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RESEARCH PATHWAYS FOR NET-ZERO TRANSPORT

CONTENTS

This report presents the emerging research pathways required to decarbonise the transport sector. It has been led by Drew Pearce at Imperial College London with input from a variety of experts.

OVERVIEW

The future is uncertain and there are many different pathways ahead for technology and society. Some, but not all, of these pathways will deliver the required amount of decarbonisation to comply with the Paris Agreement. Whilst we cannot know for certain which of these pathways will be chosen, research allows us both to identify the patterns and trends that can help shape the pathways, and ultimately our future, and to develop the technologies and approaches that can assist decarbonisation.

Reaching net-zero requires a complex set of interventions across all sectors, designed to be effective at a whole system level, and this report will outline the research that could contribute to achieving this goal as part of meeting the Paris Agreement to limit warming to well below 2 degrees Celsius above pre-industrial levels. In addition to meeting the challenge of reducing greenhouse gas emissions towards net-zero levels (as is required to prevent further warming) any intervention should also account for the need to build in resilience to the environmental change that is already baked in and the need to sustain and improve biodiversity.

In this report we focus on the transport sector, a significant and stubborn emitter. Decarbonisation of transport has wider ramifications beyond the sector as large amounts of society depend on transport to function.

NET-ZERO PATHWAYS RESEARCH

01 → UNDERSTANDING AND MODELLING THE PROBLEM

- End-use origin of Greenhouse Gas emissions
- Modelling of Demand, Modal Choices
- Data and Digital Tech Interventions

02 → ENERGY DEMAND REDUCTION

- Trip Avoidance
- Trip Modal Shifts
- Vehicle Utilisation
- Vehicle Right Sizing
- Vehicle Efficiency

03 → DECARBONISATION OF ENERGY DEMAND

- Electrification
- Hydrogen Fuel
- Other Low-Carbon and Renewable Fuels

04 REMAINING STUBBORN EMITTERS

- Carbon Capture and Storage Options
- CO_2 Sequestration Options
- Emerging Future Technologies

MODELLING AND DATA RESEARCH

Modelling and data methods have long been used for climate change mitigation, and new sources of data alongside cutting-edge systems modelling is leading this to be of increasing importance. Any successful intervention requires a better understanding of how human and societal behaviours lead to carbon emissions at a granular level and how the whole system might respond.

Understanding the sources of greenhouse gases is the first step in being able to design, implement and monitor interventions to reach net-zero. Greenhouse gas accounting seeks to fully determine where different greenhouse gas emissions arise in different processes and behaviours.

At present, it can be hard for individuals and organisations to understand their own impacts within the wider system, and that is why accounting must occur at the level of behaviours and activities within their remits.

Once an understanding of sources of emissions is achieved, the next step is to design effective interventions. Systems modelling is an interdisciplinary field that integrates complex interactions between sources of energy, energy flows and behaviours at different scales. Systems modelling helps identify changes and explore different scenarios that might occur, including unexpected or undesirable outcomes. For example, electric cars are on average about 40% more energy efficient than combustion engine cars. This leads to reduced running costs which in turn can lead to increased usage. As such, any energy savings may be partly or wholly overcome if coupled with an increase in driving due to this or other policies.

Research is also needed in order to fully account for emissions across the complex global energy and materials supply chains, with a particular focus needed on lower income and emerging economies where data may be lacking. Systems modelling can then be used to design a suite of measures and technologies to operate constructively to achieve the desired environmental goals.

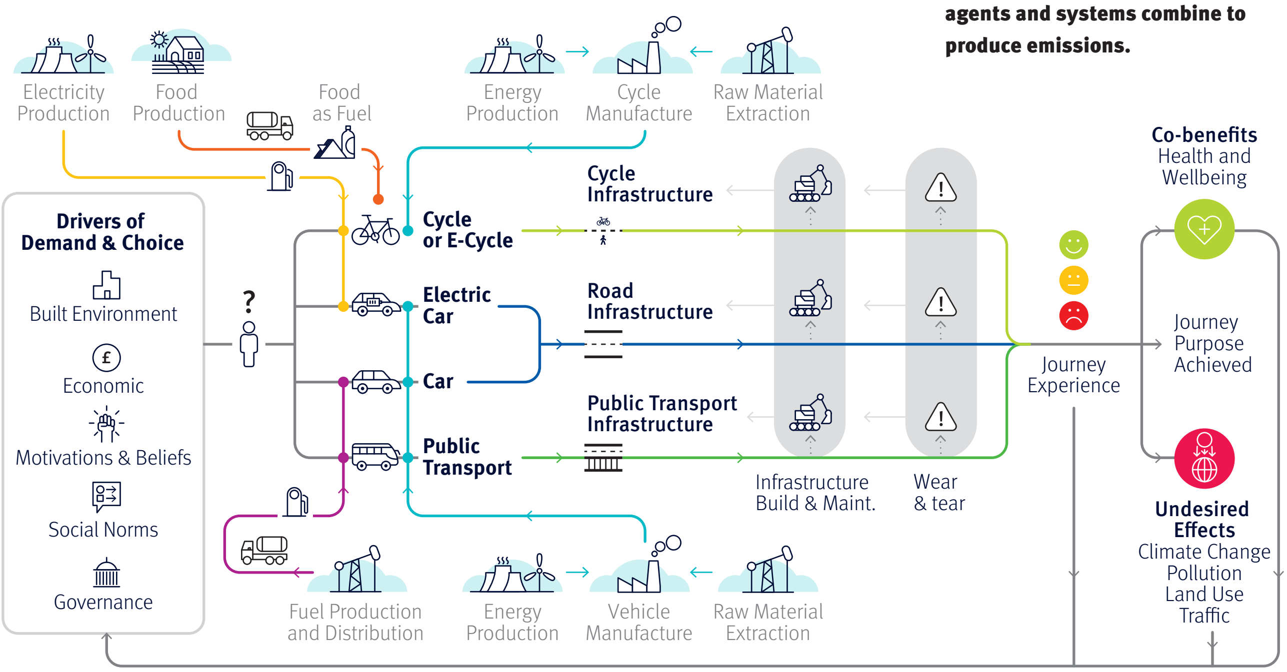
"My modelling tries to represent social as well as technical aspects. To examine and model the whole system to understand how the behaviour is generated and leads to energy demands. We don't use energy for the sake of using energy. We're using it for a specific purpose."

Koen van Dam
Imperial College London

RESEARCH SNAPSHOT

- Annual national reporting of GHG emissions has been mandatory since the Kyoto protocol.
- Current accounting research has unequal coverage globally and lacks fine-grained information at the level of individual behaviours.
- Effective modelling of system-wide impacts of interventions is an emerging and important area of research.
- New sources of data, such as the Internet of Things (IoT), are emerging as a way to provide information in order to determine the most effective interventions.

Transport Systems Modelling: complex interactions between agents and systems combine to produce emissions.



ENERGY DEMAND REDUCTION

Meeting the goals of the Paris Agreement requires Net-Zero emissions and it is clear that in order to do that energy demand per person must decrease and total demand must fall in richer nations. This means we must demand less of our transport systems as well as use what we do demand smartly and efficiently.

The global trend in energy demand is an exponential increase and whilst certain events have stimulated short-term blips, the trend has always returned. The Covid-19 pandemic led to a 5% decrease in global energy demand, the largest drop in a single year since the start of the industrial revolution. It remains highly uncertain if, as restrictions lift and stimulus packages set in, this drop can be leveraged for further reductions or if the previous march towards climate disaster will resume.

"Don't jump straight to finding new ways to generate energy, but really, really, start reducing the demand. We can only do that by understanding the behaviour and the activities and the environment within which we make those decisions."

Koen van Dam
Imperial College London

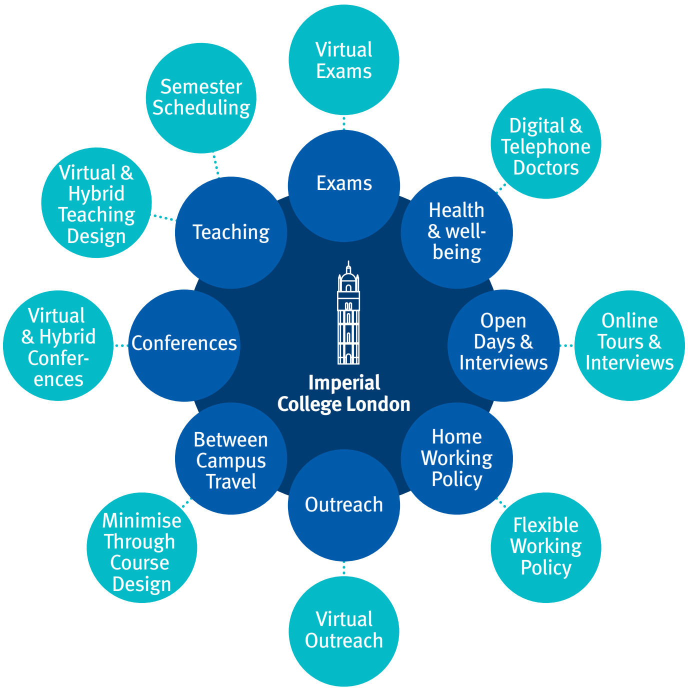
TRIP AVOIDANCE

Avoiding demand sits at the top of the food chain of climate mitigation: savings are felt instantly, and there are no or minimal upfront costs. Every trip that is avoided immediately reduces greenhouse gas emissions.

Demand for travel arises from a complex interplay between our transport systems and the social, economic and governance structures in which we exist.

Research will increasingly need to grapple with all of these elements to eliminate unnecessary demand and protect the transport services that we, as a society, deem to be the most important.

Core activities of an institution like Imperial College London could be redesigned to minimise the trips they generate.



"Obviously any problem is going to be easier if you reduce the size of it. And the problem of decarbonising transport is going to be easier if we reduce the amount of people and goods that move around."

Jenny Nelson
Imperial College London

RESEARCH SNAPSHOT

- Trip avoidance research is a subset of traffic demand management research which seeks to use technology and other measures to make certain trips superfluous.
- Prior to the Covid-19 pandemic this work has focussed primarily on working from home through teleconferencing.
- Lockdowns due to the Covid-19 pandemic forced a wider array of activities to transition to online modes which has led to increased research and development in technologies and policies to determine which of these changes are recommended for permanent adoption.

THE COVID-19 PANDEMIC FACILITATED A NEAR COMPLETE TRANSITION TO WORKING FROM HOME IN MANY SECTORS

TRIP LENGTH REDUCTION

The built environment we live in dictates how far we need to travel for a given purpose; interventions in the built environment can drastically change how far we need to travel.

The distance of a given journey is controlled by several different factors including the built environment and social dynamics. Hyper-local neighbourhoods in which everyone has access to their necessities (e.g. leisure, shopping and healthcare) within a short walk, often described as fifteen- or twenty-minute neighbourhoods, are being proposed more frequently.

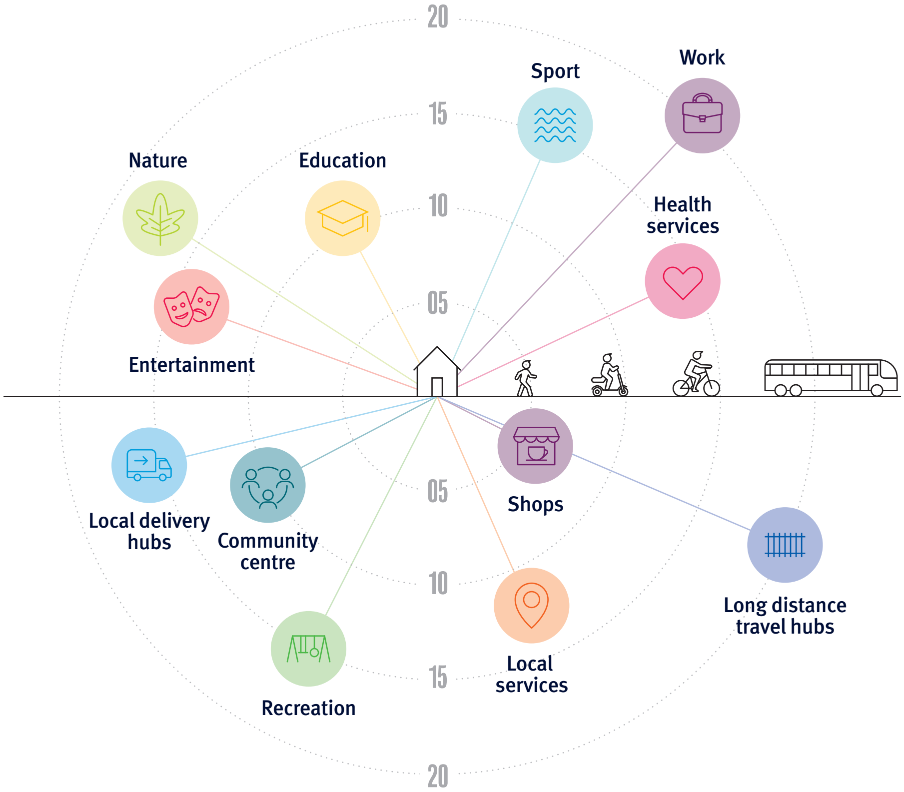
Although shorter everyday trips are common, long-distance trips dominate total transport energy requirements because each trip uses more energy. Demand for long-distance trips is poorly understood. Hyper-local neighbourhoods will likely impact car ownership, which will in turn modally shift short trips, however they are unlikely to directly impact on long-distance trips.

How decisions are made about the layout of our environments is an important topic of research. This might highlight sustainable travel opportunities, but we must also be able to design transport systems that are sustainable in many different geographical, social and economic contexts.

"Interventions in the built environment can drastically change how far we need to travel"

In addition, we must grapple with the state of existing buildings and built environments. Lifetimes for buildings are likely to be much longer than vehicle lifetimes and as such the questions around building retrofits, and early building replacement costs and benefits are even more present.

We can build our neighbourhoods to contain everything we need within a short walk or cycle.



RESEARCH SNAPSHOT

- Energy demand reduction research tends to focus on energy policy. Research is needed to understand the implications of non-energy policy for energy demand, for example impacts of the centralisation of NHS services.
- In transport, decisions about planning and the built environment are rarely made in order to minimise transport demand. Research must focus on the design of urban environments to minimise the distances that people and goods need to travel, as well as on transforming existing layouts.
- Research must also expand beyond narrow single policy focuses to investigate the best package of policies.

ENERGY DEMAND REDUCTION

MODAL SHIFT

Not all transport is created equal - some modes are substantially more energy efficient than others. Using technology, policies, the built environment and behavioural interventions we can switch from less efficient modes to highly efficient modes like cycling and public transport.

For most people their choice of mode for a given transport trip will be determined by a range of factors including the trip requirements, availability, safety, comfort, habit, and economic and social factors.

Research is needed in order to determine how to design sustainable modes that are the most comfortable, safe and convenient as well as ensuring that less sustainable modes are discouraged through incentive structures.

In addition, research is also needed to establish the most effective new infrastructure to facilitate modal shifts, and further maximise the efficiency of existing networks.

> ***"In congested city centres, we need to achieve modal switch"***
>
> **Sally Cairns**
> University of Leeds

Freight and cargo movements present a different challenge to passenger transport for modal shifts. They are far more likely to move between hubs (such as ports and stations) and be more driven by economic than other factors.

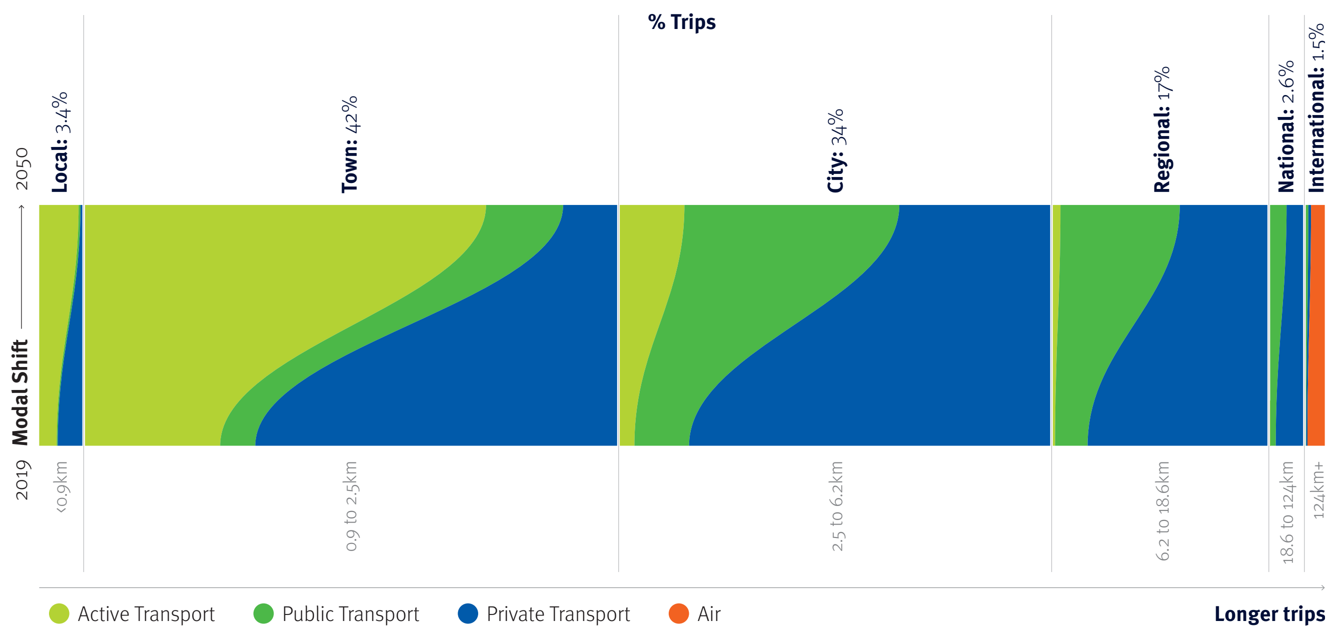
Another issue, made more topical by the Covid-19 pandemic, is that some passenger transport trips could instead be cargo movements, such as deliveries. A modal shift for delivery organisations to sustainable modes will involve different levers and incentives and may be easier because the number of agents to influence are fewer.

RESEARCH SNAPSHOT

- Modal shift for passenger transport can be split into pull (things that make low-energy modes more attractive) and push (things that make high-energy modes less attractive) measures.
- Existing research addresses the effectiveness of different policies and technologies.
- Few studies have analysed modal shift measures in concert with the speed and scale of the necessary changes. There is also an increasing need to study arrays of measures taken simultaneously.

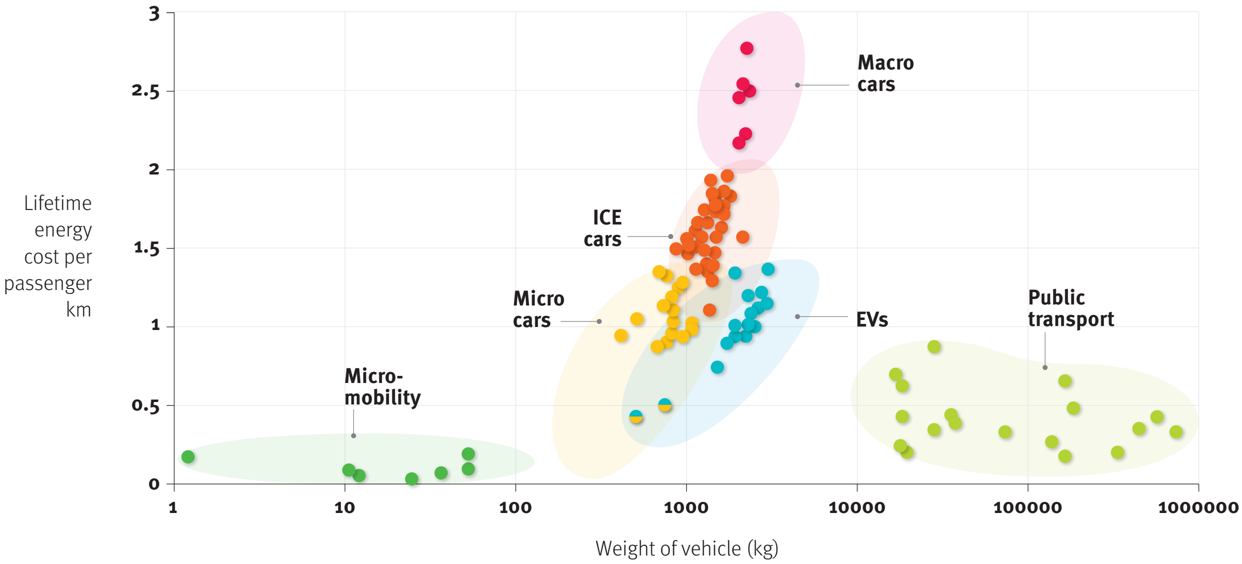
> ***"The types of strategies that will have the greatest level of co-benefits and generate the greatest impacts are the types of policies that change our urban land use and transportation system to encourage walking, cycling and public transportation."***
>
> **Audrey de Nazelle**
> Imperial College London

Example of how different trips could modally shift to greener modes depending on their length.



RIGHT-SIZING OF VEHICLES

Energy costs increase with vehicle size unless they are shared for public transport.



Physics tells us that no matter the medium, the heavier the object the more energy it takes to move. Ensuring that the lightest vehicle possible is utilised in all trips can reduce overall energy usage.

Reducing the average weight per passenger (or per tonne carried, in the case of cargo movements) in usage is a necessary component of reducing the energy demand for transport overall. There are three ways of achieving this:

1. Use innovative techniques such as 3D printing (also known as additive manufacturing) to design and retrofit vehicles to minimise the weight whilst still meeting safety requirements. In addition we need incentives and policies (including legislation) to promote these lighter vehicles and to undo the ongoing "SUVisation" of cars.
2. It is also important to recognise that current ownership models do not allow for much trip-by-trip choice in the size of vehicle used, and instead a system of alternative ownership models would allow for flexible choice and better incentives for using vehicles appropriately sized for the demands and purpose of the trip.
3. The third option is to share out the energy cost per vehicle between as many people and goods as possible. This is the principle behind public transport. In most situations public transport will already be more efficient than any lightweighting of small occupancy vehicles like cars. There are also several things that can be done to improve public transport even further: lightweighting of those vehicles (such as an ongoing approach for Very Light Rail infrastructure) and ensuring average occupancy is high. One approach seeks to ensure public transport is well used for a diversity of purposes and at all times.

"All airplanes that are being manufactured should undergo a robust, holistic lightweighting exercise via additive manufacturing. All cars should do that, all ocean going vessels should do that."

Connor Myant
Imperial College London

RESEARCH SNAPSHOT

- The impact of vehicle weight on energy efficiency has long been understood.
- Materials innovation led to decreasing average fleet weight until trends for bigger cars reversed this.
- Alternative models of ownership are increasingly being researched as a way of ensuring the right size vehicle is used for any given trip.
- Further innovation in lightweighting using additive manufacturing is an emerging focus, particularly for aviation where the energy cost is strongly related to vehicle weight.

ENERGY DEMAND REDUCTION

VEHICLE EFFICIENCY IN USE

Various factors around how vehicles are designed, maintained and used will control their overall energy efficiency. Interventions already exist at the design stage, for example in engine design, but these will have limited impacts unless paired with an accurate understanding and control of real-world usage conditions.

Vehicle efficiency tends to be discussed in terms of lab-tested performance of different designs, but the real world efficiency of a vehicle depends at least as much on the behaviours of its users.

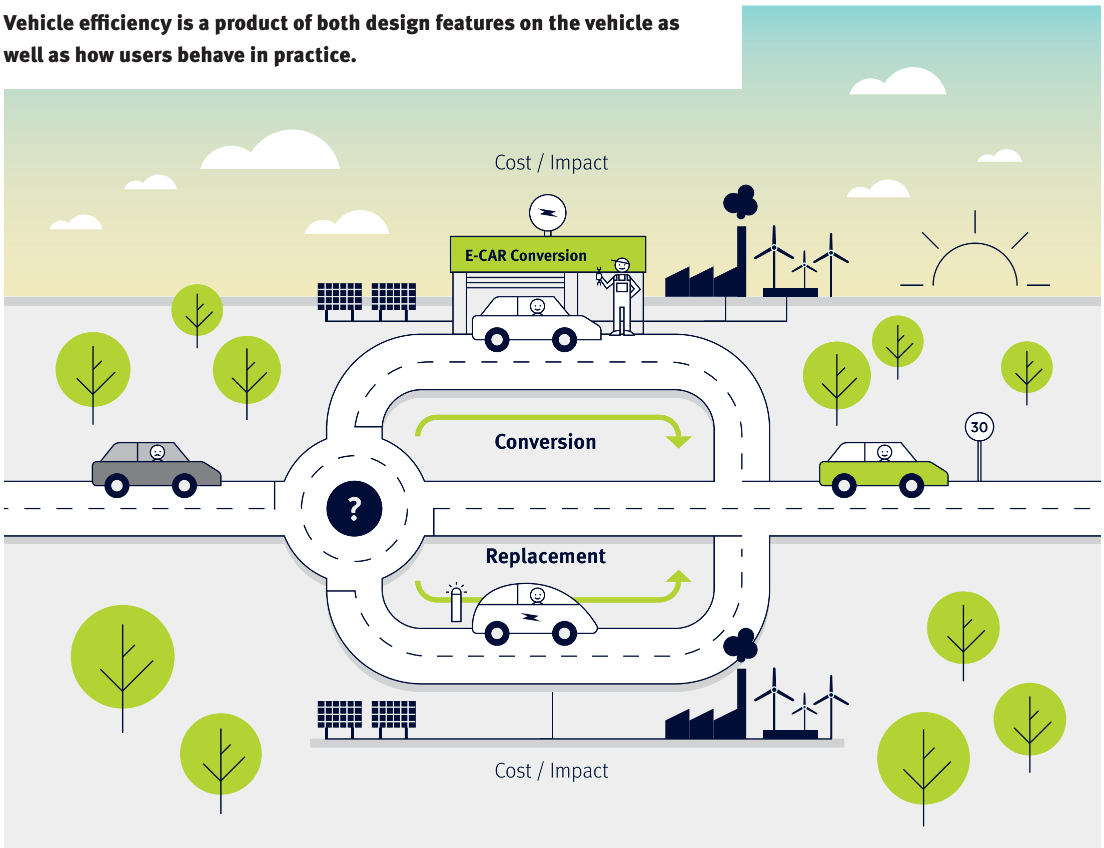
In many cases (particularly when considering ships and aeroplanes) the timescale of the challenge to reduce emissions is shorter than the vehicle's lifetime, and as such retrofit interventions will need to play a key role, such as new lubricants and new blends of fuel.

Of particular importance in many cases is the speed of the vehicle. Most vehicle types will have an optimum speed for efficiency. Ensuring users travel at the optimum speeds is vital and research is needed to help develop systems and tools to enforce appropriate speed limits in international as well as domestic transport.

RESEARCH SNAPSHOT

- Research and development has focussed on vehicle efficiency measures at the point of manufacture in lab conditions.
- Increasingly, research has found inconsistencies between laboratory and real-world conditions. One recent example was the so-called Dieselgate which found cars on the road had significantly higher emissions than in lab tests. Vehicle turnover rate is also, in many cases, too slow compared to the required speed of the transition.
- Research into increasing the efficiency of use of a vehicle is a highly interdisciplinary field that requires interventions in ensuring adequate maintenance as well as interventions in driver behaviour such as speed limits.

Vehicle efficiency is a product of both design features on the vehicle as well as how users behave in practice.



"In International Shipping, one option is reducing emissions through slowing, so optimising your speed to minimise your emissions."

Jamie Spiers
Imperial College London

DECARBONISATION OF ENERGY SUPPLY

As well as reducing the total demand for energy for transport we must also develop and implement alternative low-carbon sources of energy. Two approaches have emerged: combining sources of low-carbon electricity with electrification of the demand, and the production of low-carbon fuels to replace fossil fuels.

ELECTRIFICATION

Electrification in the transport sector is the process of replacing fossil-fuel based engines with electric motors. This presents different challenges and opportunities in different types of transport.

In some ways electric transport is older than fossil fuel transport, with early cars and railways being electrified. The challenge and opportunity today is to combine modern innovations and engineering alongside low-carbon electricity to ensure it is the cheapest and most sustainable option.

Due to the maturity of the technology today, electrification of rail and increasingly also passenger cars and light goods vehicles is beginning to be deployed at scale. Research is needed into the systemic implications of integration of new electricity demands on the grid alongside its rapid decarbonisation.

As can be seen from figure X, current levels of decarbonisation of the grid in the UK have occurred primarily through two mechanisms: the phase-out of coal generation alongside the increase in renewable generation. The figure also highlights the level of demand for electricity that would be required for cars alone if the current fleet and usage was electrified. This extra demand alone would exceed the current non-fossil fuel generation capacity. This highlights the need to minimise demand in all sectors in order to allow decarbonisation of the grid to continue at pace. As well as understanding the source of total energy, it is also important to research how new demands will affect peak power demands and how demand and supply can be managed for the system to function sustainably.

There are, however, certain sectors where more fundamental research is still needed to make electrification a viable route: heavier road vehicles, aviation and international ocean-going vessels.

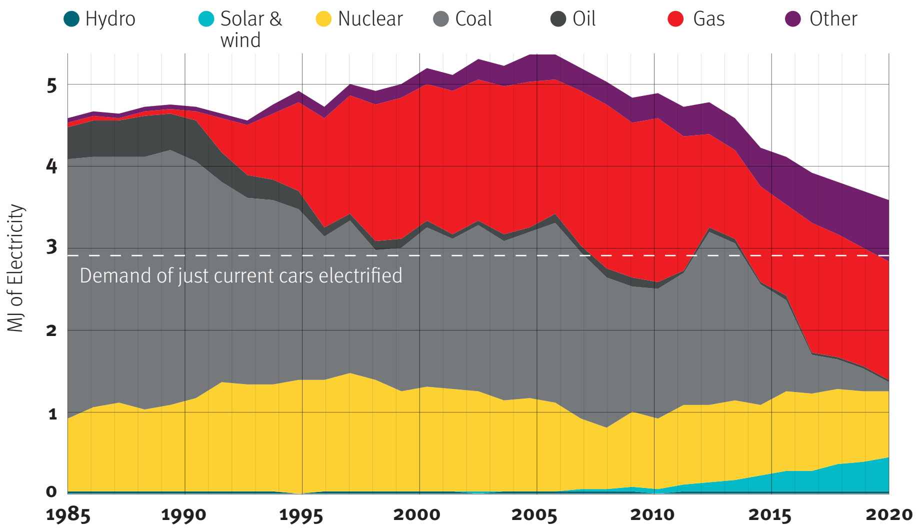
For aviation, weight poses a particular challenge and batteries currently do not have an energy density sufficient to power long-haul aviation. It is unlikely that battery technology will develop sufficiently to change this limitation in the timescale of a 1.5°C compliant pathway to net-zero. One option that still allows long-distance travel by aviation might be replacing a long-haul flight with many short-haul hops, though this has trade-offs with increased energy usage due to more landings and take-offs. Electric infrastructure near airports would also have to be rolled out rapidly to enable the electrification of aviation. The uncertainty about the future of aviation will make an electrification pathway difficult with risks of locking in technologies that do not pan out.

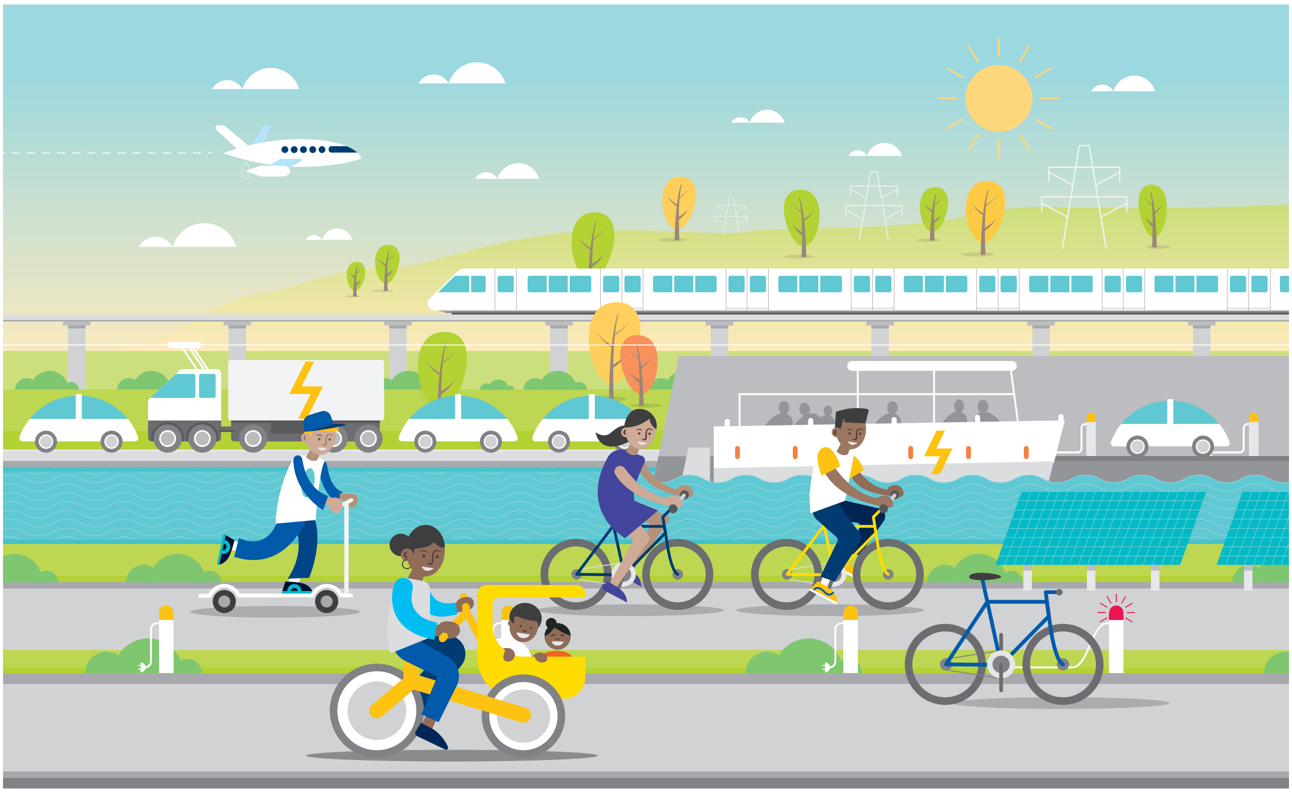
For heavy road vehicles, questions remain about the type of electric system that might prove effective. The energy density of batteries means that electric HGVs are unlikely to have the range to compete with existing technologies. One consideration is the use of so-

"We already now have active buildings where the excess electricity from the photovoltaics is powering the electric cars."

James Durrant
Imperial College London

History of electricity production by source alongside an estimate of 2019 car usage if all were Evs.





called e-highways where main roads have overhead charging cables that eHGVs can use via retractable systems to connect to overhead power cables. This allows the battery component to be smaller as it does not need to provide the full required range. In addition, they can be used as a retrofit to current vehicles to increase the chance of quick, impactful interventions. As will be discussed in the next section, the other potential strategy for heavy road vehicles is the use of low-carbon fuels.

For buses there are broadly three options: battery electric, trolleybus-like systems, and fuel cell buses. Full battery electric buses may struggle with the high mileages and usage patterns of certain bus routes. A return of the trolleybus (a bus connected to fixed electric infrastructure) might be the optimal solution for overcoming such limitations. Much like with HGVs, a pantograph system alongside a battery could allow the bus to charge on main routes and use the battery for the areas not fit for the electric infrastructure. The decision between electric and low-carbon fuel options is much less clear cut. For routes that are more central, trolleybuses and battery electric vehicles might be the most suitable and for more rural longer distance routes low-carbon fuels may be more appropriate. Initial indications from existing roll-outs seem to imply that electric options are both more efficient and easier to manufacture.

For ocean going vessels, the range of batteries is unlikely to ever meet the requirements without significant challenges. For this reason, low-carbon fuels are considered the most viable transition for this sector. They are currently expensive and incentive structures to switch are not in place.

Even in sectors where roll-out is ongoing there are significant challenges and questions for research to influence. For example, policies need to be designed to simultaneously incentivise the transition from combustion engine cars to electric cars whilst also significantly disincentivising car usage overall.

This involves ensuring that the required infrastructure for electric vehicles does not remove space for active modes and also that other incentives (such as subsidies) do not promote the mode over more sustainable modes.

"In trying to be more energy efficient and reducing demand, we can strengthen the electrical grid and reinforce it and make it smarter. We can invest in regional hydrogen projects and support the adoption of electrification of heating and vehicles; those are all things that should be progressed quickly."

Nilay Shah
Imperial College London

RESEARCH SNAPSHOT

- For passenger and rail vehicles, prior research into electrification has made roll-out an immediate and viable option.
- Further research is needed to ensure batteries are optimised, recyclable, and made of non-toxic materials as well as minimising the impacts of additional charging infrastructure.
- Heavy vehicles require substantial research to overcome range and weight issues.
- Research is needed to examine the optimal combinations of use-cases between different options; for example, fixed infrastructure versus battery systems and retrofits versus new systems.

DECARBONISATION OF ENERGY SUPPLY

"The focus right now, in the next 30 years, should really be on what fuels we can make sustainably by solar fuels, and which transport sectors would they be most useful in. And certainly for freight, heavy transport, ships, aviation, trucks... electric vehicles are just not going to cut it right now."

Andreas Kafizas
Imperial College London

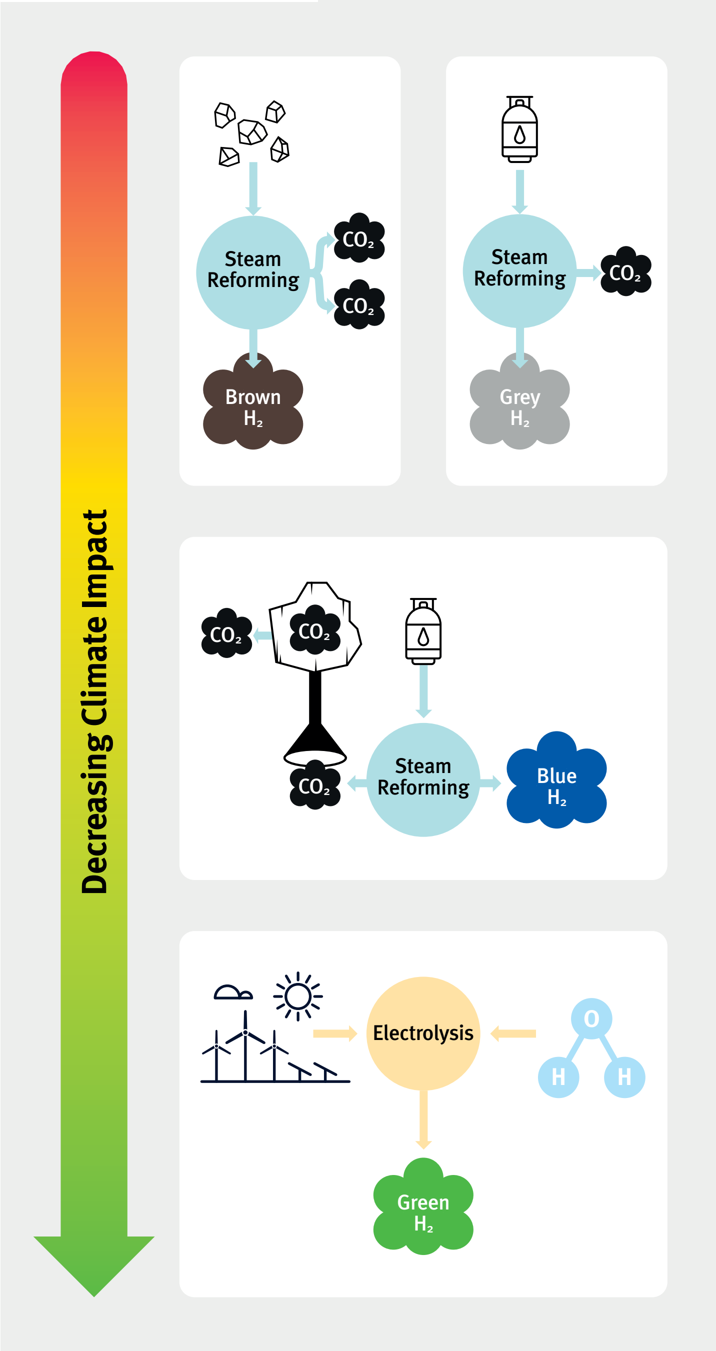
LOW CARBON FUELS

Alternative low-carbon fuels involve the production of fuels using renewable or other low-carbon sources. The most well-developed fuel for production is hydrogen but use of hydrogen as a fuel involves more substantive infrastructural changes at the demand side than other fuels might.

To qualify as sustainable and low-carbon, synthetic fuels must be produced from low-carbon energy sources. As can be seen in Figure X, for every additional step away from energy generation there are losses. Any low-carbon fuel will need to start with a source of low-carbon energy, for example solar energy, and that energy should either be converted into electricity in order to drive hydrogen production, e.g. by electrolysis, or used directly to generate hydrogen from water using photocatalysis. Synthetic fuels most likely need to use hydrogen as a feedstock and as such require a further conversion step or steps. Due to the compounding conversion losses, the additional benefits of fuel in either hydrogen or synthetic fuel form have to be significant enough to outweigh the additional losses of conversion. The benefits of fuels are likely to be in the increased storability of the energy allowing for the energy source to be decoupled from the usage in both space and time.

In addition to energy losses there are other considerations. Hydrogen has a very high energy density when considering the mass but requires larger volumes to store. As such hydrogen is likely to require substantial changes to existing infrastructure at point-of-use as well as additional distribution systems. The potential advantage of further conversion of hydrogen to synthetic liquid fuels is that those fuels might make better use of embodied emissions in current

Hydrogen production methods



vehicles, by allowing those vehicles and associated infrastructure to continue to be used with little conversion. For example, methanol is already used to help shipping meet its environmental regulations. Producing methanol through Green Hydrogen could provide a synthetic fuel compatible with current engines.

Hydrogen is already produced and used for a number of purposes, including the production of fertiliser for agriculture. There are different ways of producing hydrogen and they tend to be referred to using a colour scheme:

- **Grey or Brown Hydrogen** produced using fossil fuels (Natural Gas and Coal respectively). This forms the vast majority of current production.
- **Blue Hydrogen:** Grey Hydrogen combined with carbon capture of the emissions.
- **Green Hydrogen:** Hydrogen that is made using electrolysis to split water using low-carbon electricity sources or hydrogen that is made through photo or photoelectrocatalysis where sunlight is captured and used to directly split water.

Alongside current usage, if hydrogen was used at scale for low carbon transport and fuels, production would need to be massively scaled up. The 2019 EU hydrogen roadmap suggests that a 2050 'ambitious' level of demand for hydrogen would represent 136 times more production than current rates of green hydrogen. It is clear from this that large scale sustainable hydrogen production will be challenging. Additional demands on the hydrogen supply will need to be scrutinised carefully in terms of the value they generate and other options modelled and evaluated. With limited supply of low-carbon energy, each use will also come with opportunity costs that need to be weighed and balanced.

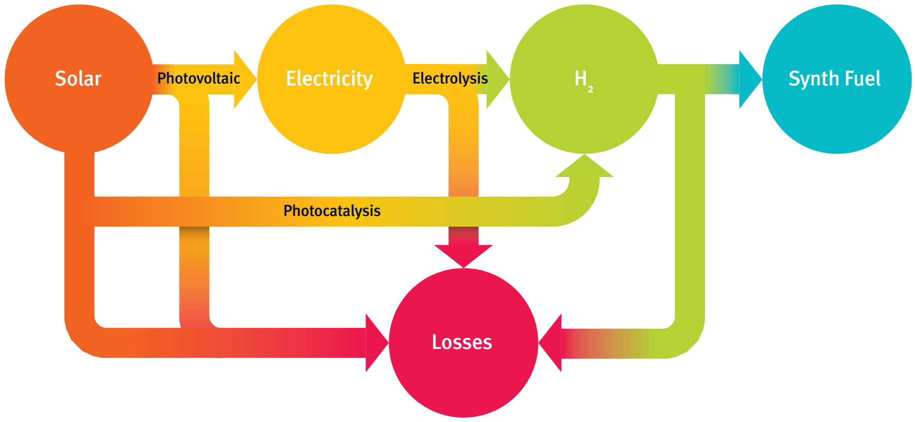
'Synthetic fuels' refer to other, mostly liquid, manufactured fuels. Most pathways for synthetic fuels require hydrogen as an input and as such low-carbon hydrogen is a prerequisite for low carbon synthetic fuels. The core potential benefit for synthetic fuels is being able to produce a fuel that would integrate directly into existing infrastructure. Research into synthetic fuels is still very active and poses questions about what molecular compound would represent the best balance of efficient production and efficient usage.

One method of producing synthetic fuels is using the Fischer-Tropsch process which requires input from carbon dioxide as well as hydrogen. By sourcing the carbon dioxide from a form of carbon capture this helps to keep the resulting fuel close to low-carbon. However, this only works effectively for mitigation if the carbon is removed from the atmosphere and not captured at the point of new emissions.

One alternative is using catalytic conversion systems that combine biomass or waste with the hydrogen to produce a synthetic biofuel. Biofuels (including synthetic ones) are often discussed as routes to decarbonisation, however, emissions from biofuel production and use can incur substantial energy and emissions penalties. Emissions are highly dependent on the choice of feedstock (the crops grown to turn into biofuels) while land area requirements severely limit the scale of biofuel production. In order to be sustainable and fair biofuel production would need to have very low land-intensity requirements and not indirectly impact another use of the feedstock (e.g. food). Biofuels from waste can be positive, however the supply will be unable to respond to large changes in demand. Small amounts of biofuels can be blended into existing fuel stocks to provide small reductions in emissions whilst transitions take place; for example, in 2021 the main petrol blend in the UK was altered to contain 10% biofuel.

International shipping, heavy road haulage and aviation, are the transport sectors that will likely be the most suited for any hydrogen or synthetic fuel interventions due to the difficulties faced using other alternatives, but significant impacts are unlikely to be felt in the early stages of the net-zero decarbonisation timeframe.

Energy flow of electricity and low-carbon fuel production from solar energy.



"The debate between hydrogen and synthetic efuels is a tradeoff between the technology maturity of the hydrogen onboard the vehicle versus the extra cost of making a synthetic fuel, and then using the relatively mature engine technology. From an environmental footprint you certainly need a lot less renewables to make the hydrogen than you need to make a synthetic efuel."

Nigel Brandon
Imperial College London

RESEARCH SNAPSHOT

- Sustainable pathways for the generation of hydrogen is a highly active field of research. It encompasses both green electricity-powered electrolysis as well as direct photo generation of hydrogen through water-splitting (catalysis).
- Research into low-carbon production of synthetic fuels is much less well developed than for hydrogen but liquid fuels could be more compatible with existing infrastructure.
- Research is needed to establish the most effective method of generation, accounting for the entire systems, as well as best use cases for maximising carbon abatement for limited supplies of sustainable fuels as they develop.

STUBBORN EMITTERS: AVIATION

Aviation is a particularly problematic sub-sector. The impacts are outsized due to high energy intensity, and issues such as contrail formation lead to larger warming potentials than just their greenhouse gas outputs would suggest. The mechanics of this form of transport make either electrification or alternative fuels much harder to roll out.

In all sectors (be they transport, buildings or industrial manufacturing) there will be sub-sectors which are particularly difficult to tackle. For transport this is aviation and international shipping. Aviation poses particular challenges that make it a stubborn emitter:

- It is an energy intense mode.
- Demand for it has been significantly increasing.
- Decarbonisation options for the supply of the energy are very limited.
- Non-CO_2 factors (condensation trails) are significant and multiply the harm.
- It has limited options for modal shift: the majority of carbon emissions come from long-haul flights where high-speed rail is not feasible.
- Some trips, e.g. business trips might be avoidable through alternatives such as video-conferencing, but the majority of flights (81% of UK flights) are for visiting family and friends and for leisure purposes where this intervention is likely to be limited.

Flying is an energy intensive mode of transport and the negative impacts are dominated by a minority of wealthy users who have an outsized impact. Currently, around 90% of people in the world do not fly and the total global warming potential is between 2.5 and 3% of all human activity. As such, measures must be developed in order to fairly control aviation's use and to reverse its growth, as well as to determine which aviation trips to prioritise until effective mitigation strategies can be put in place.

Within the necessary timescales for decarbonisation, electrification is unlikely to be able to tackle medium and long-haul flights due to the limited energy density of batteries. Sustainable aviation fuel options such as biofuels and synthetic fuels are being actively researched. Both of these options for alternative fuels have limitations, as we discuss in the low-carbon fuels section, and are unlikely to be developed and production scaled up enough to meet demand sustainably within the terms of the Paris Agreement.

One non-CO_2 factor is the formation of persistent contrails. Contrail formation results from emission of particles from a jet engine in humid and cold conditions, where water condenses onto the soot particles and then freezes, leaving ice crystals that remain rather than sublimate as the plume gets diluted.

Contrails can have significant extra warming impacts such that an average flight has roughly double the global warming impact of the CO_2 emitted. Recent research suggests that contrail-related warming could be reduced significantly by implementing methods to identify and avoid areas where the conditions to generate these warming contrails prevail.

Research into a range of such greenhouse gas removal (GGR) technologies is active and increasing. GGR technologies remove carbon from the atmosphere, however they are currently in their infancy and only come into practice late in any net-zero timeframe. The IEA (International Energy Agency) net-zero plan, which sits at the higher end of expected use of these technologies, suggests that in 2050 GGR will be providing only 6% of the total CO_2 reductions. With many different and difficult sub-sectors competing for this technology it is clear that the vast majority of progress needs to be in effective non-GGR strategies with GGR capacity being prioritised for the areas that add the most value to society as a whole. For aviation, this is likely to mean that more stringent demand management systems and focussed research into the drivers of demand will be needed.

> ***"By making small changes to the altitudes of flights and flight planning, the contrail impact could be dealt with in a relatively short space of time, certainly compared to decarbonising aviation and the scaling up of alternative fuels or other forms of aviation."***
>
> **Marc Stettler**
> Imperial College London

RESEARCH SNAPSHOT

- Research is needed into the drivers of demand and effective, socially-robust and just strategies for demand limitation.
- Research into the exact non-CO_2 warming effects on a flight by flight basis is a very active research topic, as well as the development of flight control systems that minimise the formation of persistent warming contrails.
- Research is needed in order to maximise occupancy further to make maximal use of flights that do continue.
- Research into electric power and alternative fuels for aviation is highly active and will need to continue at pace if aviation can begin to expand again in the second half of the century.

THE TALE OF TWO ERAS: RESTRAINT AND FUTURE TECH

We stand at a crossroads. To stave off the worst impacts of the climate crisis we must enter an era of rebalancing and restraint: prioritising energy usage to meet our most important needs and limiting its use for luxury purposes. Action must be taken now but there are a number of exciting developments that may in the longer term help to alleviate the pressure. Here we spotlight just a few of them.

Innovative Pedal Power

Ebike usage has brought a significant change in how we understand the value of pedal-powered vehicles. Current legislation limits the speed and power of these vehicles but future pathways might include a much wider array of pedal-powered vehicles.

Velomobiles are recumbent bicycles with aerodynamic fairings coupled with electric assist technologies; with the right policy environment, velomobiles could significantly erode the dominance of private car use over longer distances.

Innovations in electric assistance could also facilitate a wider use of pedal power for heavier forms of cargo, perhaps by coupling it with the advantages of lowered friction for rail systems. As these vehicles get bigger and more valuable, theft and storage will increasingly become issues and research is needed to develop secure and simple solutions.

VR/AR Technologies

Virtual Reality or Augmented Reality systems allow users to experience entirely virtual environments. During the Covid-19 pandemic we have seen how some human interactions have adapted well to current online forms of communication whilst others, particularly social interactions and care, have struggled. During the pandemic VR and AR technologies have been trialled in medical settings to lower the risk of transmission.

VR systems might allow interactions that occur virtually to feel more authentic than current systems, which might facilitate more profound trip avoidance, particularly for international trips. One potential issue for VR / AR systems is that they are expected to use much more bandwidth and therefore consume more energy than current ICT systems. As a result, careful checks and balances will need to be in place to ensure that usage of these systems does not lead to further escalations in energy demand.

Airships

Airships have at various points been considered as alternatives to aeroplanes and have potentially much lower emissions. High-profile disasters and the higher speeds of aeroplanes led to them fading out. They offer potentially much lower carbon emissions than aeroplanes and, if a culture of decarbonisation is embedded in their development, overnight or multi-day low-carbon airship flights may become a future mode of transportation and travel.

In addition to passenger flights, airships offer a great deal of potential for replacing freight aviation. Many freight movements are not so time-pressured as to need the high speeds of aeroplanes, and the potentially lower costs of airships could make them the more economical option. Though refinement and development is clearly needed, with some companies already trialling passenger flights, blimps might turn out to be more than just a blip on the horizon.

"I think there are innovations and really exciting developments in the early stages. I definitely think some strategic thinking is needed. We've got core technologies, but the process itself is quite slow. How can we accelerate that?"

Billy Wu
Imperial College London

"Interest in AR and VR has hugely increased in light of the Covid-19 pandemic, with a number of organisations successfully using these technologies and considering their potential to replace long-distance travel."

Adrian Cowell
Imperial College London

FUTURE PATHWAYS

Although we can not know the exact pathway the world will take to decarbonise, if indeed it manages to at all, we have isolated the key trends that will need to take place. In this final section we outline one possible timeline of events.

2020s

Research and Technology

- Systems models are built on accommodating energy systems and better models of behaviour and social science. Increasing data and digital integration makes the models accurate and widely applicable.
- Open source, easy-to-use tools are released for policy makers allowing them to start planning and implementing the most effective policies.
- Fundamental research in materials development for electrolysers and catalysts for water-splitting for low-carbon fuels is ongoing.

Society and Policy

- A renewed focus on our and the planet's health and well-being emerges. Outlooks on the local environment combined with sustainable policy changes leads to the reworking of urban environments to prioritise active and public transport leading to mass modal shifts.
- Most countries begin banning new fossil fuel passenger vehicles, and frequent flying levies are imposed. Mandatory reporting of emissions is introduced for organisations. The foundations for the future are built and big green infrastructure projects are launched.

2030s

Research and Technology

- Systems research starts to respond rapidly to adaptation and resilience issues as the climate becomes hotter and more variable.
- Significant focuses on lightweighting and behavioural interventions in vehicle use.
- Low-carbon fuels research begins to look at the challenges of scaling up and full integration into the system.

Society and Policy

- Intra-continental high speed and sleeper train services begin to cut significantly into aviation demand.
- Cities have been completely reconfigured: sustainable transport dominates, as does working from home and videoconferencing for all purposes.
- Policies are in place that ban all fossil fuel cars alongside support for retrofitting. Electric vehicles of all kinds have become the dominant form of land transportation.

2040s

Research and Technology

- Research will rapidly respond to our inevitably changed environment, a result of baked-in climate change.
- Focus will remain on adaptation and resilience, alongside a continued relentless focus on the final push to reach net-zero.
- New materials for batteries are researched and developed, leading to more recyclable and sustainable batteries beginning to replace traditional lithium-ion batteries.

Society and Policy

- The impacts of climate change bring significant changes, such as migration, but countries have prepared and resilient homes and transport networks are in place.
- Greenhouse gas removal technologies begin to be deployed and ramped up in this decade, allowing for further headroom and minimisation of harm.
- New communities are formed and thrive around common goals of mitigation and regeneration of nature.
- International shipping begins to be powered mostly by sustainable hydrogen and wind, which coupled with more localised production leads to large drops in shipping emissions.

2050 and onwards

Research and Technology

- With mitigation achieved, more research resource can be dedicated solely to adaptation, resilience and regeneration.
- Negative Emissions Technologies research continues and more significant roll-outs are prepared to more quickly repair the damage.
- Future technologies research moves from fundamentals to implementation.

Society and Policy

- With the reaching of net-zero emissions by 2050 humanity has been able to cap the amount of warming. Countless lives have been saved in the process. Transport and attitudes towards it have been completely reshaped: we travel less but our local communities thrive and provide for most of our needs. Work is less location restricted allowing us to live nearer our friends and families. Longer distance travel still occurs but using more energy efficient, slower modes.

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Grantham Institute
Climate Change and the Environment
An Institute of Imperial College London

energy futures lab
An institute of Imperial College London

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The Grantham Institute is committed to driving research on climate change and the environment, and translating it into real world impact. The institute's researchers are developing both the fundamental scientific understanding of climate and environmental change, and the mitigation and adaptation responses to it.

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