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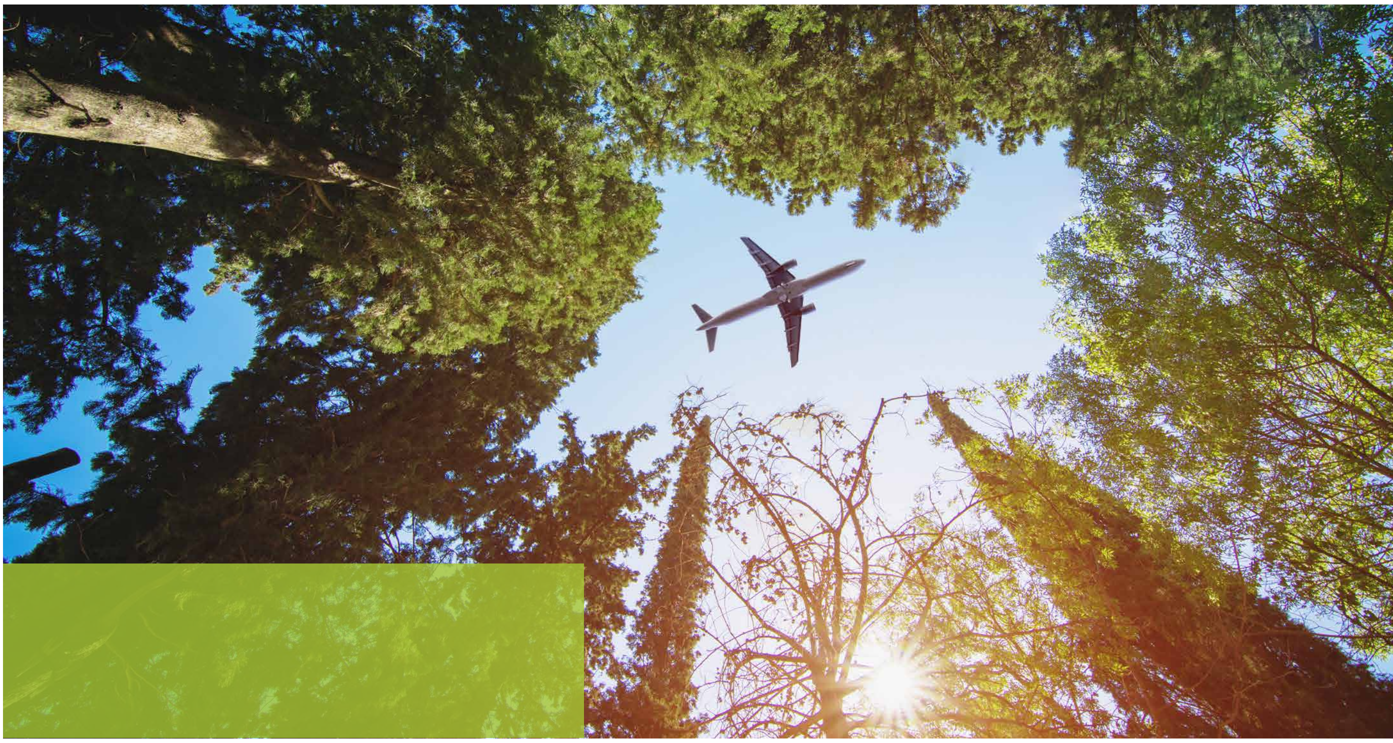
Engineering and Physical Sciences Research Council



Destination Net Zero

Accelerating progress towards carbon-neutral transport through research and innovation

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The Institution of Engineering and Technology

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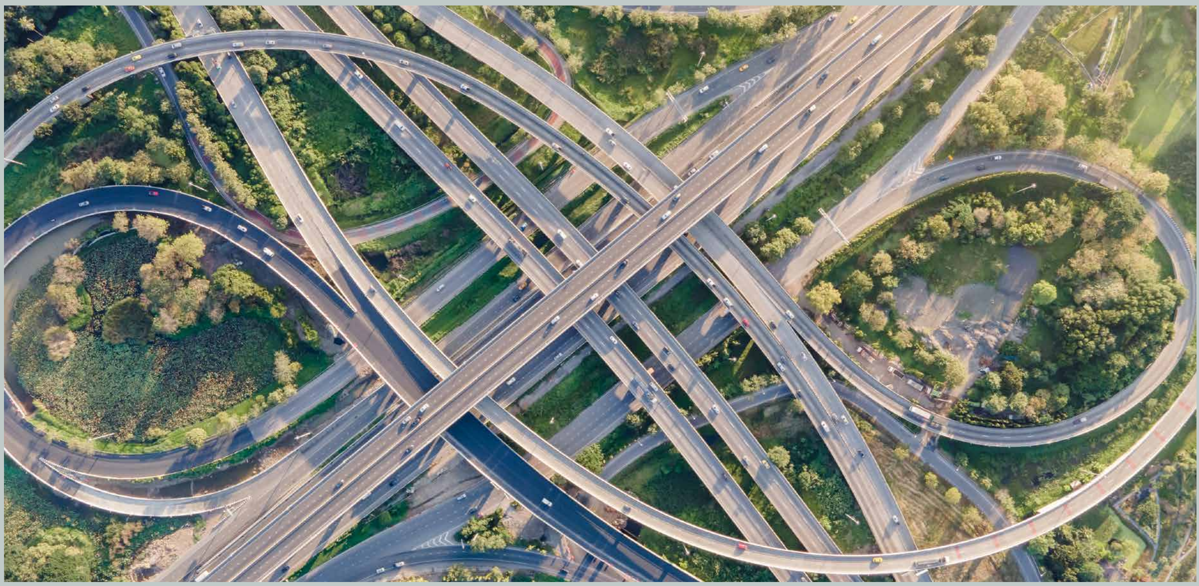


Research and innovation are central to the drive to achieve net zero across the UK's transport system by 2050, in line with the legally binding target set by the government. However, there remain important research challenges that need to be addressed in order to unleash the national decarbonisation strategy. In the first instance we need to define the whole life cycle of greenhouse gas (GHG) emissions for every mode of transport that will then enable optimum technological solutions for low and zero emission transport systems to be developed and selected.

We asked a range of experts from industry, academia and government, their views, at a workshop convened in May 2022 by the Engineering and Physical Sciences Research Council (EPSRC) and the Institution of Engineering and Technology (IET). This report distils key points from conversations at the workshop, as well as the insights of seven leading experts in transport technology, and offers ideas and suggestions for further research and innovation with a view to accelerating the transition to a net zero transport system.

The research challenges proposed by participants spanned road, rail, aerospace and maritime transport, and all stages of the innovation cycle from discovery to deployment. Materials characterisation for hydrogen and ammonia; developing interoperable public charging networks for electric vehicles; improving the thermal efficiency of hydrogen fuel-cells; and using digital twins and sensing technology to decarbonise infrastructure, are among the wide range of challenges that were put forward.

Participants were also keen to emphasise the importance of socio-economic research and a whole systems approach in decarbonising transport. Suggestions included research into how mode-shift between transport types could be encouraged through regulation and smart travel apps; and studies of regulatory measures that could push the shipping industry to decarbonise more quickly. Many favoured whole systems research for coordinating transport decarbonisation with renewable energy development; and for deciding between alternative technologies in a given mode.

While the barriers to decarbonising transport vary between market segments, with heavy goods vehicles (HGV), aerospace and maritime transport still in the early stages of development, the task is huge and time is short across all modes. Close coordination between government, industry and academia and swift and agile decision-making will be required for cutting-edge research to be effectively translated into real-world solutions. Participants' ideas and suggestions for actions that could help to accelerate technology transfer are given in the Recommendations section.

2. Introduction

The UK was the first major industrialised country in the world to set legally binding targets for reducing greenhouse gas (GHG) emissions and all sectors of the UK economy are required to achieve net zero by 2050.[1] Transport is the single largest contributor to domestic emissions, contributing 27% of the total in 2019, and GHG output from the system has declined only marginally since 1990, as efficiency gains have been offset by higher traffic levels.[2] Road vehicles account for more than 90% of all transport emissions.[3]

The Department for Transport (DfT), which is leading the drive to transform the system, published its masterplan *Decarbonising Transport: A Better, Greener Britain* in July 2021.[4] The plan contains more than 70 commitments to action by government across every mode of transport along with targets that industry and consumers must meet by specific dates. It has six strategic priorities:

- **Accelerating** modal shift to public and active transport
- **Decarbonising** road transport
- **Decarbonising** the freight system
- **Developing** the UK as a hub for green transport technology and innovation
- **Place-based** solutions to emissions reduction
- **Reducing** carbon in a global economy

Putting heads together

The Engineering and Physical Sciences Research Council (EPSRC) and the Institution of Engineering and Technology (IET) have been collaborating to understand the key science and engineering research challenges that will enable the transition. The IET's Transport Panel has adopted the drive to decarbonise transport as a key focus area and set up an expert group to look at how the IET can inform UK policy-making in this area. The panel has recently launched a report on hydrogen's potential as a road transport fuel – and the opportunities and challenges that this presents. In addition, the IET held two workshops in 2021 that proposed broad topics for further research in the areas of low and zero emission propulsion systems; and transport infrastructure.

The EPSRC has been developing its strategic priorities, which include a focus on Engineering Net Zero. This priority encompasses how we will decarbonise our economy and society; creating an alternative energy future; and developing truly circular economies for the decarbonisation of transport. It is based on the following analysis of actions needed to achieve the government's targets:

- **Reduce** demand for GHG-intensive products, processes and services that cannot be decarbonised
- **Remove** - Capture, store and use GHGs from essential processes that cannot be decarbonised
- **Replace** GHG-emitting products, processes and services with zero-carbon solutions.

and the types of research and innovation that will enable such actions:

- **Deploy** at scale the technologies and solutions that are ready
- **Develop** those technologies and solutions that are not ready
- **Discover** solutions to problems that we cannot yet solve.

1 www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law
2 www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2019
3 www.gov.uk/government/publications/transport-decarbonisation-plan p15
4 www.gov.uk/government/publications/transport-decarbonisation-plan

In May 2022, the two organisations joined forces to hold a workshop that aimed to identify the key research challenges that need to be addressed in order to achieve net zero across the whole life cycle of GHG emissions from all modes of transport. A wide range of experts from across industry, academia and government attended the event. This report captures key points from conversations at the workshop, as well as the views and insights of seven leading experts in transport technology. It offers a range of ideas and suggestions for further research and innovation that could accelerate the transition to a net zero transport system.

Recommendations from the workshop attendees are to:

1. Commission a range of living labs in partnership with local authorities to trial carbon reduction measures and zero emission road vehicles in rural and urban settings and across diverse communities.
2. Introduce a carbon tax on diesel oil used by locomotives to address the price competitiveness issue for hydrogen and electric battery trains in the short term.

3. Set up a research competition similar to the Faraday Battery Challenge to fund research, innovation and scale-up facilities for the development of hydrogen gas turbines as the leading net zero option for medium-range aircraft.
4. Launch a living lab in a major port to trial shore power for maritime transport, allowing ships to plug in to renewable energy while they are docked, and simultaneously providing a smart-energy hub for multiple purposes.
5. Commission an independent study to examine ways of coordinating decarbonisation strategies for and between different transport modes. It should take into consideration the decarbonisation strategies in other sectors, alongside the establishment of an agency to promote such collaboration.

Roadmap to net zero

With technological solutions in some modes still in their infancy, achieving net zero in transport represents a huge and urgent challenge that requires intensive research and development (R&D) across all stages of the innovation process from fundamental science through to demonstrator projects and "living labs". The DfT is working with UK Research and Innovation (UKRI) and its constituent research funding councils, as well as industry and investors, to identify and support the necessary R&D. Liaison with government departments and stakeholders in other sectors is also being fostered to achieve synergies and avoid duplication.

Priority areas

One outcome of such collaboration is the Net Zero Research and Innovation Framework, which outlines R&D priorities across six sectors of the economy, including transport. Commissioned by the government's Net Zero Innovation Board, it lays out a roadmap to net zero that sets five priority research areas for transport centred on electric vehicles; buses and heavy goods vehicles (HGV); rail; aviation; and maritime transport; and spanning technology readiness levels one to nine, with time-frames for producing results (see Table 1).[5] The roadmap also outlines five systems-wide research themes, which include "enabling an integrated, multi-modal transport system" and related issues such as its role in the energy system. A delivery plan for transport based on the framework is being jointly prepared by the DfT and the Department of Business, Energy and Industrial Strategy (BEIS).

Trials in progress

The DfT has already commissioned four major R&D programmes, after receiving its largest ever R&D settlement in the 2021 spending round, with £377 million out of the three-year £575 million grant earmarked for decarbonisation projects. These include:

- Zero-emission road-freight trials of three technological options: battery electric; hydrogen fuel cell; and overhead catenary.
- The maritime programme UK Shore, including a Clean Maritime Competition Demonstration and a new institute to assess results
- JetZero, an aviation programme looking at decarbonising airports
- The Tees Valley Hydrogen Hub, a living lab that aims to demonstrate how a multi-modal hydrogen hub can work in a commercially sustainable way.

[5] www.gov.uk/government/publications/net-zero-research-and-innovation-framework

Table 1 – Net Zero Research and Innovation Roadmap for the UK

Key
- Research – Technology Readiness Levels 1-3
- Development – Technology Readiness Levels 4-6
- Demonstration – Technology Readiness Levels 6-9

Sector	2020s	2030s	2040s
Transport	Improve the efficiency of EV manufacture; trialling infrastructure improvements including charging, vehicle to grid, flexible/smart charging; novel battery technology		
	Research deployment options for hydrogen and electric buses; demonstration of HGV technologies including hydrogen, battery, electric road systems; mega-charging for HGVs		
	Demonstrate hydrogen trains and infrastructure; research hydrogen distribution by rail to support other sources of demand		
	Develop zero emissions aircraft and airside vehicles; prepare UK airports for zero emission aircraft; facilitate UK R&D on aerospace manufacturing	Continued development of more efficient aircraft; and certification and infrastructure requirements; develop and trial sustainable aviation fuel manufacture	
	Demonstrate zero emission vessels, including with batteries, hydrogen and ammonia; hydrogen and ammonia bunkering and dispensing at ports; zero emission ports		
Systems-wide/ cross-cutting	Understand optimal net zero pathways, interdependencies and trade-offs across physical, natural, social and technological systems		
	Integrate changes to energy supply, storage and use with increasing interlinkages between energy vectors and across different sectors of the economy		
	Enable an integrated, multi-modal transport system and accelerate the adoption of active travel and public transport; understand the role of transport in the wider energy system, including the hydrogen economy		
	Digital solutions and technologies to support cross-sector integration, enable systems-level understanding and unlock resource and energy efficiency		
	Beyond technology, there is a need to understand how more sustainable behaviours can be incentivised; to develop new types of business and financial models; and to deliver locally and regionally appropriate solutions		

Source: UK Net Zero Research and Innovation Framework, Department for Business, Energy and Industrial Strategy, HM Government.
https://www.gov.uk/government/publications/net-zero-research-and-innovation-framework

"The role for the Department for Transport is setting the direction. The primary method is the transport decarbonisation plan and I would say it is the most important agenda at the DfT at this point in time. The targets we have set – for example that all cars will be fully net zero emission by 2035 and all HGVs will be so by 2040 – are really important signals to industry that this is how it has to be."

Siobhan Campbell, Deputy Chief Scientific Officer for Science, Innovation and Technology, Department for Transport

3. Assessing the whole life cycle of carbon emissions

The drive to decarbonise the UK's transport system in order to meet legally binding targets over coming decades raises the question of how you define the total emissions that the system produces. The urgency and scale of the task, which is set to involve the overhaul of entire vehicle fleets, networks and industries, highlights the importance of such assessments and the need to take a rational and consistent approach.

New vehicle and infrastructure technologies that are aimed at achieving zero emissions will have to demonstrate that they can do so. Decisions between competing alternative technologies that aim to decarbonise a particular mode of transport will rely on assessments of their relative emissions. Strategies for disposing of existing petrol and diesel vehicles will need to be devised so as to minimise further GHG emissions.

Life cycle assessment

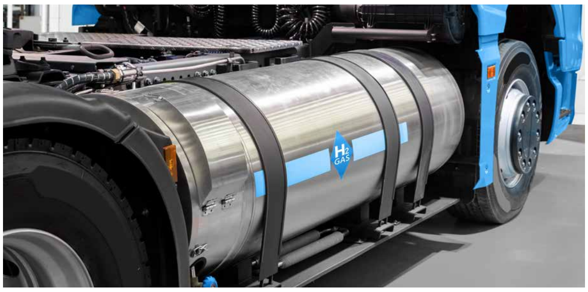
The leading methodology for measuring environmental impacts from a product, process or service is the life cycle assessment (LCA), which has been developed into the environmental standards ISO 14040 and ISO 14044 by the International Standards Organisation (ISO), and PAS 2050 and the GHG Protocol Product Standard by the British Standards Institute (BSI).[6,7]

The LCA aims to measure environmental impact by accounting for the whole life cycle of a product from raw materials extraction, production and distribution, to use, repair and maintenance, and finally disposal or recycling. Under the ISO standard, an LCA study involves four phases: a goal and scope definition; a life cycle inventory analysis; a life cycle impact assessment; and an interpretation.[8]

As well as the full "cradle-to-grave" LCA, there are several variants for specific purposes, including a "well-to-wheel" model designed for transport fuels and vehicle use. This model includes an "upstream" stage from fuel production and processing to fuel delivery or energy transmission, and a "downstream" stage that covers the operation of the vehicle.[9]

6 https://www.frontiersin.org/articles/10.3389/fenrg.2020.00015/full
7 https://ghgprotocol.org/sites/default/files/standards_supporting/GHG%20Protocol%20PAS%202050%20Factsheet.pdf
8 https://www.frontiersin.org/articles/10.3389/fenrg.2020.00015/full
9 https://joint-research-centre.ec.europa.eu/welcome-jec-website/jec-activities/well-wheels-analyses_en

It is used to assess – and compare - the energy conversion efficiency and tail-pipe emissions impacts of road vehicles, aircraft, and maritime vessels and their fuels. However, it does not include embodied emissions from the mining of raw materials, the transportation of materials and vehicle parts, and the manufacture of vehicles; or emissions involved in maintenance and disposal.



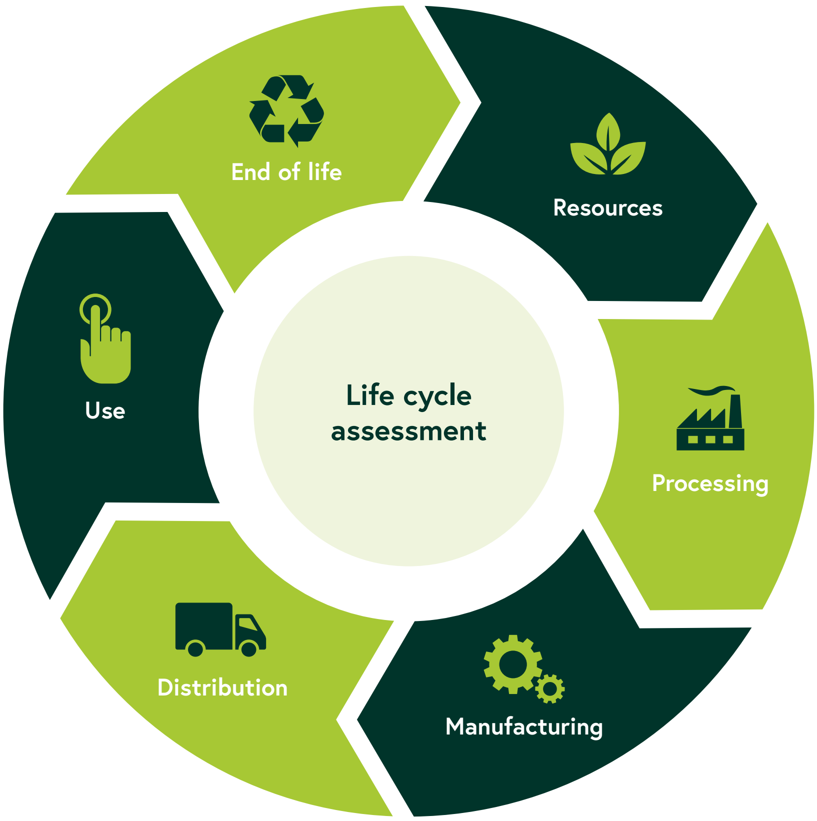
Widening the scope

This limitation of the well-to-wheel model has been addressed by the Argonne National Laboratory, a science and engineering research centre in the United States, to create a tool for evaluating the environmental impacts of new transport fuels and vehicle technologies.

Its Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) model measures the emissions of fuels using a well-to-wheel assessment, but assesses the impacts from vehicles using a cradle-to-grave LCA, from raw materials mining to vehicle disposal. The GREET model covers all greenhouse gases as well as other pollutants including particulates and volatile organic compounds.

The "whole life cycle" approach to measuring emissions from a vehicle can also be extended to transport infrastructure, which typically contains large amounts of carbon-intensive steel and cement. In 2018, BSI produced the world's first standard for managing infrastructure carbon: PAS 2080.[10] The DfT has since launched a carbon management programme based on PAS 2080, which aims to embed an integrated system for managing whole life carbon into government-led infrastructure projects.[11]

Life cycle assessment for transport is an emerging field, and many different methodologies are adopted in practice, which results in variations between LCA studies that can limit their value in supporting decision-making.[12] The range of GHGs that are measured, and the geographical scope of an assessment are among other aspects that have to be defined. Developing a coherent set of LCA methodologies that will match the variety of large-scale technological and infrastructure changes involved in achieving net zero across the UK's transport system presents an R&D opportunity in itself.



10 https://www.bsigroup.com/en-GB/about-bsi/media-centre/press-releases/2018/june/bsi-launches-verification-scheme-to-help-organizations-reduce-carbon-footprint/
11 https://www.gov.uk/government/publications/transport-decarbonisation-plan p19
12 https://www.frontiersin.org/articles/10.3389/fenrg.2020.00015/full

EXPERT VIEW

3.1 Design for 'end of life' to cut carbon

When Professor Kerry Kirwan designed and built the world's first F3 racing car made from sustainable materials, it won a clutch of innovation awards and was showcased at the British and European Grand Prix.

The WorldF3rst racing car featured a recycled, carbon-fibre chassis; a steering wheel made from root vegetables; a flax-fibre and soya-bean-oil seat; and a bio-diesel engine run on fuel derived from waste food products including chocolate, beef fat and cheese residues.

Now, the principles that the car embodies are being developed into a new approach to innovation spanning all modes of transport through EPSRC's Circular Economy Network+ in Transportation Systems group, which is led by Professor Kirwan.

Challenging tradition

The WorldF3rst project set out to challenge the traditional idea in manufacturing that recycled materials are somehow inferior to virgin materials, taking as an example the carbon fibre used for light-weighting in racing cars – and aircraft.

"The question is: do you need the performance of an airliner in a set of skis or a tennis racket?" he said. "Probably not. So why do you make them out of the same materials, when actually 98% of the performance of airliner is more than adequate?

"Carbon fibre is one of the most energy-intensive materials to make, so when you make it, you want to keep it as carbon fibre for as long as possible. It's that whole life cycle thing: the amount of energy that goes in versus the carbon that you save over the life of the product."

Optimising whole systems

"The other interesting thing we are finding is that everyone optimises for their particular system. That's great but the minute that you want to move it to another system, it doesn't work. If you take a whole systems approach, you can actually start getting some optimal overall solutions for three or four different things.

"Another important aspect of the circular economy is that you need to design your products with an understanding of the end of life before you make them - we call it 'back to front'. If we take that back end and include it in the design thinking, we can design it so that it is useful for several other things, when it comes to the end of its first life. It is absolutely paramount to have this end-of-life thinking built into the entire drive to decarbonise transport."

Professor Kerry Kirwan, Deputy Pro-Vice Chancellor (Research) and Chair of Sustainable Manufacturing and Materials at WMG, University of Warwick.

4. Overcoming barriers

Transport sectors vary in their progress along the route to net zero, but major barriers need to be overcome in all modes, and across the whole system, for the government's ambitious decarbonisation targets to be met.

Road traffic accounts for more than 90% of carbon emissions from the UK's transport sector. Creating a viable and interoperable charging infrastructure for electric vehicles (EV) and ensuring a stable, efficient and affordable supply of renewable electricity are major hurdles to overcome.[13] Minimising emissions from the disposal of existing diesel and petrol cars and encouraging mode shift also involve multiple issues. For HGVs, buses and coaches, the technological route to decarbonisation is yet to be resolved, with both EV and hydrogen options being explored.[14] Time is short, with deadlines ahead in 2030, 2035 and 2040.

Targets for road transport

2030 Sale of new petrol and diesel cars and vans to end

2035 All new cars and vans or light goods vehicles (under 3.5t) to be 100% zero emission at the tailpipe. Sale of new non-zero emission HGVs (3.5t-26t) to end

2040 Sale of new non-zero emission HGVs above 26t to end

For **rail**, extending electrification of the network is the main solution, with cost posing a barrier to electrifying low-use routes. For these, battery electric trains and hydrogen trains are being trialled. Converting or replacing existing diesel locomotives and adapting and replacing infrastructure will involve major works. With around 1,500 diesel trains, which have a long lifespan, due to be removed from the system by 2040, decarbonisation will also be costly. Government plans to shift 900,000 HGV loads of freight to rail or shipping each year will require additional infrastructure changes.[15]

Long R&D cycles

A host of fundamental research questions have to be answered in **aerospace** and **maritime transport**, where the technological route to zero carbon vehicles has yet to be clearly identified.[16] For aviation, hydrogen is the leading zero-emission pathway, while for shipping, ammonia holds some long-term promise. Increasing the low-carbon element in the fuel supply is the strategy for reducing emissions in the short-term. For shipping, this is supplemented by operational measures, battery power and wind-assisted technologies. Both sectors also have very long development cycles, due to the high safety certification standards required, while aircraft and ships also have long active service lives. Internationally binding emission and safety standards will have to be established to achieve net zero. Ports and airports will require extensive changes to vehicles and infrastructure and the hydrogen supply chain needs to be developed.

Global issues

There are also many barriers that are common to several modes or need to be addressed for transport to work effectively and efficiently as a **whole system**. The supply of renewable energy amid intense competition for electricity from multiple sectors is one major issue. Global competition for the scarce minerals that are involved in sustainable technologies is another, along with the related question of how to maximise use of their whole life cycle.[17] Potential costs and risks to industry are high across all modes. Finally, there are many social and behavioural issues to resolve – how to help people engage with the changes that are taking place; ensure a just transition; encourage mode shift.

13 Decarbonising Transport, pp 89, 93
14 Decarbonising Transport, p 136
15 Decarbonising Transport, pp 82, 138-9,
16 Jet Zero Consultation, p 12 Decarbonising Transport, p 108
17 https://www.iea.org/news/clean-energy-demand-for-critical-minerals-set-to-soar-as-the-world-pursues-net-zero-goals

EXPERT VIEW

4.1 Hydrogen poses a host of research challenges

Hydrogen is a key option for decarbonising large vehicles that offers potential advantages across land-based and maritime transport, with some longer term potential for aviation too, said Professor Phil Blythe of Newcastle University.

It could also serve as a medium for storing renewable energy that is generated when consumer demand is low, which could help to address the impact of decarbonisation efforts on the grid, according to the former Chief Scientific Officer at the Department for Transport.

Hydrogen technologies with research and development potential for decarbonising transport include fuel-cell technology, hydrogen internal combustion engines, hydrogen storage, hydrogen transmission, and steam methane reforming with carbon capture, Professor Blythe said.

"There are two ways of powering vehicles with hydrogen," he said. "One is that you put hydrogen into the engine, like you do with diesel, and burn it. The other way – and certainly if you have a new vehicle, this is the way you would probably do it – is that you have a fuel-cell."

Hydrogen retrofit trial

Newcastle University is involved in a demonstration project at RAF Leeming in Yorkshire to convert an airside tug from diesel to hydrogen with industrial partner ULEMCo, which proved the concept of 100% hydrogen combustion with zero emissions, the evaluation of which is on-going at the moment.

"We are putting all the sensors on the tailpipe to see if there are any emissions when that happens," he said. "If you can get that right, you could enable millions of vehicles with diesel engines to be converted to work on hydrogen, which is a real prize because it means that you are not having to build all these new vehicles – you can retrofit old vehicles (saving on new embedded carbon)."

Professor Blythe said the advantage of fuel-cell vehicles is that they can carry more hydrogen, which gives them a longer journey range – with hydrogen cars now achieving ranges of 300-400 miles, but the fuel-cell technology needs improving.

Research opportunities

"We have good expertise in storage; we need to understand the transmission of hydrogen in pipes better; and we also need to improve the processes of generating hydrogen, either through electrolysis or through steam methane reforming, and also have the carbon capture," he said.

"The last thing that is really important is to understand that tipping point, particularly in road and rail transport, where it would be better to make that vehicle a battery electric vehicle or a hydrogen one.

"I think there is quite a lot of work to look at that whole ecosystem and the efficiency of both those technologies to work out whether you should be investing in large electric vehicles or large hydrogen vehicles."

Professor Phil Blythe,
Professor of Intelligent Transport Systems, Newcastle University.

5. Research challenges

Workshop delegates and interviewees were asked for their views on the top research challenges for accelerating progress towards a net zero transport system. Here are some of their ideas for high-impact research in the main transport modes and across the whole system.

Road

Develop: Identifying the optimum technology for HGV fleets. Further development of dynamic mobile wireless charging, overhead catenary, and hydrogen fuel cell models with related infrastructure. Systems-level research and modelling to identify the best solution.

Develop: EV charging networks. Develop fully interoperable public charging networks; conduct studies to identify best locations for public charging; resolving ultra-rapid chargers' negative impact on the grid; eliminating cybersecurity risks to the grid from EV charging.

Develop: Vehicle-to-grid charging technology and services. Further development of new battery usage models that enable car owners to sell energy to the grid and local business or retail centres. Developing second-life EV battery aggregators to power the grid.

Discover: Encouraging mode-shift. Conduct socio-economic research on optimum policy and regulatory measures to encourage mode-shift from car ownership to active travel, public transport and mobility as a service, using data from schemes across the UK and abroad.

Rail

Develop: Improving battery performance. Research into optimal battery management for longevity of battery cells to inform the charging frequency and charge point locations for bi-modal battery trains.

Develop: Retrofitting diesel trains. Several hybrid models are in development for the retrofit of diesel trains, involving combinations of pantograph, battery, hydrogen fuel cell and diesel. Conduct studies to find the most carbon-efficient models that are suitable for different lines.

Develop: Develop and trial optimum refuelling infrastructure to support the roll-out of hydrogen trains on a low-use stretch of railway line and conduct associated research into manufacturing capability and supply chain availability.

Develop: Hydrogen supply by rail. Conduct studies on the current capability of the UK rail network for transporting hydrogen and the technological adaptations and safety standards required to develop a nationwide supply network for the green hydrogen economy.

Aerospace

Discover: Materials characterisation for hydrogen. Hydrogen is prone to leakage and cryogenic hydrogen can cause embrittlement. Research is needed into hydrogen's effect on aircraft components such as metals, composites, sealing materials and insulation.

Discover: Climate science for hydrogen aircraft and their contrails. Both hydrogen fuel cells and hydrogen propulsion release water, while the latter may also produce nitrous oxides. Research is needed into their impact on the atmosphere at high altitude to ensure hydrogen-powered flight does not have adverse climate effects.

Develop: Improve the thermal efficiency of hydrogen fuel cells. Development work is needed to improve the performance of the proton exchange membrane in the heat exchanger of hydrogen fuel cells.

Develop: Higher efficiency electro-fuels. Develop and scale efficient technology for producing electro-fuels through direct carbon capture from the atmosphere as a lower-carbon alternative to Sustainable Aviation Fuels produced from biomass and carbon capture, use and storage.

Maritime transport

Develop: Hybrid retrofitting. Test and trial a range of hybrid retrofit options for different vessel types with potential to reduce emissions in the near-term, including combinations of operational measures, wind-assisted technologies, batteries and in-port charging.

Develop: Policy and regulation. Conduct socio-economic research on how to facilitate adoption of near-term carbon-reduction through measures such as emissions trading, fuel taxes, and knowledge-sharing forums that bring together different actors across the maritime sector.

Discover: Materials characterisation for ammonia. Conduct detailed research on the impact of ammonia, which is highly corrosive, flammable and toxic, on the range of materials used in ship engine components and equipment for fuel storage and supply.

Discover: Safety standards & training. Conduct socio-economic studies on the safety standards, skills and training needed for safe use and handling of ammonia by crew and stevedores and the acceptability of ammonia-powered ships for communities living in ports.

Whole systems

Discover: EV-grid compatibility. Conduct research on how to integrate the development of electrified and green hydrogen-powered transport modes with the expansion of renewable energy production for the grid, and develop positive interactions and synergies between the transport and energy sectors.

Develop: Decision tools. Devise decarbonisation data analysis and decision tools to support strategic decision-making on which technology to adopt, when alternative R&D programmes for transport modes such as rail and aviation reach a tipping point.

Discover: Infrastructure reviews. Conduct infrastructure carbon reviews in each transport mode and devise life cycle assessments for infrastructure projects, repairs and upgrades. Research the use of digital twins and sensing technology for decarbonising infrastructure.

Develop: Smart travel apps. Use intelligent transport systems to devise smart travel apps that exploit data and digital connectivity to help travellers to reduce their carbon footprint and choose the most sustainable transport route to a destination.

EXPERT VIEW

6.1 Charging is a hot research topic for roads

Developing a successful charging infrastructure is among key research priorities for decarbonising road transport, said Professor Liana Cipcigan, Leader of Cardiff University's Electric Vehicle Centre of Excellence.

"We need to develop it more," she said. "We still have challenges with rapid chargers, ultra-rapid chargers, and diversification of the technology in order to offer mass charging of electric vehicles."

Professor Cipcigan, who also leads EPSRC's Network+ Decarbonising Transport through Electrification group, said there are opportunities to develop new battery usage models that could encourage customers to see an EV as an energy asset.

Vehicle-to-grid charging

Such models would enable EV owners to enrol in business services that pay them for selling energy to the grid or to local business parks, she said, citing a project at Manchester Science Park, where batteries in a fleet of commercial EVs are used to top up the energy supply to buildings during peak times using vehicle to grid, when the price of electricity is high.

Professor Cipcigan said aggregation of second-hand EV batteries, which typically have 70% to 80% of their life remaining, to provide a higher-capacity source of power for the grid or EV charging stations is another area with potential for research and development.

"With the electrification of transport, we will end up in a number of years with a huge number of batteries that are not suitable for transport anymore," she said. "So how valuable it is to have this circular economy.

Battery recycling

"The next stage is recycling. This is a complex process to recover important metals (for example lithium, cobalt and nickel) at the purity that is needed to rebuild batteries. We don't have from my knowledge a big [battery] recycling factory in the UK and this is something that is missing.

"This could be an interesting materials research area to develop the technology for recycling lithium-ion batteries and extract metals from them at this level of purity. Again, it is part of the circular economy, since recovered metals will be needed in manufacturing batteries for electric vehicles."

Professor Cipcigan said resolving problems with the interoperability of different charging points and payment systems; and ensuring the cyber-resilience of EV charging transactions in relation to the grid also require further R&D.

Other important research challenges include HGV fleet charging, where a megawatt charging solution has yet to be developed; and socio-economic research related to EVs, including how to prevent "transport poverty" and promote active transport, she added.

Liana Cipcigan, Research Theme Leader – Sustainable Transport, Cardiff University.

EXPERT VIEW

6.2 Hydrogen has the edge for zero carbon aircraft

The aviation industry faces massive barriers to decarbonising air transport on two main fronts, said Mark Scully, Head of Technology, Advanced Systems and Propulsion, at the Aerospace Technology Institute.

"First, you've got the existing conventional aircraft," he said. "We are looking at introducing technology to enable these aircraft to become ultra-efficient, consuming less fuel and generating lower emissions. Scaling up [Sustainable] Aviation Fuels (SAF) production for use by all aircraft is also important in the path to net zero carbon.

"But in parallel with that, we've got this massive challenge of also introducing a new zero- carbon fleet. In our view, from the work that was done in FlyZero, hydrogen is one potential answer for that."

Green liquid hydrogen

FlyZero was a one-year intensive research project carried out by the ATI, which aimed to identify the best pathways to zero-carbon emission commercial flight. It compared batteries, hydrogen and ammonia and found green liquid hydrogen to be the most viable alternative.

The project came up with three hydrogen aircraft concepts: regional, narrowbody and mid-size, with the first two powered by fuel cells and the third by gas turbines. The ATI also includes battery electric solutions in its research and technology (R&T) strategy for the short range sub-regional market and SAFs for all segments.

"We are seeing the development of electric vehicle take-off and landing aircraft – very small aircraft acting almost as air taxis," said Scully. "With the vertical take-off battery system, you are looking for power density, because you need an enormous amount of power for take-off and landing. They are relatively short duration flights, so the energy density is less important, although it's a limiting factor on range and payload.

Higher energy density

"But for larger, longer-range aircraft, carrying more passengers, we need a lot more energy density," said Scully. "Typically, today, we are seeing something like 250 Watt hours per kilo [Wh/kg] as a battery energy density, while kerosene is greater than 12 kWh/kg.

"We see hydrogen with its significantly higher energy density (33.6 kWh/kg) offering an opportunity, in terms of fuel cells being used to convert the hydrogen to an electric propulsion system, and we are supporting the development of this technology. But fuel cells only get you part of the way on this journey.

"For larger aircraft fuel cells and the associated systems to become less competitive, aircraft will need to burn the hydrogen in gas turbines to realise the benefits. There are lots of challenges with burning hydrogen … and the non-CO_2 emissions you get from it, although this will be addressed by an intensive R&T campaign. And there are other fundamental challenges in terms of how you store liquid hydrogen and get the cryogenic hydrogen from the fuel tank to the engine."

Mark Scully, Head of Technology – Advanced Systems & Propulsion, Aerospace Technology Institute.

EXPERT VIEW

6.3 Hybrid measures could cut ships' emissions now

There are two important aspects to decarbonising maritime transport, said Professor Alice Larkin, Professor of Climate Science and Energy Policy at the University of Manchester.

"One is that we've got to find measures to reduce emissions in the very short-term – as in days, months and years, rather than a decade," she said. "And then there is the 'What do we do in later decades?' issue, which is about a fuel switch."

Professor Larkin, who is Head of Manchester's School of Engineering, said the leading solutions for the early years were limiting the speed at which ships travel – or 'slow steaming,' operational measures, retrofit wind propulsion and shore power – all options that could be applied to existing ships.

Cutting fuel consumption

"Slow steaming has probably shown the greatest potential to date," she said, adding that slowing ships down has a huge impact on fuel consumption, while retrofitting them with wind-assisted technologies such as the Flettner rotor along with route optimisation technology would enable them to reduce fuel consumption further.

"That means you are actually reducing your CO2 emissions now and that is absolutely critical," she said. "From a scientific point of view, the timing really matters. With greenhouse gases, particularly carbon dioxide which is so long-lived, the less you do now, the more you have to do later."

Shore power would enable ships to plug in to renewable electricity to power their operations when they are in port, while also incentivising ports to become smart energy hubs and creating opportunities for more hybrid battery vessels on short sea routes.

Uncertain future

Professor Larkin said there is no leading candidate yet in terms of the optimum zero-emission fuel for the longer term, with uncertainty both over which fuel it will be and whether it will be one fuel or multiple options.

"I don't think anyone yet would say they are absolutely convinced that it's going to be ammonia for ships," she said. "There is still quite a lot of interest in methanol, there is a whole school of thought around liquid natural gas, which I would say is a disaster really because it's not low carbon, and there are some people who just think it's going to be multiple options.

"What is interesting about shipping is the variety of ship types and activity. You could see this diversity playing out, with certain technologies being appropriate for certain types of shipping and others not. So maybe tankers are going to be fuelled by ammonia and ferries will all be battery."

Alice Larkin, Professor of Climate Science and Energy Policy, University of Manchester.

EXPERT VIEW

6.4 Catenary plus hydrogen is winning formula for rail

The best way to decarbonise railways is to push ahead with electrification and hydrogen from either end of the network, said Stuart Hillmansen, Professor of Railway Traction Systems at Birmingham University.

"If I could click my fingers and electrify every railway network in the world, that would be the best way of decarbonizing rail," he said. "However, it is just not economically viable to do it and also it would take too long to electrify the entire network.

"So, the heavily used parts of the network should be electrified and, in the lightly used parts, we should push ahead with hydrogen technology. At some point, they will meet in the middle and, at that point, we will have got rid of all of the diesel fleet."

R&D breakthrough

Birmingham was the first university to show that hydrogen is a viable fuel and energy source for rail applications in certain environments, through studies conducted by its Centre of Excellence in Rail Decarbonisation, where Professor Hillmansen is a lead engineer.

This led to development of the prototype HydroFLEX train, a hydrogen battery train with a pantograph, in partnership with rolling stock company Porterbrook. The train's second version, which was showcased at COP26, can run for about 300 miles on hydrogen alone.

"It shouldn't be seen as a competition between electrification and hydrogen," Professor Hillmansen stressed. "Ultimately, it is about finding the right solution for the particular part of the railway system that you are interested in.

Complementary solutions

"There are battery electric multiple units that are being developed by major manufacturers, and they would work really well with gaps of about 50 to 80 kilometres, so if you have those sorts of distances between electrification, they can work really well," he said.

"If you had a railway similar to Germany, then a battery electric unit with a pantograph plus a battery would be the ideal solution. Whereas in the UK, we don't have that - we've got electrification and it all spans out from London.

"The routes that we are looking at in the UK may have electrification at the start of them – if they are in and around London, or on the East or West Coast Main Line or the Great Western – but then the vehicles may have to run several hundred miles without using electrification – and that is where hydrogen comes in. The advantage of hydrogen is the range of the vehicles."

Professor Stuart Hillmansen,
PUniversity of Birmingham

7. Tackling issues along the way

The rapid translation of cutting-edge research into technology trials and demonstrators – and ultimately full commercialisation – depends upon close coordination and collaboration between government, industry and academia and swift and agile decision-making about which technological pathways to take based on research outcomes.

In transport modes where the technological pathway to net zero is not yet clear, the government is taking a technology-neutral approach and aims to look at the outcomes of trials to determine which option offers the greatest advantages.[18] Infrastructure for the chosen pathway will then be developed to unlock further commercial investment.

Such decisions will be affected by wider systems issues, such as the relationship between the electric vehicle market and growth in electricity supply from renewable sources; or the relative efficiency of electric and hydrogen technologies for a particular transport mode.

Whole systems research

With decarbonisation taking place simultaneously across modes and economic sectors, whole systems research is likely to play a crucial role in assessing the potential impact of different technologies, while tools such as life cycle analysis and multi-criteria decision analysis will help to enable evidence-based decision making in complex scenarios.[19] A systems approach will be needed not only to realise synergies across the transport sector but also in its linkages with other sectors, such as energy, residential and business.

Links with the energy sector and the multiple demands upon it present a particular challenge, with many research solutions needed to ensure adequate supply of renewable energy, so that carbon emissions are not merely shifted from one sector to another. Developing a range of services and systems that enable battery-to-grid charging, with incentives for vehicle owners, could help to stabilise electricity supply from renewable sources and ensure sufficient supply amid stiff competition for energy.

Whole systems research combined with life cycle analysis could also help to determine when to retrofit and when to replace an existing fleet and how to manage the transition from interim measures such as low-carbon synthetic drop-in fuels and SAFs to long-term zero-emission technologies.

[18] Decarbonising Transport, p136
[19] https://onlinelibrary.wiley.com/doi/10.1002/9780470400531.eorms0683

Living labs

Place-based solutions are central to the roll-out of decarbonised transport.[20] Large scale demonstrator projects such as the Tees Valley Hydrogen Hub, which will have an R&D campus at its heart, provide excellent opportunities for bringing new technologies to commercialisation and providing joined-up solutions for different sectors.[21]

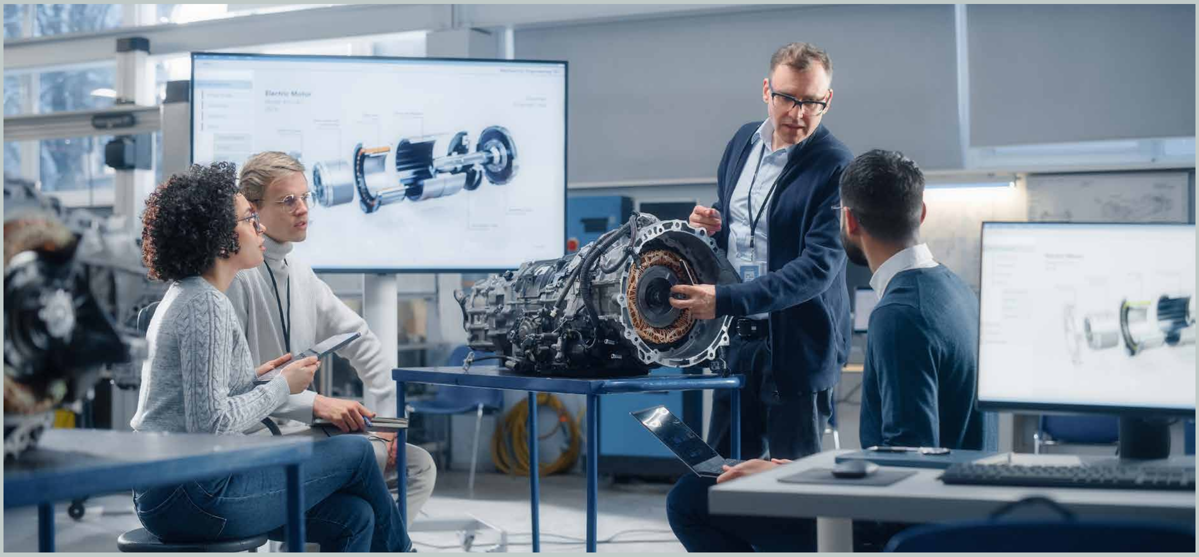
Such living labs can also engage communities in decarbonisation strategies to ensure that measures provide employment, meet other local needs and serve all sectors of society. Many local authorities are setting ambitious targets for achieving net zero in their cities or regions and launching green transport initiatives, which could form the basis for further living labs.[22] Conducting socio-economic research to assess such projects, will enable schemes to be adjusted and enhanced, and successful models to be replicated.

Living labs could examine the potential of innovations such as autonomous and connected vehicles, mobility as a service, and even electric vertical take-off and landing aircraft to reduce carbon emissions in regional transport networks. Demonstrator projects could incorporate the digital and data capabilities of intelligent transport systems and employ designs based on circular economy principles to make further decarbonisation gains.

Green hydrogen

Linkages with the hydrogen economy will be vital for the transport sector, with aviation, shipping, buses, HGVs and rail all potentially making use of hydrogen fuel. Rail could play a central role in transporting green hydrogen, while hydrogen production and storage hubs will need to be strategically located close to ports and airports. Devising an optimum cross-modal production landscape and transmission system for green hydrogen will involve extensive multi-disciplinary research.

In a tableau of transition spanning more than 25 years, there are many other unknown factors to be resolved. The best way to incentivise mode-switch; how to tackle international emissions; ways to decarbonise last-mile logistics; and how best to cut the cost of renewable energy in the near-term are among other urgent questions that would benefit from further research.



20 Decarbonising Transport, p147
21 https://www.gov.uk/government/publications/tees-valley-multi-modal-hydrogen-transport-hub
22 https://www.greatermanchester-ca.gov.uk/news/greater-manchester-aiming-to-be-first-city-region-to-deliver-carbon-neutral-transport-network/; https://www.cdp.net/en/cities/cities-scores

8. Recommendations

Decarbonising transport is a huge task that will lead to new technologies and systems being rolled out at pace and at scale. After addressing some of the barriers and research challenges involved, workshop participants and interviewees shared their ideas and suggestions for a range of potential actions that could help to translate discoveries and innovations into real-world solutions. These are:

1 Commission a range of living labs in partnership with local authorities to trial carbon reduction measures and zero emission road vehicles in rural and urban settings and across diverse communities.

A coherent national programme of demonstrator projects should be mounted to trial technologies and schemes in a range of suitable settings; socio-economic assessments should be carried out, and a one-stop shop set up to share best practice.

2 Introduce a carbon tax on diesel oil used by locomotives to address the price competitiveness issue for hydrogen and electric battery trains in the short term.

Diesel fuel for the rail network is currently untaxed. Reducing the price differential would promote the deployment of new zero-carbon prototypes and smooth the transition process, enabling economies of scale that will eventually cut the price of renewable fuels.

3 Set up a research competition similar to the Faraday Battery Challenge to fund research, innovation and scale-up facilities for the development of hydrogen gas turbines as the leading net zero option for medium-range aircraft.

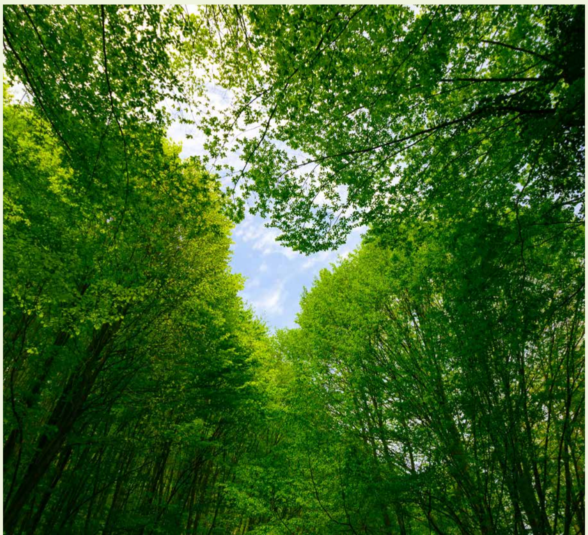
The contest could fund projects looking at operational issues for hydrogen gas turbines such as safety and reliability; and address capability gaps in the infrastructure and skills required to develop manufacturing capability.

4 Launch a living lab in a major port to trial shore power for maritime transport, allowing ships to plug in to renewable energy while they are docked, and simultaneously providing a smart-energy hub for multiple purposes.

The living lab could also support hybrid retrofitting of short and medium range vessels with battery electric power and should benefit from special tax relief on electricity for port uses, to overcome the price differential with heavy duty oil.

5 Commission an independent study on how to coordinate decarbonisation strategies for different transport modes with each other and with strategies in other sectors; and establish an agency to promote intersectoral collaboration up to 2050 and beyond.

Commission an independent study to examine ways of coordinating decarbonisation strategies for and between different transport modes. It should take into consideration the decarbonisation strategies in other sectors, alongside the establishment of an agency to promote such collaboration.



9. About the IET

We are the IET – a charitable engineering institution with over **158,000 members in 150 countries** – working to engineer a better world.

Our mission is to inspire, inform and influence the global engineering community to advance technology and innovation for the benefit of society.

As a diverse home across engineering and technology, we share knowledge that helps make better sense of the world in order to solve the challenges that matter. It is why we are uniquely placed to champion engineering.

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The Institution of Engineering and Technology

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