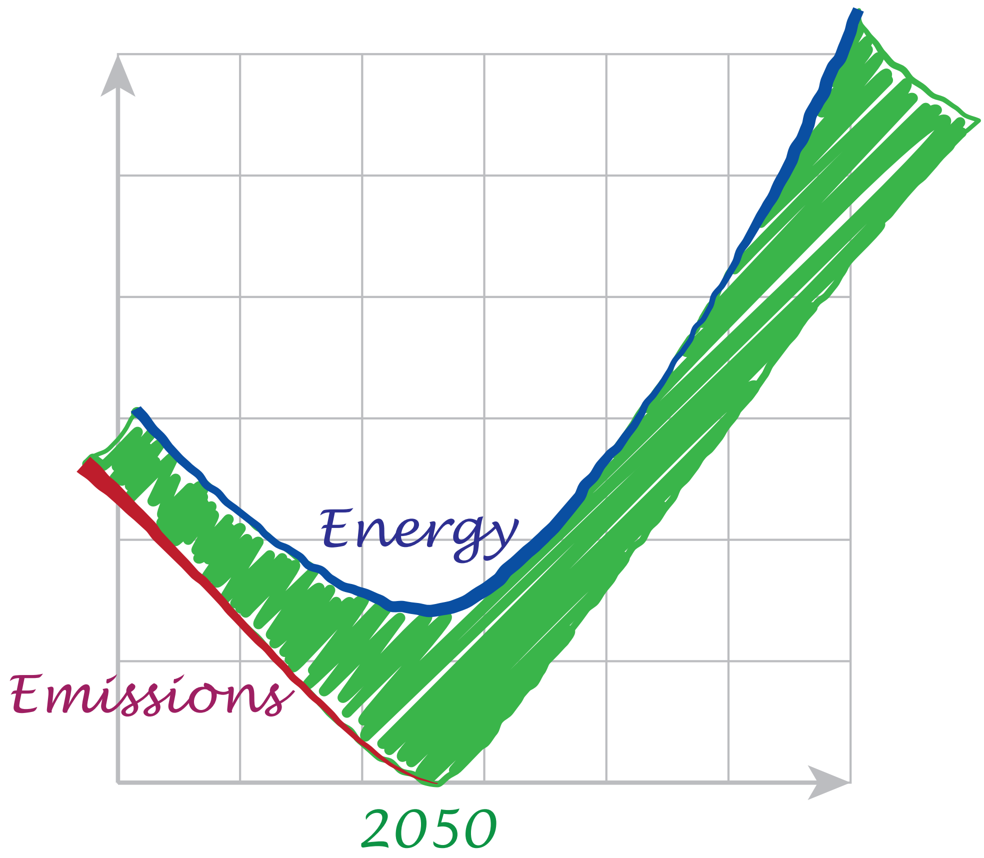
Absolute Zero



Delivering the UK's climate change commitment with incremental changes to today's technologies

UK FIRES

Absolute Zero

UK demand for energy-intensive materials is growing, driving increased emissions in the UK and abroad. UK FIRES is a research programme sponsored by the UK Government, aiming to support a 20% cut in the UK's true emissions by 2050 by placing Resource Efficiency at the heart of the UK's Future Industrial Strategy.

Industry is the most challenging sector for climate mitigation – it's energy efficient and there are no substitutes available at scale for the energy-intensive bulk materials - steel, cement, plastic, paper and aluminium. UK FIRES is therefore working towards an industrial renaissance in the UK, with high-value climate-safe UK businesses delivering goods and services compatible with the UK's legal commitment to zero emissions and with much less new material production.

UK FIRES

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Executive Summary

We can't wait for breakthrough technologies to deliver net-zero emissions by 2050. Instead, we can plan to respond to climate change using today's technologies with incremental change. This will reveal many opportunities for growth but requires a public discussion about future lifestyles.

We have to cut our greenhouse gas emissions to zero by 2050: that's what climate scientists tell us, it's what social protesters are asking for and it's now the law in the UK. But we aren't on track. For twenty years we've been trying to solve the problem with new or **breakthrough** technologies that supply energy and allow industry to keep growing, so we don't have to change our lifestyles. But although some exciting new technology options are being developed, it will take a long time to deploy them, and they won't be operating at scale within thirty years.

Meanwhile, our cars are getting heavier, we're flying more each year and we heat our homes to higher temperatures. We all know that this makes no sense, but it's difficult to start discussing how we really want to address climate change while we keep hoping that new technologies will take the problem away.

In response, this report starts from **today's technologies**: if we really want to reach zero emissions in thirty years time, what does that involve? Most of what we most enjoy - spending time together as families or communities, leisure, sport, creativity - can continue and grow unhindered. We need to switch to using electricity as our only form of energy and if we continue today's impressive rates of growth in non-emitting generation, we'll only have to cut our use of energy to 60% of today's levels. We can achieve this with **incremental** changes to the way we use energy: we can drive smaller cars and take the train when possible, use efficient electric heat-pumps to keep warm and buy buildings, vehicles and equipment that are better designed and last much longer.

The two big challenges we face with an all electric future are **flying** and **shipping**. Although there are lots of new ideas about electric planes, they won't be operating at commercial scales within 30 years, so zero emissions means that for some period, we'll all stop using aeroplanes. Shipping is more challenging: although there are a few military ships run by nuclear reactors, we currently don't have any large electric merchant ships, but we depend strongly on shipping for imported food and goods.

In addition, obeying the law of our Climate Change Act requires that we stop doing anything that causes emissions regardless of its energy source. This requires that we stop eating **beef and lamb** - ruminants who release methane as they digest grass - and already many people have started to switch to more vegetarian diets. However the most difficult problem is **cement**: making cement releases emissions regardless of how it's powered, there are currently no alternative options available at scale, and we don't know how to install new renewables or make new energy efficient buildings without it.

We need to discuss these challenges as a society. Making progress on climate change requires that the three key groups of players - government, businesses and individuals - work together, rather than waiting for the other two to act first. But until we face up to the fact that breakthrough technologies won't arrive fast enough, we can't even begin having the right discussion.

Committing to zero emissions creates tremendous **opportunities**: there will be huge growth in the use and conversion of electricity for travel, warmth and in industry; growth in new zero emissions diets; growth in materials production, manufacturing and construction compatible with zero emissions; growth in leisure and domestic travel; growth in businesses that help us to use energy efficiently and to conserve the value in materials.

Bringing about this change, and exploring the opportunities it creates requires three things to happen together: as individuals we need to be part of the process, exploring the changes in lifestyle we prefer in order to make zero emission a reality. **Protest is no longer enough** - we must together discuss the way we want the solution to develop; the government needs to treat this as **a delivery challenge** - just like we did with the London Olympics, on-time and on-budget; the emitting businesses that must close cannot be allowed to delay action, but meanwhile the authors of this report are funded by the government to work across industry to support the **transition to growth compatible with zero emissions**.

Breakthrough technologies will be important in the future but we cannot depend on them to reach our zero emissions target in 2050. Instead this report sets an agenda for a long-overdue public conversation across the whole of UK society about how we really want to achieve Absolute Zero within thirty years.

Key messages for industrial sectors

Key Message: Absolute Zero creates a driver for tremendous growth in industries related to electrification, from material supply, through generation and storage to end-use. The fossil fuel, cement, shipping and aviation industries face rapid contraction, while construction and many manufacturing sectors can continue at today's scales, with appropriate transformations.

Leisure, sports, creative arts and voluntary work: These sectors can expand greatly and should have a central position in national definitions of welfare targets.

Electricity sector and infrastructure: Absolute Zero requires a 3x expansion in non-emitting electricity generation, storage, distribution and load-balancing.

Construction sector: All new builds should be to zero-energy standards of use. The impacts of construction are primarily about the use of materials: primarily steel and cement. By 2050, we will have only very limited cementitious material and will use only recycled steel, but there are myriad opportunities for radical reductions in the amount of material used in each construction.

Steel sector: All exsiting forms of blast furnace production, which are already under great pressure due to global over-capacity, are not compatible with zero-emissions. However, recycling powered by renewables, has tremedous opportunities for growth exploiting the fact that steel scrap supply will treble in the next 30 years. There are short term innovation opportunities related to delivering the highest quality of steel from recycling, and longer-term opportunities for technologies for zero-carbon steel making from ore that could be deployed after 2050.

Cement sector: All existing forms of cement production are incompatible with zero emissions. However, there are some opportunities for expanded use of clay and urgent need to develop alternative processes and materials. Using microwaves processes to recycle used cement appears promising.

Mining and material supply: Zero emissions will drive a rapid transition in material requirements. Significant reduction in demand for some ores and minerals, particularly those associated with steel and cement, are likely along with a rapid expansion of demand for materials associated with electrification. It seems likely that there will be opportunities for conslidation in the currently diffuse businesses of secondary material collection, processing, inventory and supply.

Rail: The great efficiency of electric rail travel suggests a significant expansion in this area, domestically and internationally, is likely and would see high demand. The most efficient electric trains are aerodynamically efficient, like those designed for the highest speed operation today, but travelling at lower speeds.

Road vehicles: The transition to electric cars is already well under-way, and with increasing demand, costs will presumably fall. We already have targets for phasing out non electric vehicles, but by 2050 will have only 60% of the electricity required to power a fleet equivalent to that in use today. Therefore we will either use 40% fewer cars or they will be 60% the size. Development of auto-grade steels from recycling is a priority, and the need to control recycled metal quality may require changed models of ownership. The rapid expansion of lithium battery production may hit short-term supply constraints and create environmental concerns at end-of-life unless efficient recycling can be developed.

International freight: We currently have no non-emitting freight ships, so there is an urgent need for exploration of means to electrify ship power, and options to transfer to electric rail. This would require an enormous expansion in international rail capacity.

Aviation: There are no options for zero-emissions flight in the time available for action, so the industry faces a rapid contraction. Developments in electric flight may be relevant beyond 2050.

Fossil fuel industries: All coal, gas, and oil-fuel supply from extraction through the supply chain to retail must close within 30 years, although carbon capture and storage may allow some activity later.

Travel and tourism: Without flying, there will be growth in domestic and train-reach tourism and leisure.

Food and agriculture: Beef and lamb phased out by 2050 and replaced by greatly expanded demand for vegetarian food. Electricity supply for food processing and storage will be cut by 50%.

Building maintenance and retrofit: Rapid growth in demand for conversion to electric heat-pump based heating matched to improvements in insulation and air-tightness for building envelopes.

Key messages for individuals

Key Message: The big actions are: travel less distance, travel by train or in small (or full) electric cars and stop flying; use the heating less and electrify the boiler when next upgrading; lobby for construction with half the material for twice as long; stop eating beef and lamb. Each action we take to reduce emissions, at home or at work, creates a positive ripple effect.

As individuals we can all work towards Absolute Zero through our purchasing and our influence. Each positive action we take has a double effect: it reduces emissions directly and it encourages governments and businesses to be bolder in response. Where we cause emissions directly we can have a big effect by purchasing differently. Where they are released by organisations rather than individuals, we can lobby for change.

The actions stated as absolutes below are those which will be illegal in 2050 due to the Climate Change Act.

Living well

The activities we most enjoy, according to the UK's comprehensive time-use survey, are sports, social-life, eating, hobbies, games, computing, reading, tv, music, radio, volunteering (and sleeping!) We can all do more of these without any impact on emissions.

Travelling

The impact of our travelling depends on how far we travel and how we do it. The most efficient way to travel is with a large number of people travelling in a vehicle with a small front, and we can all reduce our total annual mileage.

1. Stop using aeroplanes
2. Take the train not the car when possible.
3. Use all the seats in the car or get a smaller one
4. Choose an electric car next time, if possible, which will become easier as prices fall and charging infrastructure expands.
5. Lobby for more trains, no new roads, airport closure and more renewable electricity.

Heating and appliances:

Our energy bills are mainly driven by our heating and hot water.

1. Use the boiler for less time, if possible, staying warm by only heating rooms if people are sitting in them, sealing up air gaps and adding insulation.
2. Wear warmer clothes in winter.
3. Next time you replace the boiler, choose an electric air or ground-source heat pump if possible
4. Buy smaller more efficient appliances that last longer
5. Lobby for zero-carbon building standards, means-tested support for housing retrofit and more renewable electricity

Purchasing:

Most industrial emissions relate to producing materials, which are made efficiently but used wastefully so we need to reduce the weight of material made. The highest volumes of material are used not by households, but to make commercial and public buildings and infrastructure, industrial equipment and vehicles.

1. Lobby businesses and the government to make buildings and infrastructure with half the material guaranteed to last for twice as long.
2. When extending or modifying your home, try to choose recycled or re-used materials and avoid cement.
3. Aim to reduce the total weight of material you purchase each year.
4. Lobby for border controls on emissions in materials (like we have with food standards) to allow businesses fit for Absolute Zero to grow and prosper in the UK

Eating:

Small changes in diet can have a big effect.

1. Reduce consumption of beef and lamb as these have far higher emissions than any other common food.
2. Choose more locally sourced food if possible, to reduce food miles, particularly aiming to cut out air-freighted foods.
3. Aim to use less frozen and processed meals as these dominate the energy use of food manufacturers.
4. Lobby supermarkets to support farmers in using less fertiliser - it has a high impact, but much of it is wasted as it's spread too far away from the plants.

Why this report matters

Key Message: We are legally committed to reducing the UK's emissions to zero by 2050, and there isn't time to do this by deploying technologies that don't yet operate at scale. We need a public discussion about the changes required and how to convert them into a great Industrial Strategy.

Timelines:

In her last significant act as Prime Minister, Theresa May changed the UK's Climate Change Act to commit us to eliminating all greenhouse gas emissions in the UK by 2050. This decision is based on good climate-science, was a response to a great wave of social protest and has been replicated in 60 other countries already.

However, 30 years is a short time for such a big change. Politicians in the UK and internationally talk about climate change as if it can be solved by new energy technologies alone, and UK government reports are over-confident about how much progress has been achieved; in reality most UK cuts in emissions have been as a result of Mrs Thatcher's decision to switch from coal to gas fired electricity and to allow UK heavy industry to close. The UK has been successul in reducing methane emissions - by separating our organic waste and using it in anaerobic digesters to make gas for energy, but new energy technologies are developing slowly.

There are no invisible solutions to climate change so we urgently need to engage everyone in the process of delivering the changes that will lead to zero emissions.

Confusion about technologies

In this report we're using three different descriptions of the technologies which cause emissions:

- **Today's technologies** are the mass-market products of today - such as typical petrol or diesel cars.
- **Incremental technologies** could be delivered today if customers asked for them - for example smaller cars.
- **Breakthrough technologies** such as cars powered by hydrogen fuel cells, may already exist, but haven't yet captured even 5% of the world market.

Incremental technologies can be deployed rapidly, but breakthrough technologies can't. We're concerned that most plans for dealing with climate change depend on breakthrough technologies - so won't deliver in time.

Why we've written this report now

The authors of this report are funded by the UK government to support businesses and governments (national and regional) to develop a future Industrial Strategy that's compatible with Zero Emissions. To do that, we have to anticipate how we'll make future goods and buildings, and also think about what performance we want from them.

What we mean by "Absolute Zero"

The UK's Climate Change Act contains two "escape" words: it discusses "net" emissions and targets on those that occur on our "territory." However, in reality, apart from planting more trees, we don't have any short-term options to remove emissions from the atmosphere, and even a massive expansion in forestry would have only a small effect compared to today's emissions. Furthermore, shutting factories in the UK doesn't make any change to global emissions, and may make them worse if we import goods from countries with less efficient processes.

Public concern about the Climate is too well informed to be side-lined by political trickery on definitions. In writing this report, we have therefore assumed that:

- the target of zero emissions is absolute - there are no negative emissions options or meaningful "carbon offsets." Absolute Zero means zero emissions;
- the UK is responsible for all emissions caused by its purchasing, including imported goods, international flights and shipping.

Invitation to participate

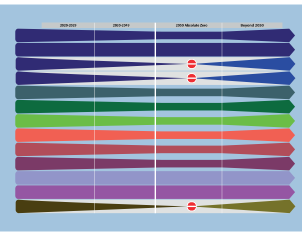
This report presents our best estimate of Absolute Zero, based on publicly reported data and peer-reviewed evidence. Undoubtedly there are more opportunities that we don't know of, and if this report proves useful, there will be other aspects of the journey to Absolute Zero that we can help to inform. We welcome contributions and comment and will provide an edited summary of any discussion on www.ukfires.org. If there is demand, we will update and re-issue the report in response.

Please contact us via info@ukfires.org and if you found this report useful, please share it through your networks.

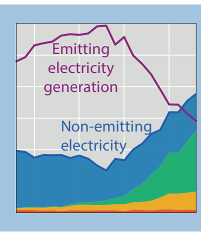
Guide to the report

Opening material

What actions can we take - as individuals and in the key sectors to reduce emissions now and to develop future choices to deliver Absolute Zero?



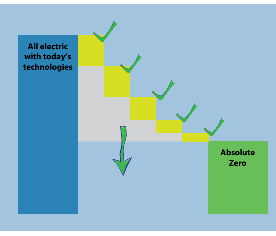
1. Absolute Zero with today's technologies



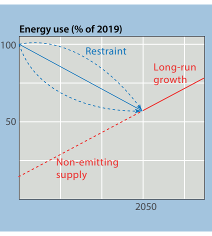
The UK Climate Change Act commits us to zero emissions in 30 years time - based on good climate science. The lowest risk way to get there is to change the way we use today's technologies.

2. Options for incremental and breakthrough innovations

The goods we buy will of course change over the next 30 years, but it takes decades for breakthrough technologies to reach full scale, so we focus on likely incremental innovations.



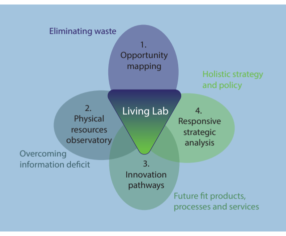
3. The process of change towards Absolute Zero



Reaching Absolute Zero requires a collaboration between individuals, government and businesses. None of them can act unilaterally, so reaching the target will be a process.

4. Opportunities created by Absolute Zero

One of the benefits of considering Absolute Zero is that it allows us to recognise how many opportunities are created by pursuing the strict emissions target.



Notes to the figures

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Figure 1.2: Data from the International Energy Agency (IEA, 2018) with data on CCS installations at power-stations from the Oil and Gas funded pro-CCS lobby, Global CCS Institute.

Figure 1.3: This analysis by Vaclav Smil (2014) looks at global deployments of the three major fossil fuels, relative to total world energy demand at the time. Some faster transitions have occurred in individual countires, as shown in the box story on page 3.

We've tried to make this report as easy to read as possible, but all our analysis is firmly rooted in data. These notes show how we've sourced and used the evidence

References

These references point to the sources we used for data or other evidence.

References

Haberl, H., et al. (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences, 104(31), 12942-12947.

Haerl, H., Erb, K.H., Krausmann, F. Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries. Annual Review of Environment and Resources, 2014, 39 (1): pp. 363-391.

HM Government, 2018. Our waste, our resources ...

	2020-2029	2030-2049	2050 Absolute Zero	Beyond 2050
Road vehicles	Development of petrol/diesel engines ends; Any new vehicle introduced from now on must be compatible with Absolute Zero	All new vehicles electric, average size of cars reduces to ~1000kg.	Road use at 60% of 2020 levels - through reducing distance travelled or reducing vehicle weight	New options for energy storage linked to expanding non-emitting electricity may allow demand growth
Rail	Growth in domenstic and international rail as substitute for flights and low-occupancy car travel	Further growth with expanded network and all electric trains; rail becomes dominant mode for freight as shipping declines	Electric trains the preferred mode of travel for people and freight over all significant distances,	Train speeds increase with increasing availability of zero emissions electricity
Flying	All airports except Heathrow, Glasgow and Belfast close with transfers by rail	All remaining airports close		Electric planes may fly with synthetic fuel once there are excess non-emitting electricity supplies
Shipping	There are currently no freight ships operating without emissions, so shipping must contract	All shipping declines to zero.		Some naval ships operate with onboard nuclear power and new storage options may allow electric power
Heating	Electric heat pumps replace gas boilers. and building retrofits (air tightness, insulation and external shading) expand rapidly	Programme to provide all interior heat with heat pumps and energy retroifts for all buildings	Heating powered on for 60% of today's use.	Option to increase use of heating and cooling as supply of non-emitting electricity expands
Appliances	Gas cookers phased out rapidly in favour of electric hobs and ovens. Fridges, freezers and washing machines become smaller.	Electrification of all appliances and reduction in size to cut power requirement.	All appliances meet stringent efficiency standards, to use 60% of today's energy.	Use , number and size of appliances may increase with increasing zero-emnis-sions electricity supply
Food	National consumption of beef and lamb drops by 50%, along with reduction in frozen ready meals and air-freighted food imports	Beef and lamb phased out, along with all imports not transported by train; fertiliser use greatly reduced	Total energy required to cook or transport food reduced to 60%.	Energy available for fertilising, transporting and cooking increases with zero-emissions electricity
Mining material sourcing	Reduced demand for iron ore and limestone as blast furnace iron and cement reduces. Increased demand for materials for electrification	Iron ore and Limestone phased out while metal scrap supply chain expands greatly and develops with very high precision sorting	Demand for scrap steel and ores for electrification much higher, no iron ore or limestone.	Demand for iron ore and limestone may develop again if CCS applied to cement and iron production
Materials production	Steel recycling grows while cement and blast furnace iron reduce; some plastics with process emissions reduce.	Cement and new steel phased out along with emitting plastics . Steel recycling grows. Aluminium, paper reduced with energy supply.	All materials production electric with total 60% power availability compared to 2020	Material production may expand with electricity and CCS, CCU, hydrogen may enable new cement and steel.
Construction	Reduced cement supply compensated by improved material efficiency, new steel replaced by recycled steel	All conventional mortar and concrete phased out, all steel recycled. Focus on retrofit and adaption of existing buildings.	Any cement must be produced in closed-loop, new builds highly optimised for material saving.	Growth in cement replacements to allow more architectural freedom; new steel may become available.
Manufacturing	Material efficiency becomes promiment as material supply contracts	Most goods made with 50% as much material, many now used for twice as long	Manufacturing inputs reduced by 50% compen-sated by new designs and manufacturing practices. No necessary reduction output.	Restoration of reduced material supplies allows expansion in output, although some goods will in future be smaller and used for longer than previously.
Electricity	Wind and solar supplies grow as rapidly as possible, with associated storage and distribution. Rapid expansion in electrificiation of end-uses.	Four-fold increase in renewable generation from 2020, all non-electrical motors and heaters phased out.	All energy supply is now non-emitting electricity.	Demand for non-emitting electricity drives ongoing expansion in supply.
Fossil fuels	Rapid reduction in supply and use of all fossil fuels, except for oil for plastic production	Fossil fuels completed phased out		Development of Carbon Capture and Storage (CCS) may allow resumption of use of gas and coal for electricity

1. Zero emissions in 2050 with today's technologies

Key Message: Apart from flying and shipping, all of our current uses of energy could be electrified. With tremendous commitment the UK could generate enough non-emitting electricity to deliver about 60% of our current final energy-demand, but we could make better use of that through incremental changes in the technologies that convert energy into transport, heating and products.

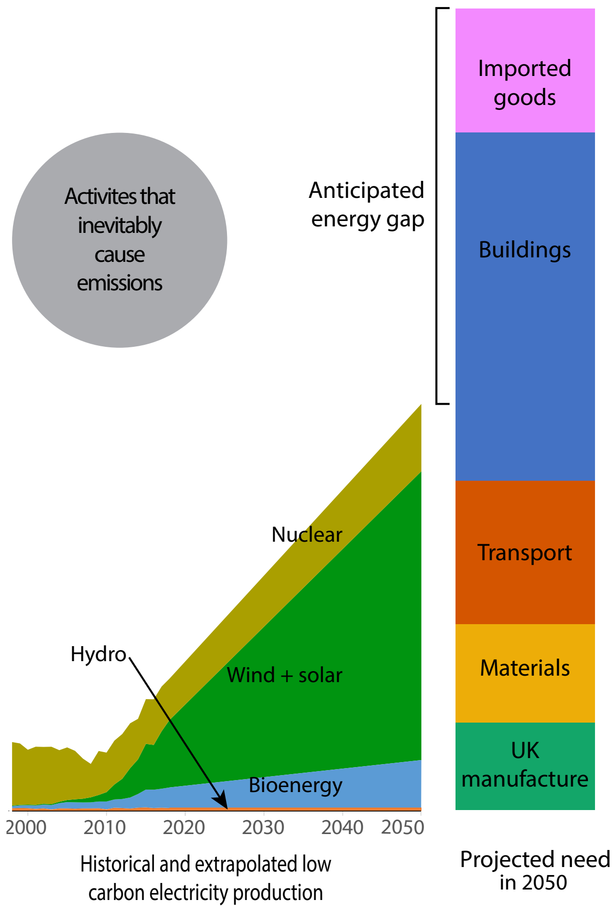
About three quarters of the greenhouse gas emissions caused by humans are emitted when we burn the fossil fuels - coal, gas and oil - and the rest arise from our agriculture (particularly cows and sheep), our conversion of land from forestry to pasture, the way we allow organic waste to decompose, and our industrial processes. Using today's technologies, all of these sources unrelated to energy have no alternative, so reducing our emissions to zero means phasing out these activities.

Our emissions related to energy come from our use of oil (as diesel, petrol or kerosene) for transport, our use of gas for heating our homes and industrial processes, and our use of coal and gas to generate electricity. Some of our electricity is also generated without burning fossil fuels - for instance by nuclear power stations, wind turbines or solar cells - and in a zero emissions future these will be our only source of energy. Most of our current uses of energy could be electrified - as is becoming familiar with electric cars - but there are currently no options for electric flying or shipping. With today's technologies, these modes of transport must therefore be phased out also.

Over the past 10 years in the UK, we have made a significant change to the way we generate electricity and about half of our generation is now from non-emitting sources. If we continue developing the generation system at the same rate, then by 2050 we will have around 50% more electric power than we have today. Data on the efficiencies of today's motors and heaters allows us to estimate that this will be enough to power about 60% of today's energy-using activities (apart from flying and shipping). However, because energy has been so cheap and abundant in the past 100 years, in many cases we could make small changes to existing technologies to make much better use of less energy.

Fig. 1.1 summarises this overview of Absolute Zero with today's technologies: the left side of the figure shows the recent history of the UK's non-emitting electricity generaton extrapolated forwards to 2050. The right side shows the amount of electricity we'd need if we electrified everything we do today, apart from those activities that inevitably cause emissions, which we'll have to phase out.

Figure 1.1: Gap between today and Absolute Zero



1.1 Energy Supply Today

The science is clear: we must stop adding to the stock of greenhouse gases in the atmosphere to control global warming. In response, the best estimates of science today predict that annual global emissions from human activities must be reduced rapidly and should be eliminated by 2050 – in thirty years' time. This target, which requires extraordinarily rapid change, is now law in the UK, and several other countries. However, despite the science and the laws, global emissions are still rising.

The critical choice in planning to cut emissions is about the balance between technology innovation and social choice. Is it possible to develop a new technology that will cut emissions while allowing people in developed economies to continue to live as we do today and to allow developing economies to develop the same behaviours? Or should we first modify our behaviour to reach the emissions target, with different aspirations for development, and then take the benefits of technology innovation when they become available later? To date, as illustrated in Fig. 1.2, every national and international every national and international government plan for responding to climate change has chosen to prioritise technology innovation, yet global emissions are still rising.

For twenty years, two technologies have dominated policy discussions about mitigating climate change: renewable energy generation and carbon capture and storage (CCS). The two renewable technologies now being deployed widely are wind-turbines and solar-cells. These critical forms of electricity generation are essential, and should be deployed as fast as possible, but Fig. 1.3 shows that, they combined with nuclear power and hydro-electricity, still contribute only a small fraction of total global energy demand. Meanwhile, although CCS has been used to increase rates of oil extraction, its total contribution to reducing global emissions is too small to be seen. The technological elements of CCS have all been proven at some scale, but until a first fleet of full-scale power-plants are operating, the risks and costs of further expansion will remain high and uncertain. To illustrate the current importance of CCS in global power generation, the total output of all CCS enabled power-generation is shown on Fig. 1.3 - still very definitely on top of the y-axis.

All previous transitions in the energy system, for example in Fig. 1.4, have occurred relatively slowly. Early installations experience problems due to human error, and the installation of large generation requires lengthy public consultation on land-rights, environmental protection, safety and financing. Despite this, CCS looks very attractive to policy makers. Twenty years ago, the International Energy Agency stated that "within 10 years we need 10 demonstrators of CCS power stations" but none are operating at full-scale today. Yet in 2019 the UK's Climate Change Committee published its plans to deliver zero emissions, requiring deployment of CCS in six of thirteen sectors within thirty years. However, the UK has no current plans for even a first installation and although CCS may be important in future, it is not yet operating at meaningful scale, but meanwhile global emissions are still rising.

The hope of an invisible, technology-led, solution to climate change is obviously attractive to politicians and incumbent businesses. However, a result of their focus on this approach has been to inhibit examination of our patterns of energy demand. Fig. 1.6a shows that the UK's demand for energy is only falling in industry. This is because in the absence of a meaningful industrial strategy, we have closed our own industry in favour of increased imports. As a result, this apparent reduction in energy

Figure 1.2: Acting now or waiting for new technologies

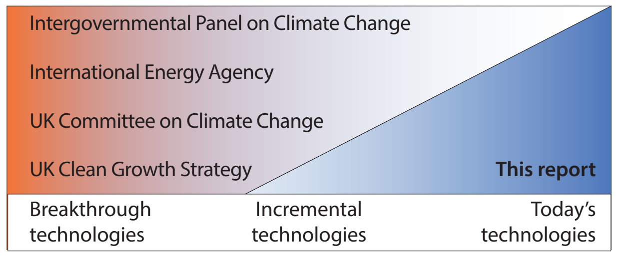


Figure 1.3: World primary energy supply ('000 Mtoe)

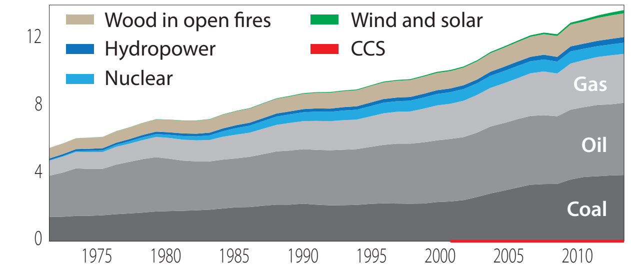
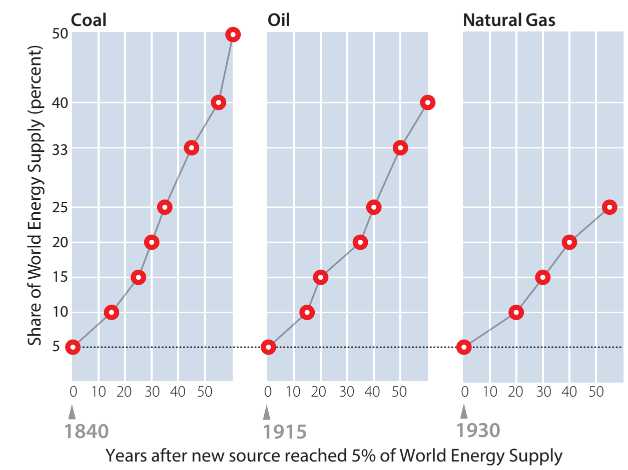


Figure 1.4: Major transitions in global energy supply



Technology Transitions in the Energy System

New computers, clothes and magazines can be put on sale soon after the are invented. However new energy technologies have typically required much longer time to reach full scale: even if the technology is well-established, building a power station requires public consultation about finance, safety, land-rights, connectivity and other environmental impacts all of which take time. For new technologies, it takes much longer, as investors, operators and regulators all need to build confidence in the safety and perfomance of the system. Figure 1.5 summarises the rates of introduction of various new energy technologies in the countries where they grew most rapidly. The green arrow corresponds to the start points of the linear periods of growth shown in Fig. 1.4.

Figure 1.5: Years to deploy energy technologies

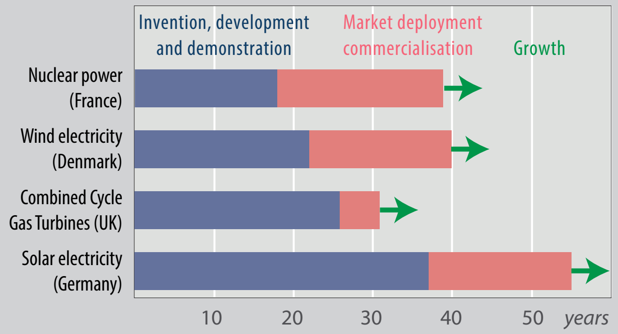
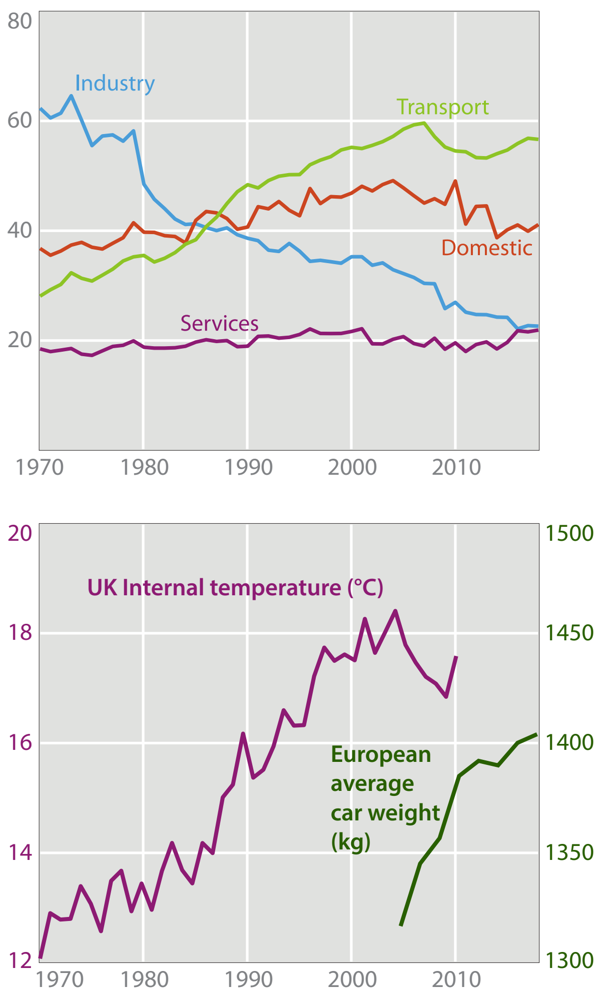


Figure 1.6: Energy demand (a) by sector (Mtoe) influenced by (b) car weight & internal temperature



use is compensated by an increase in other countries. Meanwhile, demand in other sectors is rising, driven, for example, by an increase in the weight of our cars and increased use of heating to raise internal temperatures in winter (Fig. 1.6b). With thirty years remaining to deliver zero emissions and global emissions still rising, we cannot risk waiting for a different energy system, so must have an inclusive public discussion about how we use energy.

2019 has seen a great rise in public concern about climate change, driven by science and growing evidence of changes occurring. So far, social protesters have called for dramatically increased awareness, while engaging in discussion about specific solutions has had less emphasis. However the only solutions available in the time remaining require some change of lifestyle. This report therefore aims to trigger that critical discussion. The report starts with a plan to reach zero emissions by 2050 using only technologies that are already mature today, to minimise the risk that we continue emitting beyond 2050. This is possible but requires some specific restraint in our lifestyles. Innovation can relieve this restraint so the report then presents an overview of the range of options for innovation in the way we use energy as well as how we generate it.

Global emissions are still rising and the need for action is urgent. This report aims to allow us to start an informed discussion about the options that really will deliver zero emissions by 2050.

Key Message: Global demand for energy is rising. In the UK our demand has fallen, but only because we have closed industry and now import goods elsewhere. Policy discussions have prioritised breakthrough technologies in the energy system, particularly carbon capture and storage, but it is at such an early stage of development that it won't reduce emissions significantly by 2050.

1.2 UK Energy System now and in 2050

Climate change is driven by greenhouse gas **E**missions. Most emissions arise from burning fossil fuels to create **E**nergy; some of our energy use is in the form of **E**lectricity. These three words beginning with "E" are often confused in public dialogue, but Fig. 1.7 separates them. Three quarters of global emissions (slightly more in the UK because we import 50% of our food) arise from the combustion of fossil-fuels (coal, gas and oil). Most coal and one third of gas is used in power stations to generate electricity. However, we also generate electricity by nuclear power and from renewable sources. The third column of the figure shows that nearly a half of the UK's current electricity supply is from non-emitting sources, of which nuclear power and the use of imported bio-energy pellets are most important.

Fig. 1.8 shows how the UK's energy supply has developed over the past twenty years. Total demand has fallen, due to the loss of industry shown in Fig. 1.6, but our use of oil and nuclear power has been relatively constant. (The data in both figures disguise the fact that over this period the UK's population has grown by 16% so we have improved the efficiency of our energy use by around 0.5% per year.) The other major change in the figure is the switch from coal to gas powered electricity generation which has reduced UK emissions significantly.

Fig. 1.9 extracts from Fig. 1.8 our generation of electricity – the numbers in this figure for 2018 correspond to those shown in Fig 1.7c – and divides them into emitting and non-emitting sources. This figure shows the UK making good progress in de-carbonising its current levels of electricity supply, and if the linear-trends in the figure continue, then

Figure 1.7: Emissions, Energy and Electricity in the UK

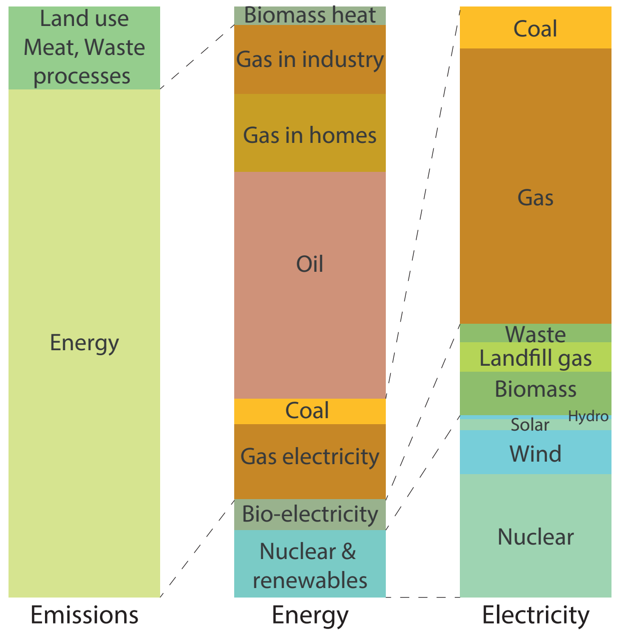
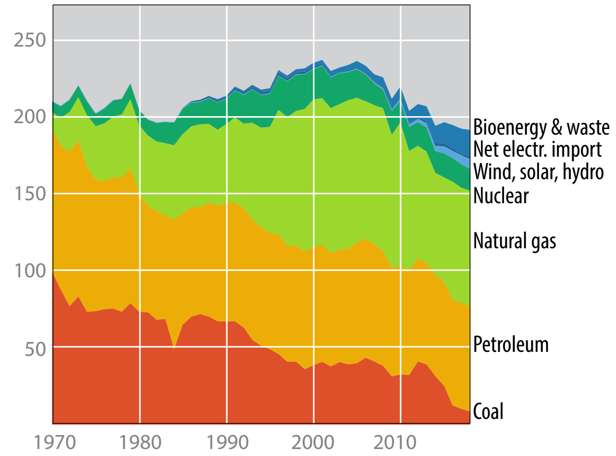


Figure 1.8: UK Primary Energy supply (Mtoe/yr)



by 2050, the UK can be expected to generate around 580 TWh of electricity without emissions. This is the figure shown on Fig 1.1 at the beginning of this chapter.

If we can manage our electricity distribution system and find ways to store electricity from windy/sunny times to be available at still/dull times this suggests that by 2050 we will have around 60% more electricity available than today, all from non-emitting sources. Physically, although the Hinckley C Nuclear Plant will probably by completed by 2030, delivering this increase will largely come from increasing wind-generation. To meet this growth from offshore wind would require an addition of around 4.5 GW of generation capacity each year of the next 2 decades (allowing time for them to be fully operational by 2050). By comparison, the Crown Estate have just launched a process to award 7-8.5 GW of new seabed leases over the next 2 years, but the Offshore Wind Sector Deal expects Government support for the delivery of only 2 GW/year through the 2020s.

Figure 1.9: UK Electricity generation (TWh/year)

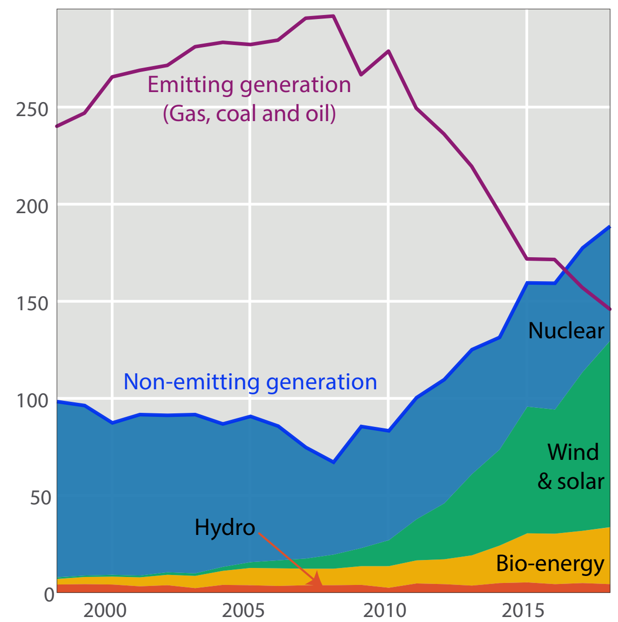
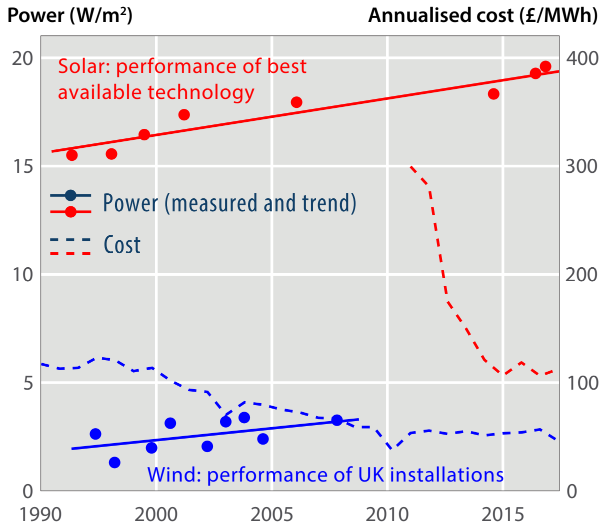


Figure 1.10: Development of wind and solar power



Meanwhile Fig 1.10 shows how the two options for on-shore generation, wind-turbines and solar power, are developing. Both technologies are becoming cheaper, although the amount of power generated from each unit of land is increasing only slowly. Replacing existing on-shore wind turbines with much taller models could increase total generation by 50%. Increasing solar generation depends on the commitment of area, but is plausible: if every south-facing roof in the UK were entirely covered in high-grade solar cells, this would contribute around 80TWh per year

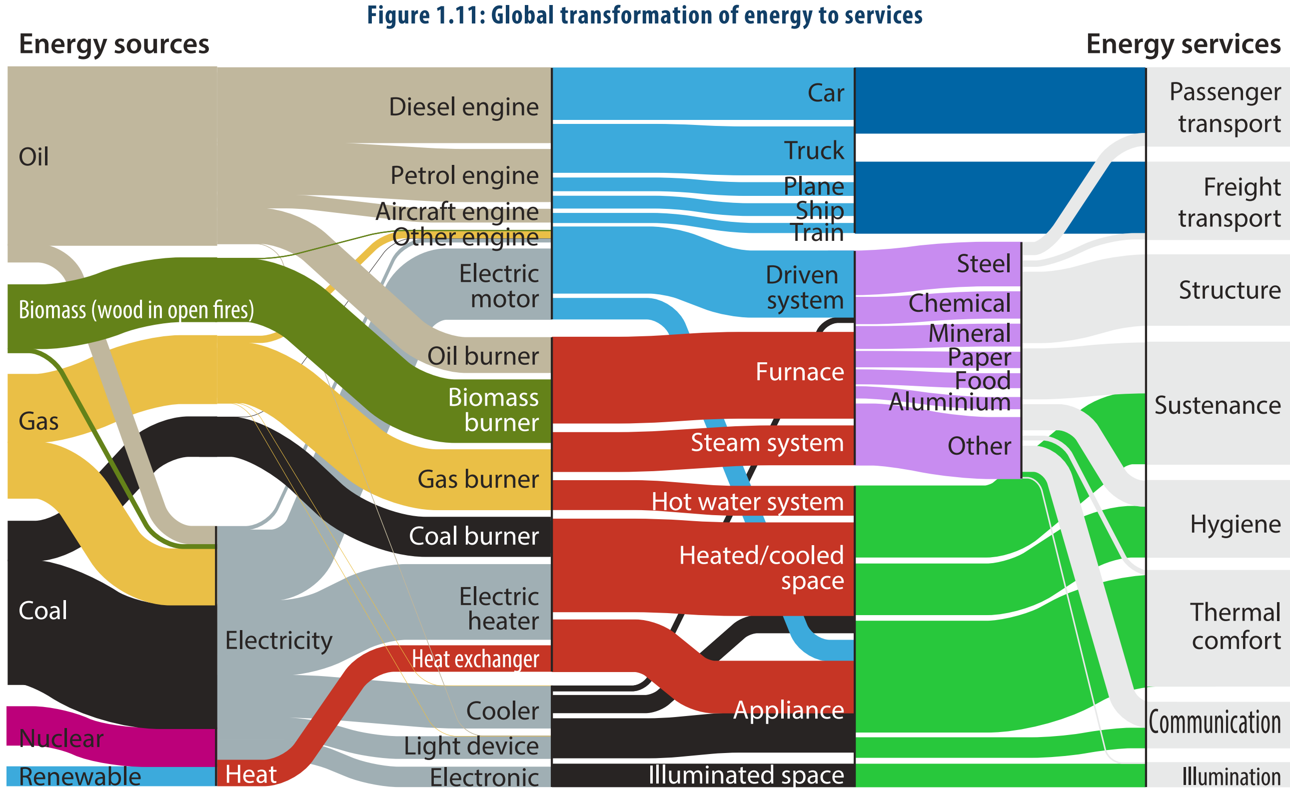
Fig. 1.7 also shows a range of bio-energy sources contributing to the UK's energy supply. All these supplies are combusted, leading to the release of CO_2, but because the fuel derives from plants, these releases form part of the normal cycle so do not accelerate climate change. Waste policy has been a success in UK mitigation since 1990, with organic waste separated and largely processed in anaerobic digestors to produce methane for electricity. However, this source is unlikely to increase further. Meanwhile, bio-energy derived directly from new plant growth is in competition with the use of biomass for food so unlikely to increase (see box story on p13).

This discussion suggests that, using today's technologies and with plausible rates of expansion, the UK will in a zero-emissions 2050 have an energy supply entirely comprising electricity with about 60% more than generated than we have today.

How much of the benefit of all of today's use of energy will we be able to enjoy without any fossil fuels, but with 60% more electricity? At first sight, this sounds like a significant reduction - Fig. 1.7 showed that today, electricity provides only about one third of our total energy needs, so apparently we would need a 200% increase in electricity output? In fact this isn't the case, because the final conversion of electricity into heat or rotation is very efficient compared to the fossil fuel equivalents.

If the UK is to run entirely on electricity, then all devices currently powered with fossil-fuels must be replaced by electrical equivalents. Fig. 1.11 presents a view of how energy is used globally. (We don't currently have an equivalent of this for the UK, but the UK is likely to be similar, although with less industrial use, due to our dependence on imports.) The widths of the lines in the figure are proportional to energy use, and any vertical cut through the diagram could be converted into a pie-chart of all the world's energy use. In effect Fig. 1.11 shows six connected pie-charts, each breaking out the statistics of all the world's energy use into different categories.

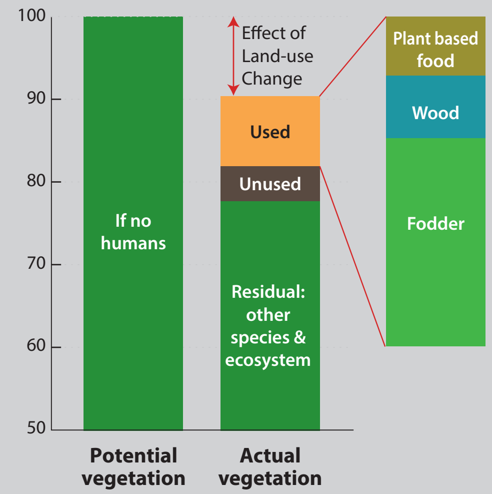
Figure 1.11: Global transformation of energy to services



What's the problem with bio-energy?

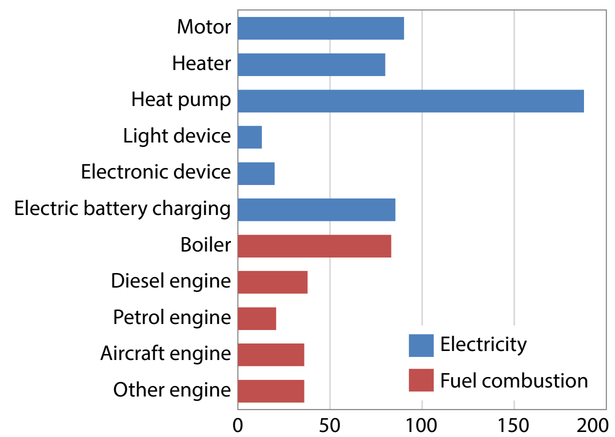
The world's poorest people stay warm and cook with wood burnt on open furnaces, and this energy source shows up significantly in the global energy supplies of Fig. 1.11. Could we use modern technology to harness even more biomass to make other fuels, such as biodiesel or kerosene? Fig 1.12 reveals that more than 20% of the world's total annual harvest of new biomass is already 'appropriated' by humans for wood, food and fodder. This annual harvest is the fundamental source of habitat and food for all non-aquatic species. Any further appropriation by humans is likely to be dangerously harmful to other species and the effect of deforestation rates is already a major contributor to the emissions in fig. 2.10. This evidence suggests that modern bio-fuels are incompatible with any wider sustainability of life on earth.

Figure 1.12: Human appropriation of biomass



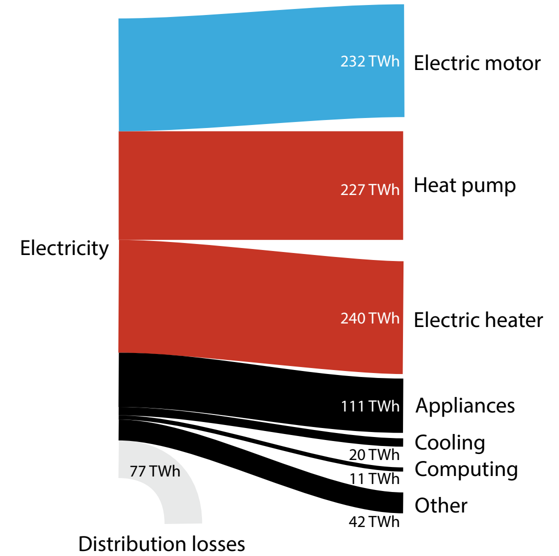
The figure shows that most energy is used in engines, motors, burners and heaters to create motion or heat. To estimate the electricity required if all of these devices are replaced, we use the average efficiencies presented in Fig. 1.13: for example, we know how much power is currently delivered in the UK's cars by petrol engines, so can use Fig. 1.13 to predict how much electricity would be required to provide the same power from electric motors. Combining this conversion with an estimated 11% population growth, leads to our prediction that we would need 960 TWh of electricity by 2050. (A terawatt hour, Twh, is a thousand million kilowatt hours - the unit normally used in UK energy bills.) The final requirement for electricity is split between motion, heating and appliances as shown in Fig 1.14.

Figure 1.13: Efficiency of enegy conversion devices (%)



If the UK is fully electrified by 2050, and we used the same final services as today, our demand for energy as electricity will be 960 TWh. However, based on a linear projection of the rate at which we have expanded our non-emitting electricity supply in the past 10 years, we estimate that we will have just 580 TWh available. Therefore, our commitment to Absolute Zero emissions in 2050 requires a restraint in our use of energy to around 60% of today's levels.

Figure 1.14: UK requirement to electrify today's services



Key Message: If we only used electricity, delivering all the transport, heat and goods we use in the UK would require 3x more electricity than we use today. If we expand renewables as fast as we can, we could deliver about 60% of this requirement with zero emissions in 2050. Therefore in 2050 we must plan to use 40% less energy than we use today, and all of it must be electric.

1.3 Zero emissions in the UK in 2050

In addition to restraining our energy demand to 60% of current levels, meeting our legal commitment to zero emissions will require that we phase out any energy using activities that cannot be electrified and any sources of emissions beyond fossil-fuel combustion. Planning for this requires that we make a collective decision about the scope of our responsibility. The UK's Climate Change Act was written to make commitments based solely on emissions that occur on UK territory. However, this excludes international aviation and shipping and our net imports of goods. As a result, it appears to be a success for UK climate policy when we shut UK industry and instead import goods – even though this will not reduce global emissions, and may often increase them if the closed UK processes were more efficient. Although these limitations were helpful in passing the Climate Change Act into law, they now look morally questionable, and they also fail to create the stimulus to innovation and growth in UK businesses and industries fit for a zero emissions future. This report therefore assumes that the UK should be responsible for the emissions of all its consumption.

Fig. 1.15 shows an analysis of all global greenhouse gas emissions, using a format similar to Fig. 1.11. In this case, the final services that drive the activities that cause emissions are shown at the left of the diagram, leading to the greenhouse gases on the right side of the diagram which cause global warming. The yellow-loop in the middle of the figure demonstrates that most industrial emissions are associated with producing the buildings, vehicles and other equipment which provide final services from energy, but which themselves require energy in production. This is important because most of this year's industrial output is to produce equipment (durables) that will last for several years. The services provided in one year therefore depend on the accumulation of a stock of goods made in previous years - and this long-lasting stock limits the rate at which change can be made to our total emissions. For example, if cars last on average for 15 years, then to ensure that all cars are electric in 2050, the last non-electric car must be sold no later than 2034. As with Fig. 1.11, Fig. 1.15 is based on global data - again to reflect the consequences of UK consumption, rather than its "territorial" emissions.

The top three quarters of this figure demonstrate the emissions consequences of our use of energy. The two critical forms of equipment that cannot be electrified with known technology are aeroplanes and ships. Although Solar-Impulse 2, a single-seater solar-powered electric aeroplane circumnavigated the Earth in 2016, it is difficult to scale up solar-powered aeroplanes due to the slow rates of improvement in of solar cell output put unit of area shown in Fig. 1.10. Meanwhile battery-powered flight is inhibited by the high weight of batteries, bio-fuel substitutes for Kerosene face the same competition for land with food as described in section 1.2 and there are no other ready and appropriate technologies for energy storage. As a result, under the constraint of planning for zero emissions with known technologies, all flying must be phased out by 2050 until new forms of energy storage can be created. At present we also have no electric merchant ships. There isn't space to have enough solar cells on a ship to generate enough energy to propel it, and as yet there has been no attempt to build a battery powered container ship. Nuclear powered naval ships operate, but without any experience of their use for freight, we cannot safely assume that nuclear shipping will operate at any scale in 2050. This is a serious challenge: with today's technologies, all ship-based trade must be phased out by 2050.

Figure 1.15: Global Greenhouse Gas Emissions - from service to emissions, with most industrial emissions adding goods to stock

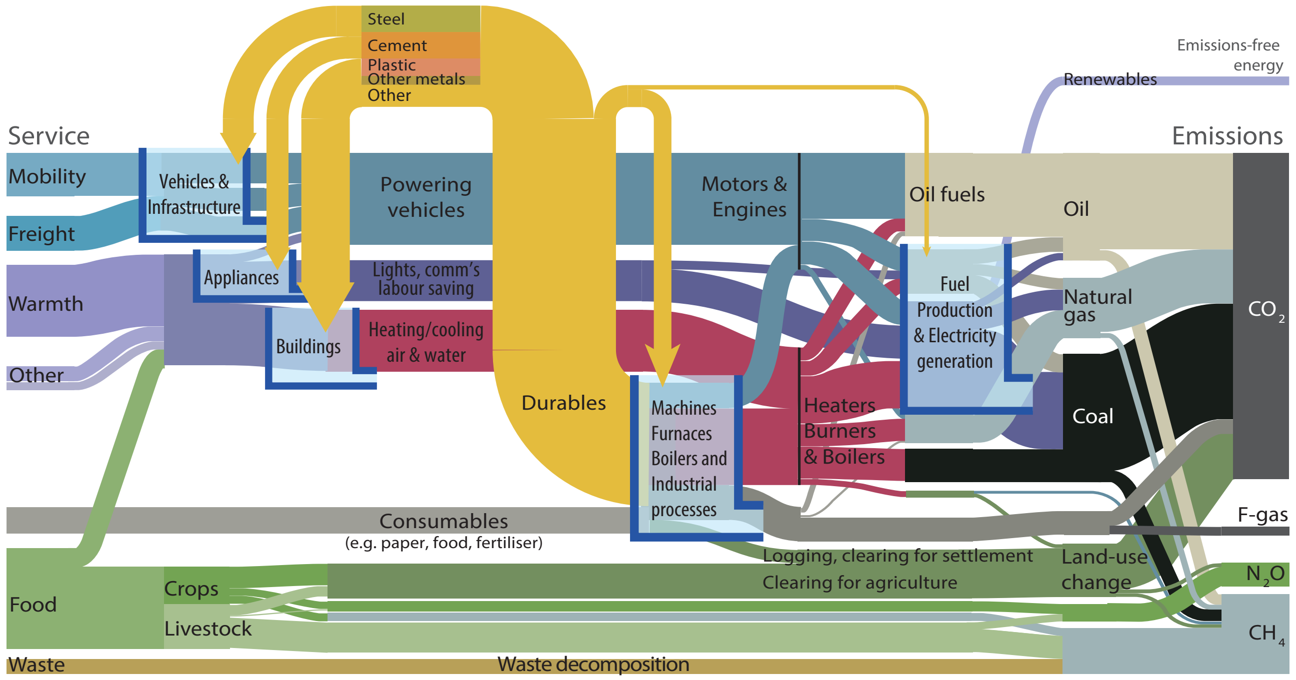


Fig 1.15 further reveals that the two key sources of non-energy related emissions are in agriculture and industrial processes. Agricultural emissions arise primarily from ruminant animals – in particular cows and sheep – which digest grass in the first of their two stomachs in a process that releases methane and from land-use change. Converting forestry to agricultural land leads to the release of the carbon stored in the forest and the loss of future carbon storage as the trees grow. In addition, ploughing the land releases carbon stored in the soil, and using Nitrogen based fertilisers to stimulate plant growth leads to further emissions. The motivation for this conversion of forestry land is to increase food production, but is greatly exacerbated by the demand for meat eating. Growing grain and other feed for cows, pigs and sheep is exceptionally inefficient, as up to 80 times more grain is required to create the same calories for a meal of meat as for a meal made from the original grain. As a result, our commitment to zero emissions in 2050 requires that we refrain from eating beef and lamb.

Three industrial processes contribute significant emissions beyond those related to energy. Blast furnaces making steel from iron ore and coke release carbon dioxide, and half of the emissions from current cement production come from the chemical reaction as limestone is calcined to become clinker. There are no alternative processes available to deliver these materials, and although old steel can be recycled efficiently in electric arc furnaces, there are no emissions-free alternatives to cement being produced at any scale. As a result, a zero-emissions economy in 2050 will have no cement-based mortar or concrete, and no new steel. The absence of cement is the greatest single challenge in delivering Absolute Zero, as it is currently essential to delivering infrastructure, buildings and new energy technologies.

The final source of direct industrial emissions is the group of "F-gases" which have diverse uses, including as refrigerants, solvents, sealants and in creating foams. It may be possible to continue some of these applications beyond 2050 if the gases are contained during use and at the end of product life.

Delivering Absolute Zero in thirty years with today's technologies is possible. Our energy supply will be 40% less than today, and solely in the form of electricity, but apart from flight and shipping, all other energy applications can be electrified. Socially motivated action is leading some change in both travel and diet. The most challenging restraint is on the bulk materials used in construction, in particular in the absence of cement, which will constrain the deployment of new energy supplies and economic development which depends on building.

However, despite these restraints, the most striking feature of this analysis is how many features of today's lifestyles are unaffected. Many of the leisure and social activities we most enjoy can continue with little change, many forms of work in service sectors will flourish, and the transition required will also lead to substantial opportunities for growth, for example in renewable electricity supply and distribution, in building retrofit, in electric power and heat, in domestic travel, material conservation, plant-based diets and electrified transport. Delivering Absolute Zero within thirty years with today's technologies requires restraint but not despair and of course any innovation that expands service delivery without emissions will relieve the required restraint. That's the theme of the second chapter of this report.

Key Message: In addition to reducing our energy demand, delivering zero emissions with today's technologies requires the phasing out of flying, shipping, lamb and beef, blast-furnace steel and cement. Of these, shipping is currently crucial to our well-being - we import 50% of our food - and we don't know how to build new buildings or install renewables without cement. The need for this restraint will be relieved as innovation is deployed but many of our most valued activities can continue and expand, and Absolute Zero creates opportunities for growth in many areas.

2. Innovations to make more use of less energy

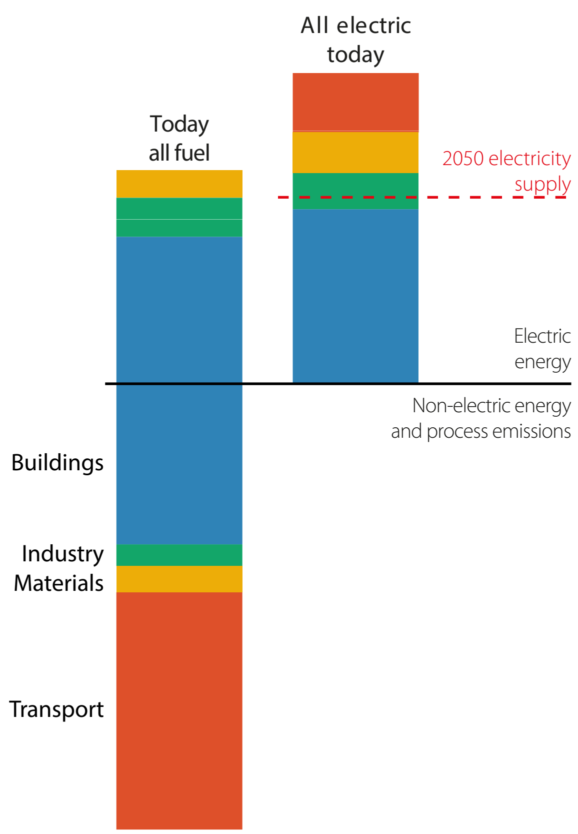
Key Message: With incremental changes to our habits and technologies, there are multiple options for living just as well as we do today, with 60% of the energy. With electric heat pumps and better insulation we can stay just as warm. With smaller electric cars we can keep moving, and by using materials better, we can make buildings and goods compatible with our zero emissions law.

This chapter starts from the analysis of electricification in chapter 1, summarised in Fig. 2.1: below the line, all of today's non-electric uses of energy must be electrified. Any activities that lead to emissions regardless of energy source or that cannot be electrified must be phased out. If we electrify all remaining activities with today's technologies, we require the amount of electricity shown in the second column - but we'll only have 60% of that amount available. For each of the sectors in Fig. 2.1, we therefore look at all the options for a more efficient future.

Section 2.1. focuses on the way we use energy directly - in buildings and vehicles - and on the way we source our food. Sections 2.2-2.4 explore how we make things - firstly looking at how we produce materials, which is what drives most of today's industrial emissions, and then in how we use them in construction and manufacturing. It turns out that we are already very efficient in our use of energy when making materials, but wasteful in the way we use the materials - so there are plenty of options for living well while using half as much material for twice as long.

For completeness, in section 2.5 we survey the "breakthrough technologies" that are unlikely to be significant by 2050, but could expand afterwards.

Figure 2.1: Absolute Zero overview



2.1 Products in-use and consumables

In the UK, the use of final products and consumables accounts for almost three quarters of current annual emissions. 12% of UK emissions come from domestic food production, waste disposal and land use changes, but two thirds are produced by our use of vehicles and buildings. These mostly come from road transport and heating in buildings, but to what extent can innovation help reduce these emissions to zero?

Using energy in buildings

Fig. 2.2 shows that most energy uses in buildings are for heating air (space) and water, mostly by combustion of gas in individual boilers in each building. Absolute Zero emissions requires a complete electrification of energy uses in buildings. Although appliances and lighting are already electric, space and water heating must change.

Heat pumps, based on principles similar to the familiar domestic fridge - but in reverse, offer a viable alternative to gas boilers. Since heat pumps are around four times more efficient than direct heat of combustion, complete deployment of best-practice heat pumps could save approximately 80% of current energy demand for heating. Heat pumps can be used in two forms: as a direct replacement for a gas-boiler they can provide hot water for a conventional radiator system. However, the best use of heat pumps is with ducted air heating - which requires a more intrusive modification of a building, but saves more energy. Deploying heat pumps would almost double the demand for electricity in buildings from current levels, so further interventions to reduce the demand for heating are also important.

New buildings are much more efficient than old Victorian houses still in use today — better insulation and design result in much smaller heating requirements. However, the turnover of the UK's building stock is very slow - we like old buildings - so refurbishment of old houses is important. Already, we have made substantial efforts to retrofit double glazed windows and to install high quality insulation in roofs and attics, and this could be completed to ever higher-standards to reduce national energy demand for heating.

For new build homes, Passive designs which only use the sun for heating, and need electricity only for ventilation, lighting and appliances are now well established. Until 2015, the UK's zero-carbon homes standards promoted this form of design, which is applied rigorously in Sweden, and at current rates of building, would affect 20% of the UK's housing if enforced now. The cost of houses built to the Passive standard is approximately 8-10% more than standard construction, and the thick walls required slightly reduce the available internal space, in return for zero energy bills.

Fig. 2.3 summarises the options for operating buildings under the conditions of Absolute Zero: whatever happens we must electrify all heating. We could then either use the heating for 60% of the time we use it today, or apply other incremental changes in building design to maintain today's comfort with 60% of the energy input.

Figure 2.2: Energy use in buildings

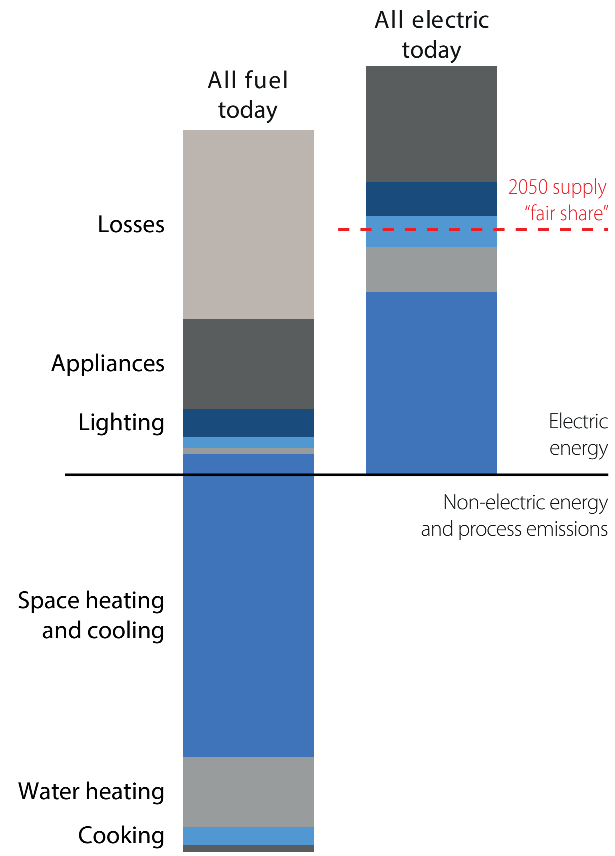
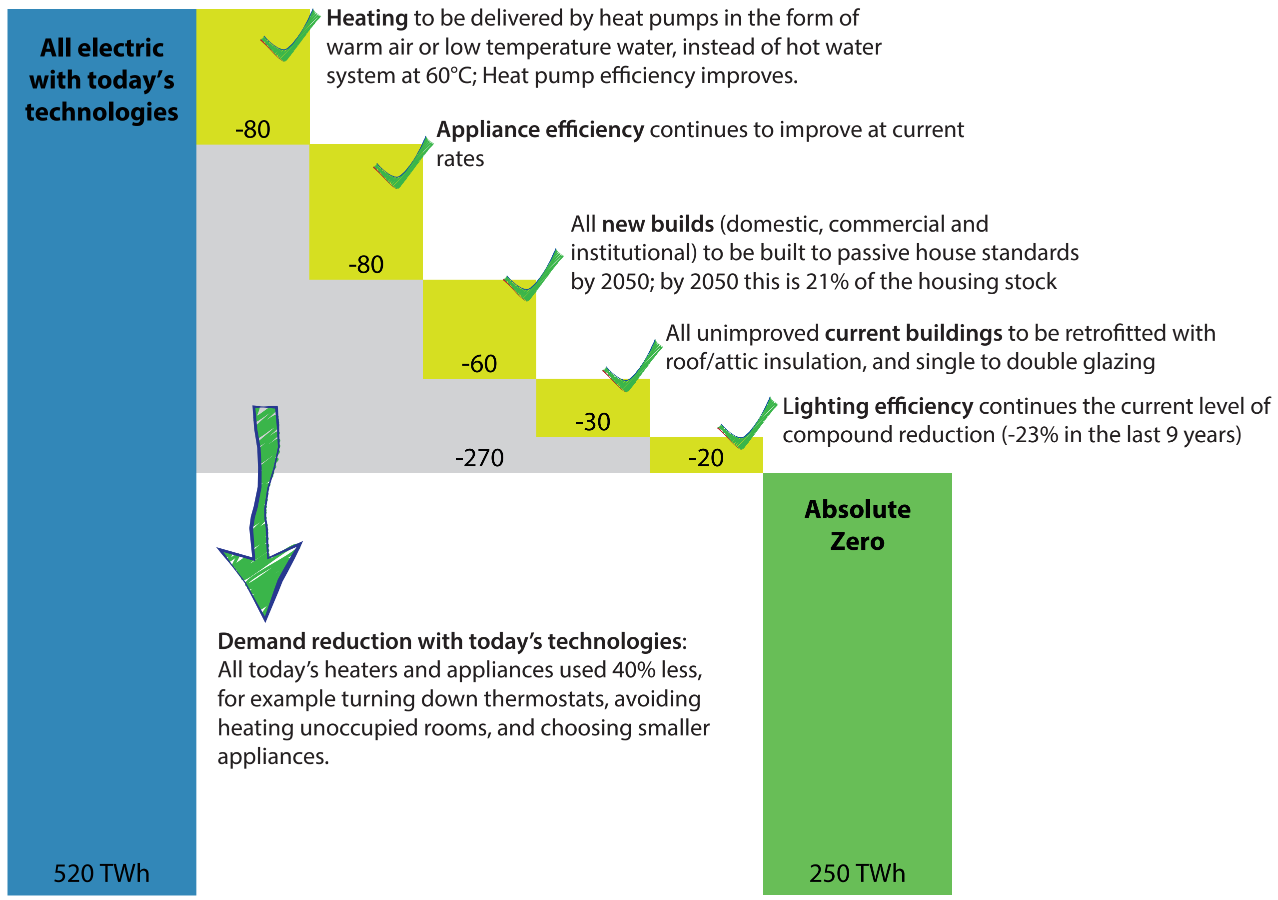


Figure 2.3: Reducing energy use in buildings with incremental technologies or reducing demand with today's technology



Using energy in transport

Fig. 2.4 shows that almost all of today's transport involves the direct combustion of fossil fuels in the vehicle, with only 1% of transport powered by electricity, in electric trains. Without technology options to replace aeroplanes and ships with electric equivalents, the second column of the figure assumes that these modes have been phased out in thirty years, so the electricity available for transport can be divided between rail and road vehicles.

Fig. 2.5 demonstrates the opportunity for energy saving through adjusting the way we travel. The figure shows both the energy and emissions consequences of a person travelling a kilometre by different modes: these two figures are closely correlated except for flight, where the emissions at high altitude cause additional warming effects. The figure underlines how important it is to stop flying - its' the most emitting form of transport and we use planes to travel the longest distances. A typical international plane travels at around 900km/hour, so flying in economy class equates to 180kgCO_{2e} per person per hour (double in business class, quadruple in first class, due to the floor area occupied.) Flying for ~30 hours per year is thus equal to a typical UK citizen's annual emissions.

The key strategies to reduce energy use in transport depend on the form of journey. Short distance travelling involves frequent stops and restarts, so a substantial

Figure 2.4: Energy use in transport

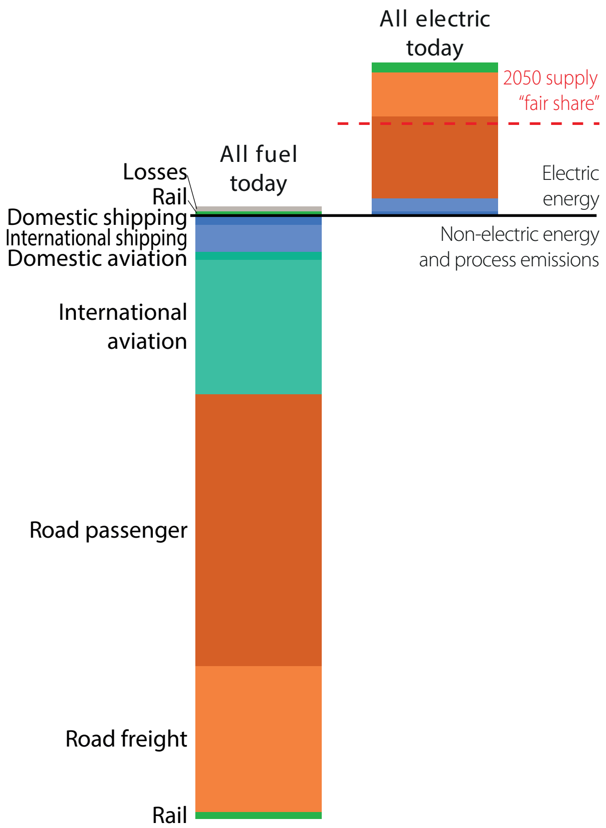
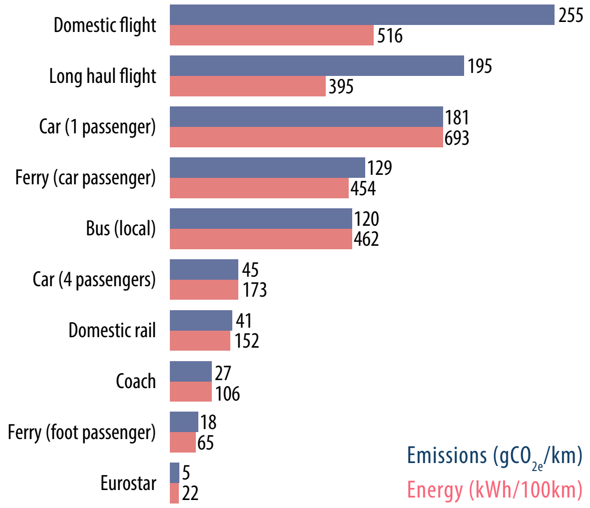


Figure 2.5: "Mode shift" for personal transport



share of energy is used to accelerate a vehicle and its contents. As a result, reducing the weight of the vehicle and travelling less become key strategies to reduce energy demand. At present UK cars are on average used with 1.8 people inside, but weigh around 1,400 kg, which is ~12 times more than the passengers, so almost all petrol is used to move the car not the people. Fig. 2.6 illustrates how reducing the ratio of the weight of the vehicle to the weight of the passengers trades off with distance travelled and energy used. Regenerative braking offers a technological opportunity to recapture some of the energy used in accelerating vehicles, and is under active development.

For long-distance travelling most energy is used to overcome air resistance, so the key to reducing energy demand is to reduce top speeds (aerodynamic forces increase with speed squared) and drag by using long and thin vehicles — trains. Rail transport is thus the most efficient transport mode for long-distance travelling, and if a higher share of trips is made by train rather than car,

Figure 2.6: Car travel - trading weight and distance

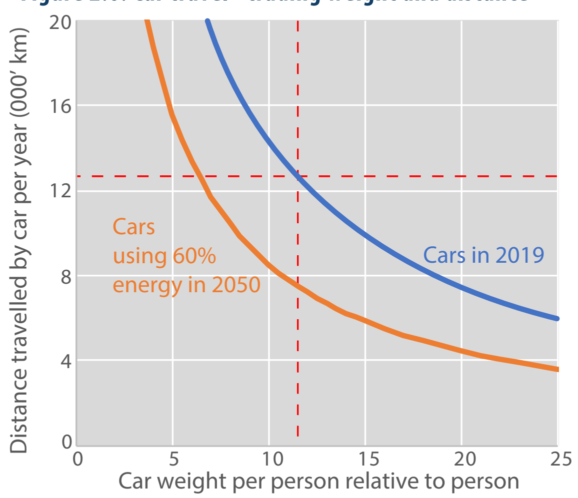
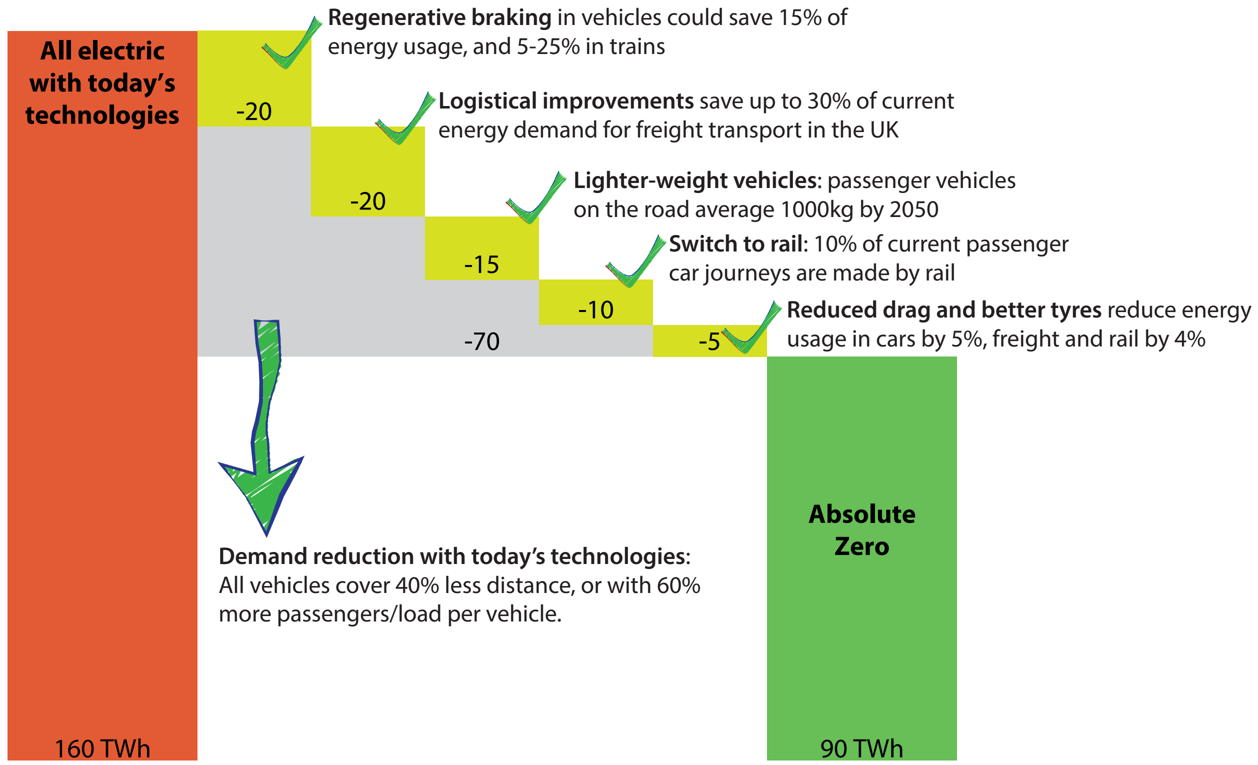


Figure 2.7: Reducing energy use in transport with incremental technologies or reducing demand with today's technology



substantial energy savings can be achieved without loss of mileage. A full electric train can move people using 40 times less energy per passenger than a single-user car.

Other modes of transport can also reduce energy demand in transport. For example, in the Netherlands, approximately 20% of all distance travelled is by bicycle, compared to only 1% in the UK.

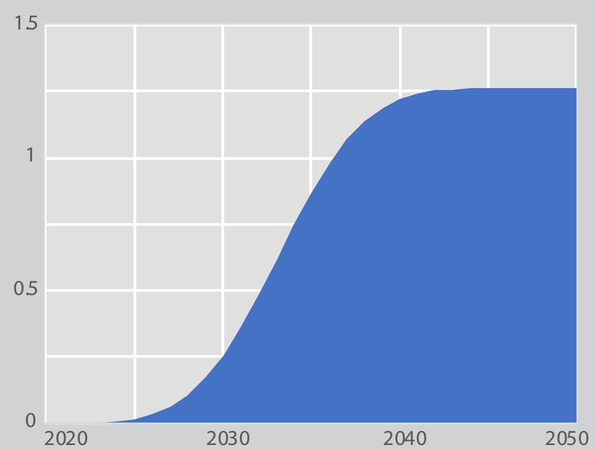
Although there are opportunities to reduce energy demand by mode shift in freight transport, substantial savings could also be achieved by logistical improvements. Up to 30% of energy demand in freight could be saved with an optimised location of distribution centres and with the creation of new collaborative networks to promote co-loading. Technology to facilitate the implementation of these logistical strategies already exists or is expected to become available over the next five years, although this also requires new corporate partnerships.

Fig. 2.7 summarises the options for electrifying UK transport and using 60% of the energy. Either vehicles are modified - with regenerative braking, reduced drag and rolling resistance (better tyres), and weight reductions, or we can choose to use them less - through ride-sharing, better freight management, or an overall reduction in distance travelled.

Can we make & recycle enough batteries?

Lithium battery manufacturing requires a wide range of metals, most of which only exist in nature at very low concentrations. Cobalt is one of the most valuable and is currently essential to the stability and lifetime of batteries. If new car sales are to be completely electric within 5 years, we will need to make 50 million batteries by 2050, just in the UK. Most cobalt production is obtained as a by-product of nickel and copper mining, so could only expand if demand for these materials expand in proportion. Batteries can be recycled, but separating the materials in them is difficult and mining new metals is tehrefore currently cheaper than recycling. There is no simple route to recycle lithium batteries at present, but the surge in old batteries shown in Figure 2.8 should trigger innovation to address this.

Figure 2.8: Estimated volumes of electric car batteries reaching their end-of-life in the UK (millions/yr)



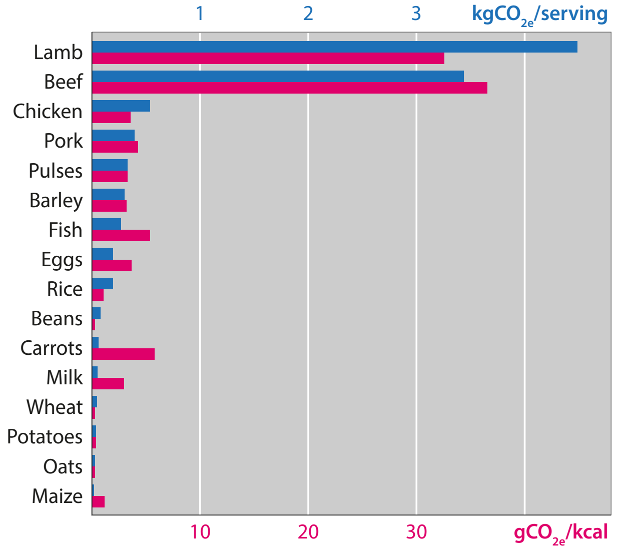
Land-use, food and waste

Fig. 1.15 demonstrated that around a quarter of global emissions arise from good production and the decomposition of organic wastes. The UK figures in Fig. 1.7 show this fraction being closer to one sixth, which reflects the fact that the UK imports around half of its food. Fig 2.10 provides more detail on these non-energy and non-industrial emissions.

As waste biomass breaks down to compost, it releases either carbon dioxide (if the biomass is in contact with air) or methane, which is a much more potent greenhouse gas and is the main driver of the emissions from waste decomposition. However, methane is the gas we use in cooking or in gas fired electricity generation, and the greatest success of recent UK climate policy has been to reduce these emissions significantly. Households across the UK now expect to discard organic wastes in their green bins, which are collected as the feedstock for anaerobic digesters which generate methane for energy production as shown in Fig. 1.7. As a result, UK landfill methane emissions have reduced by more than 50% since 1990 and will be close to zero by 2050.

The other major sources of emissions in Fig. 2.10 are largely related to ruminant animals – cows and sheep – grown for meat and dairy consumption. Ruminants digest grass in their first stomach, leading to methane emissions (enteric fermentation) while also releasing methane with their manure. In parallel, rising global demand for food is driving demand for increased biomass production, around half of which is to feed animals and in turn this drives forestry clearance. Trees are a substantial store of carbon, so clearance increases emissions either as CO_2 if the wood is burnt, or more damagingly, as methane if left to rot. The clear implication of Fig 2.10 is that eating lamb and beef will be incompatible with Absolute Zero.

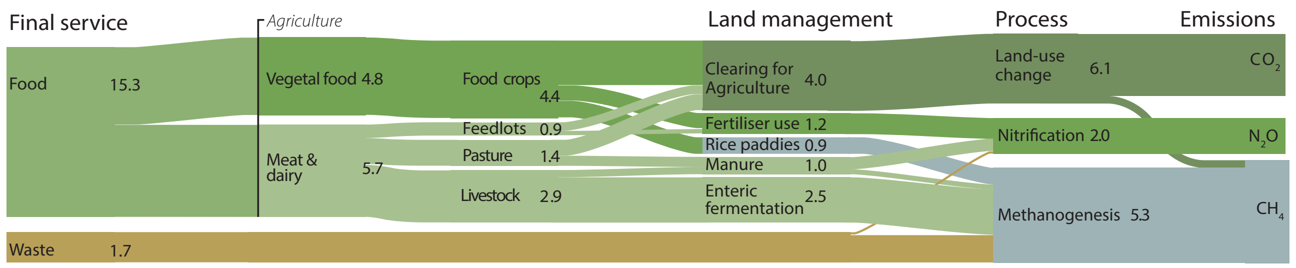
Figure 2.9: Emissions intensities of food



This message is underlined in Fig. 2.9 which gives an estimate of the emissions associated with a meal with typical portions of different diets. The figure demonstrates that a vegetarian meal isn't emissions free, and a meat-based meal (with pork or chicken) may not have much more impact than one based on pulses. However, the ruminant meats stand out so are a priority action in moving towards Absolute Zero.

The market for vegetarian food is currently growing rapidly, as rising social concern about emissions has motivated many individuals to switch to a more plant-based diet. There is significant potential for innovation in extending and developing new manufactured meat substitutes. Research has also begun to examine whether alternative feeds could eliminate ruminant emissions, but this is not yet mature.

Figure 2.10: Global emissions from agriculture, and organic waste (total in 2010: 17 Gt CO_{2e})



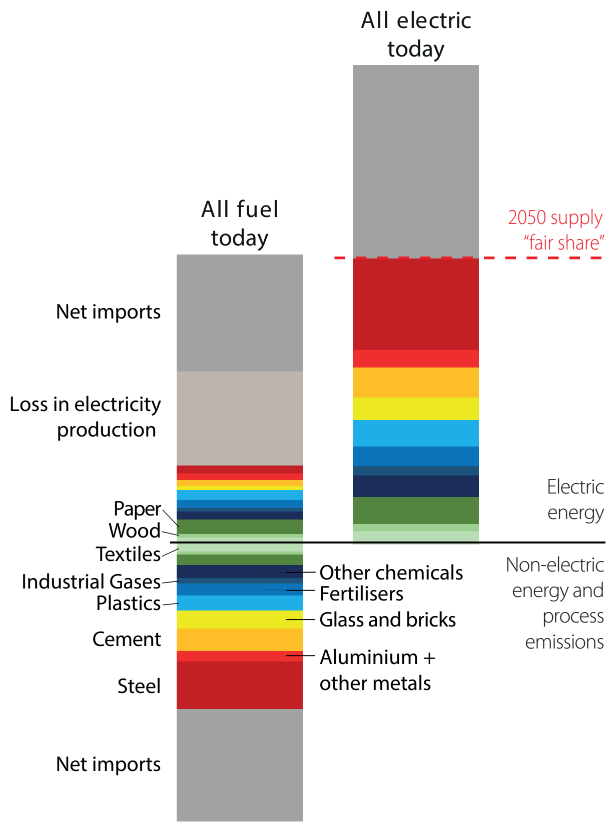
Key Message: Most of today's UK lifestyles can continue and grow within the target of Absolute Zero. Changing the way we travel (in particular not flying, and making better use of wheeled vehicles), stay warm (using electric heat pumps instead of gas boilers) and eat (cutting out lamb and beef) are the most important changes that we would notice. In parallel, small changes in the design of buildings and vehicles can make them more efficient. However the biggest challenge revealed in this section is the use of shipping for freight: at the moment we have no alternatives.

2.2 Materials and Resources

The implications of the analysis of chapter 1 for material production are summarised in Fig. 2.11. The UK imports much of our material requirement - either as materials, components or finished goods - so around half of the impact of our consumption today leads to the release of greenhouse gas emissions in other countries. Of the bulk materials that drive most industrial emissions, paper and aluminium production are the only two for which electricity is the dominant energy source. The processes that make materials can nearly all be electrified, but the challenge to Absolute Zero is to deal with the production processes that inevitably lead to emissions. Blast furnace steel can be replaced by steel recycled in electric furnaces, and this leads to the expansion of electricity for steel production shown in the figure. However, we currently have no means to avoid the emissions of cement production - even if the process were electrified - because the chemical reaction that converts limestone into cement inevitably releases carbon dioxide. Without innovation, we will be unable to use concrete or mortar - the two forms in which we generally use cement - but because this is so difficult to envisage, we have allowed some electric supply for the production of cement alternatives.

Starting from cement, this section explores the opportunity for innovation to expand the available supply of materials within Absolute Zero emissions.

Figure 2.11: Energy use in producing materials



Cement

Cement hardens when mixed with water because the solid products of the reaction (called hydrates) have a higher volume than the cement powder and thus form a solid skeleton. Only a few elements in the periodic table have this property and are also widely found in the Earth's crust. The elements available in the earth's continental crust with an abundance higher than 1% are silica (60.6%), alumina (16.9%), iron oxide (6.7%), lime (6.4%), magnesia (4.7%), sodium oxide (3.1%) and potassium oxide (1.10%). Of these, Portland cement mainly uses calcium and silica, with aluminium, iron, calcium and sulphur also playing a minor role. Calcium and aluminium together can form a heat-resistant cement used in refractory applications. Magnesium, sulphur and aluminate can also work together as a cement, but attempts at making a reliable product from them have proven unsatisfactory. Iron does not form hydrates with a high volume. Thus, the key ingredient to Portland cement is calcium, which is found mostly in the form of limestone (or calcium carbonate), as the fossilised remains of micro-organisms which have combined CO_2 and calcium to form shells for billions of years.

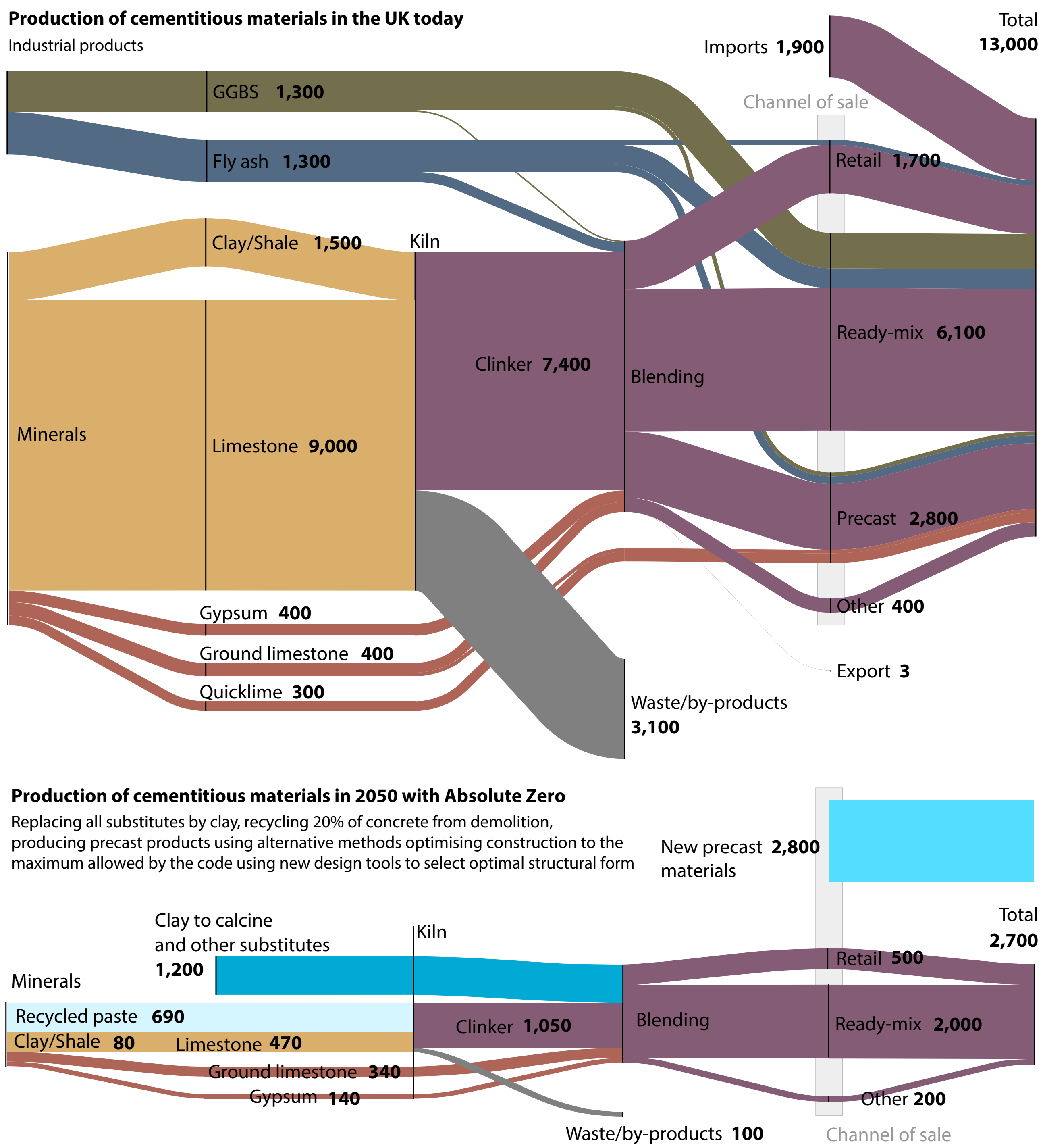
60% of emissions from cement production arise from the chemical reaction of calcination in which limestone is converted to clinker - the precursor of cement. The remaining emissions are due to the combustion of fossil fuels (and waste materials) in kilns. Although heating processes may be electrified in the future, process emissions from calcination would be unavoidable, unless alternative sources of calcium oxide are found to replace limestone in cement production. Currently it appears to be impossible to produce cement with Absolute Zero emissions. Technology innovation on the alternatives to calcination and reconfiguration of the cement industry could enable zero emissions in cement production. However, any innovation in these processes would probably require a substantial reduction in cement demand from current levels.

Currently, the construction industry makes use of many substitute materials to reduce the total demand for cement: both fly ash a by-product of burning coal, and ground granulated blast furnace slag, a by-product of the steel industry are used. Together, they reduce the need for pure Portland cement by about 20%. However, in a zero-carbon world, neither of these products would be available - as coal combustion and blast furnaces would not be possible - which leads to an increase in the need for new cement.

It is possible to produce pre-cast products (bricks, blocks, or slabs) with zero or even negative emissions, whether using micro-organisms which transform CO_2 to calcite or through bubbling CO_2 through magnesium sulfo-aluminate cement-based mixes. These could satisfy some of the construction industry's needs, but we have no alternative binders to replace Portland cement on construction sites. It is often claimed that geopolymers (fly ash or slag which react to form hydrates in the presence of alkalis) could replace Portland cement. However, this is not an option in a zero-carbon world because the base materials for geopolymer come from highly emitting industrial processes (burning coal and coking steel) which will not continue.

Pre-cast products could replace at most 14% of current uses of cement, but without binders, they could not be used for foundations or repairs even of critical infrastructure. One of the most common structural elements in today's commercial buildings, the flat slab which is cast in place from liquid concrete brought to site in mixer trucks and used to build floors, would disappear: the only available option would be pre-cast elements, but these could not be finished, as they are now, with a thin layer of concrete (called a screed). A currently popular construction method, composite construction using thin concrete slabs poured over corrugated steel sheets and beams, would also be

Figure 2.12: Production of cementitious materials in the UK and with innovation for zero emissions in 2050 (kT/yr)



impossible, despite being more materially efficient than the reinforced concrete flat slab.

There are two complementary paths that might lead to reducing the emissions from cement production.

Firstly, there may be new sources of cement replacement, and new low-carbon feeds for the production. A promising source of cement replacement is kaolinite-rich clay. Kaolinite is an oxide of aluminium and silicium, which when calcined at 850 C transforms into metakaolin which is an amorphous, reactive product. Because of the lower calcination temperature, this material is about half as energy intensive as Portland cement. It has the interesting property that it can react with raw limestone to form hydrates, as well as substitute cement. Thus substitution levels of up to 65% can be achieved without lowering strength. In the UK, waste from kaolinite mining in Wales can provide a good source of clay to calcine. London clay is of a poorer quality but could still be used if the strength requirements of new construction were lowered.

The second path to producing zero-carbon cement is to eliminate limestone from the feed of cement. An abundant source of calcium which is not carbonated is concrete demolition waste. Current best practice suggests that approximately 30% of the limestone feed of a cement kiln can be replaced by concrete demolition waste. This limit is due to the presence of the concrete aggregates, but if a separation process was established, and only the cement paste from concrete demolition waste was used, then it could be possible to produce cement without chemical process emissions.

The amount of demolition waste available yearly in the UK could cover an important fraction of our yearly needs, provided heroic efforts were made to make good use of this available source of materials. 30 Mt of demolition waste is produced yearly (2007 value from the National Federation of Demolition Contractors), 59% of which is concrete of which 20% is cement paste. An 80% yield in separating aggregates from paste would then provide 3 Mt of low carbon feed for the kilns to produce new cement.

Fig. 2.12 illustrates a summary of this narrative, comparing today's UK requirements for cement (or more generally, "cementitious material") in the upper picture, and the maximum possible supply we can envisage within the constraints of Absolute Zero in the lower picture. Section 2.3 will consider the opportunities to deliver construction with the 75% reduction in cement production implied by this figure.

Finally, there are many possible options for structural elements not using concrete and steel, including rammed earth, straw-bale (ModCell), hemp-lime, engineered bamboo and timber (natural or engineered). Often, these materials claim superior carbon credentials, which may be exaggerated, but they also come with enhanced building-physics attributes, including insulation, hygrothermal and indoor air quality benefits. These could be used to substitute concrete in some applications, but would require different design processes and choices of architectural forms.

Steel

Recycling steel in electric arc furnaces powered by renewably generated electricity could supply most of our needs for steel, as it already does in the US. Almost all steel is recycled already (the exception is where steel is used underground, in foundations or pipework) and as Fig. 2.13 shows, the average life of steel-intensive goods is around 35-40 years. The amount of scrap steel available globally for recycling in 2050 will therefore be approximately equal to what was produced in 2010. Fig. 2.14 shows how the balance of global steel production can evolve in the next 30 years to be compatible with Absolute Zero: blast furnace steel making, which inevitably leads to the emissions of greenhouse gas due to the chemical reaction involved in extracting pure iron from iron ore using the carbon in coal, must reduce to zero. Meanwhile, recycling which happens in electric arc furnaces could be powered by renewable electricity to be (virtually) emissions free, and can expand with the growing availability of steel for recycling. Even without action on climate change, the amount of scrap steel available globally for recycling will treble by 2050. In order to meet the requirements of Absolute Zero, this valuable resource can be the only feedstock, as there is currently no alternative technology for producing steel from iron ore without emissions.

Figure 2.13: Life expectancy of steel by application

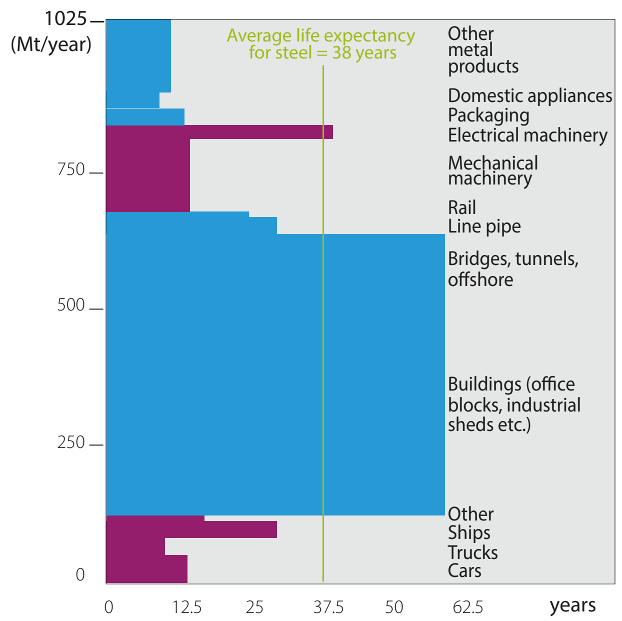
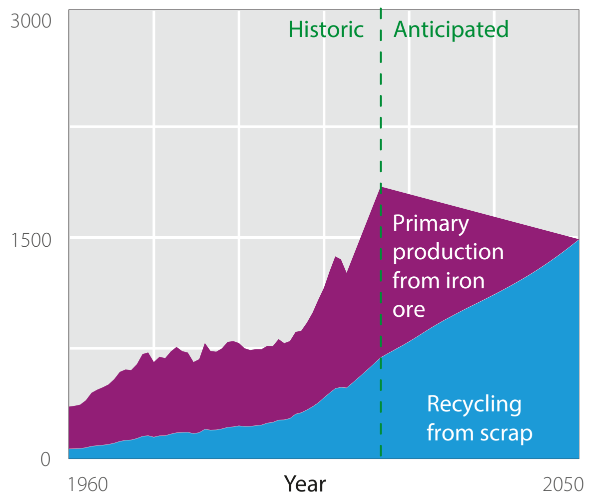


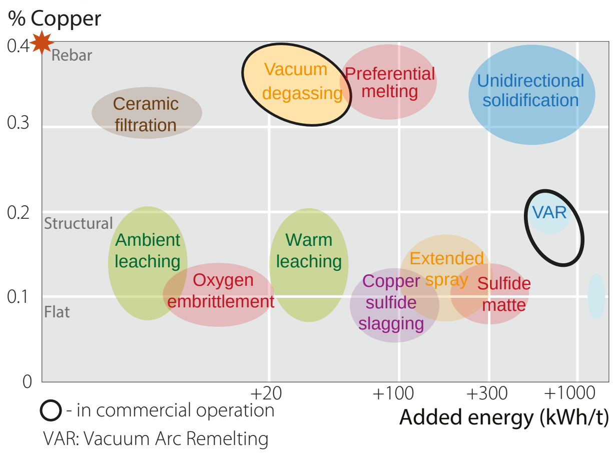
Figure 2.14: Global steel output in Absolute Zero (Mt/yr)



Recycled steel can have the same quality as blast furnace steel. In fact, some of the highest quality aerospace grades of steel used in the UK are made in Rotherham by recycling. However, the quality depends on the mix of metals supplied to the electric arc furnace, and is degraded in the presence of any significant quantity of tin or copper. Tin enters the steel recycling stream because of the use of tin-plate to make food cans, but this is relatively easily managed: these cans can be separated from other end-of-life steel and a mature process already operates at scale to separate the tin from the steel.

Copper is more of a problem in steel recycling, because current waste management involves shredding used cars and domestic appliances to separate metal from other materials, and these products contain many electric motors and associated wiring made from copper. There is a rich field of opportunity in responding to this problem, which could include: removing motors and wiring prior to shredding; improved separation of metals after shredding; metallurgical processes to remove copper from the liquid metal created by the electric arc furnace; developing new downstream processes to cope with copper contamination in the steel; eliminating copper for example by substituting it with aluminium. Fig. 2.15 presents a survey of metallurgical processes for reducing copper concentrations in liquid steel, from 0.4% (a typical value today for average UK steel scrap recycling) to around 0.1% (the threshold for higher quality applications such as car bodies) as a function of energy input. The high grade steels made in Rotherham are purified with vacuum arc remelting, with high energy (and therefore financial) cost, but the figure demonstrates how many other opportunities could be developed given the motivation provided by Absolute Zero.

Figure 2.15: Options to reduce copper concentration



Steel production is extraordinarily energy-efficient, and consequently steel is remarkably cheap. As a result, it is used wastefully, and in most applications we could deliver the same end-user service from half the amount of steel used for twice as long – i.e. requiring only 25% of annual steel production. This strategy of material efficiency depends on practices in construction and manufacturing so is discussed further in sections 2.3 and 2.4.

Non-ferrous metals

The production of non-ferrous metals is already almost completely electrified. The most notable example is aluminium production, which alone uses 3.5% of global electricity and the demand for this metal is currently growing rapidly. In theory, Aluminium recycling requires only 5% of the energy used to produce primary aluminium, although in reality with additional processing for cleaning scrap aluminium prior to melting it, diluting it with primary metal to control quality, and with inevitable downstream processing, a more accurate figure is around 30%. However, as demand for aluminium is growing rapidly, there is currently not enough scrap available to supply current demand, so within Absolute Zero future, primary production must continue - with output reduced in proportion to the supply of non-emitting electricity. Problems of contaminations which undermine the quality of recycled aluminium, could be a basis for innovation in improved processes to separate aluminium in end-of-life waste streams or modify composition in its liquid state.

Critical metals

Critical metals are so called, because of their growing demand and risks associated to their supply. There are no problems of scarcity for these metals, but their global availability is very unequal — most reserves are concentrated in very few locations, often in countries with volatile political environments, and several critical metals are produced as by-products of other larger-volume metals. Most of the production processes for critical metals are already electrified, but these are very energy-intensive due to the need to concentrate these metals from ores in which they naturally have very low concentrations. Unfortunately, recycling critical metals may require even more energy than primary production, because they are typically used as alloys and it is more difficult to separate them from the complex mix of metals in recycling than from the more controlled compositions in which they are found in nature. Absolute Zero, which requires a significant expansion of electrification, is likely to increase demand for critical metals which enhance the performance of motors, but this demand will come at the cost of an unavoidable growth in demand for electric power.

Ceramics

Ceramics and bricks are mostly produced from clays. These need to be vitrified at high temperatures in a kiln. Currently, heat is obtained from fossil fuel or waste combustions, but electric alternatives exist for all temperatures of kiln. Some colours in ceramics require reduction firing, which requires a stage in the kiln with a reducing atmosphere. This is currently obtained by fuel combustion, and thus alternatives to this practice will required. The 60% constraint on available electricity implies a 60% constraint on ceramics production in 2050.

Mining

Mining uses energy for two main purposes: shifting rocks and mined products in heavy "yellow" vehicles, and crushing them to allow the chemical processes of extraction. Both uses can be electrified but at present, yellow vehicles largely run on diesel while the power for crushing and grinding depends on local conditions. Potentially, there may be more energy efficient technologies for crushing and grinding, but already there is a competitive market looking for these, so breakthroughs are unlikely. However, within the constraints of Absolute Zero, the elimination of coal and iron ore mining will significantly reduce the total energy demand of the sector, providing "head-room" in the non-emitting electrical-energy budget for the expansion of mining associated with wide-scale electrification.

Glass

Most current glass production uses natural gas-fired furnaces. These could be electrified, but a reduction in production would be required in proportion with the available supply of emissions-free electricity.

Fertilisers

CO_2 from ammonia production is currently captured and used for urea production. Urea is then used as a fertiliser, delivering nitrogen to the roots of plants and crops, but as urea decomposes in the soil it releases the embedded CO_2 to the atmosphere. Overall, 2 tonnes of CO_2 are produced per tonne of urea used. Ammonium nitrate is an alternative fertiliser to urea, but it is produced from ammonia, thus leading to the same emissions, although all occurring in the chemical plant.

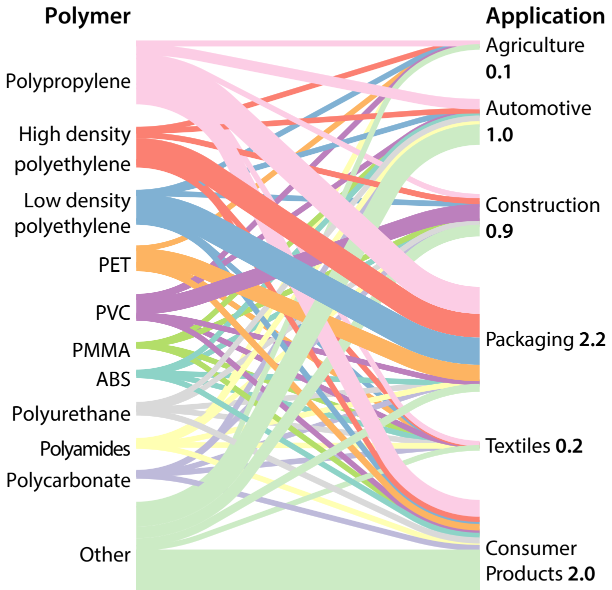
Carbon capture technologies could eventually be deployed, but this would only be compatible with a substantial reduction from current production. However, there are substantial opportunities to reduce energy use by reducing demand for fertilisers. Existing evidence suggests that more fertilisers are used than the nitrogen requirements to grow crops. For example, a study for the Netherlands shows that the use of fertilisers could be halved without loss in productivity, if used more efficiently.

Plastics

Approximately 1 tonne of CO_2 is emitted per tonne of plastic produced, but more than double this CO_2 is produced when plastic waste is incinerated. Plastics are made from oil - and they are therefore the most valuable component of existing waste streams, if the waste is burnt for energy. However, if plastic is combusted, it is in effect a fossil-fuel. As a result, plastic incineration is not compatible with the goal of Absolute Zero.

Plastic can be recycled, rather than incinerated, either by mechanical or chemical means. Mechanical recycling preserves the chemical structure and composition of polymers, and is normal practice within existing manufacturing processes: scrap at the exit of a plastic extrusion machine, for example, can be fed directly back into the machine for re-extrusion. However, this is possible only when the composition is known and under control. The great attraction of plastics is that they can be tailored to every application - with different colours, densities, textures, strengths and other characteristics according to each design specification. However, this tremendous variation is a curse for recycling: in current mechanical recycling of end-of-life plastics, the composition of the resulting product is uncontrolled and therefore of little

Figure 2.16: UK polymer applications (Mt/ year)



value. Furthermore, plastic waste is often mixed with other materials, hence the levels of purity of new plastics cannot be achieved by recycling, which therefore leads inevitably to down-cycling. A frequent example is packaging PET, which cannot be recycled back to food-grade standards and is thus used in lower-value applications.

In contrast, in chemical recycling, polymers are broken down into their constituent monomers which are then recovered to synthesise new plastics. At present, it is only economically attractive to recycle plastics mechanically, requiring less than half of the energy for new production. However, in future, chemical recycling by pyrolysis and gasification may allow plastic waste recovery for high-value applications. As yet, it has proved difficult to operate pyrolysis processes at scale, they require high temperatures, and have yield losses of up to 40%, partly due to use of part of the feedstock to generate heat.

Recyclability is also dependent on the type of polymers available in waste streams. Fig. 2.16 shows the annual flows of plastics in end-use products purchased in the UK by type of polymer and application. Although approximately 40% of annual plastics demand is used in packaging, these have short service lives and are quickly returned to waste streams. A great variety of polymers is used for each application, which hinders the identification and separation of polymers in waste streams, thus limiting the recyclability of plastics. Currently, land-filling plastics leads to almost no emissions. Plastics are stable when landfilled so do not generate methane. However, land-filling neither saves the production of new primary plastics, nor does it contribute to the future availability of material for recycling, unless it is cleaned and separated prior to landfill for storage.

Other chemicals

The chemicals industry produces a wide variety of products. Methanol, olefins and aromatics are produced in much smaller quantities than most plastics and fertilisers, but are important precursors to a variety of chemical products. Emissions arise from energy uses and chemical processes. Although most energy uses can be electrified, it may be very difficult to continue producing many of today's chemicals without releasing process emissions.

Paper

The paper industry globally uses a third of its energy from its own biomass feedstock. Yet, in Europe biomass accounts for half of its total energy requirements, suggesting a global potential for improvement. Absolute Zero emissions would require a conversion of existing fossil fuel-based combined heat and power systems to electrical power processes. Given the constraint on non-emitting electricity availability required by chapter 1, then after complete electrification, paper production would be reduced by approximately 80% of current volumes, to be consistent with UK targets.

Textiles

Most energy uses in the textile industry have already been electrified. However, leather production (which depends on cows) would not be compatible with Absolute Zero for the same reasons given for beef earlier. As washing, drying and ironing account for more than half of the energy uses for most clothing textiles, the industry could promote fabrics that need no ironing and support a reduction in the frequencies of washing and drying.

Engineering composites

Novel nano-materials offer promising properties, which could enable the substitution of some metals across different applications. However, the current total volume of these materials could probably fit into a water bottle. For this reason, it seems unlikely that these materials will have any value in reducing demand for the bulk materials by 2050.

Key Message: Because of the emissions associated with their production, cement and new steel cannot be produced with zero emissions. Steel can be recycled effectively, but we need urgent innovation to find a cement supply. Under the conditions of Absolute Zero, the availability of most other materials will be proportion to the amount of non-emitting electricity available to the sector.

2.3 Resource Efficiency in Construction

Most emissions associated with the construction arise due to the use of materials: the process of erecting buildings and infrastructure requires little energy compared with making the required materials, which are predominantly steel and cement. Under the conditions of Absolute Zero, all steel used in construction will be from recycling - which is largely the case already in the USA, and poses no significant challenge. However, as discussed in the previous section, the industry must learn to make use of considerably less cement. A parsimonious use will make the transition to Absolute Zero possible without putting the material industry under impossible strain. Furthermore, all efficiency gains in one material usually cause reduction in the use of the other, because lower loads always translate to lower structural needs. Fig. 2.17 shows the current uses of cement in the UK as a guide to the search for material efficiencies.

The causes of material *in*efficiency in construction are relatively well understood. The most common is over-specification. The amount of steel in a typical floor of a steel-framed building is about twice what the structural requirements would dictate. This is because the choice of steel beams or steel reinforcement in concrete slabs is not fully optimised and because the decking (the thickness and type of floor slab) is typically oversized.

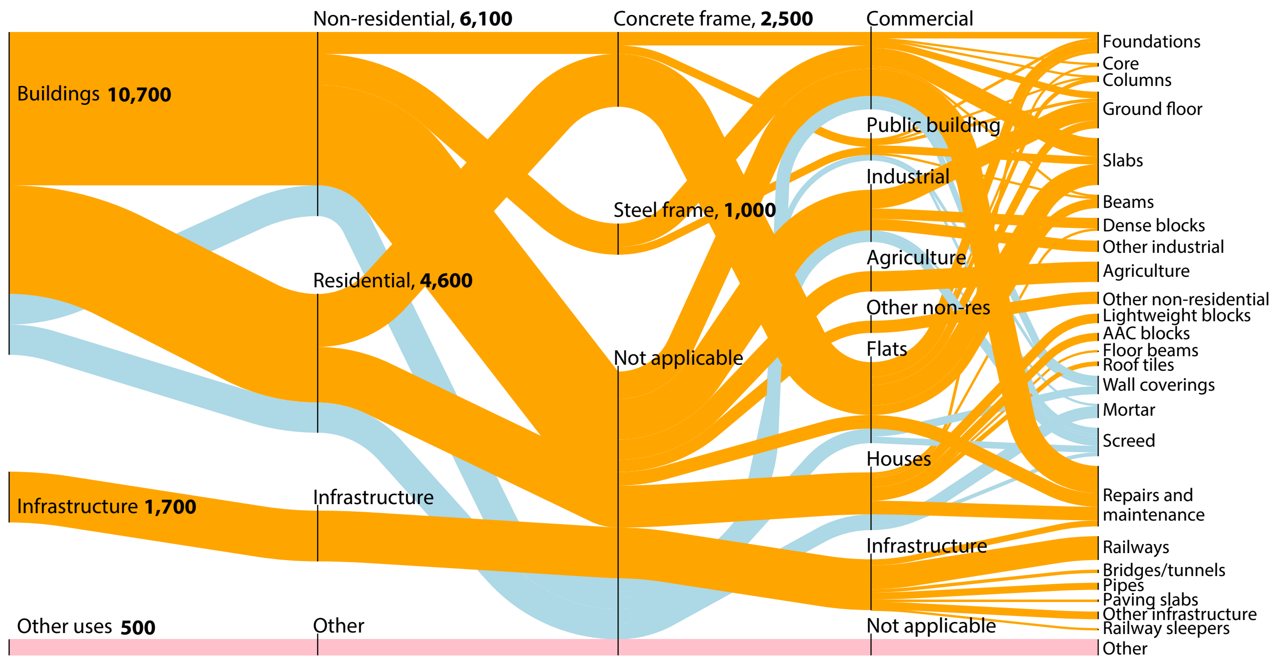
In current UK construction of steel-framed buildings, on average the steel is over-specified by a factor of two, even after accounting for our conservative safety factors. This does not mean that it would be possible to half the amount of steel, be we estimated that it was possible to save at least 15% of the mass of steel with no loss in service or safety. The deckings, are also oversized: the thickness of the concrete layer is larger than required, and the steel plate supporting the concrete in composite construction is frequently double the required thickness.

The building codes currently only specify the minimum amount of material to be used (including the margin of safety). But they could also enforce an upper limit, adding an "and no more" clause. There is also no existing benchmark to compare the embodied energy of the materials in a building per square metre of but this would help drive the efficiency of structural design.

In addition to these sources of over-specification, buildings are often designed for much higher loads than they will ever bear: gravity loading in buildings, predominantly from people, is specified to a far higher level than the physical proximity of groups of people could allow or that ventilation systems could sustain for life in the building. An overestimate of design loading leads directly to material being wasted in buildings. We do not routinely measure loading in buildings, and therefore a research effort is needed. Measuring loading in our buildings, would provide lessons from our existing buildings to transform structural design efficiency.

When specifying the vibration behaviour of buildings, which governs their "feel," engineers usually exceed the requirements of our building codes. However, in use this feel is usually governed by the choice of flooring and the location of partitions, but designers usually ignore those factors, which are not set when the structural frame is

Figure 2.17: Current patterns of cement use in the UK (kT/yr)



chosen. Therefore, a lot of effort goes into making stiff buildings, which require more material and which may be entirely wasted. Better methods of predicting the feel of buildings would help guide design towards more efficient outcomes.

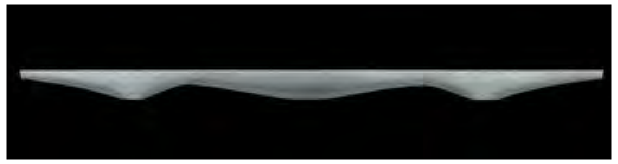
A further driver of inefficiency in our use of materials in construction, independent of over-specification, is the choice of structural form. The choice of the grid (the spacing between columns) is the most important factor in the CO_2 intensity of construction, yet there is little awareness of its importance. The carbon intensity of a building could double if very long spans are specified in preference to shorter ones, even when the users of such buildings frequently install partitions to sub-divide over-large rooms.

Scheming tools, which help guide early design towards a suitable architectural form are being developed. Currently, a designer is faced with a staggering array of options, not obviously different from each other, and will be naturally inclined to choose one with which they have experience. This is probably the cause of the over-design of decking. As the number of options grows – for example with growing enthusiasm for timber construction – the number of options in design will keep expanding, and designers may not be able to realise the promise of new constructions methods New scheming tools to support their decisions can halve the material requirements in construction.

The regularity of structures is also a currently underestimated source of in-efficiency: regular grids can be up to 20% more efficient than more complicated layouts. Novel tools can help structural designer make the right choices early in their projects, and link the choice of architectural form to the best currently available technology, as well as giving a context which may support architects to choose more efficient forms.

Resource efficiency can also be improved by using optimised structural members (slabs, beams, columns). Prismatic structural members in either concrete or steel are highly wasteful, because maximum stress in such members will only occur at one location along the entire length. Modern manufacturing processes can be used to specify appropriate structural shapes (e.g. Fig. 2.18.) Even when designing flat concrete slabs, the pattern of reinforcement is rarely optimised, in part because a complex reinforcement pattern would increase the odds

Figure 2.18: Concrete beam made with fabric formwork



of errors on the construction site. New products such as reinforcement mats which have been tailored for specific site and can be simply unrolled have appeared, but they are not yet fully integrated in the design process of the structural design firms.

Finally using alternative construction material at scale will require considerable changes in design habits. Engineered timber, if it lives up to its promise, will probably take its place besides steel and concrete as a standard frame material. However, engineers are only now being trained to design with timber, and it will take time before it can be used broadly. The trade-off between building tall (probably using high-carbon materials) with low transport requirements, and building low-rise (using low-carbon materials) but with higher transport requirements in a more sprawling approach, needs to be explored.

Steel production, even using a fully recycled route is energy intensive. It would require less energy to re-use beams rather than recycling them by melting. Currently, steel reuse is only a marginal practice, mostly because steel fabrication is an efficient, streamlined process which relies on beams being standardised products. It would be possible to increase the rate of reuse if legislation was adapted to help the recertification of steel beams, but more importantly the construction value chain must develop to accommodate the collection and reconditioning of beams to make them ready for refabrication.

Together, these material efficiency techniques can considerably reduce the need for materials in construction. This is vital to reduce the requirement for cement production to manageable levels. Putting into place all of the material efficiency techniques described here would allow us to keep meeting the needs in Fig. 2.17 with the cement supply implied by the second of Fig. 2.12a and thus to meet the challenge of Absolute Zero.

Key Message: Construction uses half of all steel and all cement, but has developed to use them inefficiently. The requirements for materials in construction could be reduced to achieve Absolute Zero by avoiding over-specification and over-design, by structural optimisation and with reuse.

2.4 Resource efficiency in manufacturing

The manufacturing of basic materials into products and goods is a major source of greenhouse gas emissions. For most products, manufacturing processes themselves cause a relatively small fraction of a product's total embodied emissions, compared to the material input – see Fig 2.19. However, constraints caused by manufacturing practices strongly influence both the material input, and emissions caused by the product during its use. Therefore, under the conditions of Absolute Zero, major changes in manufacturing are needed; driven not just by changes up and downstream of the sector, but also by the need for greater resource efficiency within it.

These changes have some impact on all products, but a critical priority in planning the delivery of Absolute Zero is to focus effort on the sectors with most impact. Having recognised that material production drives most current industrial emissions, Fig. 2.20 allocates the energy use in the first column of Fig. 2.19 to applications to reveal the specific target sectors where material demand reduction is essential. Section 2.2 focused on construction, the single biggest user, and the strategies described there are relevant also to the non-cement components of infrastructure. But the figure clearly prioritises vehicles, industrial equipment and packaging for most attention.

Figure 2.19: Energy use in Manufacturing & Construction

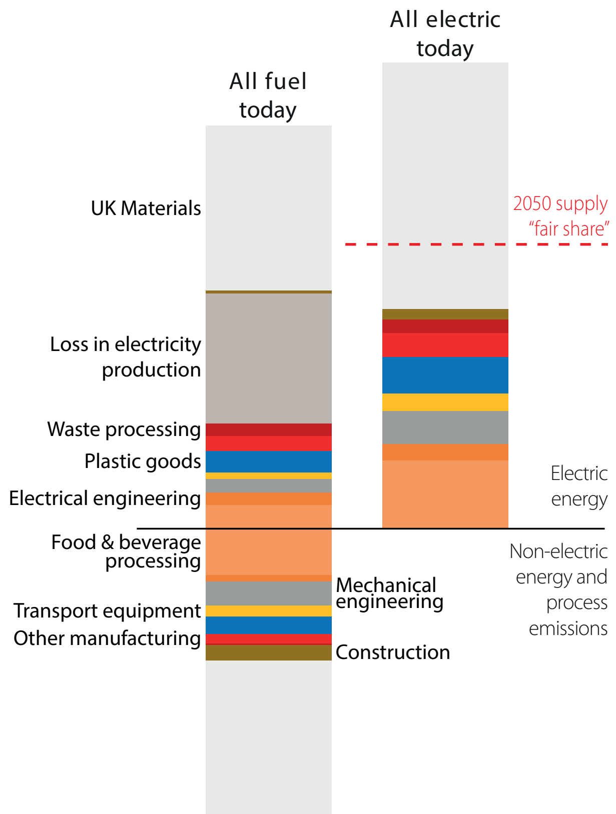
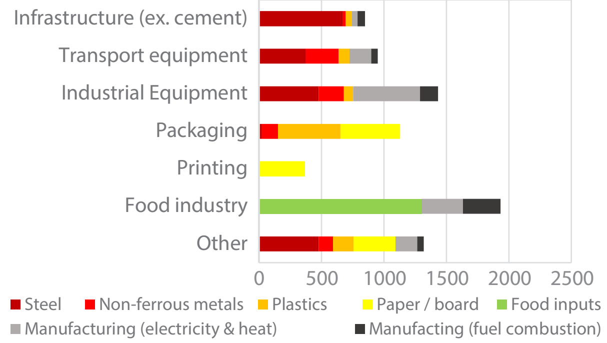


Figure 2.20: Emissions of key product categories ($MtCO_{2e}$)



Responding to changed material availability

In section 2.2 we saw that the availability of materials which today directly emit greenhouse gases in their production will be reduced by 2050. This includes major raw materials such as steel from iron ore and cement, and multiple products of the chemical industry including F-gases, solvents, lubricants, and certain types of plastics. The knock-on effects for manufacturing are huge:

Lubrication is critical for much of manufacturing; from metal forming, to motors, pumps and compressors; but almost all current commercial lubricants are derived from fossil fuels and directly emit greenhouse gases by oxidation either in production or use and so – by a strict definition of Absolute Zero – are ruled out.

Similarly, solvents which emit Volatile Organic Compounds cannot be used. Yet these play a significant role in many industries, including paper coating, degreasing, printing and textiles, but also in coating or painting manufactured goods. Alternatives will be prized and their use widely expanded by 2050. Currently most steel used in manufacturing derives from iron ore; recycled steel is used almost exclusively in construction. New methods will be needed to shape, certify and steel derived from recycled sources. Processes will need greater tolerance to input variation.

Whilst cement and concrete are not widely used in manufactured goods, they are of course ubiquitous in industrial floors, machine foundations and the like: placing a significant constraint on future factories at a time when flexibility and adaptability is key.

Meeting changed product requirements

By 2050 and beyond, the product and composition of many manufacturing industries will be significantly different. For example, Chapter 1 anticipated a 3-fold increase in non-emitting electricity generation over the next 30 years which means that the need for energy storage will sky-rocket. Section 2.1 predicted major shifts in demand for transport equipment: large uptake in electric vehicles and an end to plane or ship building. Similarly, widespread electrification of domestic and industrial heating will require a massive increase associated equipment such as heat pumps. A shift to vegetarian diets would change the food industry significantly. Increased consumption of processed meat substitutes with lower emissions embodied in the food inputs, would require new processing capability and could need more energy in processing.

The scale of material and resource input to enable these changes is significant; looking at wind electricity generation alone, increasing capacity at the rate predicted creates the opportunity for a substantial increase UK industrial output. On the other hand, Section 2.1 anticipates that by 2050 consumers will require products that last longer and can be used more intensively. This will present manufacturers with the challenge of producing higher quality, higher value products. These may be individually more materially intensive but, with a reduction in total volume of sales, manufacturers will see a reduction in their total throughput.

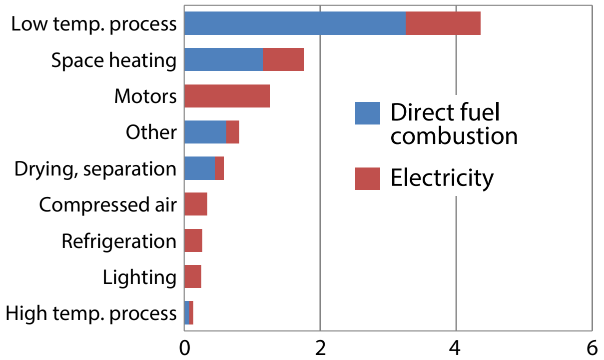
Improving resource efficiency

In a world with much-reduced primary energy availability manufacturers will need to make a step change in resource efficiency; both in material and energy input.

Material efficiency

Various material efficiency measures are technically possible in the manufacturing of goods, components and equipment, including the reduction of process scrap, optimised component design and re-use or re-purposing of components. Large emission savings are possible by reducing process scrap. In machining up to 90% of material can be wasted. For example, machining of aerospace fan blades from solid titanium can produce 90% waste in the form of machining chips. The paper industry produces pulp residue as waste containing high cellulose fibre and high calcium oxide, both of which can be used in fired clay brick production. Other uses are for land-filling, incineration, use in cement plants and brickworks, agricultural use and compost, anaerobic treatment and recycling.

Figure 2.21: Annual energy use (MToe) of key processes



The automotive industry in the UK generated 0.5% of the total commercial and industrial waste in the UK, at 1.85 million tonnes, 41% of which is metallic, 28% is mixed ordinary waste, 8% chemical and medical waste, and the remainder mineral, paper, wood and plastic. Many nascent technologies have been proposed that could reduce process scrap such as additive manufacturing, precision casting or forging and so on. However, the significant variation in performance between companies illustrated in Fig. 2.22 suggests that the problem is just as much in the management of component and manufacturing design processes.

Shape optimisation of components could further reduce the material requirements of manufacturing. Whereas a given component - whether it is food or beverage can, drive shaft, or a structural beam – would often ideally have variable thickness along its length, or a hollow interior, current manufacturing process are not set up to produce such features. Material savings could be achieved by the development of new manufacturing processes: the economies of scale promote production of components with uniform cross-sections, but optimising material use would require a distribution, and new computer-controlled equipment can facilitate this change. Functional grading – generating different mechanical properties in different parts of the component - or using higher strength or lighter materials can also contribute.

Figure 2.22: Material utilisation rates for selected cars

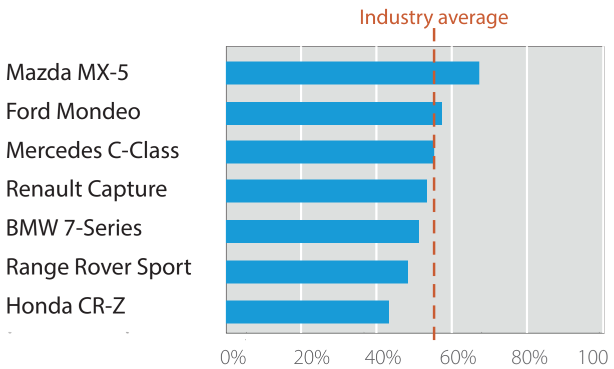
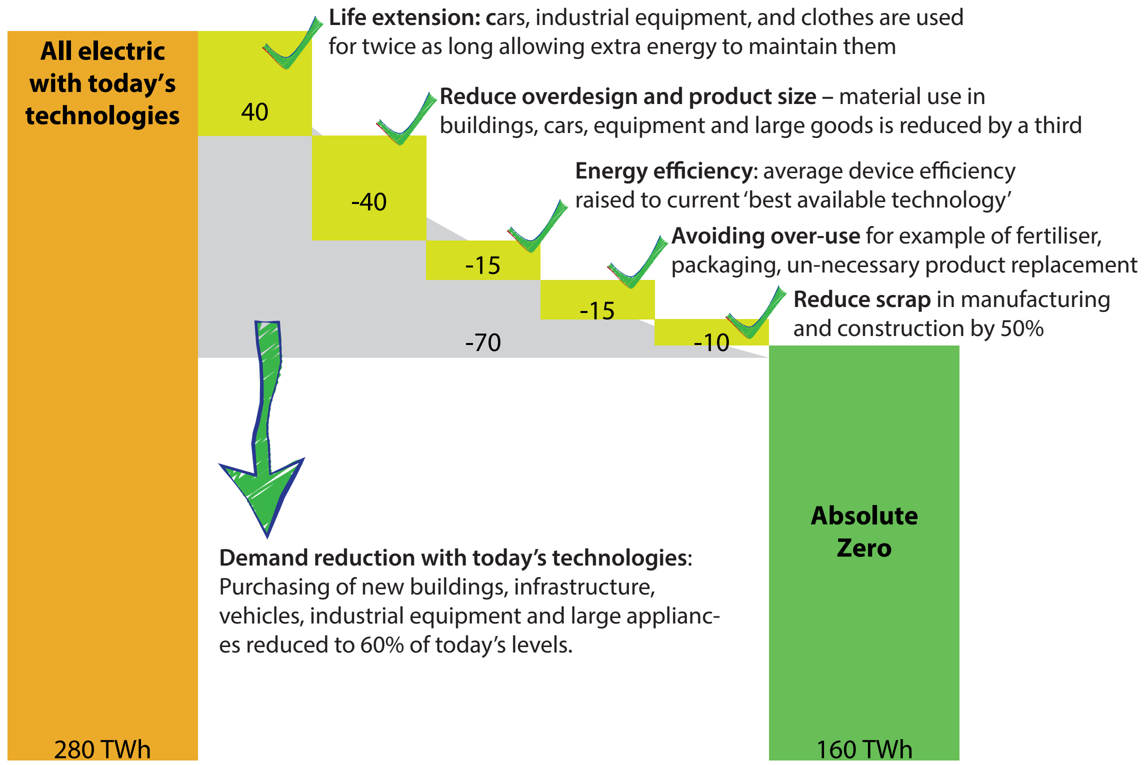


Figure 2.23: Reducing energy use in manufacturing and construction with incremental technologies or reducing demand



Changes of the nature described have all been demonstrated at differing technical 'readiness' but their deployment requires large disruptive changes in management practices, skills and manufacturing processes.

Energy efficiency

Direct energy use in manufacturing will need to reduce if electricity supply is restricted to zero-carbon sources by 2050. Some of this reduction could be achieved by energy efficiency. In the UK, the use of energy in downstream industries is dominated by low temperature process heating, space heating and motors, with a long tail of other uses as shown in Fig 2.21. Recent estimates suggest that it may be possible to quarter electricity consumption over the next 10-15 years with the appropriate deployment of conventional technology such as motor drives, pump and compressed air efficiency measures, and the use of heat pumps.

Product standards

Many positive changes are already occurring and many others are both technically feasible and cost-saving in the long run. To deliver the rapid pace of improvement needed we propose that stretching, and imaginative embodied emissions standards are phased in for almost all manufactured product and imposed equally on UK manufacturers and imported goods. Such standards are already widely familiar within manufacturing, whether for safety, inter-operability or use-phase energy efficiency. These must now be extended to embodied emissions and – as matter of urgency - be attached to the major programmes of industrial product development delivering the widespread changes in energy, transport equipment, food infrastructure. If these are imposed fairly on traded goods, it would create a great incentive for UK manufacturers to develop and benefit from the novel products and processes compatible with Absolute Zero.

Fig. 2.23 summarises the analysis of this and the previous section: the energy required to power UK manufacturing and construction, once electrified, can be reduced by a combination of changes to product specification and design, product longevity and process efficiency.

Key Message: Driven by inventive new embodied emissions standards, manufacturing will adapt to three major changes: 1) reduced availability of current inputs, 2) radically different product composition and requirements, and 3) the existential need for improved resource efficiency.

2.5 Breakthrough Technologies

The purpose of this report is to focus attention on how we can really deliver zero emissions by 2050, using today's technologies and incremental changes in use. This is because breakthrough technologies take a long time to deploy - as shown in the box story on page 10 - and we don't have enough time left. However, beyond 2050, new technologies will emerge to transform the energy and industrial landscape, and some of them will be those under development today.

The options surveyed on this page are therefore post-mitigation technologies: after we have met Absolute Zero through complete electrification, a 40% cut in energy demand and the elimination of emitting activities without substitutes, these technologies may later grow to be significant.

Generation

Of the non-emitting technologies in current use, hydro-electricity is difficult to expand, due to geography, and as discussed earlier, the use of biomass for food will exclude its use at scale for energy generation. However, nuclear power could expand. Following the Fukushima disaster in 2011, Japan closed its nuclear reactors and Germany decided to move permanently away from them. However, France continues to generate much of its power from nuclear power, and in the UK, Hinckley Point C is under construction although this is a big, costly project with uncertain completion date. New "small" modular reactors are also under discussion. At present, none are operating world-wide, with two under construction, but potentially beyond 2050, these could make a significant addition to generation. More remotely, nuclear fusion which has been under development since the 1940's is still decades away from generating any energy even at laboratory scale, so cannot be included in planning.

Beyond wind and solar power, the other renewable generation technologies under development are geothermal, tidal and wave power. Geothermal generation which operates at scale in Iceland, New Zealand and Costa Rica is unlikely to be significant in the UK and is operated only at very small scale. Two large tidal power stations operate world-wide, in France and Korea, at a scale of about a quarter of a gigawatt, but although the Severn Estuary has been explored as an attractive site, the UK has no current plans for a first installation. World-wide there is no significant generation based on wave-power. As a result, while these are important areas for development, it is not possible to anticipate any significant new generation from these new renewable technologies.

Energy storage and transfer

Wind and solar power are intermittent, so create a challenge of matching the availability of electricity supply to demand for its use. This can be addressed by storage (for example by batteries or the pumped hydro-station at Dinorwig) or by controlling demand to match availability, for example by allowing network operators to decide when domestic appliances and industrial processes can operate. There are already many developments in this area in the UK, and we assume that they can operate at sufficient scale in 2050 to prevent the need for excess generation.

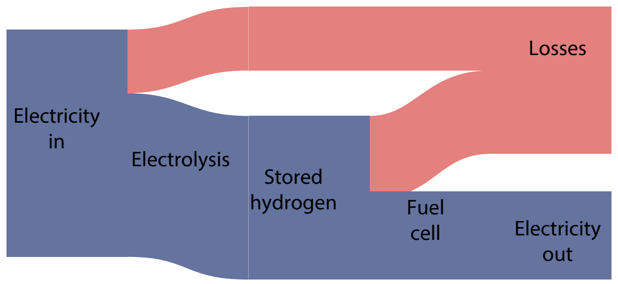
Batteries can operate at large scale, but remain heavy. For static applications this is not a problem but for transport it is constraining: the battery accounts for around one quarter of the weight of a two-tonne Tesla Model S. Technology developers have therefore looked for alternative forms of energy storage to use in transport, and found two important options: hydrogen and ammonia.

Hydrogen is currently produced mainly (95%) from fossil fuels by steam reforming methane, which leads to the release of a significant quantity of greenhouse gases offering no benefit as a form of energy storage. However, it can also be made from water by electrolysis, although as Fig. 2.24 shows, this involves losses which depend on the application, but may be higher than those in the figure depending on the form of storage used. If, in future, we have an excess supply of electricity from non-emitting sources, we could use it to make hydrogen, which could then be used to power vehicles.

Ammonia combustion for shipping may be available in the future, but it currently leads to the production of NOx, which is a powerful air pollutant. Additionally, ammonia is currently produced from fossil fuels, which results in emissions. Although it is possible to use fuel cells to produce ammonia using renewable electricity, there is currently no such process in commercial operation, and its implementation at scale would again be an additional burden to the decarbonisation of the power grid.

One further opportunity for energy storage and transfer is through heat networks which capture "waste heat" from industrial processes and use it, for example, for domestic heating. Around 1% of the UK's homes are heated by heat networks, but expanding this number has proved difficult due to the high cost of the required infrastructure.

Figure 2.24: "Round-trip" efficiency of hydrogen storage



Emissions capture

Although not all related to the energy system, several novel approaches have been proposed to capture carbon emissions. Carbon Capture and Storage (CCS) is used to a very small extent by the oil industry to increase production through the process called "Enhanced Oil Recovery": compressed CO_2 is pumped into the rocks in which oil is stored to drive more of it to the well.

For over twenty years CCS has been proposed as the key technology to allow continued generation of electricity from gas and coal. However, the only power plant operating with CCS – the Boundary Dam project at Saskatchewan in Canada, a very small 0.1GW power station – does not produce transparent figures on performance, and when last reported on by researchers at MIT, was capturing but then releasing its emissions. This technology, despite the very well-funded lobby supported by the incumbent oil and gas industry, is far from mature or ready to be included in meaningful mitigation plans.

Plans for "Bio-energy CCS" or "BECCS" claim to be carbon negative – burning biomass and storing carbon permanently underground – are entirely implausible, due to the shortage of biomass, and should not be considered seriously.

Carbon Capture and Utilisation (CCU) has become a key technology promoted by the industrial operators of conventional plant, particularly the steel and cement industry, but it requires significant additional electrical input, which clearly will not be available before 2050. In future CCU allow conventional steel and cement production to re-start, but only when we have excess non-emitting electricity.

In fact, the idea of carbon capture and storage requires no new technology, as it could be developed by increasing the area of land committed to forestry or "afforestation". We aren't short of tree-seeds, and instead the world is experiencing deforestation under the pressure of needing land for agriculture to provide food. Planting new trees is the most important technology on this page, and does not require any technological innovation.

Industrial processes

In addition to its potential application in energy storage, hydrogen creates a further opportunity in industrial processes because it is sufficiently reactive that it could be used to reduce iron ore to pig iron without releasing carbon emissions in the reaction. Steel has been produced at laboratory scale by hydrogen, and pilot plants are now being developed to demonstrate higher scale production. However, it will only be consistent with a zero-emissions future when the hydrogen is produced with non-emitting electricity, and we have no spare non-emitting electricity to allow this to happen.

Beyond 2050, the incumbent operators of blast furnace steel making, have several process concepts for making new steel from iron ore without emissions. The three main areas being discussed are: separating CO_2 from other blast furnace gases, and applying CCS to it; using hydrogen instead of coke to convert iron ore to steel; separating CO_2 from other blast furnace gases, and using it for other purposes via CCU. All three routes show rich technological opportunities, but will not be operating at scale before 2050.

Flight and shipping

Electric planes are under development, but difficult: the limited rate of improvement in solar cell efficiency shown in Fig. 1.10 suggests that solar power will be never be sufficient for multi-passenger commercial flight. Meanwhile, we have yet to find a sufficient breakthrough in battery development to anticipate sufficient light-weight storage. The most promising route appears to be synthetic jet-fuel - which, inevitably, will be important only after a substantial increase in non-emitting electricity generation.

The decarbonisation of shipping is difficult with current technologies. Although short-distance shipping can be electrified using battery-powered engines, long-distance shipping requires a combustion process. Nuclear propulsion of ships offers a viable alternative to current long-distance shipping and it is already used, although almost only in military vessels. Some commercial operators are currently exploring the opportunity to add sails to conventional ships to reduce their diesel requirements.

Key Message: The problem with breakthrough technologies is not our shortage of ideas, but the very long time required to take a laboratory-scale idea through the technical and commercial development cycle before it can begin to capture a substantial share of the world market.

3. Transitions:

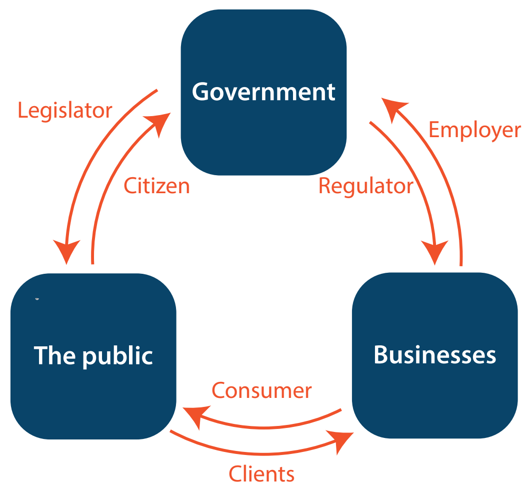
Key Message: No one actor can bring about Absolute Zero. Delivering it is a journey depending on co-operative action by individuals, businesses and governments acting on good information

Absolute Zero is a journey

Action on climate change depends on the co-operation of three "players" illustrated in Fig. 3.1. The public, the government and businesses must act jointly to transform the way we produce, consume and live. Large sections of the public are increasingly concerned with climate change, and some take individual actions such as eating less meat, looking for locally sourced products or taking the plane less often. Politically, this has translated to a growth in the support for Green parties across Europe. Businesses, driven by the demands of the public and driven to efficiency are seeking more efficient production methods and developing products consistent with a zero-emissions future. Governments embrace the drives of the public and businesses to grow the economy and gain votes.

Despite this goodwill towards change, the important transformations outlined in this report do not seem to be happening, or at least not at a sufficient pace. A key reason for this is that these transformations are attempted without the required trust building between the actors which can make them successful. The actors of change are in effect locked in a prisoners' dilemma, and the changes proposed make it seem like a static version of the game. The prisoner's dilemma is a theoretical game where the best outcome for the players cannot be achieved if the players only follow their own best interests. There are many variants to the story but in substance it runs like this: two bandits just successfully robbed a bank and were caught soon after for some minor offence. They are kept in separate cells, and each is told their accomplice has also been caught. They can defect and accuse their accomplice of the robbery, in which case they'll get at least a reduced sentence, or they can cooperate and refuse to accuse each other. Should they both defect, they'll both have a reduced sentence. Should they both cooperate, they'll both have a small fine, should one cooperate and the other defect, the defector will go out free and the cooperator will get a full sentence.

Figure 3.1: The three "players" of climate mitigation



Game theory predicts they should both defect: indeed, there is no outcome from cooperating which cannot be improved by defecting… Every day, all of us are faced with many such dilemmas – but every day we cooperate rather than defect! This is because the prisoner's dilemma when played over and over is a completely different game which is won by achieving cooperation. When considering the so-called iterated prisoner's dilemma, it's not single moves but strategies which matter. This is a well-studied problem, and the winning strategies which achieve cooperation share a number of basic characteristics: they punish defectors, they reward cooperators, they are simple enough that they can be understood by observers. Other research looking at how humans play in games compared to the predictions of game theory suggests another crucial quality of winning strategies: the cooperative strategies must also be fair. Marginally cooperative moves will be treated as defections.

Similarly, the transformation required for climate change mitigation needs to be played out like the repeated game, and not seen as a single huge step which will most likely be resisted and fail. Fortunately, three-player games favour cooperation somewhat, unlike the two-player variant. Unfortunately, having more players may drive each one individually to try and delay making changes. To achieve the scale of transformation required, small incremental changes are the immediately necessary steps to build and reinforce trust between the actors.

Case study: reusing steel

Currently, most of the steel from demolitions is recycled. There is nothing else which can be done with the reinforcing steel of concrete, but steel beams having standard sections and not being damaged from their service as structural elements could be reused. If not directly, after some sand-blasting and the fitting of new connexions the beams are as good as new. Most of the research on the barriers to steel reuse focuses on the certification problem: steel to be used in construction needs to be certified, but the process of obtaining certification assumes the beam is coming out of a mill and is not transposable to already used beams. However, is is possible for a small price premium to test the beams and guarantee that they have all the appropriate properties.

What we found is that the key obstacle in the supply chain was that steel re-use puts the buyer of the building wanting to use steel from reuse and the fabricator responsible for the conditioning of beams in a prisoner's dilemma. Reconditioning the steel takes approximately twice the amount of time to condition a new steel beam direct from the foundry. Although the fabricator can charge for this time, a project being abandoned – always a risk in construction – will translate to large losses. Therefore, all projects that we could study where the fabricator was not part of the planning, failed. Our proposed solution is for steel stockist to take on the job of reconditioning and recertifying steel so that the fabricators need never know whether the steel is from reuse or not. Acting as a trusted intermediary, this would avoid the project failures due to fabricators not wanting to shoulder all the risk. The upfront investment could be helped by government grants, and we showed that this would be overall profitable.

Case study: Cycling in the Netherlands

After the second world war, the Netherlands had, like the rest of Europe embraced cars as a symbol of freedom and mobility and had built highways and roads to accommodate this new transport mode. In 1971 alone, 300 children died in the Netherlands from accidents involving cars, leading to widespread protests. In 1973-74 the oil crisis caused oil shortages, leading the Dutch government to look for strategies which would lower the oil dependency. The protesters were demanding a return to the biking culture which had been an important part of Dutch habits until the war, and the government took this occasion to launch a number of bike-friendly initiatives: a number of car-less Sundays in the years. Some city centres were made car-free. These moves proved popular and were followed by the construction of bike-specific infrastructure.

From the mid-70s onwards, bikes were integrated in urban planning decisions, meaning not only cycles paths being built, but traffic-calmed streets would be favoured, and bike parking be available at convenient locations, and bike traffic be integrated in the general public transport infrastructure. As the bicycle is seen as a symbol of the Netherlands, it was possible to pass more stringent legislation: for example since 1992, in an accident, it is always the motorist's insurance which is liable for the costs in the Netherlands. Safe interaction with bikes is part of passing one's driving license. As the popularity of bikes grow in the 90s and 2000, larger investments in bike infrastructure became possible with the support of the public, leading to even more bikes being ridden.

Overall, the current Dutch biking culture is the result of a long process where multiple changes to legislation, habits and infrastructure were self-reinforcing, leading to today's situation where the Netherlands is Europe's leader in kilometres cycled.

3.1 Individuals – at home and at work

Protesters and school strikers have increased our awareness of the need to address climate change. An individual wanting to reduce their personal emissions can find a wealth of information on social media, websites and podcasts detailing actions they could take. Behavioural changes required to deliver zero emissions by 2050 are already being practised by some people in some places: some people already choose not to fly, to be vegan, to car share, to lower the temperatures in their homes and offices. If large scale social amplification could occur, as it did with the 'Me Too' movement, surely a cultural change could occur to enable zero emissions by 2050?

Although public awareness of the need to act has increased, the UK has not meaningfully reduced its resource use in recent decades, with the International Energy Agency reporting total final energy consumption has reduced by only 7% since 1990 levels. Individuals continue to use nearly as much energy as they did 30 years ago, suggesting that existing strategies to motivate individuals to use less energy are not generating the scale of impact required.

Social norms and individual behaviours

There is a misalignment between the scale of actions recommended by government (e.g. energy conservation) and those most commonly performed by individuals (e.g. recycling) . Actions which can have a big effect, such as better insulation in houses and not flying, are being ignored in favour of small, high profile actions, such as not using plastic straws. This is enabling individuals to feel satisfied that they are 'doing their bit' without actually making the lifestyle changes required to meet the zero emissions target. If large scale social change is to be successful a new approach is needed.

Whilst the thought of society taking radical, meaningful steps to meet zero emission targets could be criticised for being idealistic, we can learn from historical cultural changes. Not long ago, smoking cigarettes was encouraged and considered to be acceptable in public spaces that children frequented, drink-driving was practiced with such regularity that it killed 1000 people per year in the UK, and discrimination based on sexual orientation was written into law. These behaviours now seem reprehensible, showing society is capable acknowledging the negative consequences of certain behaviours and socially outlawing their practice. Focus should therefore be centred on expediting the evolution of new social norms with confidence that change can happen.

Evidence from behavioural science, and the long experience in public health of changing behaviours around smoking and alcohol, shows that information alone is not enough to change behaviour. To make the types of changes described in this report, we will have to think more broadly on the economic and physical contexts in which designers, engineers and members of the public make decisions that determine carbon emissions. At the same time, clear, accurate and transparent information on problems and the efficacy of proposed solutions is essential for maintaining public support for policy interventions.

The phrasing of communication is also important. Messages framed about fear and climate crisis have been found to be ineffective at motivating change. The longevity of the challenge of reducing emissions, and the lack of immediate or even apparent consequences of small individual actions mean it is challenging to link to them to the large-scale climate crisis. This allows individuals to make decisions which contrast with their desire to reduce emissions. Scientific description is not always the most effective means of communication, and language used to promote zero emissions should no longer focus on an 'eco-friendly' and 'green' lexicon, but rather candid descriptions of actions that appeal to human fulfilment. Evidence from time-use studies shows that human fulfilment does not strictly depend on using energy – the activities we enjoy the most are the ones with the lowest energy requirements. Consumers can be satisfied in a zero emissions landscape.

Individuals and industry

If net-zero targets are to be met, all of society needs to change, not just those motivated by the environment. Therefore, as well as persuading and supporting individuals to change with environmental campaigning and one-off sustainability projects, industry should embed a net-zero emissions strategy into business-as-usual, only offering products and services which meet their consumers' welfare needs without emissions.

This change will be driven by individuals acting in their professional capacity, as managers, designers, engineers, cost consultants, and so on. A structural engineer designing a concrete-framed building has vastly more influence over carbon emissions through their design decisions at work than through their personal lifestyle. Therefore, as well as the transitions in businesses discussed in the following section, this section applies also to individuals at work.

Key Message: Changes to social norms and individual behaviours can be positively framed to appeal to human fulfilment. Motivated individuals can be as effective at work as at home.

3.2 Transitions in businesses

Many of the opportunities and changes identified in the first sections of this report will involve businesses making changes to the types of technologies they use, or the way they use them. But this type of change can be difficult to motivate. This section examines why this is, and discusses the role of incentives, market pull, standardisation and collaboration in achieving the change required.

Challenges in changing technologies for zero emissions

We are surrounded by a constant stream of innovation in technology in some areas, such as smartphones – so why is it that some other industries have been slow to respond and to integrate relevant innovations into their operating models? In general, the reason is that new production technologies are introduced at the same as a new generation of products is launched. The new manufacturing technologies and processes are often not central to the functionality of the next product but are driven instead by improvements in cost, quality and logistics. So in areas without a rapid cycle of introducing new generations of products, it can take a long time for manufacturing innovations to be adopted.

In such cases, thorough assessment of technology merits, maturity and readiness are carried out, especially where change represents some form of risk. Without the driver of a new product launch, and associated new revenue stream, firms have displayed a risk-averse attitude towards making significant transformations in the production technologies they use. This is particularly true for safety-critical applications. In such cases, novel technologies have had to pass the test of time before being considered for full deployment. Another reason behind gradual technology adoption is the lack of propensity to invest, especially in highly established industries where the cost of new capital would be prohibitive.

Incentives for technology innovation

Using the "carrot and stick" analogy, it is easy to understand that innovation can have a difficult time permeating into an organisation without the right type of leverage and motivation. Governments can impose additional taxes, policies and regulations to achieve the desired changes but this could be short lived with the next batch of policy changes. Emissions and energy caps can be seen as a "stick" but financial rewards and customer-valued green credentials will be perceived as a "carrot".

Ideally there should be a market pull that is driven by the end customer. Organisations are more likely to adopt innovation and technology when there is a direct correlation to increased revenue and returns. They are also more likely to pursue targets that result in products and services that use less resources but still valued equally or greater by the customer. Consumers are more aware of the macro effects of their purchasing choices and there is a move towards companies that have the same brand values. However, for a business, it can be hard to benefit from this, as the relevant qualities are not easily visible to the end customer. For example, you cannot tell just by looking at a washing machine whether it was produced from renewably-powered recycled steel, or carbon-intensive steel from a blast furnace.

The achievement of Absolute Zero almost certainly requires life extension and better utilisation of certain categories of product, but with progressive insertion of more sustainable manufacturing and through-life engineering technologies throughout life in service. This creates a conflict: life extension and better utilisation of existing products implies that new products need to be introduced less frequently – but as described above, generally more sustainable production processes are difficult to introduce in the absence of new generations of products being developed. A new mechanism is therefore needed to drive forwards the adoption of positive technological changes. The most obvious means of doing this via public intervention would be the establishment, of some form of 'roadmap' which sets out progress.

The role of standardisation

Standardisation can play a significant role in reducing industrial and domestic energy use and CO_2 production. In many industries, standardisation and sharing best practice have paved the way to less resource duplication and greater customer experience. An example that is often mentioned is the light bulb but a more modern example would be the phone charger. In the early days of the mobile phone industry, not only did every manufacturer have their own chargers but every model had its own connector type. Once customer habits were analysed, it was found that customers wanted to upgrade to a new phone every few years, therefore very quickly there would be a build-up of useless chargers and connectors ending up in landfills. Several of the major manufactures developed a standard charger and connector that would be used for all models going forward. This had 4 main benefits:

- Reduction in unnecessary charger variation and legacy part production.
- Increased customer experience as phones could be charged with any charger and no longer limited to one connector.

- Phone manufacturers diverting funds and resources away from charger and connector design into other parts of the product that were more valued by the customer.
- Users investing in higher quality chargers that could be used for years without needing replacement and a reduction in E-waste.

In other industries current practice often requires specialised components and parts that are designed specifically for their intended use. With standardisation comes the reduction in design flexibility. In an already saturated market place, businesses are trying to differentiate their products and services form one another. Customisation currently allows them to achieve these goals, but as discussed above, the future environmental benefits of standardisation could provide an alternative source of differentiation.

It is possible that the progressive roll-out of standards over time could form a central and tangible element of any roadmap for achieving Absolute Zero. The development of standards which drive positive change would however be entirely reliant on some key principals of backward compatibility, such that the implementation of each new standard avoids immediate obsolescence of existing assets.

Making collaboration work

The achievement of Absolute Zero seems to be beyond the ability of individual firms, and even nations, to enact. It requires a level of cooperation which has perhaps only been seen during times of war.

Moving beyond the purely competition-based model and integrating some learning from the collaboration model can be beneficial to competitors as well as the environment. As well as eliminating obvious duplication of resources, a new level of cooperation would be needed so that the benefits of shared learning can rapidly permeate through supply chains, and horizontally across sectors. This presents a more complex legal and organisational challenge to the traditional manufacturing and business model, but one which could create new opportunities for early adopters.

The necessary transition will incorporate the current move beyond the traditional manufacturing line to more flexible manufacturing for increased agility while taking a balanced and holistic planning approach to enable through life considerations to be made. The role of analysis in this model based on increased computing power, but also the carbon impact of data storage and transfer is a complex one. Gathering information on the whole manufacturing process from all participants in the supply chain and then analysing the results to produce the holistic resource usage is one of the ways to truly understand what goes into the final product. Insights from this information will allow for the development of a valid roadmap to Absolute Zero, but there are challenges to obtaining and using this information that will be discussed later, in section 3.4.

A look to the future

Technology innovation and change readiness is becoming a desirable quality. With shortening product life cycles, organisations need to adopt a more agile approach to respond to market needs. Catering to this consumer mentality has led to the production of lower quality products that fail in the time the consumer would be looking to upgrade or replace the product. An extension of through-life engineering approaches beyond ultra-high capital value assets into more mainstream consumer products is needed. Essentially this means producing much higher quality products with parts that can be dismantled, retrieved and reused. Products could either be disassembled and reassembled with some modifications and resold, or they could be cascaded down into a completely new product. This would require forward planning, standardisation and modular design thinking.

Organisational and inter-organisational culture will need to match the aspiration of Absolute Zero over time to become, itself the great incentive and driver of a positive cadence of change. No organisation can outrun their legacy, therefore a roadmap that commits them to real change while keeping the business profitable now and in the future is desirable.

This section has focused on technology transitions in existing businesses, but successful disruptive transformations often come from outsiders and new players. Therefore, support mechanisms also need to exist for new businesses bringing zero-carbon-compatible business models and production processes as an alternative to the status quo.

Key Message: Agreed roadmaps, new forms of market pull and collaboration are needed to spread the required technological innovation through industry.

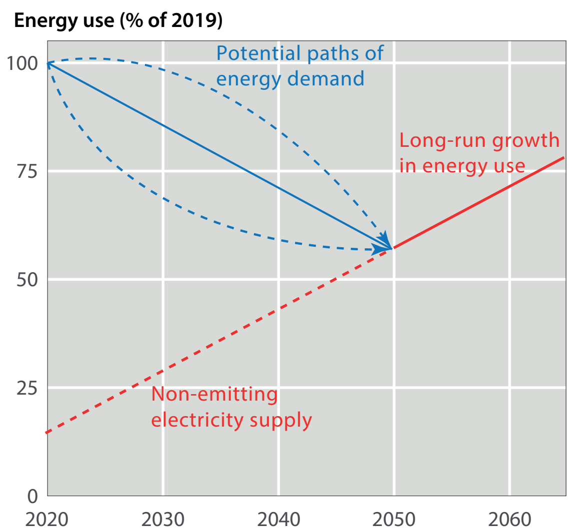
3.3 Action by Government

The government will need to act to create the context in which the individual and supply-chain changes described in the previous sections can develop. There is also a strategic choice about the speed of transition which should be pursued.

Fig. 3.2 shows three potential paths for energy reduction to reach Absolute Zero in 2050. This is predicated on growth in the supply of energy from renewables growing at the rate indicated in Fig. 1.1. This means that demand has to reduce to 60% of its current level by 2050. Growth in energy use beyond 2050 will be driven by ongoing renewable and other carbon-free technologies. The distinction between the pre-2050 and post-2050 analysis is that the steps taken to meet the 2050 target must rely on technologies which are already in existence, and have the clear mechanisms to be scaled, whereas post-2050 growth can reflect new technologies. The three potential paths for energy reduction reflect three different approaches, depending on the extent of delay. What these three paths do not show is that the cost or sacrifice needed for an extra percentage point reduction is not constant: initial reductions are likely to be much easier. This in turn implies that if the desire is to spread the cost of reduction equally over the 30 years to Absolute Zero, then the actual path needs to reflect a sharp early decline, as in the lower dashed blue line.

Absolute Zero means two things: first, that no carbon can be produced by any industry or household; second, averaged across the economy, energy consumption must fall to 30% of its current level. This distinction between the carbon reduction, which is an obligation on all industries, and an energy reduction which is on the average, leads to very different substitution possibilities: there are no substitutes for the reduction of carbon to zero, but there needs to be a mechanism for allocating scarce energy resources. Ensuring carbon is at zero is a regulation issue, with prohibitions on the use of carbon similar to prohibitions on the use of asbestos. Ensuring energy is cut in the aggregate requires an allocation mechanism, and the price of energy to reflect its scarcity. In such a scenario, the owners of the means of production of renewable energy will make very large profits. This in turn raises both efficiency and distributional issues.

Figure 3.2: Pathways of restraint and growth



We break the discussion into four components: first, on the possibilities for substitution away from carbon and energy use across different sectors; second, on the impact on the types of job and the location of jobs; third, on the overall impact on output; and finally, on the implementation.

Production Substitution

At the heart of understanding the impact on the economy of Absolute Zero is an understanding of the substitution possibilities away from carbon and energy in different industries and production processes.

Section 2.3 discusses the options for the construction sector: the production of cement involves the emission of carbon and so cement in its current form cannot be used in construction. At present there is no alternative to the use of cement and so the construction industry has to radically change its production process or close. In this case, radically change means either reverting to using wood or other natural products, or successfully developing the alternatives to current cement production described in Section 2.2. These options, however, limit the size of buildings and so the sector cannot continue as it is. This has implications for the way in which businesses and households operate. Buildings need to be reused rather than rebuilt. On the other hand, it is not clear how the existing stock of buildings will be maintained, and the conclusion is that building space (residential and commercial) will have an ever increasing premium

The difficulty of the construction industry highlights the impact on any assets being used in an industry where there are no substitutes for carbon – such as planes, or industrial plants. The value of these assets will be zero in 2050 and this should directly affect the desire to invest in those assets now. This points to the implementation issue: realising the value will be zero in 2050 may encourage greater use in the run up to 2050 – for example, putting up new buildings at a much faster rate for the next 30 years, knowing that construction must then halt. On the other hand, Fig. 1.1 makes clear that the value of investment in processes of carbon-neutral energy production will increase sharply.

Jobs and Location

There are two key implications for how we live our lives: first, buildings will become much more expensive because the restrictions on building which generate substantial scarcities; second, transport will become much more expensive because the limits on air travel will generate excess demand for other forms of transport. By expensive, we mean the direct costs to an individual or firm, but also indirect costs in terms of reduced quality. We would expect these two substantial changes to lead to pressure on the amount of space any one individual uses, and also where people choose to live and work. This points to increased centralisation, with growth in cities.

The wider problem with the changes in labour is knowing what type of labour or jobs will be in demand. Those who are starting secondary school now, in 2019/2020, will be 43 in 2050. Thinking about what education is appropriate for a very different set of industries is a key question. Should we still be training airplane pilots? Or aeronautical engineers? How are we training architects, civil engineers? Education decisions are far more persistent than capital investments. This in turn highlights the needs to take decisions on investments now where the lead times are very long or depreciation rates very low.

Overall Impact on Output

Economic growth in the industrialised world has been associated with increasing energy use. Long-term growth rates will also be constrained by the rate at which energy production can grow which depends on the growth rate of renewables. The key question in the transition is how much will output decline to reach a level where only 30% of current energy is being used and no carbon is being produced. We have discussed the direct impact of this on the construction and transport sectors. What this misses is the inter-dependence of the non-emitting and emitting sectors. Specialisation in production and the substitution of energy for labour have been key drivers for growth and increased productivity. The open question is whether specialisation can still be achieved without the reliance on energy.

These impacts on output will not be felt equally across the country. Industries are typically geographically concentrated – such as steel production – and this means that large shifts in production will have concentrated impacts. Rural or more isolated communities are likely to be disproportionately affected. The largest distributional impact, however, is intergenerational: the cost of hitting Absolute Zero will be borne by the current generation.

Implementation

The changes in behaviour to achieve Absolute Zero are clearly substantial. In principle, these changes could be induced through changing prices and thus providing clear incentives for behaviour to change. The alternative is that the government prohibits certain types of behaviour and regulates on production processes. Given the difficulty for the government of knowing what production process to change or what options for innovation are available to companies, the natural decentralised solution is for the government to either put a price on carbon or to restrict its use directly. The push for Absolute Zero means the distinction between these two approaches is irrelevant: the price of carbon must be prohibitively large by 2050 to stop all demand. In the run-up to 2050, the question is how fast must the price of carbon be increased, or equivalently, how fast must restrictions on the use of carbon be put in place. It is understanding this time-line for the price increase (or time-line for the strictness of restrictions on use) which is the key issue for the implementation.

The underlying point is that any asset which uses carbon will have essentially zero value in 2050. This in turn may encourage greater use in the run up to 2050. This sort of response is clearly counter-productive: the climate problem is about the stock of carbon, rather than the flow.

A natural question in considering implementation of the 2050 is how to evaluate the cost to the economy of various measures. For example, how to compare the cost of installing solar panels to the cost of driving smaller cars. Individuals' willingness to pay gives a measure of the value of installing solar panels (rather than take electricity from the grid) or the value of driving a small car (rather than a larger one with the same functionality).

Key Message: The effective price of carbon must be prohibitively large by 2050. A key issue for how to implement this is the timeline for how the price must grow (or restrictions must become more strict) from now to 2050.

3.4 Information

Information has a critical role to play in guiding transition to Absolute Zero emissions. Data about our present situation is needed to prioritise change and innovation, to monitor progress, and to identify 'bright spots' of good practice. We also need to understand how the future might develop and how we can make choices now that are robust to future uncertainty. However, information alone is not sufficient to cause actual changes in behaviour, and we should be aware of lessons from behavioural science to maximise the effectiveness of information.

Information on the present

Understanding the current scale of our different activities that drive emissions is key to prioritising the behaviour changes and technical innovations that would most effectively lead to emissions reductions at the scale required. Put simply, the impact of a change (whether behavioural or technical) can be represented as:

$$\text{Impact of change} = \text{Scale} \times \text{Change in flow} \times \text{Impact of flow}$$

For example, in construction it is possible to use post-tensioned floor slabs in place of the standard slab types, to achieve a 20% reduction in cement use (the 'change in flow' of cement entering construction). However, this technique is only applicable to a fraction of all the floor slabs that are constructed (the 'scale'), and the overall impact depends on the impact factor of the flow (in this case, GHG emissions per tonne of cement). Clearly, the overall impact of a change depends on all of these factors. An understanding of all three is critical to formulating a roadmap for change (Section 3.2) that can really reach Absolute Zero emissions. The same applies to research agendas, where there has been more research and policy interest in reducing food waste than on reducing meat consumption, despite the former contributing an estimated 1–2% to emissions and the latter an estimated 50% . Data on how things are currently happening can also support change through identifying 'bright spots' where good practice is already happening .

Looking to the future

However, understanding the present is not enough. Many of the decisions that will influence emissions in 2050 must be made far in advance, such as designing buildings, investing in energy infrastructure and car manufacturing plants (Section 1). These decisions should ideally be robust to a wide range of possible future outcomes, such as faster- or slower-than- expected deployment of zero-carbon energy supplies, or higher or lower loading requirements for buildings in use. When this is not done

well, the result is the situation described in Section 2.3, where structural designs are routinely excessively sized, leading to proportionally excessive carbon emissions. In contrast, it has been shown that an initially-smaller design that allows for reinforcement to be added to beams in future, if needed, would lead to lower lifetime emissions .

There are many possible pathways to zero emissions in 2050, and different reports can reach very different conclusions from by focusing on different scenarios. To provide clarity on our options to reaching Absolute Zero, we need to compare different proposals on a common basis and highlight the different starting assumptions that lead to different conclusions (see box story overleaf for an example).

Getting better information

Despite these important roles that information about our use of resources plays, the data we have is patchy and disconnected. There are two basic ways the situation can be improved: collecting better data, and making smarter use of the limited data we do have.

The UK Government's Resources and Waste Strategy has recognised that 'lack of reliable data on the availability of secondary materials is cited by industry as a barrier to their use', and proposes a National Materials Datahub to address this issue by providing 'comprehensive data on the availability of raw and secondary materials, including chemicals, across the economy to industry and the public sector, and by modelling scenarios around material availability'. The Office for National Statistics is leading the initial development of such a Datahub. As well as official statistics such as these, there is a large body of evidence contained in academic work which is currently difficult to access. Efforts towards Open Science practices ins fields such as Industrial Ecology are starting to improve the discoverability and reusability of this knowledge.

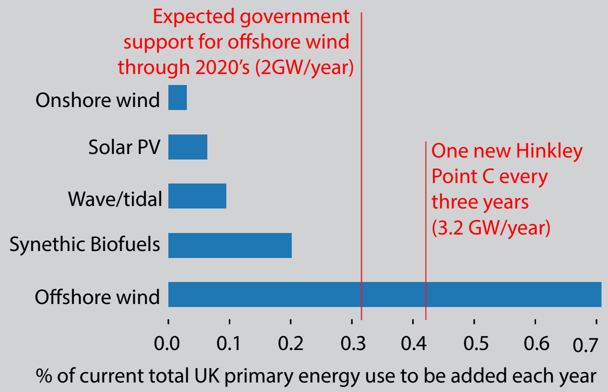
Better information will also be needed within and across supply chains, but there are challenges that will have to be overcome before this can be achieved. The first

Why aren't all plans for zero emissions the same?

Several reports have presented scenarios for how we could achieve net-zero emissions in 2050, such as the Centre for Alternative Technology's "Zero Carbon Britain" report. Unlike the need to reduce absolute energy use described in this report, they find instead that "industrial energy use is expected to remain similar to current levels". How is it possible to reach such a different conclusion on the same question?

It is easier to see the differences by looking at the different assumptions made about the energy system. The figure on the right shows the deployment rates implied by their scenario, together with some reference points to provide context. The Zero Carbon Britain report has much more optimistic assumptions about the deployment rates of renewable generation technologies, especially very early-stage technologies such as producing liquid fuels from biomass – which has not yet been proven at commercial scale – and wave & tidal generation. Assumed deployment rates for offshore wind are also high, requiring a doubling in the speed of installation envisaged in the Governments plans for support through the 2020s.

Figure 3.3: Rates of increase in "Zero Carbon Britain"



is information gathering: it is still not normal practice by suppliers to gather information on all facets of their manufacturing process. Secondly, for business to share collected data with rest of the chain rather than storing in silos. Current corporate practices mean information is often not shared even with different groups within the same organisation let alone with "outsiders". In the information age, industry has remained closed to information out-flow. This may be attributed to good reasons, but the achievement of Absolute Zero requires, possibly above all else, the will to cooperate. The final challenge is analysis of the data and making sense of it. Gathering, storing, processing and presenting data is an energy intensive and expensive task, therefore currently most organisations do not have the appetite to undertake this without proven returns.

Digital tools can potentially help to enable this position. A universal and global approach to IP law and the tracking of information using technologies such as blockchain can greatly increase the confidence of organisations into opening their doors and sharing more of their information. By doing so it is possible to dramatic reduce resource duplication whilst enhancing visibility of resource usage. This could allow businesses to make long-term strategical decisions that lead to higher profitability whilst reducing energy usage and CO_2 production.

Key Message: Good information is critical to transitions in individual behaviour, business operations and in supporting government action, but there are challenges to overcome in collecting and communicating the required information effectively to support decisions and influence behaviour.

4. Opportunity

Key Message: Absolute Zero requires societal change. This will provide opportunities for growth in business, education and research, governance and industrial strategy. To achieve zero emissions we must only pursue the right opportunities and restrain activities which are no longer compatible with a zero emission society.

4.1 Opportunities in business:

This report has revealed an overwhelming wealth of innovation potential for businesses – but not in the area that dominates current discussion about mitigating climate change. Carbon Capture and Storage or Utilisation and "the Hydrogen economy" are important development opportunities and may be significant beyond 2050, but won't play any significant part in national or global emissions reductions by 2050, because implementation at meaningful scale will take too long. Instead, taking the target of Absolute Zero seriously requires a massive expansion of wind and solar power generation, along with the infrastructure required to install, manage and deliver this power and the fertile supply chains of material extraction, production, construction and manufacturing.

The key innovation opportunities revealed in this report are not about how we generate energy, but how we use it. Meeting the target of Absolute Zero requires adapting to using around 60% of the energy we consume today, which without innovation will require restraint. However, section 2 of the report has revealed a tremendous space for business innovation and growth in expanding the benefit we receive from energy use. For the past century, our economy has grown based on an assumption of virtually unlimited energy supply without consequences. Unsurprisingly, this has led to extremely inefficient use – for example with cars weighing around 12 times more than the people within them. The more rapidly the UK commits to delivering its legally binding target, the greater the benefit it will extract from business innovation opportunities. Without question, some incumbent businesses such as the fossil fuel industries, will decline and inevitably they currently spend the most money on lobbying the government to claim that they are part of the solution. This is unlikely.

Instead, future UK growth depends on exploiting the opportunities created by the restraint of Absolute Zero. For example:

- All current aviation activity will be phased out within 30 years, which creates an extraordinary opportunity for other forms of international communication (for example using the technologies of today's gaming industry to transform today's backwards-looking video-conferencing), for the travel and leisure industry to expand more localised vacations and for developments in non-emitting mid-range transport such as electric trains and buses
- The markets for electric cars, electric heating at all scales and temperatures, electric motors at all scales, building retrofit and thermal control are certain to grow at rates far ahead of the recent past. Electric cars comprise a small fraction of new sales today, but under current regulation will, by 2040, have captured 100% of the market. Given the total energy supply constraint of Absolute Zero, the clear evidence of Fig. 2.6 is that the total market will either contract or shift rapidly towards smaller vehicles – this is a fertile and under-populated space.
- Cement and blast furnace steel production will be illegal within 30 years, yet our demand for construction and manufacturing will continue. To meet this demand our supply of bulk materials must transform and there is high-volume innovation potential for non-emitting cement substitutes, for technologies to support high-quality steel recycling, and in the open space of "material efficiency": using half the material per product and keeping the products in use for twice as long.

Beyond the 2050 target of Absolute Zero, technologies that exist at early development stages today may expand into valuable business streams. These include:

- Carbon Capture and Storage or Utilisation applied to fossil fuel power stations, steel or cement production.
- The "hydrogen economy" once there is spare capacity in the supply of non-emitting electricity
- Other forms of electrical transport, including shipping and aviation

The 100% target of the Climate Change Act creates an extraordinary opportunity for UK business to develop the goods and services that will be the basis of a future global economy. However, the biggest commercial opportunities are not breakthrough but incremental developments from today's technologies.

4.2 Opportunities in welfare and education

Today's secondary school entrants will be 43 in 2050. At that age, they will be in leadership positions, so the obvious question is what skills they should be developing now and in their subsequent higher-education years to underpin their decision-making abilities in a very different future world? The legacy of education is surely to know that it is the quality of the questions which one is able to ask which will lead to success. Asking the right questions is a sign of deep education, while answering these questions is an altogether easier proposition even if research is needed.

How do we move from answering questions as the staple of education to asking questions as the hallmark of a necessary education for future uncertainty? Climate change provides us with exactly this opportunity. Some of the current syllabi in secondary schools will be irrelevant in future, and there will be new skills that school children will require. The same is true in universities, both in teaching and in research, where a clear distinction must be made between mitigation actions that can be deployed today through chosen restraint and innovations that might ease the challenge of restraint in future. The former implies hard decision-making, while the latter implies real opportunity.

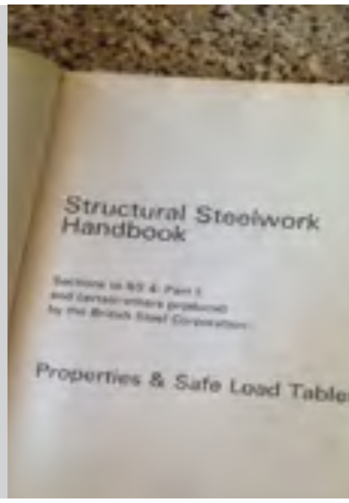
Starting with the difficult decisions, an educational setting should provide a timeline for actions to be taken by humanity in order to ensure that we hit our carbon-reduction targets by 2050. Plans cannot merely relate to actions. They must also relate to the timings of such actions, as any Gantt Chart does. By working backwards from 2050, and sequentially working out the order and timing in which key mitigation actions need to be taken, a roadmap for the necessary restraint can be established. Across the secondary school system, this roadmap is essential in eliciting the questions which will inevitably come from the school children. This will enable an exploration of real change in the mind sets of those who will need to embrace change more than ever before later in their lives. Huge questions will emerge, such as: will internal-combustion engines disappear, will aeroplanes disappear, will meat-and-dairy agriculture disappear and will we need to stop building things? By empowering school children to realise that asking the huge questions is appropriate, we will enable change to be embraced through education. The timing of the change should lead to questions of transition towards electrification, or the trade-offs between energy and labour in delivering services across a whole range of economic activities, for instance. What are the implications for consumption or ownership in a changing society, and how can we ensure that material use down to the finest granularity is all encapsulated in circularity?

Across the education system, we should be seizing the opportunity for the next generation to grow up with 'best practice': from the food available in schools, the way children get to school, to the way school buildings are used. All schools could immediately switch to providing meat-free meals – reducing emissions and promoting healthy eating. Existing efforts to change travel habits aimed at avoiding local air pollution around school gates can be extended to support parents and children in low-carbon travel to school wherever possible. Many schools already feel the need to keep heating temperatures low in an effort to make severely constrained budgets balance, which is a side-effect that could be standardised across the system to help establish the normality of lower-energy, lower-temperature heating setpoints.

Changing Building Design Practices through Education in the 1970's

In the 1970's, British Steel saw an opportunity to expand their market for structural steel sections, by persuading UK clients and the construction supply chain to switch from concrete framed buildings (which remain more common in many European countries even today) to steel framed buildings, like the one illustrated on page 35. Instead of seeking Government support to subsidise or legislate to support this change, they instead developed high quality teaching material and supported the development of new courses in all major civil engineering degree courses about design with steel. As a result, the next generation of graduate civil engineers entering the profession were equipped to use more steel, and expected it to be more normal practice.

This suggests an opportunity to develop teaching material that reconfigures society to adopt new approaches to thriving in a zero carbon economy, by changing the way we live and work.



Looking beyond the need for this kind of restraint in the short term, there are enormous opportunities in education which we could be embracing now to ensure that when the painful period of mitigation nears an end, we have an educated population ready to take advantage of the zero-carbon era. We do not have the luxury of time to wait for graduates to emerge who know something about future possibilities. We need to exploit the creativity, intelligence and ideas of our students before they have graduated. But what are the innovations which we should be teaching? We are still researching them, and research takes time.

A potential solution to this unwanted time dependency is Vertically Integrated Projects (VIP), a concept developed by Georgia Tech, and which is now also operating successfully at the University of Strathclyde in the UK. In essence, undergraduate students across all years of study are involved in major inter-disciplinary research projects, each of which is aimed at a long-term complex research question. Strathclyde ensures that the 17 UN Sustainable Development Goals are central to their VIPs. In this way, undergraduate students not only learn key skills for the future, but they are indeed themselves creating knowledge for all simultaneously. It is the combination of empowerment, inter-disciplinarity, huge research questions, confidence and space to explore without fear of failure which brings this concept alive. In an era of extraordinary change and equally extraordinary opportunity, it feels right and proper that the most fertile brains are exploited and enriched in such a manner.

There are questions which the era of restraint begs concerning research and its funding in universities and companies. Is it right, for instance, to be funding research using public funds which includes technology-developments which we know are not aligned with the 17 UNSDGs? Examples might include trying to squeeze out efficiency gains in 20th century technologies or researching products which rely on scarce materials.

Bold decisions are needed by schools, universities and funding bodies if we are to galvanise education and action towards rapid mitigation, followed by innovative opportunity. Across the span of education and research, areas of importance highlighted by this report include:

- Technologies and their constraints in efficient use of electric motors and electric heating
- The trade-offs between energy and labour in delivering services across the range of all economic activities
- Understanding of welfare dependent on self-actualisation rather than consumption or ownership
- Maximising the value of secondary materials and the realities of reduce/re-use/recycling/ "circularity" etc.
- Renewable generation and the system of its efficient use.

The opportunity in education spans from preparing for the restraint required to achieve Absolute Zero to preparing for the longer-term transformation of prosperity beyond 2050. What could a world look like without cement, internal combustion engines or aeroplanes? We need to educate students for this new reality, and embrace the opportunity, rather than the threat, which this reality offers.

4.3 Opportunities in governance

The Olympic Games was one of the biggest government projects which was delivered on time and to budget. It was a great success and a source of national pride. There are parallels between hosting the 2012 Olympic Games and delivering Absolute Zero. Both commitments were made on a world stage where failure to deliver would result in national embarrassment; both projects require collaboration of multiple government departments, industry and the general public; and both require delivery processes and structures to be built from scratch. We managed to overcome these challenges for the Olympics, but delivering Absolute Zero has additional challenges.

To achieve our emissions goal we have to sustain momentum over a longer timespan than for the Olympics. We also have to consider life beyond 2050, what is the legacy of the net-zero emissions project? The Olympic legacy has been criticised for under delivering, so we must do better this time to ensure society can thrive in a zero emissions world beyond 2050. When we hosted the 2012 Olympics we could draw on the experiences of historical Olympic Games to inform decisions being made, but no country has met a zero-emissions target before, there is no precedent for us to follow. Finally the 2012 Olympic developments generated growth in the delivery of new and improved infrastructure and services. Meeting the net-zero emission targets will generate growth in some industries, but will also require the decline of others, this is likely to be met with resistance as those who benefit from the status quo resist change.

The London Olympics highlighted the following key lessons that could be transferred to emissions targets:

- Form a responsible body in government
- Limit innovation to knowledge gaps to reduce risk
- Maintain a unified cross party vision
- Have a protected and realistic budget
- Invest in programme management & delivery with discipline on time and scope change
- Empower people, with the right skills and track record to deliver against clear responsibilities
- Ensure accountability, with scrutiny and assurance given when risk is identified.

This section attempts to explore the first three of these lessons, the most relevant to Absolute Zero commitment.

Responsible body in government:

For the 2012 Olympics an executive non-departmental public body (NDPB) called the Olympic Delivery Authority (ODA) was established to deliver the infrastructure and venues required for the Olympics. In parallel the London Organising Committee of the Olympic and Paralympic Games (LOCOG) was established as a private company limited by guarantee to fund and stage the Games. The government set up the Government Olympic Executive (GOE) within the Department for Culture, Media & Sport. The GOE was responsible for other elements of the games, such as transport and security, as well as overseeing the ODA and LOCOG. Although the governance structures were considered to be complex, it has been reported that they allowed quick decision making and ensured people remained engaged throughout the delivery process.

Figure 4.1: Olympic-style governance structure for UK Climate Emergency Response:

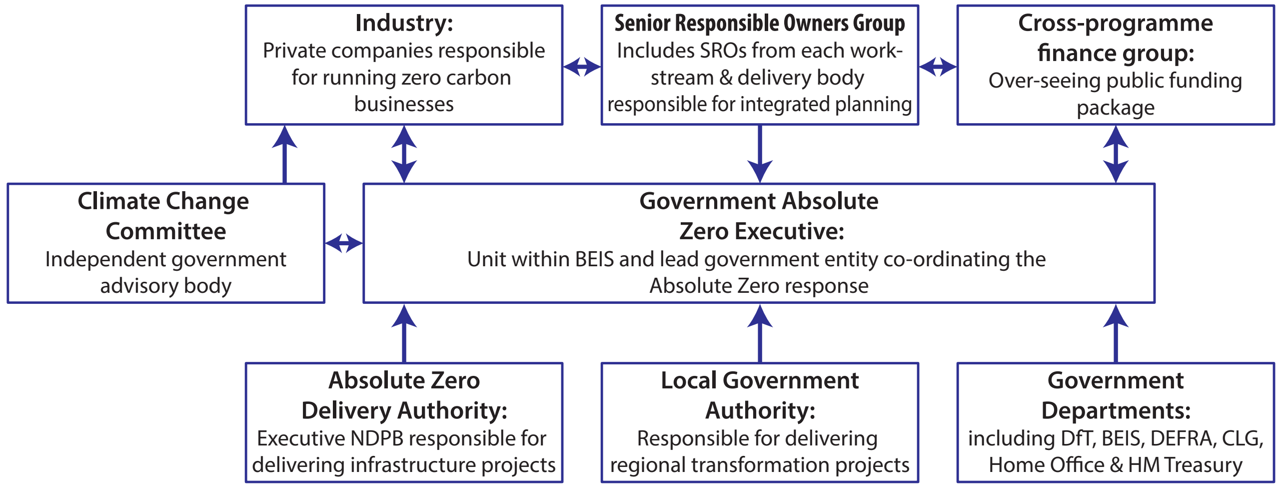


Fig. 4.1 gives an example of how this structure could be applied to delivering Absolute Zero. The proposed Government Absolute Zero Executive would be even more critical since it would be required to coordinate multiple industries and organisations, rather than just two delivery bodies as was the case in the 2012 Olympics. The governance structure proposed in Fig. 4.1 would enable fast decision making and accountability to meeting interim goals, which is essential if we are going to meet the 2050 zero emission targets.

Limit innovation:

The Government Olympic Executive deliberately limited innovation to fill knowledge gaps. This move was considered to be counter-intuitive, but it was successful. Relying only on proven technologies reduced the risk of failure and avoided the temptation to use the Games to showcase risky innovation. Although the Olympics did not innovate new ways of doing things, it did require existing activities to be scaled up to meet unprecedented demand. As Jeremy Beeton, Director General of the Government Olympic Executive explains "It was a whole new business model for London." This scaling up of proven technologies and systems was seen as a risk in itself. This lesson should be transferred to the task of meeting the 2050 zero-emission targets. We have identified in this report 'bright spots' where best practice exists and could be scaled up, if we apply the Olympic approach, this is enough of a risk, and further innovation should be limited. That said, we don't currently have all the answers to transition to a net-zero society and some innovation will be necessary, but approached with caution.

Cross party vision:

The delivery of the 2012 Olympic Games was supported by a unified cross party vision which was maintained through regular progress reports. This enabled stability throughout government changes which allowed the project to maintain momentum. The UK's approach to climate change does not currently have a unified cross party vision. For example in 2019, the Labour party proposed moving the zero-emissions targets to 2030. Whilst parties argue over goals and targets, actions are not being taken and we fall further behind on the journey to zero-emissions. It is essential that government generate a unified cross party vision to emulate the success of the 2012 Olympics which was able to create clear roles and responsibilities which fostered collaborative problem solving, not blame shifting.

If we are to learn from our previous successes, the net-zero target is more likely to be achieved through the establishment of the Government Absolute Zero Executive and the associated Delivery Authority with cross party support. The Executive should set a strategy which is realistic and risk averse, without over-reliance of innovation.

4.4 Opportunities for Industrial Strategy in the UK

With a legal target, now set by the UK government, to achieve net-zero emissions by 2050, UK business are developing organisational strategies to ensure they will prosper in a zero emissions business landscape. This report has shown how placing resource efficiency at the heart of industrial strategy can enable businesses to prosper, but this requires significant changes in the products, production processes and supply chain systems which currently make up the industrial sector.

The UK government has invested £5m in the UK FIRES research programme, bringing together the academics from six universities who have written this report with businesses across the supply-chain in a 'Living Lab'. The subscribing industrial partners pose strategic challenges to the academic research team and test emerging solutions in practice.

UK FIRES research will support businesses in developing industrial strategies to achieve zero emissions in key four areas illustrated in Fig. 4.2:.

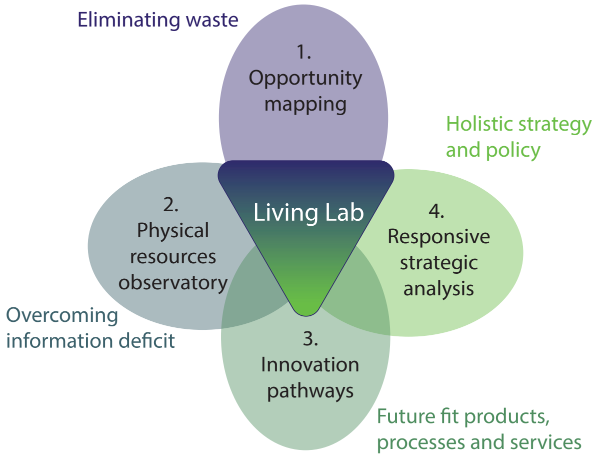
1. Opportunity mapping will identify new methods of design and manufacture which improve on existing best practices. Software tools to enumerate all options for design and delivery of resource intensive goods with today's technologies will be developed and commercialised.

2. The tools of recent advances in data science will be applied in a new Resource Observatory, to provide the highest-resolution insights into the UK's use of resources, with new metrics, scenarios and search tools used to identify opportunities for valuable innovation and efficiency gains. These tools will give UK FIRES industry partners foresight in decision making.

3. Through specific case studies of process, product and service innovation, the UK FIRES consortium will seek to define the innovation pathways by which the new practices of resource efficiency can be the basis of thriving UK businesses. The Living Lab industrial partners will be supported to exploit these opportunities in practice.

4. To support holistic industrial strategies and supply chains UK FIRES researchers will create responsive strategic analysis tools. Living Lab industrial partners can then apply these findings through the generation of new business models in collaboration with the UK FIRES Policy Champion.

Figure 4.2: UK FIRES programme structure



The output of the UK FIRES Living Lab collaboration will be published in quarterly reports, made available for government and industry, to provide reliable information to inform the development of their net zero industrial strategies. Focus themes for future Living Lab reports are now outlined.

UK FIRES connections

UK FIRES aims to provide data, tools, experience and analysis to support its partner companies in specifying new business models, diffusing innovation, giving holistic foresight to new opportunities and improving best practice as they pursue Resource Efficiency for a net-zero industrial strategy.

UK FIRES members can access the resources of the £5m programme through:

- Quarterly meetings of the Living Lab, in which members across the bulk materials supply chains specify target challenges for future work, support current activity and provide feedback on the application of programme insights in practice.
- Early access to emerging analysis of strategic opportunities
- Shared or dedicated PhD students applying the collective insights of the UK FIRES team to specific commercial contexts
- Pilot testing of new tools developed in the research programme
- Shaping the agenda and participating in the Annual UK FIRES Resource Efficiency Forum.

For more information contact info@ukfires.org.uk

Notes to the figures

Figure 1.1: Assuming an additional 400 TWh/year is needed by 2050, to be supplied by offshore wind, we need to have 115 GW of offshore wind capacity operational by 2050 (assuming an approximate capacity factor of 40% for offshore wind). The Crown Estate estimates that projects with seabed rights being awarded in 2021 would become operational by 2030, so all projects needed for 2050 would need to be started by 2040. Although current capacity is 9 GW, there is an additional 25 GW already in the pipeline. Therefore new projects need to be established and built at a rate of 4.5 GW/year for the next two decades.

Figure 1.3: Data from the International Energy Agency (IEA, 2018) with data on CCS installations at power-stations from the Oil and Gas funded pro-CCS lobby, Global CCS Institute.

Figure 1.4: This analysis by Vaclav Smil (2014) looks at global deployments of the three major fossil fuels, relative to total world energy demand at the time. Some faster transitions have occurred in individual countries, as shown in the box story on page 3.

Figure 1.5: The data in this figure come from a survey of academic reports by Gross et al. (2018) on the introductions of a range of new technologies - which generally showed that energy technology changes are among the slowest to reach full deployment.

Figure 1.6: Sectoral breakdown of UK energy demand from DUKES (2019); UK domestic internal temperature history from Official Statistics (2014); European car weight (and similar trends for all other regions) from the Global Fuel Economy Initiative a partnership with the International Energy Agency and others.

Figures 1.7–1.8: All constructed using data from DUKES (2019). n.b. there are many ways of calculating the equivalence of fuels - typically, the units of "Mega-tonnes of oil equivalent" are used, but this is not obvious when comparing primary electricity (nuclear or renewably powered electricity) which is not the result of conversion in a power station. We have attempted to be consistent in reporting the Mtoe equivalence of total UK energy demand.

Figure 1.9: Constructed with yearly data on electricity supplied in the UK from DUKES (2019). Electricity generated via non-emitting sources is shown as stacked lines whereas electricity generated from coal, gas and oil is plotted in a separate line.

Figure 1.10: The cost figures represent the weighted average of the levelized cost of electricity of commissioned solar and onshore wind projects in the United Kingdom and were obtained from IRENA (2018). For solar photovoltaic generation only cost figures after 2010 were reported. The figures were converted from US dollars to Pound sterling using yearly average exchange rates. The power density points for onshore wind were obtained using the power density of 61 wind farms commissioned between 1992 and 2007 compiled by Mackay (2009). These data-points were averaged by year of commissioning using installed capacity as averaging weight. The installed capacity and commissioning dates were obtained from Department for Business, Energy & Industrial Strategy (2019). The power density points for solar photovoltaic were estimated using best available cell efficiency data provided by National Renewable Energy Laboratory (2019) for multi-crystalline Si Cells in conjunction with the UK's annual insolation data from Photovoltaic Geographical Information System (2017) and a performance ratio of 84 % obtained from National Renewable Energy Laboratory (2013).

Figure 1.11: This chart was constructed using 2005 global energy data supplied by the International Energy Agency, and multiple sources to estimate the allocation of energy to devices and "passive systems" - the equipment (such as a car or house) in which the final form of energy (typically mechanical work or heat) is exchanged for a service. The chart is from Cullen et al. (2010), which has a lengthy Supplementary Information file giving every detail of the estimations. It is currently arduous to update this form of analysis - and a target of the UK FIRES research programme is to use the emerging techniques of Data Science to make this easier - but we assume that the proportions of energy use have remained approximately similar from 2005 to today.

Figure 1.12: Data taken from Haberl et al. (2007), subject to uncertainty due to definitions and the need for estimation of un-measurable data.

Figure 1.13: all the values represent "real world" efficiencies of conversion devices. The efficiency of electric heater, light and electronic devices was obtained by Cullen and Allwood (2010). The efficiency of electric battery charging applies to charging road vehicles and was obtained from Apostolaki-Iosifidou et al. (2017). The efficiency of heat pumps is the average of all the values reported by Shapiro and Puttagunta (2016) who quantified the coefficient of performance of these devices during use in residential buildings. The remaining values were obtained by Paoli and Cullen (2019).

Figure 1.14: Figure 1.14: This Sankey diagram was obtained using UK energy consumption data for 2018 from National Statistics (2018) and the conversion factors of figure 1.13. The data is disaggregated by energy type and sector. The total electricity demand was scaled to account for population growth using the predictions from National Statistics (2019) and the distribution losses from OECD/IEA (2018). In addition to the efficiencies of figure 1.13, the efficiency of charging electric car batteries was taken from Apostolaki-Iosifidou et al. (2017).

Figure 1.15: This analysis, building on the energy diagram of fig. 1.11 was developed in order to provide clarity for the IPCC's 5th Assessment Report, and based on global emissions data for 2010 taken from the EU's EDGAR database of global emissions. The original analysis was published as Bajzelj et al (2013) but has been modified here to clarify the difference between emissions that occur as equipment (cars, boilers, lights) are used, and those that occur in industry when making equipment that lasts for more than one year. The UK FIRES programme is largely concerned with these industrial emissions, so clarifying the way that stock of goods in service (and therefore their requirements for energy inputs) evolve over time, is of critical importance to understanding how to develop an Industrial Strategy compatible with Absolute Zero.

Figure 2.1: This figure is a summary of the analysis leading to figs. 2.2, 2.4, 2.11 and 2.19.

Figure 2.2: Today's values on energy use in buildings were obtained from UK energy statistics (HM Government, 2019). The values in the second column were calculated using the method described in the notes for Figure 1.13 and the efficiency values estimated by Cullen et al. (2010). The values in the third column were calculated considering the efficiency improvements of better insulation of roofs and attics, and the installation of double-glazed windows estimated by the IEA (2013), considering the number of surviving buildings in 2050 estimated by Cabrera Serrenho et al. (2019).

Figure 2.3: Impact of new buildings and retrofit from Cabrera Serrenho et al. (2019) and IEA (2013), use of heat pumps for space heating (MacKay, 2008), Appliance efficiency improvements (ECUK, 2019, table A1).

Fig 2.4: Today's values on energy use in transport were obtained from UK energy statistics (HM Government, 2019) and IEA energy balances (IEA, 2019). The values in the second column were calculated using the method described in the notes for Figure 1.13 and the efficiency values estimated by Cullen et al. (2010). The values in the third column were calculated considering no international aviation, the substitution of domestic shipping and aviation by rail, a reduction of energy use in passenger road transport to 60% of current levels (as demonstrated in Figure 2.6) and a reduction of 30% in road freight energy demand (Dadhich et al., 2014).

Figure 2.5: Emissions factors from the BEIS Greenhouse gas reporting conversion factors 2019. Equivalent energy intensities calculated using the BEIS values for fuel CO2e intensities, apart from rail which was calculated using the CO2e intensity factor for electric traction. Radiative forcing corrections are included in the emissions intensities for flying. Data for cars are for the current average fleet of petrol cars.

Figure 2.6: Developed assuming a linear correlation between vehicle weight and fuel consumption (there is reasonable empirical support for this) and with current vehicle weight taken from fig. 1.6.

Figure 2.7: Effect of vehicle weight reduction (Cullen et al., 2011), logistical improvements (Dadhich et al, 2014), regenerative braking (Gonzalez-Gil et al, 2014), drag and rolling resistance (Cullen et al, 2011).

Figure 2.8: developed considering the number of cars purchased and discarded in the UK estimated by Serrenho et al. (2017), with full adoption of electric cars in new sales from 2025.

Figure 2.9: This is constructed from emissions intensities reported by Scarborough et al. (2014) combined with data on portion sizes and calories per portion from the UK's National Health Service (www.nhs.uk/live-well/healthy-weight/calorie-checker/). There is significant uncertainty behind the numbers in this figure - due to the difficulty of defining the boundaries of analysis for the emissions calculation, and the arbitrary size of portions - but the scale of difference between the two foods is significant.

Figure 2.10: Is taken from Bajzelj et al. (2014) as used for fig. 1.15

Figure 2.11: Current energy consumption data from ECUK: End uses data tables, 2018, split by 2 digit SIC. Where further disaggregation was needed e.g. chemicals sector, consumption was split by the according proportions in 2007, where data is provided at 4 digit SIC level. Energy embodied in net imports for steel, cement, plastics and textiles by multiplying the energy intensity of UK production by the net imports of each material; tonnage data from Allwood et al. (2019), Shanks et al. (2019), ImpEE project and Allwood et al. (2006) respectively. Energy loss in electricity production is from DUKES aggregate energy balances, 2018. Energy for direct fuel combustion was converted to electricity using the relevant efficiency

values provided in Figure 1.11. Demand reduction interventions: 1) reduce scrap in metal processing to half of the current level, i.e. half of the savings identified in Milford et al. (2011); 2) reduce metal consumption by 20% by avoiding over-design of metal products, consistent with Section 2.3, Section 2.1 and Allwood and Cullen (2012); 3) A 75% cut in cement output based as described in Section 2.2; 4) Life extension of cars, clothes and industrial goods, reducing output of these products by 40%, 45% and 40% respectively. Proportions of steel and aluminium usage as per the global data provided in Allwood and Cullen (2012). 5) Reduction in plastic packaging by 25%; in the UK plastics packaging is 2.2Mt out of 6.3Mt total consumption estimated from the ProdCom database; 6) A 25% cut in fertiliser use, half of the reduction identified for Netherlands in Section 2.2; 7) Reduction of food waste leading to a 3% cut in output in the food processing industry as per the WRAP Courthald Commitment; 8) More efficient use of electricity in industry by improving efficiency of motors, heat pumps for space heating, process heating and lighting from 60% to 80%, 104% to 400%, 80% to 90% and 13% to 15% respectively, consistent with Cullen and Allwood (2010).

Figure 2.12: Original analysis for this report developed by C.F.Dunant

Figure 2.13: Developed from Cooper et al. (2014).

Figure 2.14: Original version of this figure published in Allwood et al. (2012) modified here to show primary production from blast furnaces declining to zero in-line with the zero emissions target.

Figure 2.15: Developed from Daehn et al. (2019)

Figure 2.16: The flows of plastics in the UK were estimated from the UK trade statistics (Eurostat, 2018), using a systematic allocation of trade product codes into the various stages of the supply chain, and by estimating the plastic content and application for each produce code.

Figure 2.17: Developed from Shanks et al. (2019

Figure 2.18: A survey of structural engineers, MEICON showed that, in general, structural engineers are prepared to over-design structures routinely in order to pre-empt any possible later changes to the brief, to deal with design risk and to cover for the possibility of construction error. Material efficient design, for example using fabric form-work, could allow substantial reduction in over-use without any increase in risk.

Figure 2.19: Current energy consumption data from ECUK: End uses data tables, 2018, split by 2 digit SIC, and where further disaggregation needed (e.g. separating primary and secondary wood processing) 2007 data at 4 digit SIC level. Energy loss in electricity production, conversion of direct fuel combustion to electricity and demand reduction interventions are all as described in Figure 2.23.

Figure 2.20: Allocation of emissions from global materials production to the six key sectors based on material flow analysis of steel (Cullen et al., 2012), cement (Shanks et al, 2019), Aluminium (Cullen and Allwood, 2013), plastic (Allwood et al, 2012), Paper (Counsell and Allwood, 2007), food (Bajzelj et al. 2014)

Figure 2.22: This data is made publicly available by the car industry. Horton and Allwood (2017) review the data, and explore several options by which this form of material inefficiency could be addressed.

Figure 2.23: Manufacturing energy efficiency imporvements (Paoli and Cullen, 2019), scrap metal reduction (Milford et al, 2011), reducing over-design and ilfe-extension (Allwood & Cullen, 2012), plastic packaging (Lavery et al, 2013), food waste (WRAP, 2018)

Figure 2.24: The proportions of losses here are indicative and based on data in Li et al (2016). The actually losses vary according to the way the hydrogen is stored and the precise pattern of demand by which electricity is extracted from the fuel cell.

Figure 3.3: The Zero Carbon Britain (Allen et al, 2013) report sets out a scenario for energy supply in 2050. We have calculated the amount that energy generation from each source would have to increase in every year from now to 2050 to achieve the target. Increases are presented as a percentage of current UK primary energy demand of about 2200 TWh (BEIS, 2019). Expectations for Government support for offshore wind in the 2020s are from the Crown Estate (2019), converted into generation values with a representative capacity factor for offshore wind of 40%. A review of Biomass to Liquid systems for transport fuel production reports that no commercial scale plants are yet operating (Dimitriou, 2018).

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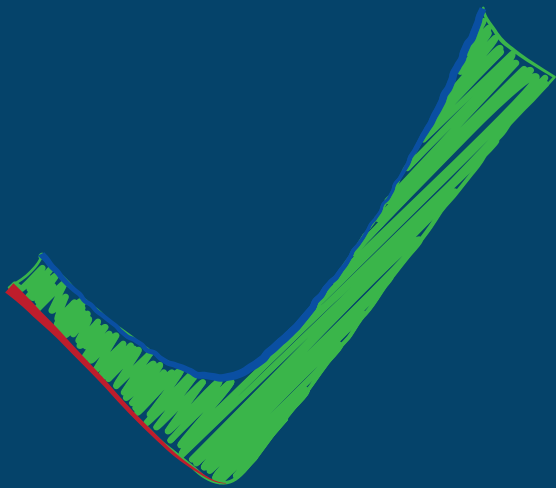

Absolute Zero: some short-term restraint in our use of energy, but no restraint whatsoever in what we most enjoy...