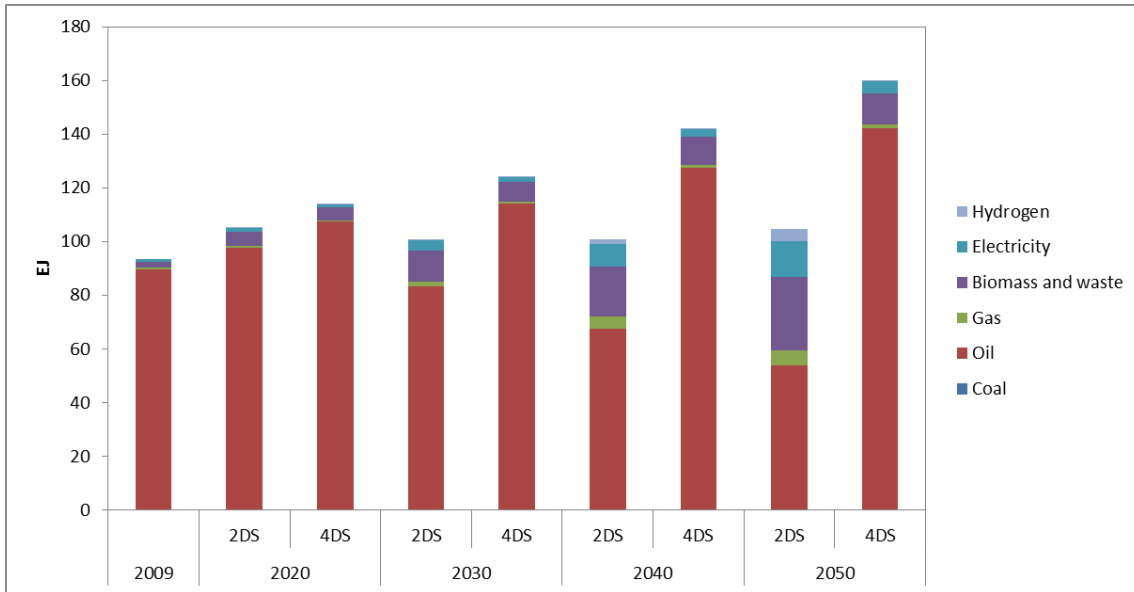


Figure 6: Projected transport energy consumption by supply¹⁷

Source: IEA Energy Technology Perspectives

2.2 UK perspectives on transport energy consumption

In 2012 transport energy consumption accounted for 42% of UK total consumption and since 1970 transport energy demand has increased by almost 90%. The majority of the increase can be attributed to road and domestic aviation. In contrast, energy demand from domestic marine and rail transport declined during this same period (Figure 7).

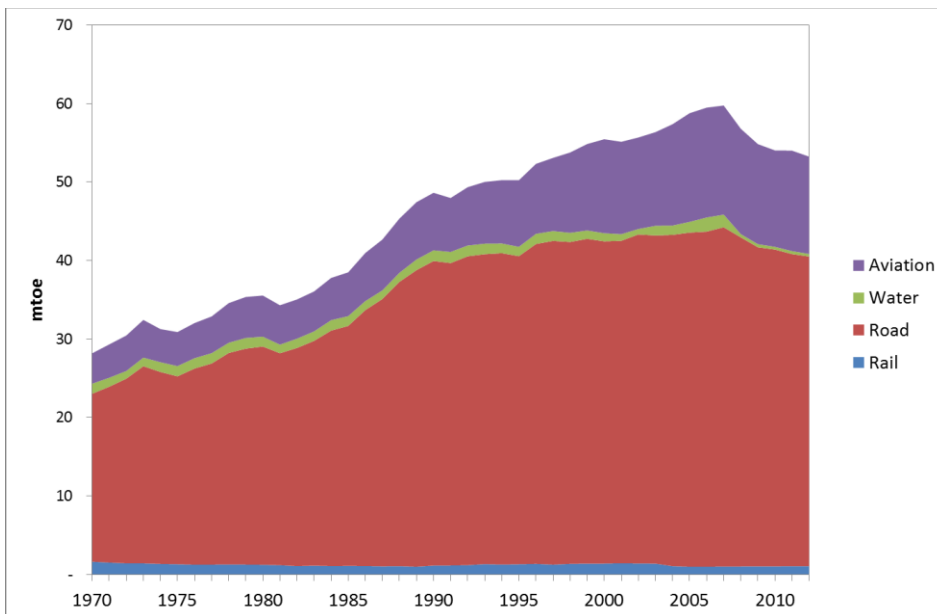


Figure 7: UK transport energy consumption by type of transport 1970 – 2012

Source: Department of Energy and Climate Change (DECC), Energy Consumption in the UK¹⁸

¹⁷ Excludes international aviation and shipping energy demand, as well as pipeline transport

¹⁸ <https://www.gov.uk/government/collections/energy-consumption-in-the-uk>

As at the global level, the majority of UK transport energy continues to be sourced from oil products. In 2012, oil products accounted for 97.5% of total transport energy consumption, with most of the remainder being met by biofuels (1.8%), a small amount of electricity and a negligible amount of coal.^{19,20}

To understand how UK transport energy consumption might change in the future, two scenario sets were reviewed. The first was the revised UK Energy Research Centre (UKERC) **Energy 2050** scenario set,²¹ which used the UK MARKAL model,²² a bottom-up, technology-rich cost optimisation model. The two scenarios reviewed from this set were the **reference scenario (REF)**, which assumes that current policies extend into the future and a **low-carbon scenario (LC)**, which is compatible with the 2050 GHG target. Current policies in **REF** include the assumption that the carbon price floor will rise to £30/tonne of CO₂ by 2020 and £70/tonne by 2030 in line with current government intentions. This provides a significant incentive for low carbon technologies even in the absence of other measures.

The second scenario set was derived using the DECC **2050 Pathways Calculator**²³ which integrates user-specified assumptions about the level of investment in different energy technologies. Two pathways, the **reference case pathway (REF)** and **pathway alpha (ALPHA)**, were selected from a set published by DECC.²⁴ The former assumes minimal efforts to decarbonise or diversify energy supply, whilst the latter assumes a balanced effort to decarbonise across all sectors resulting in compliance with the 80% GHG reduction target.

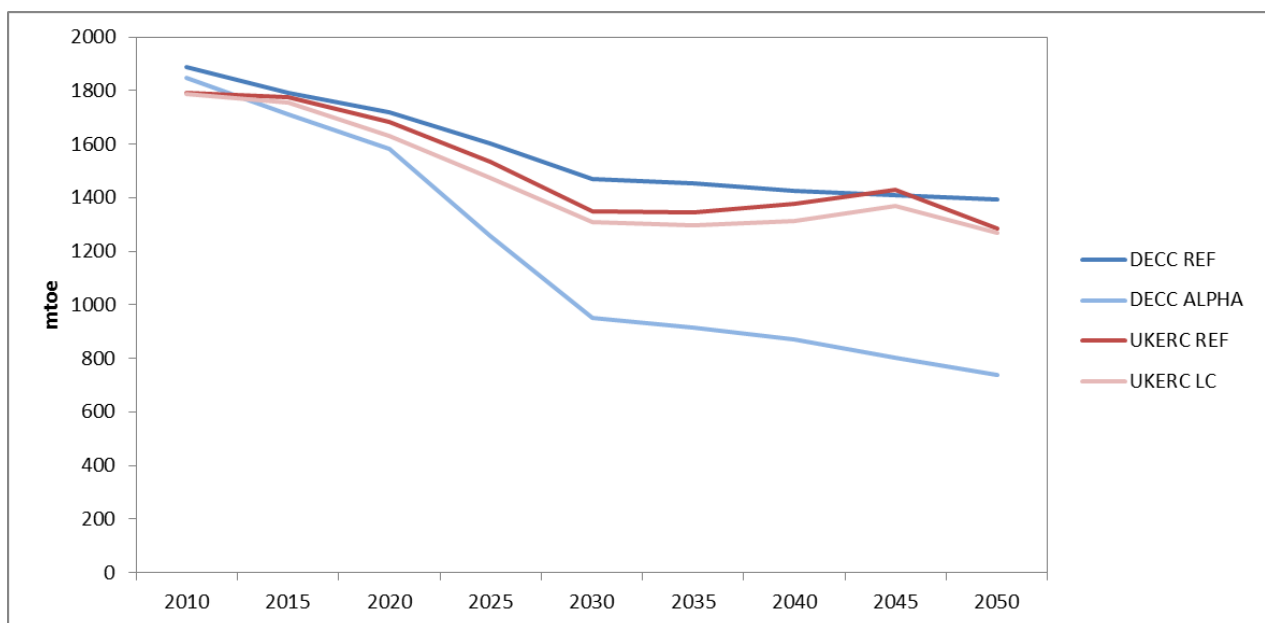


Figure 8: UK transport sector projected energy demand between 2010 and 2050

Source: DECC and UKERC

¹⁹ https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/244326/transport.xls

²⁰ Excludes electricity consumed at railway stations, including only electricity consumed on railway tracks.

²¹ UKERC, **Energy 2050 Scenarios: Update 2013**, http://www.ukerc.ac.uk/support/ES_RP_UpdateUKEnergy2050Scenarios

²² UCL Energy Institute, **UK MARKAL model**, <http://www.ucl.ac.uk/silva/energy-models/models/uk-markal>

²³ DECC, **2050 Pathways Calculator**, <https://www.gov.uk/2050-pathways-analysis>

²⁴ DECC, **2050 Pathways Analysis Report, 2010**, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/68816/216-2050-pathways-analysis-report.pdf

UK transport energy demand falls in all of the DECC and UKERC low-carbon scenarios regardless of whether GHG emission reduction targets are met. However demand falls to a lesser if targets are not met. Under DECC's **ALPHA** scenario, UK transport energy demand falls by approximately 60% by 2050. Oil based fuels continue to dominate but electricity plays a more important role with a 7% share. Under UKERC's **LC** scenario, demand falls only 29%, although oil based fuels account for a much smaller percentage (16%) of total transport energy consumption. Instead there is a significant increase in the consumption of alternative fuels, with biofuels accounting for a 46% share and hydrogen a 34% share of total transport energy consumption. Whilst there is a role for electricity in UKERC's scenario (4% share), it plays a significantly smaller role than in DECC's scenario. In summary, the two scenarios fulfil the same climate change mitigation targets in very different ways; DECC's focuses on reducing energy consumption and electrification, whilst UKERC's focuses primarily on substituting oil-based fuel consumption predominantly with biofuels and hydrogen.

2.3 Energy aspirations and expectations

The Fellowship workshop **energy strategies and energy research needs**²⁵ explored the role that different technologies and approaches (e.g. behaviour change) might make across a range of different energy futures. Participants considered key features of a future UK energy system and specified what technology mix they **wanted** to see in 2050 (aspiration) and what they **expected** to happen, given their knowledge of barriers, policy directions, technology limitations and other factors.

In general, participants at the workshop expected both hybrid and plug-in hybrid electric vehicles to account for the largest share of the UK's road transport fleet that by 2050 (Figure 9). They also expected that internal combustion engine (ICE) vehicles would still account for a larger proportion of the fleet than battery electric or hydrogen powered vehicles. In terms of aspirations, the participants hoped that battery vehicles would make up the vast majority of the road transport fleet by 2050, along with both hydrogen and plug-in hybrid vehicles. They also hoped that ICE vehicles would account for a very small proportion of the fleet, although interestingly not as small a share as hybrid vehicles.

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<https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Strategic%20Workshop%20Reports/Energy%20strategy%20fellowship%20Report%202%20-%20Energy%20strategies%20and%20energy%20research%20needs%20final.pdf>

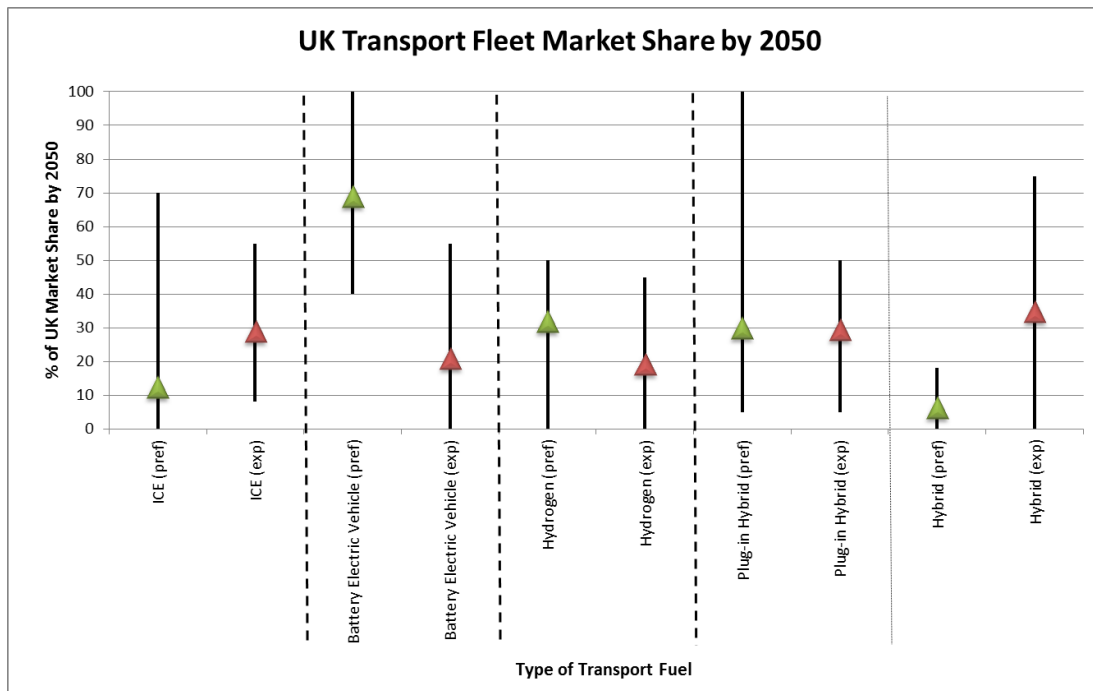


Figure 9: Preferred (green) and expected (red) ranges and mean average values for vehicle transportation technologies

3 Current UK research capabilities

3.1 Overview

This section is based on three sources of evidence: a) subjective judgements made at the first strategic workshop about UK research and industrial capabilities in relation to transport energy as well as other energy areas;²⁶ b) subjective judgments of UK research capability levels made at the expert workshop; and c) peer-reviewed assessments of UK R&D capabilities documented through the UKERC Energy Research Atlas Landscape reports.²⁷

A number of workshop participants found the distinction between vehicle system and transport system helpful in conceptualising the transport energy system, as represented by Table 1. The left hand side of the table outlines the vehicle system, identifying the various modes of transport and the transport technologies that typically relate to these modes. The right hand side of the table broadens the analysis of the transport energy system beyond the vehicle to examine the wider system in which these transportation modes operate. These include:

- the purpose or drivers of transportation (e.g. commuting, freight etc.);
- the supporting technologies and infrastructure necessary to enable transport technologies to provide mobility (e.g. fuel infrastructure; transport corridors etc.); and
- the various key processes that govern the wider transport system (e.g. policy, business models, transport planning etc.).

²⁶

<https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Energy%20strategy%20fellowship%20Report%202%20%20-%20Energy%20strategies%20and%20energy%20research%20needs%20FINAL.pdf>

²⁷ <http://ukerc.rl.ac.uk/ERL001.html>

Table 1: A conceptual framework of the transport energy system

Vehicle System		Transport System		
Mode of Transport	Transport Technology	Purpose of Transportation	Supporting Infrastructure	Key Processes
Road	ICE Battery Electric Hybrid Fuel Cells	Business and Commute	Corridors (e.g. highways, railroads)	Business Models
Rail	Electric ICE Fuel Cell Maglev	Freight and Logistics	Control (e.g. traffic, emergency response)	Land Use Planning
Air	Jet Propeller Helicopter	Leisure	Fuel production and distribution (e.g. petrol, electricity, biofuels)	Policy Design
Marine	Propeller Wind Water jet Air fans Submarine	Public Sector Governance (e.g. emergency services)	Information and Communication Technology (ICT)	Transport Control and Operation
Non-motorised	Cycle Walk	Personal Business (e.g. caring, health)	Vehicle, Manufacture, Repair and Maintenance	Transport Infrastructure

3.2 Strategic level workshops

Figure 10 represents one of the key outputs of the strategic workshop on **Energy Strategies and Energy Research Needs**. It plots subjective judgments relating to the UK's current level of industrial capability in different fields (x-axis), against their 'relevance' to the UK's energy future (e.g. in terms environment, affordability, security, economic opportunity etc.) on the y-axis. The size of the circles represents a subjective judgment about the level of scientific capability in the UK. The research areas located to the left of the vertical axis represent areas where a clear international lead is thought not to have been established. The transport research circle is coloured in yellow.

The figure shows that participants expected transport energy to play a key role in the future of the UK's energy system. Furthermore, participants recognised that whilst the UK was stronger in other areas, it possesses relatively strong scientific capabilities in terms of transport energy research. In contrast to this however, they believed that the UK possessed below average industrial capabilities in this area.

Other relevant research areas included **hydrogen, fuel cells, bioenergy** and **oil and gas**. In relation to the first three, which incorporate research into alternative transport fuels, participants believed the UK had strong research capabilities but poor to average industrial capabilities. They also regarded all three as having low to moderate importance to the UK's energy future. In contrast, oil and gas, which has relevance to ICE powered vehicles, scored very highly on all three counts. This indicates that the UK is currently stronger scientifically and industrially in traditional fuel research than that concerned with alternative fuels. Additionally, traditional fuels are expected to have a potentially greater role in the UK's energy future.



Figure 10: The UK's current and future energy R&D portfolio

3.3 Expert workshop

Participants at the expert workshop were asked to identify how well placed they considered the UK to be in terms of transport energy research capabilities. A strong theme emerging from participants' comments was the strength of the UK's fundamental science base in the transport energy field, although participants noted how research in this field had traditionally been undertaken in disciplinary 'silos', which had undermined the UK's capacity to undertake interdisciplinary research. They also highlighted the UK's poor capacity to translate and apply the outputs of its high quality transport energy research. Finally, it was noted that the UK would benefit from a greater focus on methodologically rigorous behavioural social science research into transport energy.

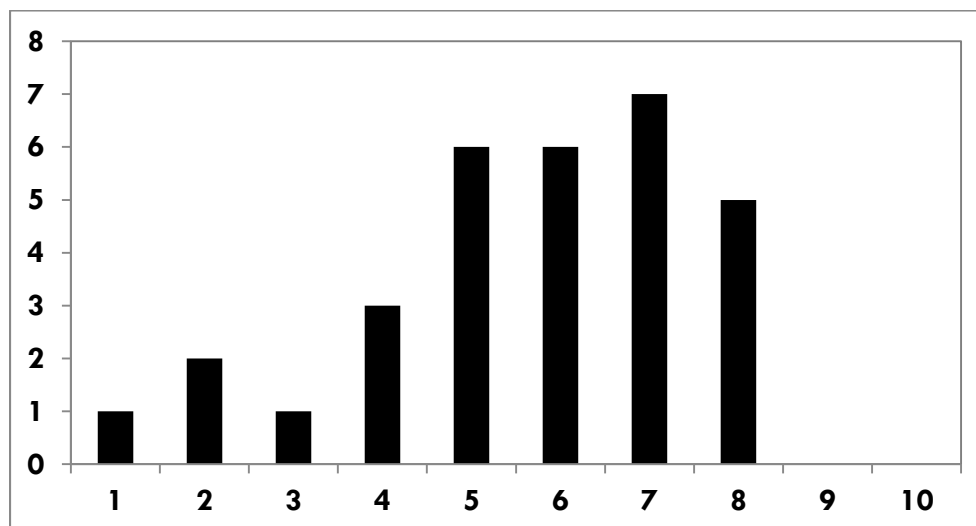


Figure 11: Distribution of perceived UK transport energy research capabilities

3.4 UKERC research landscape

The UKERC Energy Research Atlas includes a landscape document on **Transport**.²⁸ The report suggests that the UK possesses a diverse and generally strong R&D transport research community and that the 'trend towards collaborative projects is making the UK more globally competitive and starting to make some of the links between transport and energy systems and demand and supply-side solutions' (p.4). However, the report notes that despite these strengths there continues to remain little specific focus in the UK on transport energy research. This statement has however been challenged by peer-reviewers of this document who indicate that significant investments have recently been made into energy specific transport research, for example across engineering (e.g. nanotechnology), chemistry (e.g. fuels) and the social sciences.

Table 2 summarises the UK's strengths and weaknesses according to the landscape document. It should be noted that other landscape reports cover transport energy related research topics that sit outside the direct scope of this report, such as the UKERC landscapes on **Bioenergy, Hydrogen and Fuel Cells**.²⁹

²⁸ <http://ukerc.rl.ac.uk/Landscapes/Transport.pdf>

²⁹ <http://ukerc.rl.ac.uk/ERL001.html>

Table 2: Research Capability Assessment

Source: UKERC Transport Energy Landscape

UK Capability	Area
High	<ul style="list-style-type: none"> • engine design and development • aspects of vehicle design not related to engines (including batteries, materials) • technical consultancy • design of fiscal incentives • travel behaviour research
Medium	<ul style="list-style-type: none"> • transport systems engineering • railway engineering • aeronautical engineering • transport planning • study of aviation planning and demand • logistics and freight
Low	<ul style="list-style-type: none"> • vehicle assembly • shipping

Research into transport energy in the UK has predominantly been research council funded, mainly through the **Transport Operations and Management** sub-theme within EPSRC's **Process Environmental Sustainability Programme** and the cross-council **RCUK Energy Programme**. Research funding has also been provided by the UK Energy Research Centre for research into transport and energy efficiency, as well as the **Digital Economy Programme** that has funded **Digital Economy Research Hubs**, two of which are heavily engaged in information and communication technology (ICT) focused transport energy research. These funding streams have supported a wide range of research areas (shipping, aviation, walking and cycling, and travel behaviour) and associated PhD training, such as the Industrial Doctorate Centre in Transport and the Environment at the University of Southampton.

At the more applied end of the research spectrum, a Transport Systems Catapult has recently been established, with the aim of positioning the UK as the leading global provider of innovative and integrated transport solutions. It has been structured to bring together organisations across the private, public and third sectors in order to develop these solutions. It will be funded by a combination of core Technology Strategy Board (TSB) support and competitively won business and public sector funding.

3.5 Specific research areas

Drawing on the outputs from the strategic workshops, expert workshop and the UKERC research landscape, this section examines the UK's transport energy research capabilities in relation to specific research areas. The areas selected are based on the UKERC Energy Landscape and the roadmaps described in Section 4.

3.5.1 Automotive transport

The automotive sector in the UK is strong due to the presence of leaders such as Nissan, Rolls Royce and McLaren. The UK's strength in automotive research was implicit in comments made at the expert workshop about the need to expand the transport energy research base beyond the automotive sector.

The landscape document provides a clearer picture of the UK's automotive transport research capabilities. The UK possesses core research strengths in relation to automotive design and development. Many universities have strengths in relation to vehicle design and energy use, and more

specifically in engines, powertrains, fuel cells and battery technology, emissions performance, combustion and alternative fuels. However, the UK is weaker in research on vehicle assembly. Despite not having a major home-based automotive industry, the UK's research and applied R&D strengths can be attributed to close links between universities and industry.

3.5.2 Non-automotive transport

Non-automotive transport refers to all modes of transport (aviation, shipping, rail, cycling, walking etc.) other than motor vehicles. Participants at the expert workshops believed that the UK possesses strong research capabilities in the field of non-automotive transportation. However, the majority of the UK's transport research has focused on automotive.

The UKERC landscape document, records that aviation research is relatively well represented in the UK but shipping research, specifically the technological and environmental implications of shipping freight, less so. The landscape document also highlights that there remains little integration between publicly and privately funded R&D in aviation and shipping. It also questions whether the UK's strengths in aeronautical engineering and aviation are proportional to the relative importance of aviation.

3.5.3 Transport fuels

The status of oil and gas, hydrogen, fuel cells and bioenergy were assessed during one of the strategic workshops, the results of which were outlined in Section 3.2.

3.5.4 Freight and logistics

Neither participants at the expert workshop nor the UKERC landscape document identified the UK as having significant research capabilities in relation to freight and logistics. Weaknesses were identified in relation to: the efficiency of heavy goods vehicles; goods traffic logistics; and freight shipping. Whilst the UK is not a world leader, there exists a small but internationally respected freight research community in the UK. Importantly, the landscape document pre-dates the formation of the **Sustainable Road Freight Research Centre**, which represents a significant improvement in the UK's capability in relation to HGV efficiency and traffic logistics.

3.5.5 Transport behaviour and policy

Participants at the expert workshop emphasised the importance of research into both transport behaviour and policy making but noted that, despite the UK's strengths in the social sciences, there is currently little research in these areas. The UKERC landscape document presented a more positive view of the UK's research capabilities, noting that research is beginning to incorporate insights from behavioural sciences other than economics.

3.5.6 Transport planning and infrastructure

Expert workshop participants acknowledged that research into both transport planning and infrastructure (e.g. transport networks, ICT) constitutes an important part of the transport energy research landscape. Participants also considered transport modelling to be important, given its contribution to an understanding of the effectiveness of new planning and infrastructure approaches. The landscape document suggests that the UK has moderate research strengths in relation to transport systems engineering and planning. It notes that 'the UK has a long and robust tradition in spatial planning research' and is well represented at both the European and international level in this area. In recent years, transport planning has become more multidisciplinary, moving away from its traditional focus on civil engineering towards more environmental, political and behavioural sciences.

4 Existing training and research roadmaps and needs assessments

This section reviews existing transport energy research roadmaps and needs assessments at the UK, EU and international levels. It highlights priority research challenges and the types of resource or arrangement that would be required to facilitate the research. The reports, mainly from government or non-departmental public bodies, are categorised into seven areas reflecting those used in section 3, with the addition of a cross-cutting category covering reports that have analysed the transport energy research landscape as a whole. We begin with key findings.

4.1 Summary

The transport energy research agenda is broad and diverse. The traditional focus on technological challenges, with a continued reliance on engineering expertise, remains, with a strong focus on engines, vehicle and infrastructure development. However, a significant number of the priority challenges identified demand a broader range of expertise, including those in relation to freight and logistics, transport planning, transport behaviour, transport system analysis and transport policy evaluation.

The resources required to facilitate research in these areas fall into four broad categories. The first need is for high-quality training to nurture the necessary research skills. The second is greater coordination and collaboration between different academic institutes at both the national and international levels and between industry and academia. The third is the need for facilities to enable the testing of innovative transport technologies and infrastructure. The fourth is long-term, significant investment in world-class transport energy research.

4.2 Automotive transport

UK

Building upon work undertaken by both the New Automotive Innovation and Growth Team (NAIGT) and Ricardo the UK Government delivered the **Driving success – a strategy for growth and sustainability in the UK automotive sector**³⁰ report in 2013. It highlights five priority research areas which were as follows:

- internal combustion engines;
- energy storage and energy management;
- intelligent transport systems;
- lightweight vehicles and powertrain structures; and
- electric machines and power electronics.

The report underlines the need for improved co-ordination and collaboration between industry and academic research to ensure the UK remains at the forefront of R&D work. It also highlights the importance of training that is designed to attract more young people into automotive careers, which could be supported via industrial funding of university degrees.

³⁰ https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/211901/13-975-driving-success-uk-automotive-strategy-for-growth-and-sustainability.pdf

EU

At the European level the European Road Transport Research Advisory Council (ERTRAC) produced nine technology roadmaps as part of its **Research and Innovation Roadmaps** report,³¹ encapsulating the key future research challenges in the automotive sector. These are:

- future light-duty powertrain technologies and fuels;
- hybridisation of road transport;
- sustainable freight system for Europe: green, safe and efficient corridors;
- towards an integrated urban mobility system;
- road user behaviour and expectations;
- European bus system of the future;
- climate change resilient transport;
- safe road transport; and
- European Technology and Production Concept (ETPC) for Electric Vehicles (EVs).

The European Automotive Research Partners Association (EARPA), whose members were responsible for developing ERTRAC's Strategic Research Agenda, produced the report **A Vision for Integrated Road Transport Research**³². It emphasises the need to undertake research that would both accelerate the development of new transport technologies (e.g. EVs; hydrogen vehicles; fuel cells etc.) and improve the performance traditional technologies (e.g. ICEs) and fuels (e.g. petrol), given that new technologies are some way from commercialisation. It also underlines the need for holistic research covering various combinations of system components (e.g. technologies; behaviours; policies etc.) capable of meeting key societal challenges (e.g. sustainability; safety; mobility). Finally, the report stresses the need to undertake research into enabling technological building-blocks such as materials, embedded systems, and simulation tools.

International

At the international level the International Energy Agency (IEA) commissioned both the **Fuel Economy of Road Vehicles**³³ and **Electric and Plug-in Hybrid Electric Vehicles (EV/PHEV)**³⁴ Technology Roadmaps, which identify a number of research, development and demonstration (RD&D) challenges and recommendations. The **Fuel Economy of Road Vehicles** roadmap explores how existing technologies might be improved to enhance significantly the average fuel economy of motor vehicles. The report highlights the need for research to improve the commercial viability of existing energy efficient transport technologies and to undertake additional RD&D for advanced fuel economy technologies. It also recommends research into the impact of 'eco-driving' on improving fuel economy, as well as narrowing the gap between vehicles' 'tested' fuel economy and its actual 'in-use' performance. To support research in these areas the report calls for the establishment of internationally co-ordinated programmes involving governments and automobile manufacturers to help trigger faster development and uptake of new transport technologies.

Given the potential for electric vehicles (alongside low-carbon electricity generation) to significantly reduce GHG emissions, the **EVs and PHEVs** roadmap envisions the widespread adoption and use of EVs and PHEVs by 2050. The report recommends that efforts are taken to:

³¹ http://www.ertrac.org/pictures/downloadmanager/6/50/ertrac-researchinnovation-roadmaps_60.pdf

³² http://www.earpa.eu/ENGINE/FILES/EARPA/WEBSITE/UPLOAD/FILE/2010/earpa_position_paper_2010.pdf

³³ <http://www.iea.org/publications/freepublications/publication/name,31269,en.html>

³⁴ <http://www.iea.org/publications/freepublications/publication/name,3851,en.html>

- reduce battery cost and improving their durability and life span;
- move beyond today's various lithium-ion concepts to develop next generation of energy storage; and
- address resource scarcity and associated supply chain issues around the use lithium and rare earth metals for battery technologies.

The report argues that research into these areas should be supported by international collaboration, given the recognised benefits of sharing knowledge, experience and testing facilities.

4.3 Non-Automotive Transport

4.3.1 Aviation

EU

Following the recommendations outlined by the European Commission's report **Flightpath 2050 Europe's Vision for Aviation**³⁵, the Advisory Council for Aviation Research and Innovation in Europe (ACARE) developed a strategic roadmap titled **Realising Europe's vision for aviation: Strategic Research and Innovation Agenda**³⁶. The challenges most relevant to the focus of this report were:

- affordable, sustainable, alternative energy sources for commercial aviation;
- policies to reduce environmental impacts of aviation, such as climate change;
- innovative business models, regulations and incentives to accelerate aviation innovation;
- intermodal transportation systems and integrated air transport;
- improved air and air vehicle operations and traffic management; and
- efficient aviation development and manufacturing processes.

The report identifies the need for developing high quality R&D infrastructure, such as wind tunnels, to enable full-scale demonstration. It also highlights the importance of collaboration between academic institutions and other stakeholders. Finally, it emphasises the importance of nurturing skills through apprenticeships, academia and life-long professional development.

4.3.2 Shipping

UK

In 2012 the TSB **Transport** Knowledge Transfer Network (KTN) funded a series of workshops to develop the **UK Marine Industries Roadmap Cross-Cutting Report Issue 1.0**.³⁷ The report identifies the following energy specific marine transport research challenges:

- decarbonisation of marine transport via alternative fuels, electrification and hybrid technologies;
- decarbonisation of marine ports;
- integration of marine transport with other modes; and
- utilisation of marine ICT (e.g. sensors, autonomy, on-vessel data management and communications).

³⁵ <http://ec.europa.eu/transport/modes/air/doc/flightpath2050.pdf>

³⁶ <http://www.acare4europe.org/sites/acare4europe.org/files/attachment/SRIA%20Executive%20Summary.pdf>

³⁷ http://www.the-mia.com/assets/Marine_Roadmap_-_Cross_Cutting_Report_Issue_2.pdf

The report emphasises the need to support investment in testing infrastructure, skills training, research partnerships, international collaboration and knowledge exchange.

4.4 Transport fuels

International

The IEA's **Technology Roadmap: Biofuels for Transport**³⁸ identifies a number of priority research challenges. With respect to the current generation of biofuels, the IEA emphasises that research should focus on improving their conversion efficiency, cost and overall sustainability. Turning to future generations, substantial further investment in RD&D will be required to deliver commercial-scale advanced biofuel plants. In addition to this efforts will need to be made to assess the feasibility and sustainability of biofuels with respect to the tensions between land-use for biofuels compared to land-use for biomass or food production. As such, research efforts should examine the most promising feedstock types and locations for future biofuel scale-up. The IEA will soon be issuing their roadmap for hydrogen, which will incorporate similar research recommendations as outlined for biofuels.

Research priorities have also been identified for the development of alternative transport fuel infrastructures, which are covered in Section 4.7 under **Transport Planning and Infrastructure**.

4.5 Freight and logistics

There has been relatively little analysis of priority research topics and associated 'needs' in the area of freight and logistics. Some of the assessments relating to automotive, rail and aviation transport are relevant in this area.

UK

In 2012, Ricardo-AEA produced a report titled **Opportunities to overcome the barriers to uptake of low emission technologies for each commercial vehicle duty cycle**.³⁹ The report notes that the UK's heavy goods vehicle (HGV) fleet is almost exclusively made up of diesel fuelled vehicles. It highlights the following three key research areas with the greatest potential to achieve CO₂ emission reductions from HGVs:

- switching from diesel to gas as a fuel;
- improving aerodynamic efficiency and reducing rolling resistance; and
- supporting uptake of hybrid and pure electric vehicles.

4.6 Transport behaviour and policy

EU

ERRAC's **Urban Mobility Research Roadmap** emphasises the need to improve our understanding of transport users' needs and behaviour. It recommends research into the following areas:

- understanding the factors responsible for shaping the mobility behaviour of individuals and firms;
- factors shaping consumers' opinion on different mobility's options and how/why these might change;
- using customers' expectations to help design transport services without impinging upon their privacy;

³⁸ http://www.iea.org/publications/freepublications/publication/biofuels_roadmap.pdf

³⁹ <http://www.lowcvp.org.uk/assets/reports/Opportunities%20for%20low%20emission%20HGVs%20-%20final%20report%202012.pdf>

- measuring the impact of urban land use and transport policies; and
- management systems for public transport services that are resilient to disruptive events and sensitive to users reacting to real-time information.

In terms of transport policy research, the report highlights the need to explore how we might be able to improve stakeholders' awareness and understanding of sustainable mobility challenges at various institutional levels. Building upon this, it also calls for research into better integration of land use, transport and environment policy making at these different institutional levels. Finally, the report emphasises the need for the collection and dissemination of data on urban mobility, particularly to help the development of models that support data analysis, land use and transport forecasts, cost-benefit and multi-criteria economic analysis and decision-making.

4.7 Transport planning and infrastructure

UK

In 2013 the National Platform for Construction, via the Modern Built Environment KTN and Transport KTN, convened a workshop⁴⁰ that brought together construction professionals, academia and the wider supply chain to produce a roadmap for research and innovation in the UK transport sector. The workshop sought to prioritise a list of key research challenges, drawing upon the outputs of the **European Construction Technology Platform's (ECTP) reFINE roadmap** (see EU section of this sub-section).

Participants at the workshop identified the need for research into how ageing transport systems could be managed to satisfy increasing transport demand in the future. They also called for research into how new transport infrastructure could be sufficiently flexible to deal with the uncertainties around the scale and type of transport demand in the future.

EU

Looking to the European level the ECTP produced **Building up Infrastructure Networks of a Sustainable Europe: the reFINE Roadmap**⁴¹ commissioned in 2013. Whilst it is essentially a deployment roadmap, the report highlights the need for research into multimodal hubs, urban mobility and long distance corridors. ERRAC's **Urban Mobility Research Roadmap**⁴² highlights similar priority research topics in relation to transport infrastructure and planning, the general theme being that transport systems can be better integrated via innovative infrastructural and governance solutions.

Other

In 2012, the US Department of Transport commissioned the **Integrated Active Transportation System Operational Vision and Implementation Research Plan**⁴³. The report notes a number of priority research areas required to deliver Integrated Active Transportation Systems (IATS), i.e. transport systems that achieve a high degree of mobility, safety and energy efficiency by integrating vehicle systems with the overall transport system, via a closed loop feedback scheme based on progressive vehicle automation. Among other challenges the report highlights the need to explore the social acceptability, economic viability and technical feasibility of deploying IATS.

⁴⁰

https://www.innovateuk.org/c/document_library/get_file?groupId=3089626&folderId=3726755&title=Transport+construction+R%26D+roadmap+initial+report+v1.pdf

⁴¹ http://www.ectp.org/cws/params/ectp/download_files/39D2500v1_reFINE_Roadmap_Draft_P.pdf

⁴² http://demo.oxalis.be/errac/errac_website/wp-content/uploads/2013/06/errac_wp3_roadmap_year3_urban_mobility_final.pdf

⁴³ <http://tsrc.berkeley.edu/sites/tsrc.berkeley.edu/files/IATS%20Final%20Report2012.pdf>

Focusing on non-fossil fuel infrastructure rather than intelligent transport energy infrastructure, the US Department of Energy report **Alternative Fuel Infrastructure Expansion: Costs, Resources, Production Capacity, and Retail Availability for Low-Carbon Scenarios**⁴⁴ identifies research that could improve understanding of low-carbon fuel infrastructure expansion. These included:

- understanding the fuel production and retail infrastructure investment decision-making process;
- assessing the total fuel infrastructure expansion costs, not just economic;
- understanding consumer vehicle purchasing decisions in relation to the extent of the fuelling infrastructure; and
- exploring how public-private partnerships could infrastructure planning and expansion.

4.8 Cross-cutting

EU

The final report of the FP7 project **Developing a European Transport Research Alliance (DETRA)**⁴⁵ was published in 2012. The project analysed the European transport research landscape and recommended the development of a European Transport Research Alliance with a view to strengthening the transport domain and address the EU's Grand Challenges.

The report recommends the establishment of world-class European research institutes across a range of transport topics, which would be encouraged to work alongside one another. The report also recommends that this research should be managed as part of a European level programme that accommodates common priorities, coordinated implementation and joint evaluation. In addition, it also calls for knowledge exchange, not only between academics but between academia and other sectors (e.g. government, industry etc.). Specifically, it calls for incentives and research data bases to help facilitate this exchange. Finally, the report highlights the need for greater exchange between professionals engaged with basic and applied transport research, given the important interface that exists between these.

With respect to training the report called for PhD training that encourages students to study abroad and undertake internships/secondments. This training would also provide a balance between basic disciplinary skills (e.g. maths) and more specific, high-level knowledge areas and methodologies.

⁴⁴ <http://www.nrel.gov/docs/fy13osti/55640.pdf>

⁴⁵ http://www.transport-research.info/Upload/Documents/201211/20121107_141052_15790_DETRA_WP7_Deliverable_7.3_20120914-1.pdf

5 High level research challenges

This section outlines the priority research challenges identified by participants at the expert workshop. These fell into eight categories:

- automotive transport;
- aviation;
- transport fuels;
- freight and logistics;
- transport energy behaviour;
- transport energy governance and business;
- transport planning and infrastructure; and
- understanding, measuring and modelling transport system change.

A larger number of research categories are presented here than in Sections 3 and 4. Workshop participants placed a greater emphasis on social science and ‘systems thinking’ transport energy research challenges. Participants also identified specific research needs in relation to aviation and automotive transport. However, shipping and rail were covered under the heading **Freight and Logistics**. The eight research themes are outlined in the following tables, with detailed research questions set out in Annex A.

Table 3: Research challenges in the area of automotive transport technology

Research Area	Research Challenge	Example
Vehicle system	Power train innovation	modular powertrain that is adaptable to fuel changes
	Improving energy efficiency of vehicle design	energy harvesting; aerodynamics
	Retrofitting and reuse of old transport technologies	converting ICE into Hybrid Electric Vehicles (HEVs)
	Safeguarding passenger safety alongside technology innovation	autonomous vehicles
	Life Cycle Assessment (LCA) of vehicle system to determine appropriate replacement	
Transport energy storage	Examining the need and potential applications for transport energy storage	
	Analysing the performance of different storage technologies and to what extent these should be improved	
	Ability to utilise waste energy via storage technologies	
	Improving battery performance	
	End-of-life issues of vehicles batteries	
	Environmental impacts of vehicle batteries	

Table 4: Research challenges in the area of aviation

Research Area	Research Challenge	Example
Aviation	Systems analysis of airports	
	Airport solutions to reduce aviation emissions	'on stand' charging; airport vehicles
	Low-carbon aircraft retrofitting	
	Low-carbon aviation fuels	
	Improving efficiency of existing aircraft technology	
	Options to curb aviation demand and their implications	carbon taxes

Table 5: Research challenges in the area of transport fuels

Research Area	Research Challenge	Example
Transport fuels	Holistic life cycle assessment of different transport fuels	
	End-of-life issues for different fuels	
	Regulatory challenges of transport fuels	
	Appropriateness of fuels for different transport needs	leisure; freight; commute
	Opportunities to improve efficiency of ICE vehicles	
	Role for non-traditional fuels in transport system	gas; hydrogen; biofuels
	Wide-ranging impacts of biofuel consumption	
Conditions to promote 'self-powered' transportation modes	walking; cycling	

Table 6: Research challenges in the area of freight and logistics

Research Area	Research Challenge	Example
Freight and logistics	Factors driving movement of goods	e-commerce
	Opportunities to decarbonise shipping internationally	
	Decarbonising freight via innovative ICT based logistics	two-way freight flows
	Options for promoting efficiency freight behaviours	home delivery
	Improving efficiency of freight vehicles	aerodynamics
	Examining light-goods vehicle freight patterns	

Table 7: Research challenges in the area of transport behaviour

Research Area	Research Challenge	Example
Transport behaviour	What is the value of transportation?	
	Factors influencing transport behaviour	cost; convenience; safety
	Transport behaviours of different demographic groups	
	Identifying the limits to transport energy demand	
	Co-evolution of consumers' behaviour and transport system	
	Transport rebound effects and potential solutions	
	Barriers to adoption of sustainable travel behaviours and solutions	'gameification'; consumer education and engagement
	Longevity of behavioural change	
	Protecting consumer rights whilst shaping behaviour	
	Destination shifting	
Promoting sustainable travel behaviours in developing world		

Table 8: Research challenges in the area of transport energy governance and business

Research Area	Research Challenge	Example
Transport policy	Policies to promote sustainable transport energy systems	
	Evaluating impacts and effectiveness of transport policy	
	Role of pricing mechanisms in curbing transport demand	vehicle tax
	Equity implications of transport energy policy	
	International transport energy governance frameworks	
Business models, mobility services and market mechanisms	Strengths and weaknesses of traditional and emerging business models	
	Drivers and barriers to transport business model innovation	
	Perform multiple functions during transport	work; leisure; nutrition
	Innovative pricing and payment strategies for transport	
	Business model innovation to encourage public transportation	
	Relationship between technological and business model innovation	
Trade-offs between different transport modes	cost; comfort; pollution	

Table 9: Research challenges in the area of transport planning and infrastructure

Research Area	Research Challenge	Example
Transport, town and land use planning	Optimising transport system performance via town planning	minimise congestion
	Identifying barriers to sustainable transport town planning	
	Balancing civic function via responsible town planning	safety; green space
	Urban and rural transport planning	
	Land use planning to promote normative travel patterns	
Transport energy infrastructure and technology	Cost benefit analysis of transport energy infrastructure	
	Integrating transport technology and infrastructure	
	Electrification of infrastructure	
	Rolling-out and promoting uptake of new infrastructure and technologies	
	Resilience, adaptability and flexibility of infrastructure	
	Negative impacts of new technology and infrastructure	
Transport, ICT and connectivity	Simultaneous design of transport infrastructure with other system dimensions and infrastructures	
	Influence of smart technology on transport system trajectory	
	Acceptability of smart transport technology	safety; privacy etc.
	Connectivity potential of smart technology	improve multi-modal connections
	Transport energy demand reduction potential of smart technology and social media	remote working; journey planning
Data management solutions for smart transport technology		

Table 10: Research challenges in the area of understanding, measuring and modelling transport system change

Research Area	Research Challenge	Example
Understanding, measuring and modelling system change	Historic transport trends analysis to inform system dynamics	
	Horizon scanning for potentially disruptive innovations	climate change; technology
	Understanding transport energy system lock-in phenomena	
	Multi-criteria life cycle assessment of transport energy system	
	Identifying major inefficiencies in transport system	
	Refining system metrics and boundaries	
	Integrated, multi-scale modelling of transport energy demand that is robust against uncertainty	

6 Research conduct

6.1 Ways of working

Interdisciplinarity. The transport energy community appears to be more fragmented than most other energy research communities. As a result, interdisciplinary transport energy research has suffered. However, the value of interdisciplinary research in this area is evident given the cross-cutting nature of transport energy research challenges. Some participants at the expert workshop argued that the UK would benefit from the establishment of a central transport energy institute similar to the UK's End-Use Energy Demand Centres, the US Department of Energy's (DoE's) National Laboratories or Germany's Fraunhofer Institutes. This body would be responsible for coordinating large-scale interdisciplinary transport energy research projects bringing together researchers from a broad range of disciplines. Such a centre could utilise existing or new transport energy research networks to locate, communicate with and coordinate the transport energy research community. International research networks would help to ensure that any such centre, if established, would work in synergy with programmes at the EU and international levels.

There are few academic incentives encouraging interdisciplinary research, e.g. there are few high-ranking inter-disciplinary transport research journals. The peer-review process is highly disciplinary. Academics typically find career progress easier to achieve by following a disciplinary research path. However, whilst the importance of interdisciplinary research was noted, disciplinary research is still needed in order to explore specific aspects of the transport energy system in fine detail.

Interdisciplinary working could also be supported by: 1) RCUK funding calls for systems-level transport energy research; 2) greater distance between research centres and disciplinary teaching-focused departments; and 3) cross-campus inter-disciplinary energy research.

Funding processes. Cross-council collaboration between the more technically focused EPSRC and socially oriented ESRC is important given the cross-cutting nature of many transport energy research challenges. Whilst this is happening to some extent, the community believes that the research councils still operate in 'silos' and could be better integrated. One area of research that could significantly benefit from cross-council collaboration is that of smart transport systems given the overlap between transport and ICT. The RCUK Digital Economy and Energy Programmes, and the Transport and Connected Digital Economy Catapults, could be brought closer together. 'Fast-track' funding could be appropriate for smaller and more pressing projects that focus on a specific policy that is undergoing development. The academic community could also work more closely with major private-sector consultancies which undertake policy evaluation.

Research Portfolio. The transport energy research agenda should be managed strategically as an integrated portfolio of synergistic research projects, rather than an assortment of different research projects.

Methodology. It is important to take a pragmatic approach to research, beginning with a research challenge and identifying the best approach to address the problem rather than being wedded to any one methodology from the beginning (e.g. modelling). There is a need for new transport energy models to be developed that: are sensitive to both technical (e.g. technology performance) and social factors (e.g. attitudes); are capable of examining the whole transport energy system; build upon and draw together existing models; and can be validated using real data. Such models could play a key role in informing the design of effective transport energy policy. More broadly the methodological quality of field research on transport behaviour and behaviour change was considered to be poor and that there is a need to improve training in research methods and reject methodologically weak R&D proposals more readily.

6.2 Long-term perspectives

The community believed that transport energy research projects needed to be both longer and larger in order to adequately address the interdisciplinary, whole-systems nature of the research challenges identified. Longer projects would also enable longitudinal studies examining the long-lasting impact of transport energy interventions (e.g. policy; demand management schemes) or new technologies.

6.3 Data

There is a need for a central and accessible database of both private and publicly owned transport energy data. This data would open up new opportunities for research projects and help validate current transport energy models. Such a system would demand new governance arrangements addressing privacy and intellectual property (IP) issues surrounding dissemination of the data. Incentives and methods for easy dissemination should be made available to encourage organisation to share their data. The research councils and other institutions could work in collaboration with the private sector organisations that store this private data (e.g. Google). Data held in this way should be synthesised and standardised where possible to enable easy interpretation, comparison and presentation.

6.4 Infrastructure and facilities

Whilst test facilities sit largely outside of the research councils' remit, they are essential for testing and demonstrating a broad range of radical and incremental transport energy innovations (e.g. vehicle drivetrains; airport systems; traffic congestion techniques; business models; demand reduction interventions). Whilst conventional facilities for test technical innovations already exist (e.g. the Transport Research Laboratories Test Track), there is less provision for testing social interventions. Social test beds, often known as 'living labs', could be in 'real world' places with 'real' people requiring engagement with key organisations and members of the public. Access to both types of facility should be quick and easy in order to speed up the testing-period for innovations. However, testing in such environments is fraught with difficulties around safety, privacy, broader human rights etc.

7 Training

The need for additional PhD training in transport energy systems, sustainable mobility and more general transport energy research in the social sciences could be met through the Centre for Doctoral Training (CDT) model. However, too much emphasis has been placed on CDTs and not enough on

project-based PhDs, where students often gain valuable experience from working with an interdisciplinary research team. Jointly-funded PhD training between RCUK and either industry or government (e.g. Department for Transport, DECC, Department for Business, Innovation and Skills), where students spend time in both academia and government/industry, would not only build bridges between academia and other sectors but also provide students with a richer learning experience. Finally, the community emphasised the need to implement safeguards for industrially funded doctorates to avoid research bias.

8 Making connections

8.1 Connections across research areas

This research area has connections with:

- **Energy in the home and workplace (Prospectus Report 3)** in respect of the focus on demand-side consumption behaviours;
- **Electrochemical energy technologies (Prospectus Report 7)** in respect of fuel cells and batteries.
- **Bioenergy (Prospectus Report 8)** in respect of biofuels for transportation;
- **Energy Infrastructure (Prospectus Report 10)** in respect of the electricity network and charging infrastructure that will be required for the electrification of transport;
- The IEA energy research area **Refining, transport and storage of oil and gas (II.1.2)** in respect of liquid hydrocarbons to fuel ICE vehicles; and
- The IEA energy research area **Hydrogen (V.1)** in respect of hydrogen production, storage, transport and distribution.

8.2 Linkages outside RCUK

Innovation chain integration. Academics need to collaborate with both industry and government stakeholders in order to address the priority research challenges identified in Section 5. For example, the UK automotive sector includes a world-leading motorsport industry which typically showcases innovative road transport technologies. Such innovations can be developed, implemented and demonstrated on an international stage in a very short time. Technologies such as anti-lock braking, aerodynamics, efficient ICEs, light-weighting, materials technologies, tyre technology and kinetic energy recovery system were all applied first in motorsport. Collaborating with industry partners would help to link university-stage research more closely with industry-led RD&D and improve the likelihood of commercialisation.

The Transport Catapult could provide an effective platform for collaboration through communication, knowledge-exchange and collaboration across private, public and third sectors. This would establish a space where the brightest minds in transport energy could work together on shared interests. A critical mass of researchers will be required for the Catapult centre to be a success. Strong links to other research programmes and a research focus that transcends technology to include other types of innovation (e.g. business models) are also needed. Inter-sector collaboration could also be promoted via: joint funding by RCUK and other R&D bodies (e.g. the EPSRC-TSB Low Carbon Vehicles call), jointly funded PhD studentships, secondment schemes, and knowledge-exchange programmes. The latter would ensure that research findings are disseminated so as to be easily digested by both industry and government.

Government. Better links between government chief scientists and leading transport energy research institutes were recommended due the valuable knowledge that could be shared between these two communities.

Research end-users. Time should be spent identifying the end-users of transport energy research across industry, government and the general public. Efforts should be made to open up channels between those undertaking the research and likely users to maximise its impact.

8.3 International working

The research funding system should better enable UK researchers to undertake research into international transport issues as well as UK-specific challenges. Researchers face a number of barriers to engaging with international research programmes (e.g. Horizon 2020) or networks (e.g. European Energy Research Alliance EERA). These include the significant amount of effort typically required to establish international research projects and the practical issues of coordinating multiple partners. The KTNs could potentially ease the burden on researchers by being more active in identifying potential international partners for collaboration and bringing groups together. The number of research project partner numbers should be limited to a manageable size, somewhere in the region of six.

8.4 The bigger picture

Policy. Despite notable efforts (e.g. UK's Carbon Plan), the community felt that the UK government could articulate a clearer vision of the UK's future transport energy system and the steps it will need to take to realise this vision via a roadmap. Without a clear transport roadmap leading to 2050, it is difficult to understand which research challenges are likely to be most relevant to academia. A clear, long-term policy agenda would also encourage government-university collaboration given that both could operate to the same long timeframe. However, agreeing on and executing such a long-term and stable policy agenda is fraught with difficulties.

Research landscape. Awareness of the various UK transport energy research programmes and projects taking place should be raised. Whilst the UKERC Research Landscape provides an excellent starting point, more attention should be paid to research taking place outside RCUK to avoid duplication and identify potential areas for collaboration.

Promote transparency and validation of research. Researchers should make their research as transparent as possible by publishing detailed methodologies and results and by validating results via additional work.

9 Conclusions and recommendations

Transport energy demand accounts for more than third of the UK's energy consumption. Whilst most scenarios indicate that transport energy demand will fall, the UK still faces the challenge of ensuring that consumers' transportation needs are satisfied in a secure, affordable and environmentally sustainable manner. The UK is now almost entirely dependent on oil-based fuels although oil reserves are dwindling and the international price of oil is rising.

University research could play a role in helping the UK rise to this challenge. Priority research areas span technology-focused, engineering-based research through to behaviour-focused, social science-based research. Relevant spatial scales range from the micro- (e.g. vehicle component) to macro-level (e.g. transport system infrastructure). Eight categories of research have been identified: **automotive transport; aviation; transport fuels; freight and logistics; transport energy behaviour; transport energy governance and business; transport planning and infrastructure;** and **understanding, measuring and modelling transport system change.** Whilst rail and shipping research were not highlighted specifically during the workshop, many of the other categories, such as **freight and logistics,** have direct relevance to these modes of transport.

An inter-disciplinary approach is needed for high quality transport energy research. The research councils could take the following steps to foster greater inter-disciplinary coordination and collaboration across the UK transport energy research community:

- issuing calls for systems-level transport energy research that demands input from multiple disciplines;
- introducing cross-council research calls;
- introducing cross-disciplinary peer-review panels for funding proposals; and
- supporting longer and larger research projects to provide the necessary resources and time to adequately address the interdisciplinary, whole-systems nature of the research challenges.

Some workshop participants proposed establishing a central interdisciplinary national transport energy research institute with associated research networks. We note this suggestion without necessarily endorsing it. Universities could help by forming cross-campus university transport energy research centres. Other steps to promote interdisciplinarity include cross-disciplinary peer-review panels for journals and the Research Excellence Framework (REF).

There is a need to centralise, curate and disseminate transport energy consumption data generated by a broad range of actors, in order to open up research opportunities. However, special attention should be paid to confidentiality and IP issues associated with this data. Some of these issues may be addressed via working agreements with private sector organisations.

Whilst various testing facilities exist to test technological transport innovations, there is a need for test beds or 'living labs' capable of examining the effectiveness of innovations in 'real world' places with 'real' people. However, issues are likely to emerge as to how these might impact upon public safety and privacy.

There is a need for additional PhD training in transport energy research via both Centres for Doctoral Training (CDTs) and project funding models. PhDs supported jointly by the research councils and either industry or government would provide PhD students with a rich learning experience, as well as helping to foster academic and non-academic research collaboration.

Industrial collaboration is essential if priority research challenges are to be addressed, particularly given the innovation track record of the UK's transport sector (e.g. motorsport; aviation). This can be supported by better integration of the energy innovation landscape, particularly through relationships between the research councils and R&D funders such as TSB and the Energy Technologies Institute (ETI). Solutions include: jointly-funded research projects; multi-directional secondment schemes; and knowledge exchange programmes that engage end-users and tailor information to their needs.

Researchers should be encouraged to collaborate with international research partners via networks such as EERA in order to access non-UK research funding. Such support systems should address the significant 'up-front' time and effort needed to cultivate and execute such research projects. Additionally, the KTNs are well positioned to coordinate such international engagement and could become more involved in facilitation.

Annex A: Detailed research needs

The following section expands upon the priority research challenges identified in Section 0, as identified from the outputs of the expert workshop. These have been grouped in the same categories and where possible have been framed as specific research questions.

A.1 Automotive transport

A.1.1 Vehicle system

- What is the best powertrain fuel system going to be? Can we develop a modular power train that is adaptable to fuel changes?
- Improve the energy efficiency of conventional vehicles via in-vehicle energy harvesting; vehicle sensors; light-weighting; reducing rolling resistance; liquid air in engine processes etc.
- Improve performance of existing vehicles via reconditioned, for example making old ICE buses into hybrids? How can this be done at scale?
- When does it make environmental sense to buy a new vehicle?
- Designing vehicles to make re-cycling/re-use easier.
- Safeguarding passenger safety whilst decarbonising transport (e.g. autonomous vehicles; hydrogen powered vehicles).

A.1.2 Transport energy storage

- Why do we need energy storage for transportation?
- Role of energy storage technologies in different vehicles, such as batteries, super-capacitors, flywheels etc.?
- How can storage technologies help harvest 'waste' energy, such as vehicle braking?
- How might automotive storage technologies be used for non-motive uses, such as EVs and domestic energy storage?
- Performance analysis of different storage technologies (e.g. energy input vs. output).
- How can the energy density; weight; charging time; and lifetime of batteries be improved?
- What opportunities are there for battery re-use or recycling?
- How can we effectively balance different battery cells?
- How can vehicle-to-grid be employed without significantly damaging batteries (e.g. slower cycling, trickle charging etc.)?
- What are the environmental impacts of batteries?
- How close to ICE vehicle performance do battery vehicles need to be to be for uptake?

A.2 Aviation

A.2.1 General

- Ways to effectively decarbonise aviation despite its international dimension?
- Examining the airport system, such as internal and external linkages; key decision makers etc.

A.2.2 Decarbonising aviation

- Trade-offs around low-carbon aviation technology?
- Role of low-carbon 'airside' vehicles and 'on stand' power sources in reducing emissions?
- Development of low-carbon aviation fuels (e.g. liquid, bio-fuel, dual fuel etc.).
- Opportunities for low-carbon aircraft retrofitting?
- Opportunities for low-carbon runway taxiing, such as electric tugs?
- Innovative baggage solutions to reduce aviation emissions like baggage delivery services?
- Identifying and improving energy efficiency aviation technologies (e.g. turboprops).

A.2.3 Aviation demand management

- How do we curb aviation demand, particularly in rapidly developing countries?
- Can we improve connectivity/mobility without relying aviation (e.g. marine transport)?
- What is the public's perception of the various mechanisms for 'rationing' UK aviation?

A.3 Transport fuels

A.3.1 General

- Holistic assessment (e.g. life-cycle analysis) of different transport fuels across the whole supply chain (i.e. production; distribution; utilisation; disposal) to analyse their impacts in terms of climate change; air quality; health; geopolitical tensions; energy security; safety etc.
- End-of-life issues for different fuels and how these can be resolved via re-use; repurposing etc.
- What are the regulatory challenges around transport fuels?
- Which fuels are most appropriate for different situations?

A.3.2 Fossil fuels

- Improve energy efficiency of existing fleet of ICE vehicles.
- Can Carbon Capture Storage (CCS) realistically be used in conjunction with ICE transport?
- Role for natural gas in the transport energy system and how it will be sourced (e.g. biogas)?

A.3.3 Renewables

- Role of non-liquid forms of renewable energy in transport such as wind, solar etc.?
- Potential role for hydrogen and associated challenges (e.g. reliability; storage; costs etc.)?

A.3.4 Biofuels

- Wide-ranging impacts of biofuel use, such as on the wider environment, food security etc.?
- Scope for commercially viable, sustainable biofuel production in UK, particularly for aviation?
- Role for new generations of biofuels be used in the transport system?

A.3.4 Walking and cycling

- Conditions required to make a transition to a Dutch style, 'active travel' culture happen?
- What are the impacts of walking and cycling on health, energy and travel?

A.4 Freight and logistics

- What is driving the need to transport goods, such as 'just in time' manufacturing, e-commerce etc.?
- How can we promote two-way freight flows, i.e. drop off and pick-up?
- Ways to effectively decarbonise shipping despite its international dimension? For example, examining the barriers and opportunities to utilise renewable energies in shipping.
- How can ICT technologies be utilised to optimise freight logistics? For example, ensuring that someone is home to take receipt to avoid making a repeat journey.
- Ways of improving the efficiency of current modes of freight (e.g. one home delivery vs. multiple individual trips to supermarket) or encouraging a shift towards more efficient modes (e.g. road to rail)?
- Improving energy efficiency of freight vehicles, for example via improved aerodynamics.
- Examining light goods vehicle and aviation freight energy demand.

A.5 Transport energy behaviour

A.5.1 Understanding travel behaviour

- Why do people require transportation? What value do they take from it, for example mobility, status, fun etc.?
- Which factors influence consumers' decisions about transportation, such as cost, safety etc.?
- Reasons for gap between consumers' travel behaviour and what they report?
- Do different demographic groups exhibit different travel behaviours differ and if so, why?
- What are the travel behaviours of the 'social media generation'?
- How do cultural trends shape transport demand (e.g. popularity of car ownership)?
- Which factors constrain demand for transport services, such as available time, income, network capacity etc.?
- Co-evolution of people's lifestyles and transport system.
- How does technology influence travel behaviour?

A.5.2 Rebound effects

- What rebound effects exist in transportation and how can these be addressed?
- Rebound effects associated with normative interventions (e.g. travel planners increasing travel).

A.5.3 Initiating transport behaviour change

- Major barriers to adoption of sustainable travel behaviours, such as eco-driving, non-travel etc.
- Ways of promoting the adoption of sustainable travel behaviours (e.g. 'gameification'; in-vehicle performance feedback).
- How long do changes from interventions persist for?
- Role of education in changing transport behaviours via school, media, family etc.?
- Emphasising the 'fun aspects' of alternative modes of travel, such as walking, cycling etc.?
- How do we make public transport more desirable (e.g. better 'real-time' service information)?
- How can we persuade individuals to care about their transport energy consumption?
- Instead of 'modal shifting' can we promote 'destination shifting'?
- Can we change consumers' travel behaviour whilst protecting their freedom?

- How do we curb growing transport demand and promote sustainable travel behaviours in rapidly developing countries?

A.6 Transport energy governance and business

A.6.1 Transport policy

- Policy options to drive the transition to a sustainable, secure and affordable transport system, including carbon allowances, subsidies, taxes etc.?
- Impact of policy on transport demand and uptake of different transport modes, such as peak charging; vehicle tax etc.?
- Identifying policies to promote sustainable resource-use and disposal around transport.
- Restructuring regulatory and market frameworks to promote competition and energy efficiency.
- Evaluating the intended and unintended impacts of transport energy policy.
- Relationship between transport energy policy and economic growth (e.g. generation of IP; economic growth; employment gains; inward investment etc.)?
- Equity implications of transport energy policy (e.g. travel caps; carbon taxes etc.). Means of improving transport equity.
- Developing international transport energy governance frameworks that allow for greater engagement/collaboration to improve transport system (e.g. knowledge exchange etc.).

A.6.2 Business models, mobility services and market mechanisms

- Strengths and weaknesses of past and present dominant transport business models (e.g. Fordism; Toyotaism) in economic, social and environmental terms.
- Which 'alternative' business models could proliferate, particularly more service based models such as car clubs or car sharing schemes? Why might they?
- Key barriers to transport business models innovation (e.g. technological; regulatory; cultural).
- Most appropriate business models for urban and rural transportation?
- How could ICT open up a space for innovative mobility services and business models?
- Business models and services to promote use of public transport.
- Enabling people to undertake other functions whilst travelling, such as sleeping, eating working?
- How do transport technological and business model innovation enable one another?
- New pricing and payment plans for transport (e.g. multi-mode ticketing, carbon passes etc.).
- Costing travel to incorporate embodied energy consumption and carbon emissions.
- Trade-offs between different transport service benefits, such as cost, noise, pollution, comfort etc.?

A.7 Transport planning and infrastructure

A.7.1 Transport, town and land use planning

- Optimising the design of transport system (e.g. signalling, route planning etc.).
- Why do some cities find it easier to change and adapt their transport system than others?
- Scale at which lessons are transferrable, e.g. city to town?
- Transport system improvements without impacting on other needs (e.g. safety; green space etc.).
- Rural (i.e. non-city focused) improvements to transport system (e.g. public transport).
- How can land use planning promote normative travel patterns?

A.7.2 Transport infrastructure

- Economic inputs and outputs of different infrastructure options.
- Economic viability of overhauling existing infrastructure vs. adapting it?
- Potential to combine multiple transport infrastructure.
- Building flexibility into transport energy systems to avoid lock-in.
- Infrastructure implications of the electrification of transport (e.g. grid reinforcement).
- Potential for a low cost electricity transmission system to support electrification of transport system, such as rail?
- Overcoming the 'chicken-and-the-egg' dilemma: Without the necessary infrastructure new ways of travelling will remain niche but infrastructure will not be introduced without demand for it.

A.7.3 Transport, ICT and connectivity

- Impact of ICT technology (e.g. autonomous vehicles) on transport energy system change?
- Options for inter-modal connectivity using ICT systems?
- Safety implications of smart transport technology, such as autonomous vehicles?
- Privacy implications of smart transport technology, including the collection and storage of data?
- How can we collect data for non-digitised forms of travel, such as walking and cycling?
- To what extent can technology reduce the need to travel, for instance online remote working?
- How could the emergence of social media shape transport energy demand?
- How can social media help to manage congestion (e.g. Waze app)?
- Regulatory arrangements to manage the data generated by smart transport technology?

A.7.4 Resilience, adaptability and flexibility of transport systems

- What are the potential effects of 'mega events' on transport systems, such as natural disasters?
- Improving energy efficiency of transport system without undermining its resilience.
- Potentially negative effects of a low-carbon transport transition?

A.7.5 System integration

- How can we improve inter-modal travel?
- How can vehicles support the functionality of wider energy infrastructures, such as vehicle-to-grid reinforcement and back-up?
- How can the various components of the 'vehicle system' be better integrated?
- Importance of designing transport infrastructure simultaneously with other system dimensions (e.g. vehicles, policy, business models etc.) and other infrastructure (e.g. electricity networks)?
- How can we integrate new technologies into existing infrastructure? For example, autonomous vehicles and non-autonomous road network?

A.7.6 Technology adoption

- Which technologies should we focus on supporting the adoption of if we want to significantly reducing CO₂ emissions by 2050?
- Negative influence of new technology adoption (e.g. EVs – increase electricity demand – shortfall of supply)?

- Role for 'niche'/'old' transport modes in the future (e.g. (electric) bicycles; river transport; cable cars; conveyors belts)?
- How to support the uptake of novel transport technologies beyond early-adopters (e.g. EVs)?

A.8 Understanding, measuring and modelling transport system change

A.8.1 Understanding and predicting system change

- Examining past transport system change to inform potential future developments.
- Horizon scanning for potentially disruptive developments, including autonomous vehicles, 3D printing, climate change urbanisation etc.
- Impact of socio-technical lock-in on transport energy system change?
- Can developing countries avoid transport energy system lock-in?
- How will travel demand change in the future?

A.8.2 Measuring and analysing system attributes

- Clearer picture of today's transport energy system to provide a baseline for comparison.
- Multi-criteria LCA of transport energy system and its various dimensions.
- Measuring 'real world' fuel economy of new vehicle technologies.
- Which boundaries should we account when examining transport energy systems?
- Which metrics can enable cross-comparison of transport energy systems?
- Analysing where the greatest inefficiencies lie and how might these be tackled.

A.8.3 Modelling system change

- Modelling that is sensitive to numerous transport system characteristics, such as land use, ICT, energy demand, travel demand etc.
- Modelling energy demand from different aspects of the transport system.
- Modelling collective system impact of different developments at multiple scales.
- Embracing uncertainty to produce more robust energy transport system models.

Annex B: Process for developing the prospectus

This Energy Research and Training Prospectus Report has been developed under the auspices of the RCUK Energy Strategy Fellowship which was established in April 2013. Fellowship activities leading the production of the Prospectus have gone through three phases.

Phase I (Spring – Summer 2012), **the scoping phase**, involved a comprehensive review of relevant energy roadmaps, pathways and scenario exercises in order to provide a framework for possible UK energy futures. Extensive consultation with stakeholders across the energy landscape was carried out in order to encourage buy-in and establish clearly the boundaries and links between the RCUK Prospectus and other products related more to deployment. One conclusion arising from the consultations was that linkage should be sought across the energy research domain and that consequently related topics linked by underlying research skills should be covered in single workshops during Phase II.

Phase II (Autumn 2012 – Summer 2013), **the evidence-gathering phase**, relied heavily on workshops bringing the research community and stakeholders together round specific topics. Three ‘strategic’ workshops on **Energy Strategies and Energy Research Needs, The Role of Social Science, Environmental Science and Economics, and The Research Councils and the Energy Innovation Landscape** were held October 2012-February 2013. Six expert residential workshops on **Fossil Fuels and CCS, Energy in the Home and Workplace, Energy Infrastructure, Bioenergy, Transport Energy and Electrochemical Energy Technologies** were held January- June 2013. In addition, ‘light-touch’ activities were conducted in respect of: **Industrial Energy; Wind, Wave and Tide; and Nuclear Fission**. A final strategic level ‘synthesis’ workshop was held in July 2013. During Phase II, reports on each of these workshops were prepared and web-published following comments from participants.

During Phase III (Summer- Autumn 2013), **the synthesis stage**, the workshops reports were ‘mined’ and combined with contextual information to produce the Prospects Reports which were put out for peer review. The Prospectus, including a hard-copy Synthesis Report, was launched in November 2013.

Annex C: List of prospectus reports

No 1	Investing in a brighter energy future: energy research and training prospectus
No 2	Industrial energy demand
No 3	Energy in the home and workplace
No 4	Transport energy
No 5	Fossil fuels and carbon capture and storage
No 6	Electrochemical energy technologies and storage
No 7	Wind, wave and tidal energy
No 8	Bioenergy
No 9	Nuclear fission
No 10	Energy infrastructure