Net Zero Societal Change Analysis

WP4: Behaviour change analysis

Energy Systems Catapult

January 2021

Contents

Context

In commissioning the Net Zero Societal Change Evidence and Analysis project, HMG's goal was

- To develop and consolidate the evidence base in areas relating to the role, and importance, of societal change in reaching net zero in the UK, as well as make recommendations for practical action that could help facilitate this change.

This included three objectives, of which

- **Objective two** is to identify and assess how different levels of societal change/responsiveness can affect the deliverability (e.g. costs/benefits and feasibility) of transitioning to net zero.
    - How might different future societal scenarios be associated with differing levels of shifts in behaviour, demand and technology adoption (and rates of technology adoption)?

Approach

Energy Systems Modelling Environment (ESME)
ESME is a linear optimisation model of the whole UK energy system. The optimisation generates the lowest-cost energy system designs which satisfy constraints such as provision of energy service demands in buildings, transport and industry, subject to CO_2 budgets. It is focussed on the physical components of such a system – infrastructure, energy flows and associated costs – and does not look at other layers of the system such as commercial aspects or communications between actors.

- Performed 26 model runs (including Reference Case used as comparator) across 4 themes in ESME:
- All runs compared with the Reference case:
  - System cost impacts
  - Emissions (behaviour specific and system-wide)
  - Changes in the energy system design
- Exploratory analysis
  - What if analysis exploring high, medium and low degrees of behaviour change

Net Zero reference case

BEIS approved reference case based on ESC's Clockwork scenario [1] with some modifications agreed in an earlier project (LINES)

BEIS approved modifications (vs. Clockwork)

- Nuclear SMR supplies electricity only (no district heat)
- DAC limited to 13mt in 2050 (down from 25mt in CW)
- 99% capture rate on CCS applied only to:
  - CCGT
  - Biomass fired generation
  - IGCC biomass
  - Steam methane reformation
- UK biomass resource is 180TWh of domestically grown (up from 140TWh in CW) and 34TWh imports in 2050
- Emissions constraint follows carbon budgets to CB5 then linear trajectory to Net Zero

Implicit behaviour change

The reference case necessarily includes implicit assumptions about adoption of behaviours needed to meet the Net Zero target. For example the deployment of different low carbon technologies is driven by cost, efficiency and CO_2 in ESME, but there are underlying assumptions about behaviours that would facilitate the uptake of such technologies by the UK population.

In this analysis, the implicit behaviour may represent a high degree of public engagement/willingness to change for some modelled behaviours, whilst for other behaviours the reference case might represent a medium or low degree of behavioural change.

Reference year

Pre-COVID 2020

For some behaviours modelled in this analysis, the degree of change is described relative to a reference year. This reference year is typically 2020. Here, 2020 refers to the pre-COVID projections of 2020 demand/deployment. In reality, it is clear that 2020 is an atypical year in light of the effects the COVID pandemic has had on energy demand and adoption of certain behaviours consistent or inconsistent with Net Zero (e.g. working from home vs. reduction in public transport use). However, until we have access to complete data related to 2020 energy use we are not in a position to make relevant updates to ESME.

System costs

- This analysis has two components: energy systems modelling and intangible cost analysis
- Results from the energy systems modelling activity are related to those typically produced by energy system models. These include GHG emissions, energy systems designs and system costs.
- System costs include the capex, opex, resource costs and transmission/infrastructure costs associated with the technologies deployed in the system.
- System costs do not include costs perceived by the end user (e.g. consumers) or policy costs (including taxes, feed in tariffs etc.) necessary to enact necessary changes to the system
- Some of the costs perceived by the end user are identified and discussed in the intangible cost analysis part of the work
- The system costs presented here are a result of underlying assumptions used to populate the ESME model. These assumptions and input data have been collected, curated and continually updated over many years by the ESC and there may be inherent differences in the data compared to similar models such as UKTIMES. Therefore the system cost figure should not be viewed as absolute but rather the cost savings relative to the Reference Case are intended to provide an indication of the relative impacts of different behaviour changes.

Behaviour vs. behavioural outcome

- A range of behaviours were identified in WP1. These were prioritised and shortlisted for modelling in ESME for WP4.
- Shortlisting was based on how this would be modelled in ESME with some behaviours best represented as changes to behavioural outcome (e.g. reduction in demand or speed of technology uptake) rather than as real actionable behaviours (e.g. wearing warmer layers). If several behaviours were deemed to have the same behavioural outcome (at least as manifested in ESME) e.g. a reduction in end-use demand, then redundant behaviours were removed from the list of behaviours to be modelled.
- Those behaviours with ranges of change that would deliver large variation in behavioural outcome were selected as being of interest given the potential for substantial impact on the energy system. In effect, these were used to probe the bounds of behavioural impacts on the system.
- However, it is recognised that there may be different intangible costs associated with different behaviours regardless of whether they deliver the same behavioural outcome. Therefore, there is discussion of the unmodelled behaviours in the intangible cost analysis. In the synthesis piece that will follow this analysis, there is also scope to delve further into alternative behaviours.

Key findings

Overview of system effects

A key metric for evaluating the impact of a behaviour on the energy system is the effect it has on the total system cost (the sum of resource, investment and operating costs of the energy system over the entire pathway to 2050).

Reducing heat demand by adopting behaviours that enable the set point temperature of homes to be limited to 19°C by 2050 delivers savings in the order of 3.9% of Reference Case total system cost.

Behaviours that limit the growth of international aviation demand also provide noticeable savings on total system cost. The particular value of such behaviours is that currently there are no technology options for decarbonising aviation. Every unit of demand therefore creates emissions that require investment in offsetting measures. Car travel on the other hand has a clear path to decarbonisation in the form of EVs, so in the long run reducing demand here has more modest impacts on emissions savings and therefore system cost.

Transport behaviour: energy systems modelling results

Transport behaviours points to note

ICE ban
At the time of the analysis, the UK's ambition to ban new sales of ICE cars by 2030 was not publicly announced. Therefore, this assumption has not been included in the Reference Case. The Reference Case sees new sales of ICE cars phased out by 2035. This is a model decision to achieve the lowest system cost and has not been programmed in as a constraint.

The runs that model different uptake profiles of electric cars all assume a 2030 ban on sales of new ICEs. This required a new constraint to be implemented that forced new ICE sales out by 2030. Adding such a constraint causes the total system cost to increase. Furthermore, based on this analysis, bringing forward the date of the new ICE sales ban will limit the emissions savings achieved through reductions in car travel demand in the 2030s because a higher proportion of the car fleet will be zero carbon.

Decarbonisation of rail
ESME relies on robust evidence to inform cost projections for technologies included in the model. A lack of such data relating to decarbonisation of rail means that up to now, no assumptions have been made about future decarbonisation of the rail network (either by electricity or hydrogen). In the majority of net zero scenarios tested in ESME, this has not impacted the feasibility of meeting Net Zero because emissions from rail are projected to be comparatively small (based on future demand assumptions for rail transport). However, in one scenario, in which car travel demand is replaced with an increase in rail demand, the Net Zero target is not met. This is because demand is being shifted from a low/zero carbon car fleet to a rail network still reliant on fossil fuels in 2050. This highlights the importance of decarbonising the rail network. This is especially true if people are to be encouraged to use public transport in the near term (which will deliver CO_2 savings whilst ICE cars are still the most commonly owned) leading to shifts in travel behaviour in the long term. It also prompts for a review of evidence related to rail decarbonisation so that suitable technology options can be added to future versions of the ESME model.

Transport behaviours modelled

Behaviour	High change	Medium change	Low change
Car pooling/lift sharing	Car occupancy increases 25% by 2050 from 2020 This equates to approx. 2ppv by 2050	Reference Case: 1.5ppv by 2050 (equivalent to a 10% decrease from 2020)	Car occupancy decreases 25% by 2050 from 2020 This equates to 1.25ppv by 2050
Fewer short journeys are made by car (e.g. by cycling/walking)	10% reduction in 2050 car travel demand relative to Reference Case reflecting overall reduction in short journeys made by car e.g. by modal shift to walking/cycling. Equates to 16% increase in car travel demand by 2050 from 2020	Reference Case: 30% increase in car travel demand by 2050 from 2020	10% increase in 2050 car travel demand relative to Reference Case. Equates to 42% increase in car travel demand by 2050 from 2020
Long journeys are made by public transport rather than car	10% reduction in 2050 car travel demand relative to Reference Case reflecting modal shift to rail for long journeys (equivalent to 82% increase in rail demand relative to Reference Case) Equates to 16% increase in car travel demand and 175% increase in rail demand by 2050 from 2020	Reference Case: 30% increase in car travel demand and 51% increase in rail demand by 2050 from 2020	5% increase in 2050 car travel demand relative to Reference Case reflecting modal shift to rail for long journeys (equivalent to 41% decrease in rail demand relative to Reference Case) Equates to 35% increase in car travel demand and 11% decrease in rail demand by 2050 from 2020
Demand for domestic flights falls as people shift to rail to make journeys within the UK	30% reduction in 2050 domestic aviation demand from 2020. Modal shift to rail equivalent to 58% increase in rail demand by 2050 from 2020. Equates to 45% decrease in domestic aviation demand and 5% increase in rail demand relative to Reference Case	No change in domestic aviation demand from 2020 to 2050. Modal shift to rail equivalent to 55% increase in rail demand by 2050 from 2020. Equates to 22% decrease in domestic aviation demand and 2% increase in rail demand relative to Reference Case	Approximately equivalent to the Reference Case. 30% increase in 2050 domestic aviation demand from 2020. 51% increase in rail demand by 2050 from 2020 (no modal shift from rail)
Growth in international aviation demand falls as people make fewer trips abroad	6% growth in international aviation by 2050 from 2020 (equivalent to 28% decrease relative to Reference Case)	25% growth in international aviation by 2050 from 2020 (equivalent to 16% decrease relative to Reference Case)	50% growth in international aviation by 2050 from 2020 (approximately equivalent to Reference Case)
Uptake of EVs increases	2030 ban on new ICE/hybrid sales. 50% new car sales in 2025 are ULEV	2030 ban on new ICE/hybrid sales. 30% new car sales in 2025 are ULEV	2030 ban on new ICE/hybrid sales. 10% new car sales in 2025 are ULEV

Car pooling

Behaviour being modelled
People are willing to share lifts thus increasing the occupancy of cars and reducing the number of cars on the road. However, the rate of private car ownership remains the same meaning total car purchases does not change.

This was modelled in ESME by making adjustments to the total car travel demand (measured in vehicle-km) as a result of changing car occupancy. However, the average annual mileage for each car was not changed and remains fixed through time. In a world where people continue to purchase their own cars but share lifts, each car would do fewer miles in a year but there would be the same number of car purchases – therefore, the total car travel demand would fall. Modifications to the model would be necessary to allow annual mileage for cars to change in each time period – these were out of scope. The impact of keeping annual mileage the same but increasing the occupancy of a car is fewer car purchases needed to satisfy a reduction in demand. This limitation in the modelling was overcome by reintroducing the costs associated with continued private car purchases (in the Reference Case) to the runs with adjusted car travel demand. This meant the system effects of fewer cars on the road could be captured but still allow system costs to reflect continued private car ownership rates.

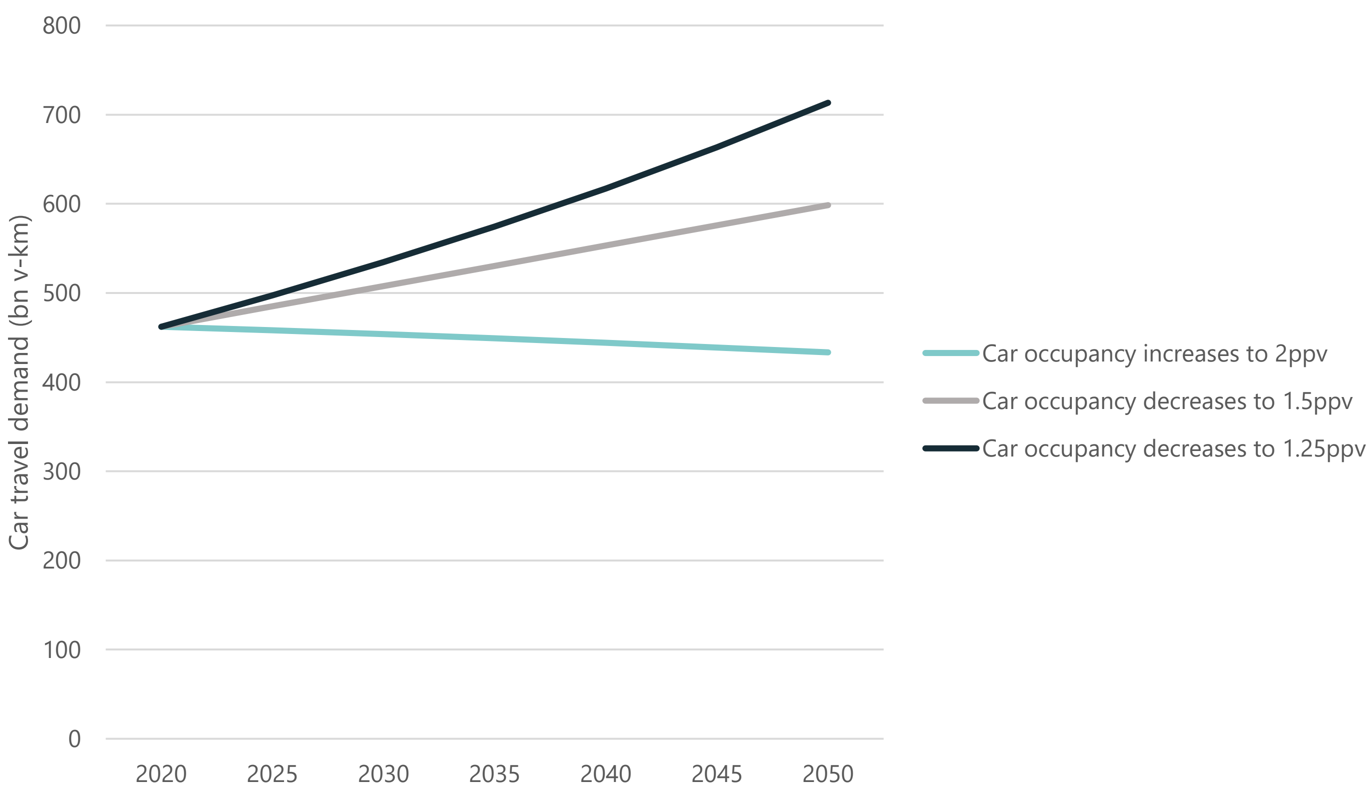
Behavioural outcome
The behavioural outcome of increasing car occupancy through lift sharing is a reduction in the total car travel demand in a year (either by the same number of cars doing fewer annual miles, or fewer cars doing the same number of miles annually).

The desired outcome is for private car ownership levels to remain the same in all occupancy runs. This means that the number of car purchases made in all runs is the same as the Reference Case. However, the effect on system cost for a world where an increase in car occupancy leads to fewer car sales is also presented.

How can car occupancy be increased?
Some examples of how the occupancy of cars can be increased include:
- High occupancy vehicle (HOV) lanes increase the people-moving capacity of roads by discouraging use by single occupancy cars [2]
- Car sharing schemes: car sharing can be informally organised amongst friends and colleagues, or people can register on to a private car sharing database connecting people who might be able to share lifts (an example of this has been developed for the University of Sheffield [3]

Car pooling

Transport behaviours	High	Medium	Low
Car pooling	Increase car occupancy by 25% by 2050 from 2020. In line with LED scenario [4]. This reaches approx. 2 occupants per vehicle by 2050.	Reference Case: car occupancy continues to decrease to 2050 reaching 1.5 people per vehicle	Lone driver rate increases with average car occupancy reaching 1.25 person per vehicle by 2050



Car usage for short journeys

Behaviour being modelled
People are willing and able to adopt active travel modes (e.g. walking and cycling) to make short trips (up to a few miles) that are currently made by car.

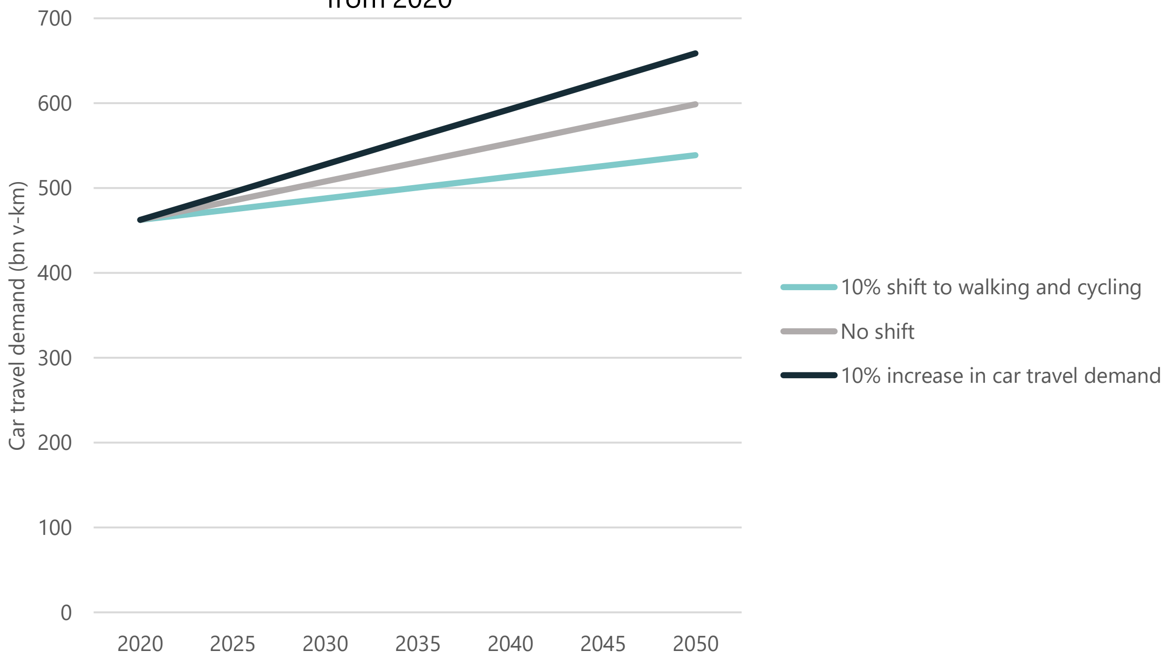
This was modelled in ESME by making adjustments to the total car travel demand (measured in vehicle-km). Adjustments were informed in part by data obtained from the National Travel Survey. A reduction in in the number of short journeys made by car was assumed. Some of these journeys can be made using other travel modes such as walking or cycling.

The annual mileage of cars was not altered. As explained on page 13 this leads to a reduction in car sales in the model. However, a shift to active travel for short trips is not assumed to lead to a reduction in car ownership. Therefore, the costs of car ownership seen in the Reference Case were reintroduced to the modal shift runs.

The medium level of behaviour change is that assumed in the Reference Case. This is a 30% increase in car travel demand informed by DfT projections. Active travel is not explicitly modelled in ESME because it is zero carbon, therefore any increase or decrease in active travel (not shifted to/from car travel) will not affect car travel demand or emissions. For this reason, the level of active travel can be assumed to be consistent with projections by DfT. This level of behaviour assumes an increase in travel demand but no additional shift to active travel modes from cars.

Behavioural outcome
The behavioural outcome of shifting short journeys to active travel modes is a reduction in car travel demand.

Transport behaviours	High	Medium	Low
Shift in the number of short journeys made by car including through modal shift to active travel	10% reduction in 2050 car travel demand relative to Reference Case reflecting modal shift to walking/cycling and reduction in short journeys made. Equates to 16% increase in car travel demand by 2050 from 2020	Reference Case: 30% increase in car travel demand by 2050 from 2020	10% increase in 2050 car travel demand relative to Reference Case. Equates to 42% increase in car travel demand by 2050 from 2020



Shifting long journeys to public transport

Behaviour being modelled
People are willing and able to make long journeys by public transport rather than car.

This was modelled in ESME by making adjustments to the total car travel demand (measured in vehicle-km). Adjustments were informed in part by data obtained from the National Travel Survey. This gave an indication of the proportion of long trips currently made by car that could reasonably be shifted to public transport. The change in car travel demand was converted from vehicle-km to passenger-km based on the assumed occupancy of the car. This was then added to rail demand (described in passenger-km). No assumptions were made about the future decarbonisation of rail in the model.

The annual mileage of cars was not altered. As explained on page 13 this leads to a reduction in car sales in the model. However, a shift to public transport for long trips is not assumed to lead to a reduction in car ownership (it is assumed that for most journeys people still rely on privately owned cars). Therefore, the costs of car ownership seen in the Reference Case were reintroduced to the modal shift runs.

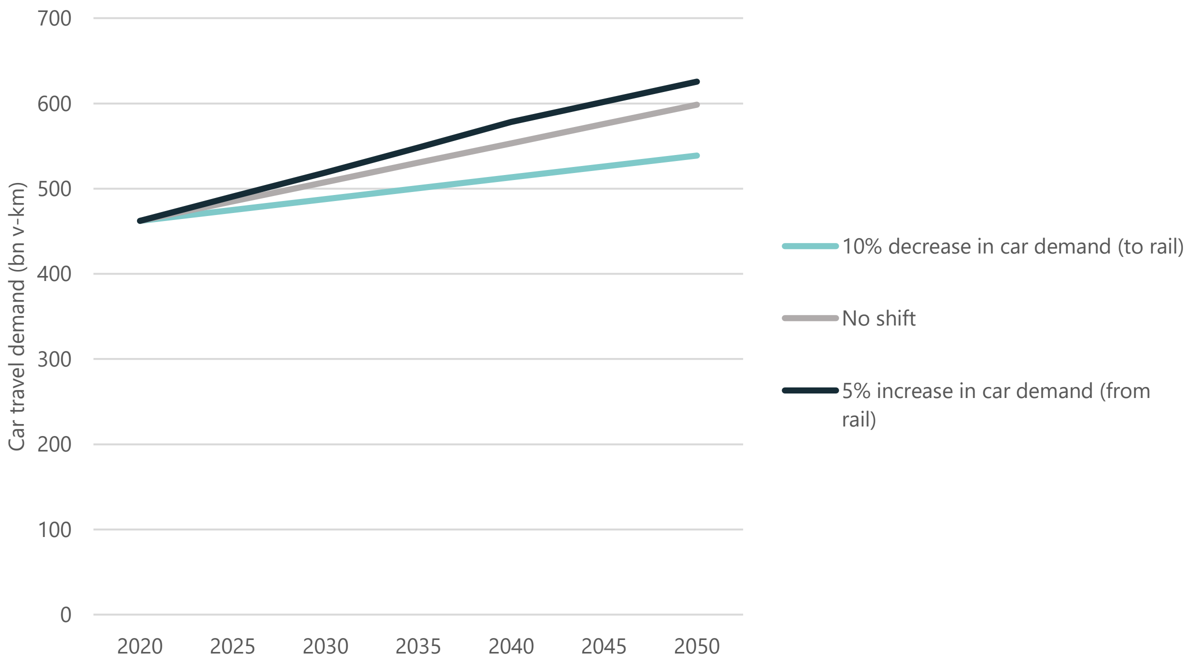
The medium level of behaviour change is that assumed in the Reference Case. This is a 30% increase in car travel demand informed by DfT projections. Public transport demand projections are also in line with DfT. This level of behaviour change assumes an increase in travel demand but no shifts to different modes of transport.

Behavioural outcome
The behavioural outcome of shifting long journeys to public transport is a reduction in car travel demand and an increase in rail demand (measured in passenger km).

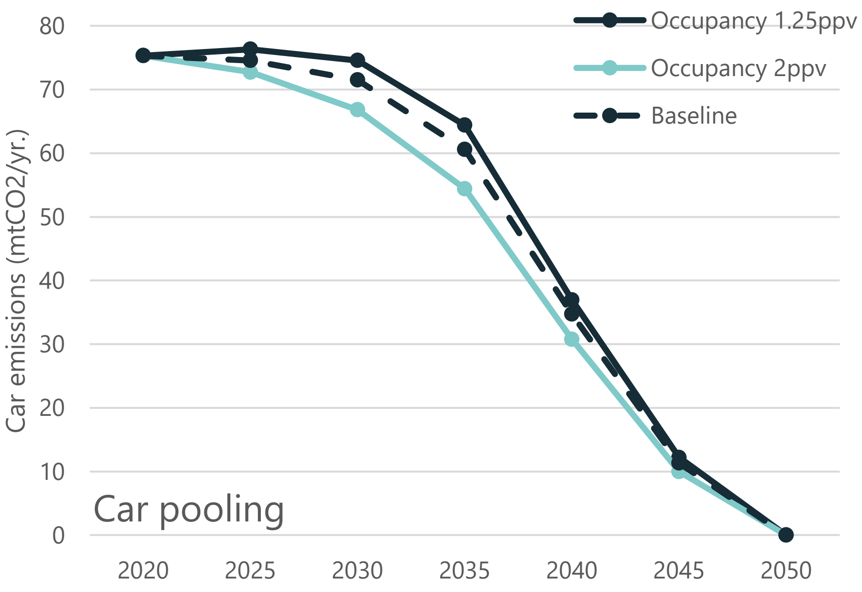
Mobility as a service (MaaS)
Depending on an individual's circumstances, public transport can either be an obvious choice being more convenient and cost-effective than owning and driving a car, or a costly and inconvenient affair that does not completely remove the need for a privately owned vehicle. MaaS can help to simplify the transport experience for users by providing a single (digital) point of access to a wide range of transport options (car, ride or bike sharing; taxis, car rental, public transport) with a single payment channel (as opposed to multiple ticketing). MaaS aims to reduce the need for privately owned vehicles by offering the best value proposition for users and helping to overcome the more inconvenient parts of a journey [5].

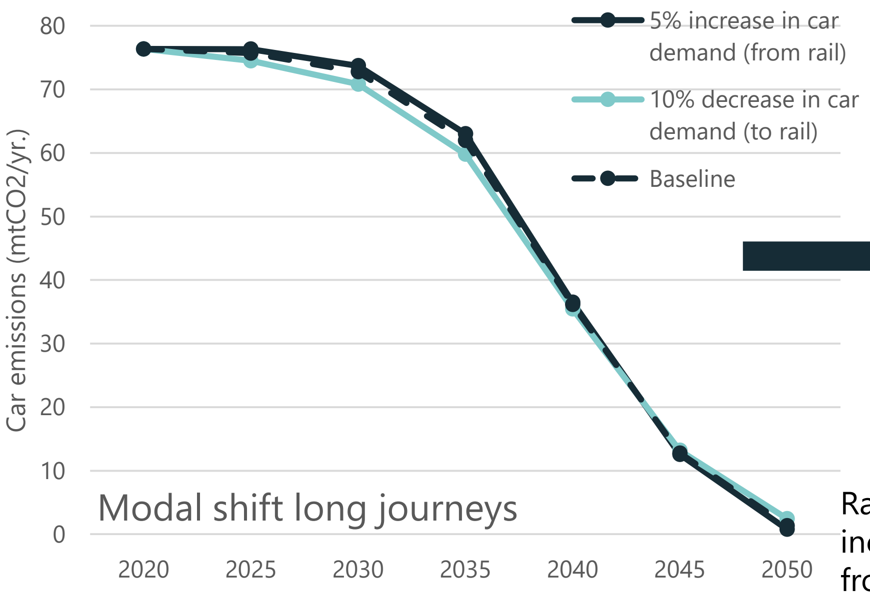
Shifting long journeys to public transport

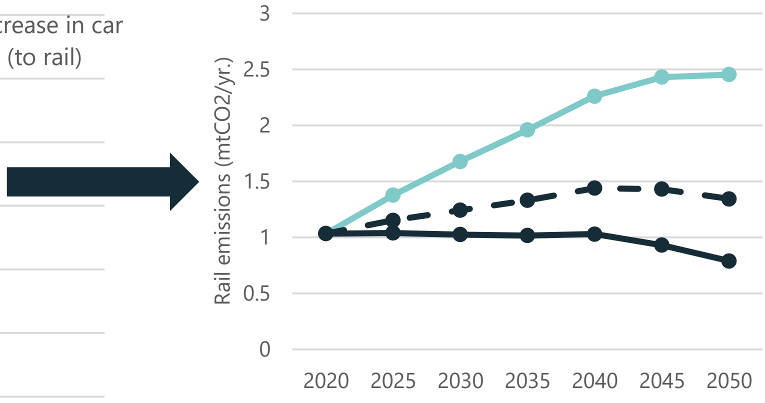
Transport behaviours	High	Medium	Low
Long journeys are made by public transport rather than car	10% reduction in 2050 car travel demand relative to Reference Case reflecting modal shift to rail for long journeys (equivalent to 82% increase in rail demand relative to Reference Case). Equates to 16% increase in car travel demand and 175% increase in rail demand by 2050 from 2020	Reference Case: 30% increase in car travel demand and 51% increase in rail demand by 2050 from 2020	5% increase in 2050 car travel demand relative to Reference Case reflecting modal shift from rail for long journeys (equivalent to 41% decrease in rail demand relative to Reference Case). Equates to 35% increase in car travel demand and 11% decrease in rail demand by 2050 from 2020



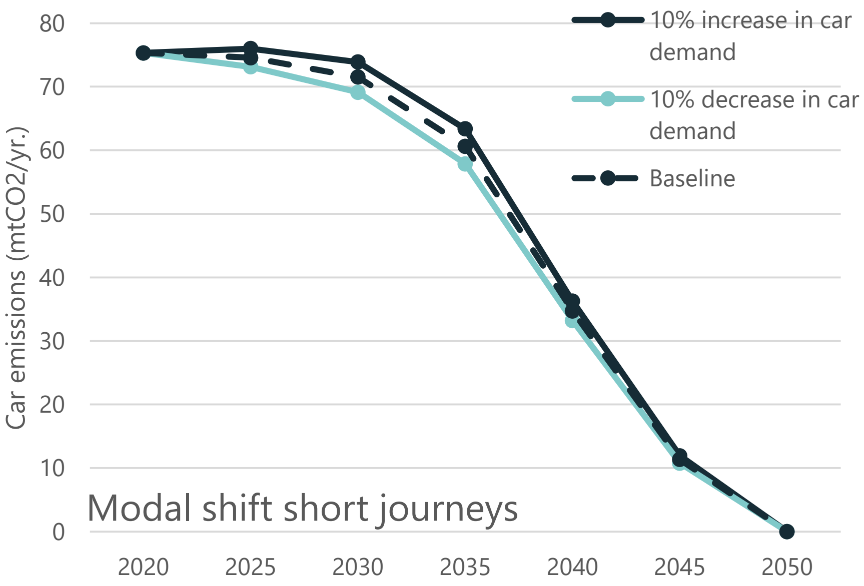
Car travel behaviours







Rail emissions increasing with shift from decarbonised car travel



- Changes to car demand impacts near/mid-term emissions because there is still a reliance on fossil fuels. By 2050 the difference in emissions from cars between low and high demand cases is zero due to a wholesale shift to EVs.
- Increasing car occupancy from average 1.6 in 2019 to 1.78 and 1.85 by 2030/35 gives a 7-10% decrease in emissions from cars.
  - Highest lone driver rates associated with business and commuting. These journeys account for 35% of the miles travelled per person per year in 2019 (NTS table 403) [6]
  - To achieve similar reductions in emissions from cars by modal shift would imply 11 and 15% reduction v-km either by shift to walking/cycling or to rail (which would result in a doubling of train demand compared to the Reference Case - this has implications for emissions if rail is not decarbonised).
- Long journeys shifting to train leads to initial drop in emissions because of a shift from fossil fuel cars but unless rail decarbonises in line with cars emissions impact gets worse by 2050

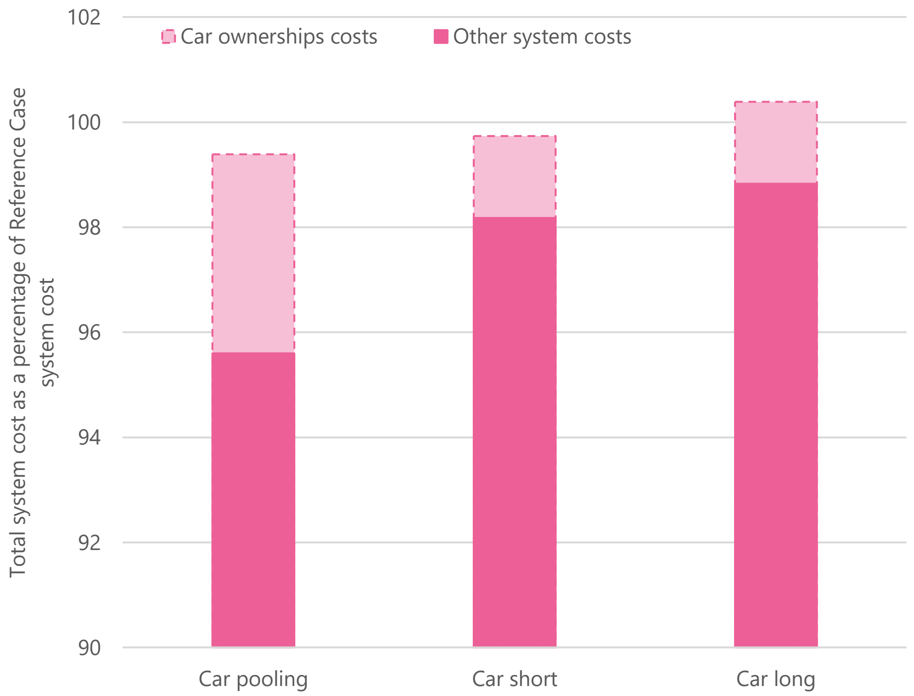
Car demand behaviours – system cost

The behaviours associated with reductions in car demand are car pooling, shifting to active travel for short journeys (car short) and shifting to public transport for long journeys (car long).

The chart to the right shows that for the high (positive) behaviour change case, savings on system cost (excluding car ownership costs – dark pink bars) are made relative to the Reference Case. However, it should be noted that the car long behaviour failed to meet net zero due to insufficient decarbonisation effort made in the rail sector*. This highlights the importance of ensuring rail/public transport decarbonises in line with private transport if the ambition is to encourage people on to these transport modes (wider benefits of shifting to public transport include reduction in traffic volume and improved air quality).

These are the savings that would be possible if the reduction in demand encouraged a fall in private car ownership (there may also be wider system benefits not captured in this analysis such as a drop in the emissions associated with car manufacture). The light pink bars show the cost associated with private car ownership and suggests that shifting to active travel or car sharing would deliver a system cost saving even if people continued with private car ownership. Shifting to higher carbon forms of public transport whilst maintaining ownership of a car would lead to an overall cost increase.

* A dummy CO_2 abatement technology at artificially high cost was deployed to ensure the simulation solved. The cost of this technology has been removed from the figure in the chart. If a technology such as direct air capture was deployed an additional £70 million in 2050 can be added to the total system cost, which once discounted leads to negligible increase in the total discounted system cost.



* A lack of robust evidence for the projected costs of decarbonising the rail network (either by electricity or hydrogen) means that there is no assumption about rail decarbonisation in the current version of ESME. In most scenarios emissions from rail are comparatively small, however this scenario involves a shift in demand from a decarbonised car fleet to a rail network reliant on fossil fuels.

Car demand behaviours – system design

CATAPULT Energy Systems

CAR POOLING

- Emissions headroom generated by high behaviour changes results in:
  - Higher capacities of waste incineration and unabated gas in the power sector in 2030-2040.
  - Higher capacities of gas boilers throughout the 2030s to mid-2040s
  - Higher levels of fossil fuel use in industry in the 2030s
- Low behaviour change results in emissions reductions in the power sector as unabated gas and waste incineration plants reduce output (but not capacity) in the mid-2030s. There is increased output from nuclear gen III and abated gas plants.

SHIFTING TO ACTIVE TRAVEL FOR SHORT JOURNEYS

- Changes in the energy system are the same as for the car pooling behaviour but to a lesser degree.

SHIFTING TO PUBLIC TRANSPORT FOR LONG JOURNEYS

- In the high behaviour (people adopting rail), headroom generated by reduced car travel in the 2030s and 2040s results in more emissions from rail.
- The power sector sees less decarbonisation up to 2035 with higher output from waste incineration plants
- In 2040 there is higher gas consumption for heating but as the emissions from rail rise, the power sector is forced to make deeper cuts to CO_2 emissions with 17GW of high capture rate CCS on CCGT installed by 2050. Deployment of high CR CCS on gas plant occurs 5 years earlier in 2035.
- By 2050, rail emissions are so high, that the Net Zero target is missed by 0.5mtCO_2.
- In the low behaviour change case, with less rail and more cars changes are more complex:
  - In the period up to 2030, there are high emissions from cars resulting in a need for the power sector to decarbonise. This is achieved
  - From 2035 onwards, emissions from cars begins to reduce as more and more EVs are rolled out. This is coupled with a reduction in rail emission allowing for emissions savings to be used elsewhere in the system. By this time the power sector is relatively low carbon and so there is a continued use of gas in heating – this is squeezed out by 2050
  - In 2050, emissions savings from rail are offset by emission from plug-in hybrid vehicles

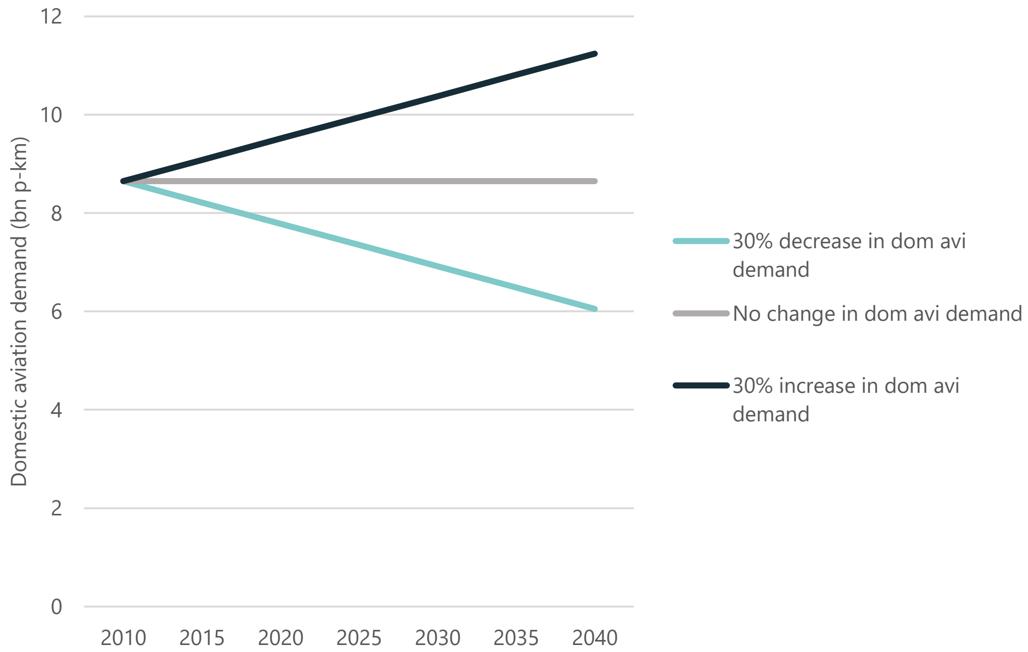
Shifting domestic flights to rail

Behaviour being modelled
People are willing and able to take the train for trips in the UK they usually fly.

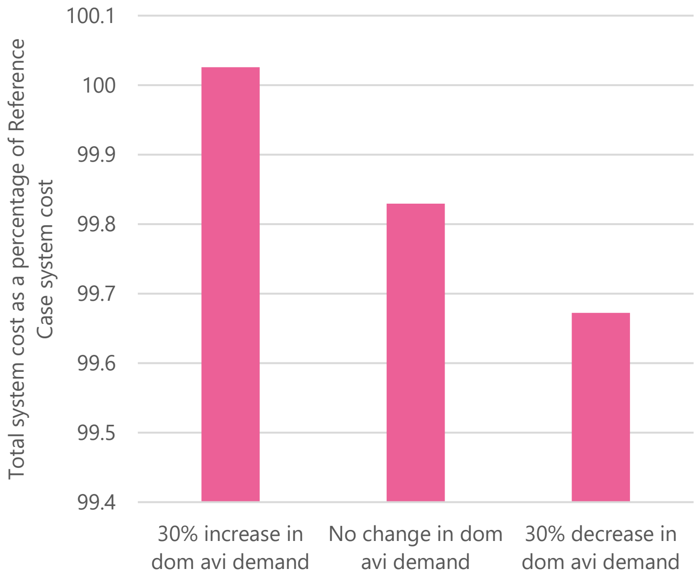
This was modelled in ESME by making adjustments to the total domestic aviation travel demand (measured in passenger-km). The change in domestic aviation demand was used to adjust rail demand. No assumptions were made about the future decarbonisation of rail in the model.

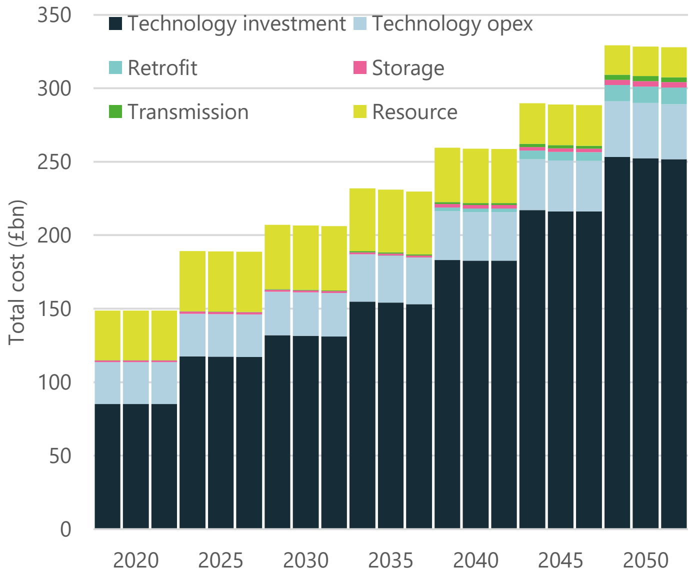
Behavioural outcome
The behavioural outcome of shifting domestic flights to rail is a decrease in domestic aviation demand and an increase in rail demand.

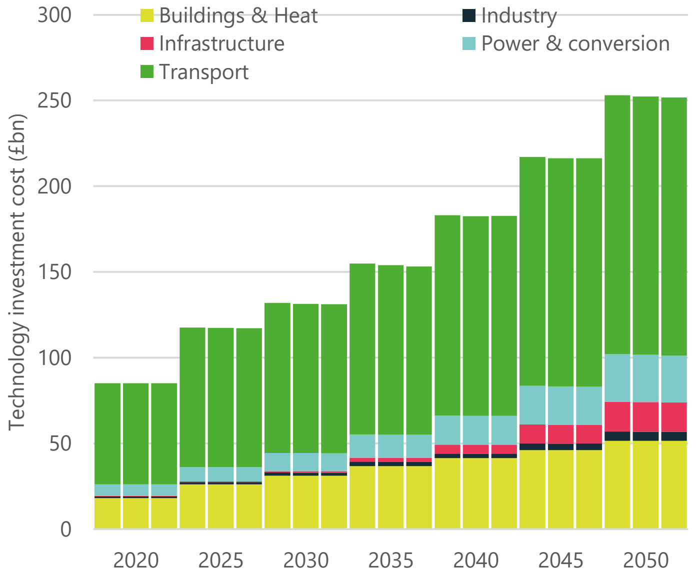
Transport behaviours	High	Medium	Low
Demand for domestic flights falls as people shift to rail to make journeys within the UK	30% reduction in 2050 domestic aviation demand from 2020. Modal shift to rail equivalent to 58% increase in rail demand by 2050 from 2020. Equates to 45% decrease in domestic aviation demand and 5% increase in rail demand relative to Reference Case	No change in domestic aviation demand from 2020 to 2050. Modal shift to rail equivalent to 55% increase in rail demand by 2050 from 2020. Equates to 22% decrease in domestic aviation demand and 2% increase in rail demand relative to Reference Case	Approximately equivalent to the Reference Case. 30% increase in 2050 domestic aviation demand from 2020. 51% increase in rail demand by 2050 from 2020 (no modal shift from rail)



Shifting domestic flights to rail: system costs







Clustered chart shows 3 stacks per time period. From L-R: 30% increase, no change (Ref Case) and 30% decrease in domestic aviation demand

A shift in domestic air travel to rail (achieving a 30% decrease in domestic aviation demand by 2050 from 2020) delivers an 0.3% saving on total discounted system cost. This is due to small savings in technology investment costs in the power sector as emissions headroom allows this sector to pull back on decarbonisation. However, Emissions differences between high and low behaviour associated with domestic aviation are small resulting in negligible impact on the energy system design.

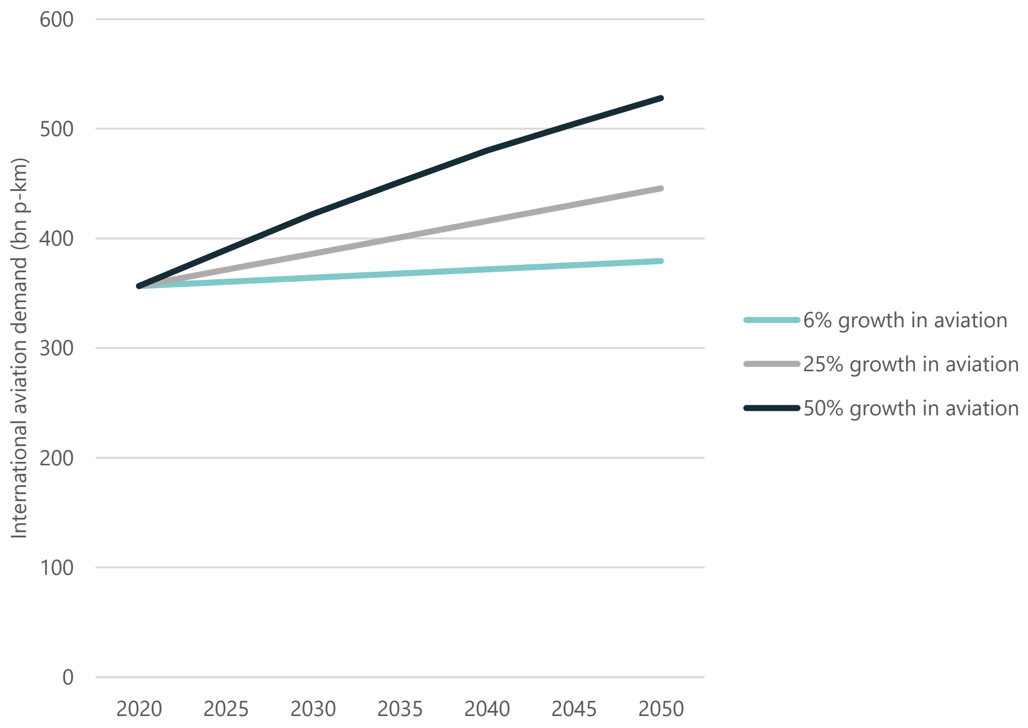
Reducing flights abroad

Behaviour being modelled
People take fewer flights abroad.

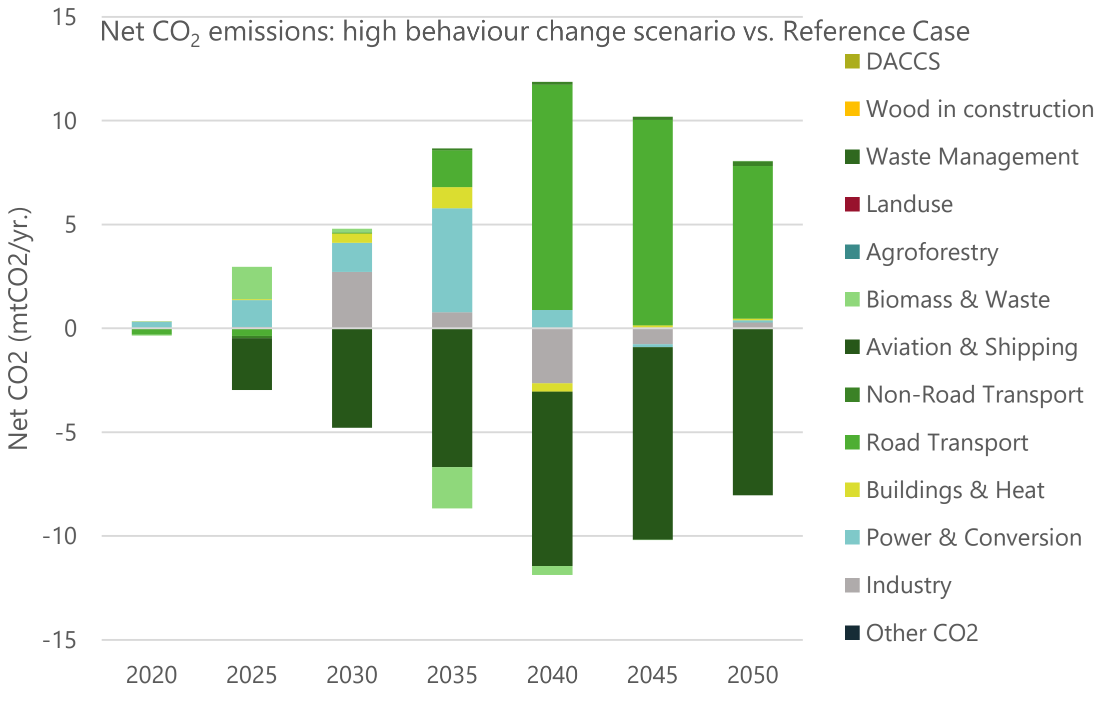
This was modelled in ESME by making adjustments to the total international aviation travel demand (measured in passenger-km).

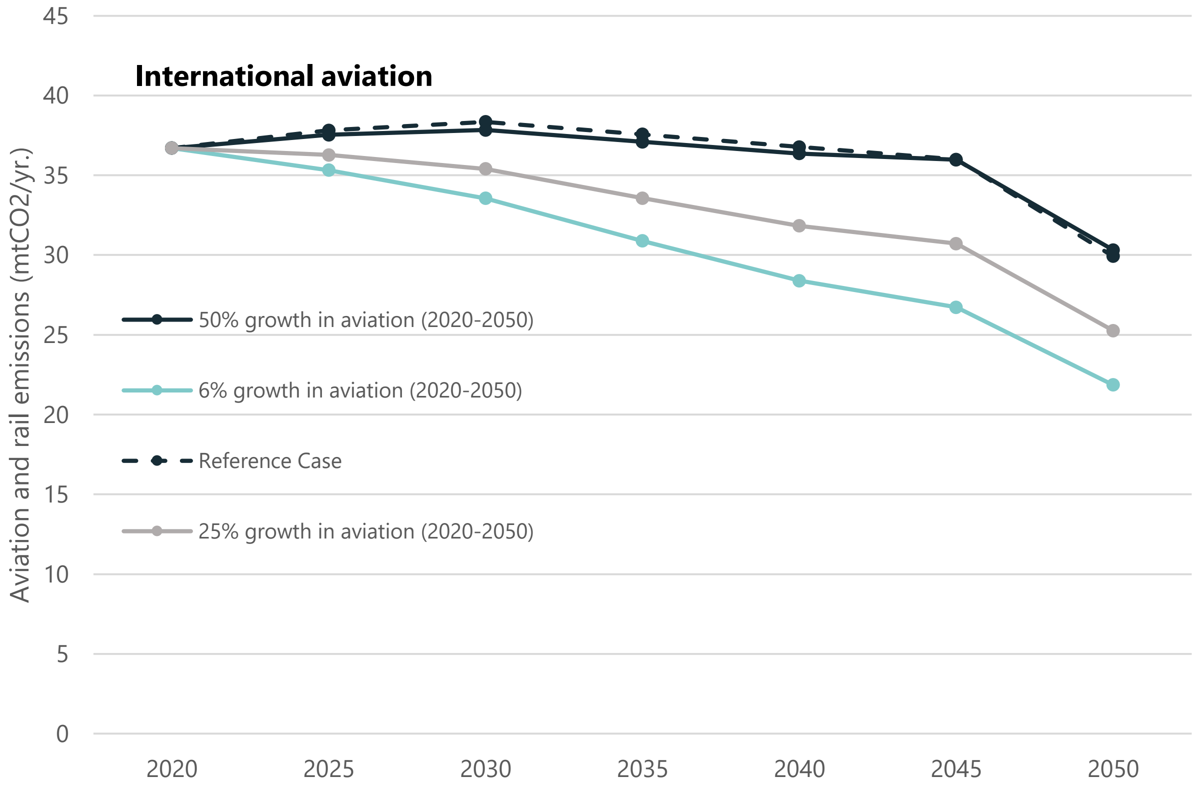
Behavioural outcome
The behavioural outcome of people taking fewer flights abroad is a reduction in international aviation demand

Transport behaviours	High	Medium	Low
Growth in international aviation demand falls as people make fewer trips abroad	6% growth in international aviation by 2050 from 2020 (equivalent to 28% decrease relative to Reference Case)	25% growth in international aviation by 2050 from 2020 (equivalent to 16% decrease relative to Reference Case)	50% growth in international aviation by 2050 from 2020 (approximately equivalent to Reference Case)



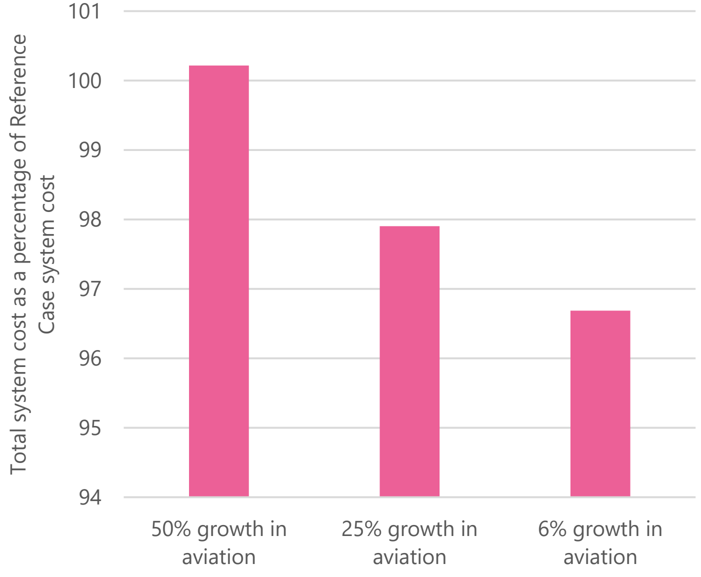
Reducing flights abroad - emissions

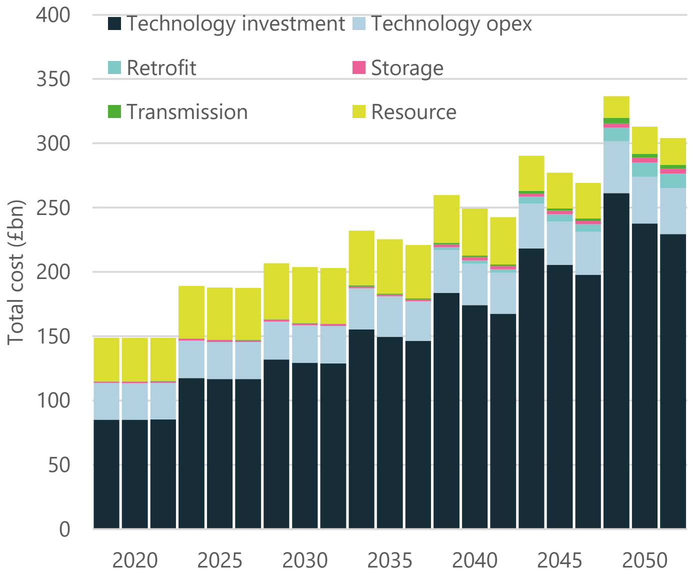




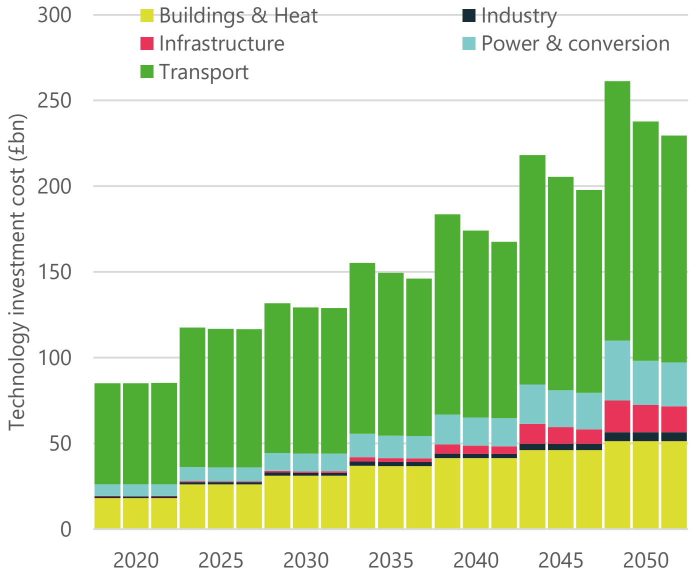
- Reductions in international aviation creates emissions headroom used by road transport
  - Less electrification = cheaper vehicles and less (low C) generating capacity needed
- Emissions headroom generated in 2030s, 2040s and 2050
- Mid-2030s: higher CCGT (unabated and with CCS) and waste incineration output
- Post-2035: ICE, hybrid and plug-in hybrids
- Emissions fall in all scenarios due to improvements to fuel efficiency

Reducing flights abroad: system costs





Clustered chart shows 3 stacks per time period. From L-R: 50%, 25% and 6% growth in international aviation demand



Behaviours that limit growth in international aviation demand to 6% by 2050 deliver a 3.3% saving in discounted total system cost. This is because of emissions headroom created by flying less, which allows difficult to decarbonise parts of the power and transport sector to continue emitting CO_2. This results in savings in technology investment costs in these sectors.

Increasing uptake of electric vehicles

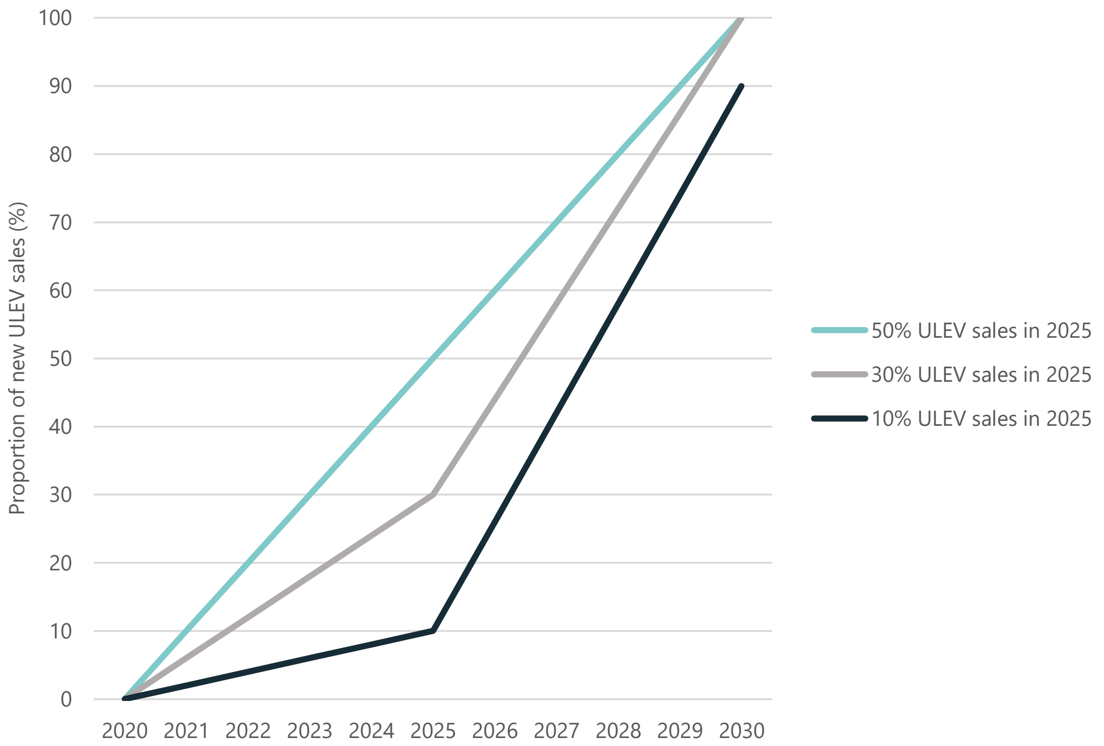
Behaviour being modelled
For this set of runs new sales of internal combustion engines (ICEs) and hybrids are banned from 2030 (the Reference Case sees new sales of ICEs and hybrids gone by 2035).

The behaviour modelled was the adoption of electric vehicles (EVs), specifically cars; operators of vans, buses or HGVs were not included in the analysis. Three different speeds of uptake from 2020 until the new ICE ban in 2030 were modelled reflecting different levels on engagement of society as a whole with zero carbon forms of transport.

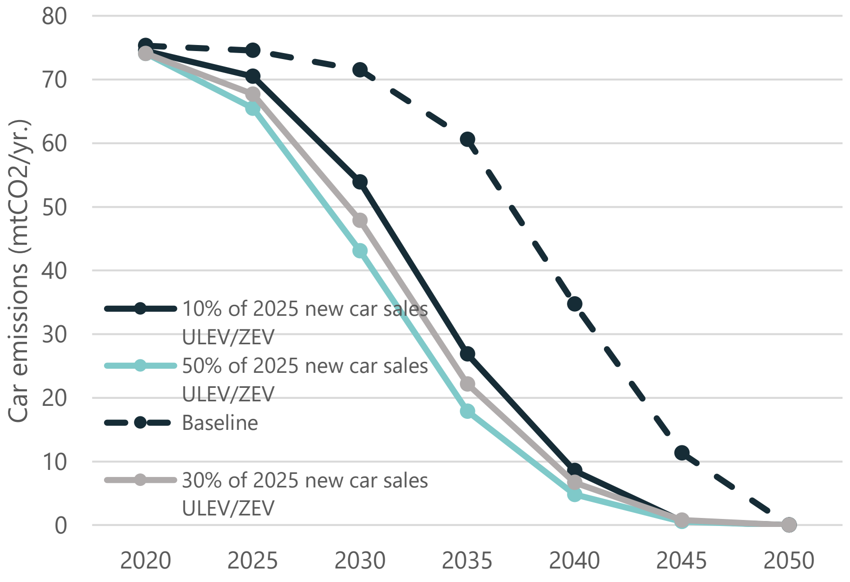
This was achieved by altering the minimum build quantities of EVs between 2020 and 2030 to obtain three levels of market penetration of EVs: 50%, 25% and 10% of new car sales being EVs by 2025. The worst case (10% new car sales) mimics late uptake of EVs as society is reluctant to move away from ICEs.

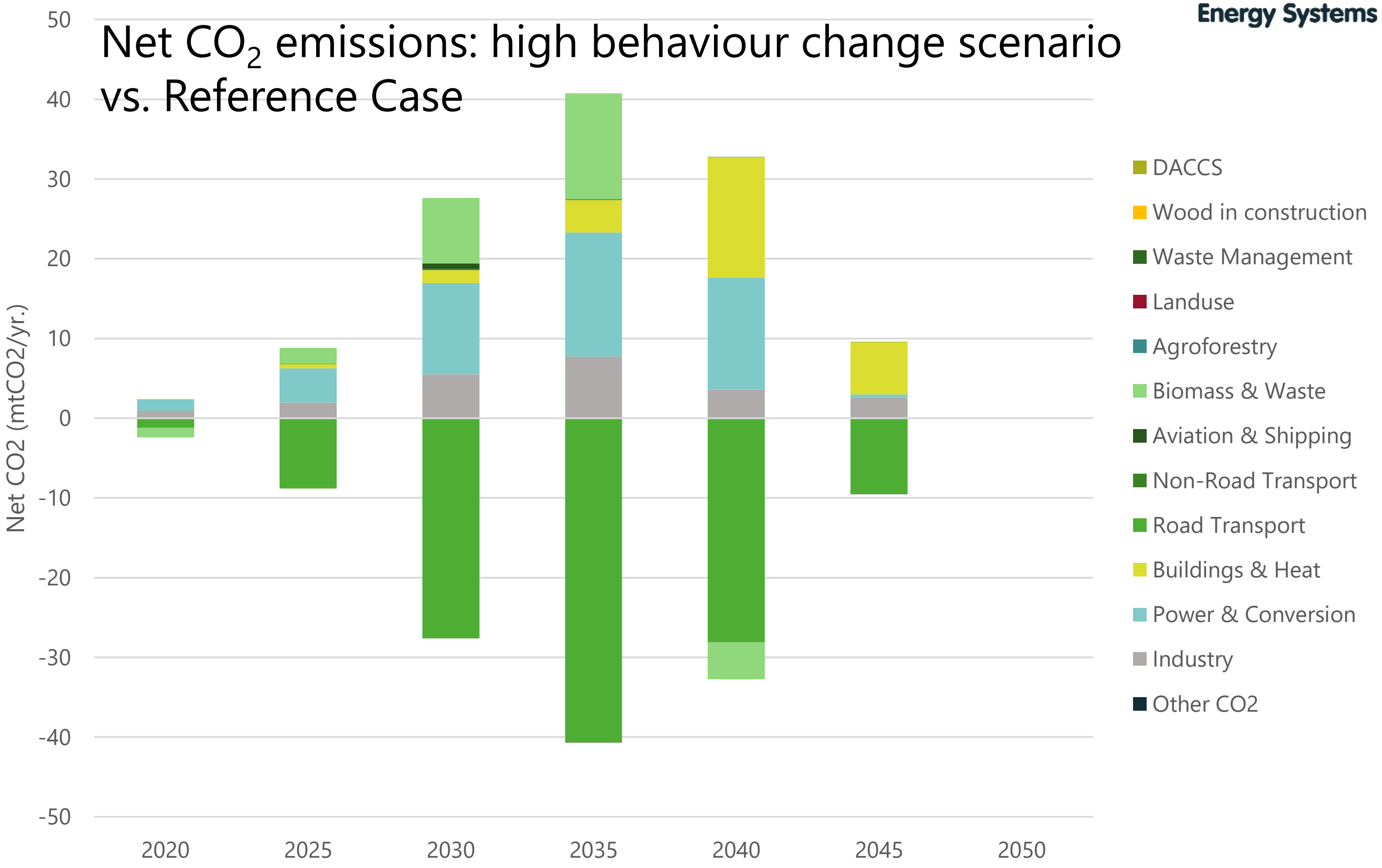
Insights from CVEI analysis [7]
- Lower upfront costs of ULEVs crucial to increasing uptake in the medium term
- Higher subsidies needed to achieve levels of ULEV deployment set out in the Road to Zero ambitions
- Access to charging also key for uptake of PiV, especially overnight access for buyers that do not have off-street parking

Transport behaviours	High	Medium	Low
Uptake of EVs increases	2030 ban on new ICE/hybrid sales. 50% new car sales in 2025 are ULEV	2030 ban on new ICE/hybrid sales. 30% new car sales in 2025 are ULEV	2030 ban on new ICE/hybrid sales. 10% new car sales in 2025 are ULEV



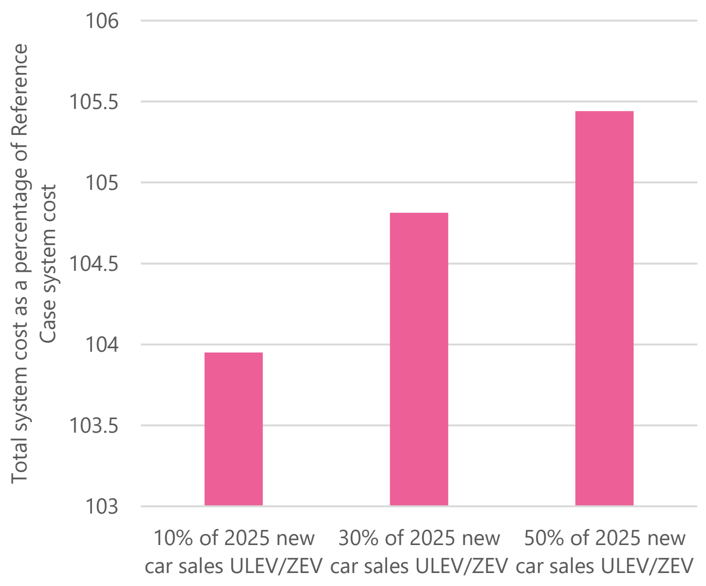
EV purchase behaviour

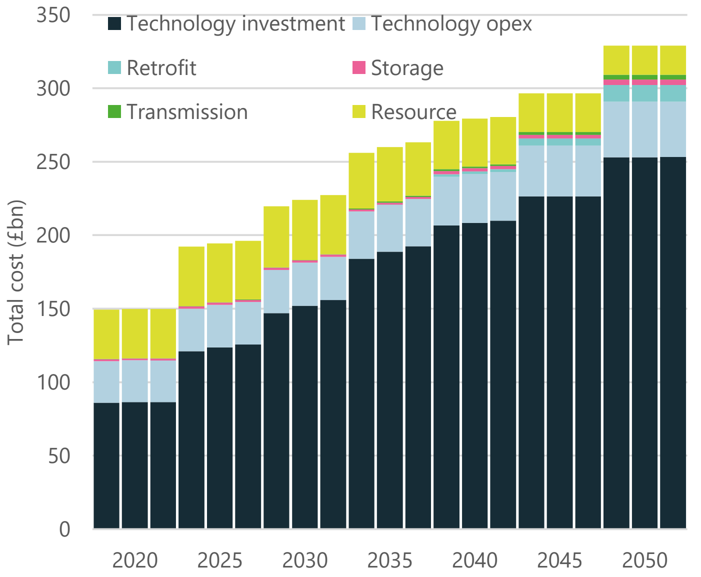




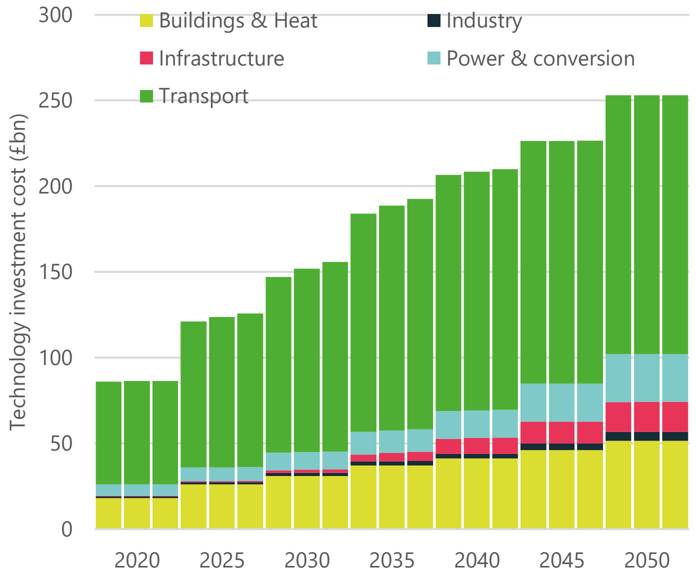
- Emissions headroom generated in 2030s and 2040s
- Unabated gas in power
- Reduction in H_2 production from biomass with CCS
- Continued use of gas for heating and industry

Purchase of EVs: system costs





Clustered chart shows 3 stacks per time period. From L-R: 10%, 30% and 50% new car sales EVs



Bringing forward the ban on new ICE and hybrid car sales by 5 years to 2030* increases the system cost. This is a result of higher technology investment costs in the transport sector earlier in the pathway. These higher costs are associated with the higher cost of EVs vs. ICE and hybrid vehicles. The cost EVs follows a cost reduction curve, which assumes a reduction in cost over time. Therefore, paying for these vehicles 5 years earlier than in the Reference Case means the investment cost is higher.

Increasing the proportion of new car sales that are EVs in 2025, increases system cost further. This is because of the higher technology investment cost of EVs vs. ICEs and hybrid cars.

* In the Reference Case, new sales of ICEs end by 2035. This is a model choice to deliver the lowest system cost and is not a programmed in as a model constraint. At the time of the analysis, the ban on new ICE sales by 2030 was not publicly announced and was not included in the Reference Case.

Transport behaviour: intangibles

Reminder of scope

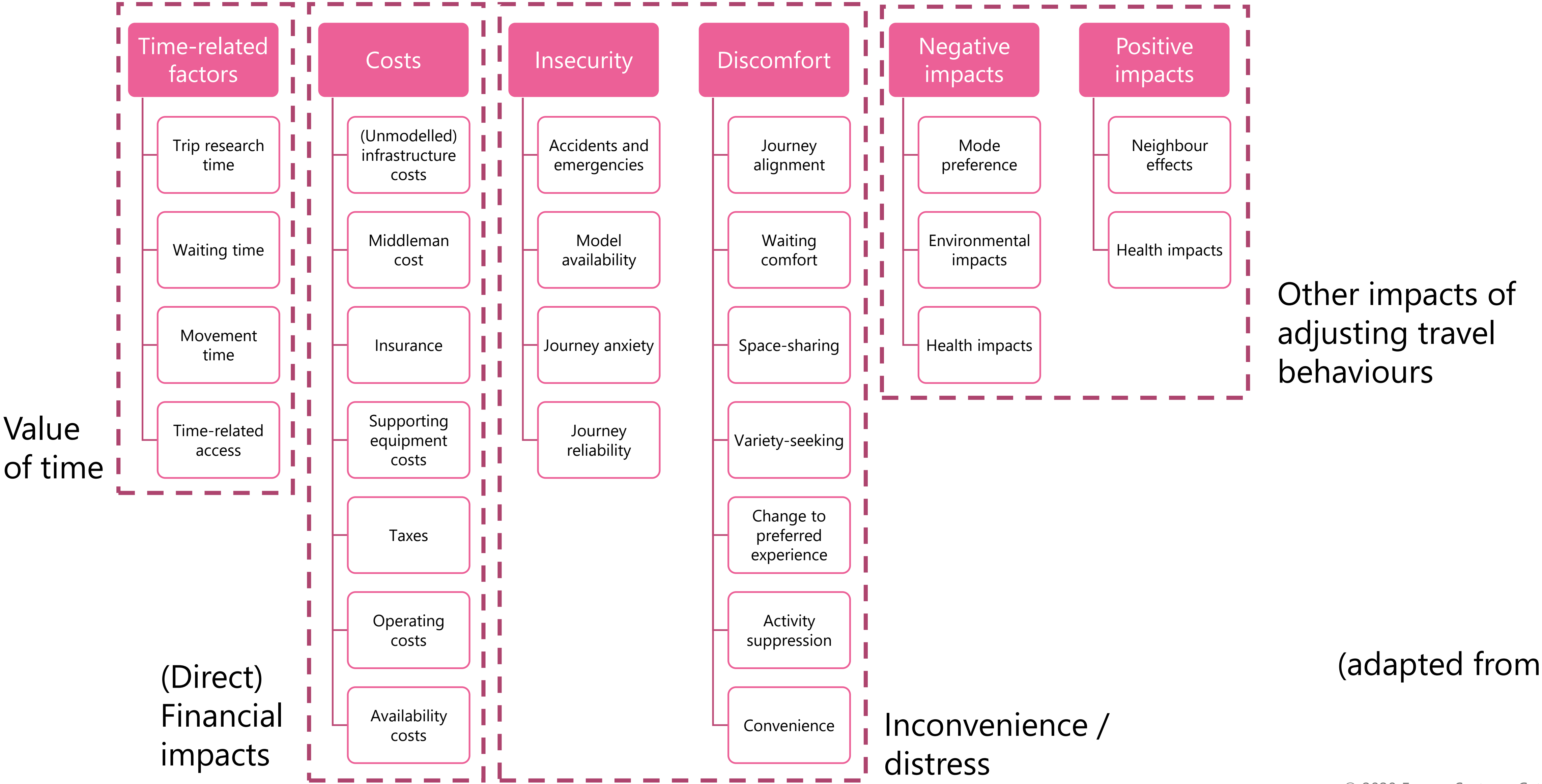
- WP4 considers "intangible costs" to represent actor perception of non-monetary costs that are not typically included within whole energy system models
- Such costs are specific to individual energy system actors (i.e. heterogenous) and are subjective. Thematically, intangible costs occur when, for a given intervention in the energy system, an energy actor:
  - Is required to spend time or effort to facilitate the intervention
  - Is subject to one-off or ongoing disruption to themselves, their property or practices
- For each transport behaviour considered within WP4, we have qualitatively and quantitatively (where possible) assessed the form and rough scale of plausible intangible costs that relate to each behaviour
- The analysis of intangible costs is exploratory and gaps that warrant further research and analysis have been highlighted where we have not been able to define useful and credible intangible costs in the limited time available

Approach for WP4

- Review of key literature already identified in WP3: focused on cross-cutting studies where possible
- Where relevant intangibles are included, characteristics directly ported across to current behaviours including quantities where available. Corrections for context applied if feasible
- Limited supplementary literature review carried out: search strings aligned to each WP4 behaviour
- Internal discussions used to summarise relevant intangibles for each behaviour, supplementing literature findings as appropriate

Costs terminology: “intangible costs”, “disutility costs”, “hidden costs”, “non-monetary costs”

Transport-related intangible costs: themes



(adapted from [8])

Value of time (VoT) central to many of the behaviours considered

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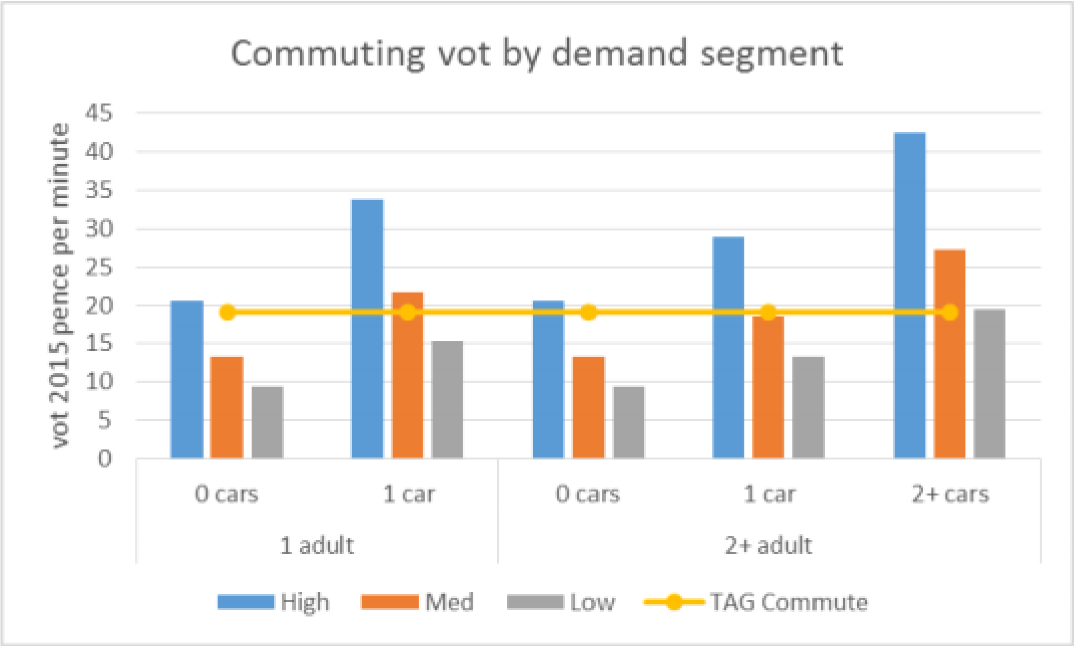
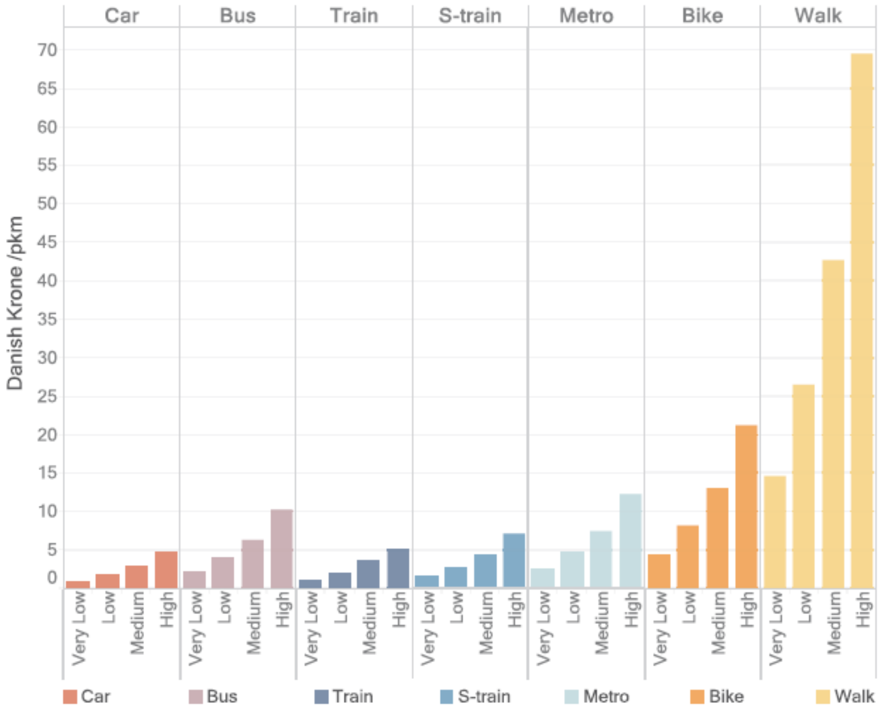
Purpose	VOT (£ per hour)	Source – WebTAG Databook Sheet A1.3.1
Commuting	11.43	Cell E45 – Perceived Cost Commuting
Business	18.59	Cell E40 – Perceived Cost Working Time – average of all working persons (not mode specific)
Other	5.22	Cell E46 – Perceived Cost Other



NTM [9]



[10]

Role of heterogeneity in intangible / disutility costs

- Top-down adjustments to demands assumed in WP4 modelling (or intrinsic adjustments using elastic demands, as in previous work) do not require detailed knowledge of *exactly who* is shifting their transport mode
- VoT estimates are strongly dependent on the party making a trip. Illustrations in previous slide outline sensitivity to consumer income, but other studies [11] also assume intangibles are adjusted for segmentations such as appetite for innovation, vehicle miles travelled etc
- As well as this heterogeneity, there is also a distribution of behaviours at the micro-level that can be consistent with macro-scale behavioural change. For transport, this distribution reflects the different types of journey shifted (e.g. distance and type)
- In this short sprint we have not investigated this heterogeneity in detail except where necessary to derive insights. This means that averages (e.g. trip distance, income/VoT) have typically been used when presenting intangible costs, supplemented or replaced by bounds/error bars if feasible. In many cases a deeper statistical analysis would be required to robustify these calculated intangibles

Behaviours modelled in WP4 transport sprint

1. Carpooling
2. Switch short journeys to active travel
3. Shift long car journeys to rail
4. Shift domestic aviation trips to rail
5. Purchase of battery EV
6. Sign up for smart charging
7. Replace or forego overseas holiday

Behaviours 1 and 2

Variables listed in the red dashed boxes are those that have had attempts at quantification made in the literature. Other variables are those that are of relevance but there is no evidence of quantification found in the literature.

Car pooling

TIMES examples [10]

- Wait time
- Detour time/distance ("dead miles")
- Early/late arrival time
- Research and coordination time

- Insurance premium
- Adjustment to vehicle O&M

- Space sharing
- Matching of commute
- Space release from smaller vehicle parc

- Impact of emergency/distress

MESSAGE examples [12]

Shift to active travel for short journeys

- Additional time per journey

- Purchase of supporting equipment
- Cost of supporting infrastructure

- Exposure to accidents
- Differential risk of mode

TIMES/ESME examples [13,14]

- Health

TIMES/ESME examples [15,16]

Behaviours 3 and 4

Shift long journeys to public transport

- Change in end-to-end time
- Interconnection time

- Fare increment
- Cost of supporting infrastructure
- Parking costs saved

TIMES examples [10]

- Comfort of alternative modes
- Comfort of transit & waiting

- Emergencies and distress events

Shift domestic aviation to rail

- Change in end-to-end time
- Interconnection time

TIMES/ESME examples [13,14]

- Fare increment
- Cost of supporting infrastructure

- Comfort of alternative modes
- Comfort of transit & waiting

Behaviours 5 and 6

Purchase of EV

- Refuelling/charging station availability
- Model availability
- Risk premium
- Range anxiety

- Towing capability
- Cargo space

MESSAGE examples [12]

Sign up for smart charging

- Cost of smart versus “dumb” charger
- Perceived risk of unavailability

Behaviour 7

Replace overseas holiday

- Waiting time
- Cost for equivalent trip
- Variety-seeking
- Experience preference

Behaviour 1: Car pooling

Literature summary: history of time-related disutilities being studied within WESM models for non-UK context [10]. Intangibles other than those associated with VoT not readily presented

Theme	Commentary	Quantification approach
Wait time	Associated with wait for carpool to arrive, or foot travel to pickup location. Variable but likely to be sufficiently low else carpool would not be utilised	Assumed negligible
Detour time	Additional travel time incurred through additional drop-offs. Variable but likely to be low, relative to individual trip time	Circa 10 mins per trip max x VoT
Early/late arrival	Associated with arrival before or after standard working hours, meaning either "dead time" or additional working time. Likely to be similar scale to detour time, but VoT of such time less clear	Unquantified
Research time	One-off or annual time to locate carpool per sharer	Assumed negligible (hours per year)
Space sharing	Penalty associated with restricted travel freedom. No research on personal comfort/freedom to deviate from planned commute found	Unquantified
Impact of emergency	Appropriate statistical method likely to be similar in ethos to approach for range anxiety – frequency of "early returns" where alternative transport mode needed for car pooler	Frequency of distress events x alternative mode costs (e.g. rail + taxi)

Behaviour 2: Shift short car journeys to active travel

Literature summary: included in WESM modelling as for Behaviour 1 [10]. Active travel also sometimes included within WESMs, typically utilising "time travel budgets" [7,8]

Theme	Commentary	Quantification approach
Additional journey time	Modelled behaviour representative of slower active journeys	Additional time per trip x trips x VoT
Purchase of supporting equipment	To achieve the scale of switched journeys modelled, cycling contribution is required. Cost of bicycle and ancillaries (e.g. wet-weather equipment) likely to be incurred for high modal shifts	Illustrative £500 one-off [11]
Cost of supporting infrastructure	WESMs often, but not always, exclude full infrastructure costs required to support mode-switching. Infrastructure likely to be a prerequisite for significant modal shift	Illustrative £20/capita to deliver cycling infrastructure 20% to 40% modal shift [13,14]
Risk/accidents	Fatal accident risk higher for cycling and walking than driving [17], and thus there may be an intangible cost associated with additional mortality	Estimation of additional fatalities x fatality cost
Health benefits	Various studies [18] have estimated health benefits of walking and cycling, offering an intangible benefit	[18] estimates £17bn cumulative NHS savings in 20 years for c. 3 km modal switch

Behaviour 3: Shift longer car journeys to rail

Literature summary: included in WESM modelling as for Behaviour 1 [3]. "Time travel budgets" and infrastructure inclusion also relevant for shift to rail. Some comparative studies uncovered [12,13]

Theme	Commentary	Quantification approach
Additional end-to-end time	End-to-end time differential is route dependent, with different routes requiring powered or active trips to station and interconnections. For the modelled 5% to 10% of demand shifted, likely to be longer journeys	Additional time per trip x trips x VoT
Waiting and interconnection time	Statistical view of access, egress and wait times are included within NTM [9]	Unquantified
Fare increment	Variability of rail and air fares (e.g. types of ticket) make it difficult to estimate fare increment. Inclusion in such studies questionable – energy system models include some costs for transport mode but not commercial elements that may present barriers to switching	Average rail fare (£/p-km) – car variable costs (£/p-km)
Cost of supporting infrastructure	Full accounting of infrastructure costs often not included in WESMs [14] but estimates have been studied	Circa 0.04p/p-km for rail [14] x shifted p-km
Comfort and useful time impacts	No useful material discovered	Unquantified
Distress events	Potential for delays and re-routings may impact modal preference and present barriers	Unquantified

Behaviour 4: Shift domestic aviation to rail

Literature summary: limited relevant literature uncovered other than inclusion of elastic aviation demands. Comparative studies of some relevance for time and fare comparisons [12,13]

Theme	Commentary	Quantification approach
Additional end-to-end time	End-to-end time differential is clearly route dependent. 5% to 10% of demand shifted likely to be longer journeys	Additional time per trip x trips x VoT
Waiting and interconnection time	Access, egress and wait times included within NTM [9]	Unquantified
Fare increment	Variability of rail and air fares (e.g. types of ticket) make it difficult to estimate robustly	Average rail fare (£/p-km) – average equivalent air fare (£/p-km)
Cost of supporting infrastructure	Full accounting of infrastructure costs often not included in WESMs [14] but estimates have been produced	Circa 0.04p/p-km for rail [14] x shifted p-km
Comfort and useful time impacts	No useful material discovered	Unquantified

Behaviour 5: Purchase of EV

Literature summary: full end-to-end costing carried out in the literature (e.g. [5,14]) albeit for different regions/markets

Theme	Commentary	Quantification approach
Refuelling/charging station availability	Examples in the literature capture fuel/charging availability and ease of refuelling/charging	Number of refuelling trips x time/trip x VoT [12]
Model availability	Attribute associated with the number of vehicle models available for a given technology	In market share models, cost premium for technologies having fewer models than incumbent (equalised when number of models is matched)
Risk premium	Cost based on willingness to bear perceived riskiness of new vehicle technology (strongly heterogenous)	Estimated at between -$1k and +$3k per vehicle [12]
Range anxiety	Cost to overcome perceived anxiety for range-limited vehicles. Proxies in literature involve willingness to pay for alternative, e.g. rental vehicle for trips beyond range	Number of "insufficient range" days x inconvenience cost penalty
Towing capability	Cost or benefit that the consumer gains from the vehicle having towing capability	Unquantified
Cargo space	Cost or benefit that the consumer gains from the availability of luggage space	Unquantified

Behaviour 6: Smart charging

Literature summary: ESC/ETI's Consumer Vehicles and Energy Integration project drawn upon as primary source of insight – few other relevant studies uncovered

Theme	Commentary	Quantification approach
Cost of smart charger versus alternatives	Likely to be some price differential between EV charger technologies (slow/fast/rapid, smart/dumb)	Likely to be small (e.g. Myenergi Zappi premium for 22kW charge point ~ £100 over 7kW charge point)
Perceived risk of vehicle unavailability	Dependent upon smart charging conditions of use	Unquantified

Behaviour 7: Replace overseas holiday

Literature summary: Some willingness-to-pay case studies assessed, but little direct application to mode switching of this type

Theme	Commentary	Quantification approach
Waiting time	Considerable waiting/interconnection time associated with overseas aviation, but surface alternatives vary in how time is spend (driving versus rail)	Unquantified
Cost for equivalent trip	Unclear whether "equivalent trip" can truly be achieved for particular types of overseas trip	Unquantified
Variety-seeking and experience preference	Some evidence from literature that individuals seek variety in experience when considering leisure travel, and thus foregoing overseas holidays will be associated with disutility unless the particular experience can be replicated elsewhere	Unquantified

Quantification: initial method / approximations of intangible costs where feasible

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- Car pooling

Detour-related intangible cost
Detour time/trip
[hours] : [0,10]
x
Pooled trips/year
: [150,250]
x
VoT
[£/hour] : £11 ± 4

Carpool research cost
Research time per sharer
[hours] : [1,2]
x
Total sharers
: < 8m (35%)
x
VoT
[£/hour] : £5 ± 2

- Short journeys to active travel

Lost time intangible cost
Additional active travel distance
[b km] : [0,90]
x
Speed differential
[km/hour] : 2-3 mins/km
x
VoT
[£/hour] : £5 ± 2

Health benefit cost
Cost saved per year
[£bn] : [0,2]

- Long journeys to rail

Lost time intangible cost
Additional rail travel distance
[b km] : [0.90]
x
Speed differential
[km/hour] : c. 50% added
x
VoT
[£/hour] : £11 ± 7

Fare increment
Travel cost comparison
[£/km] : [0,0.2]
x
Distance switched
[b km] : [0,90]
x
VoT
[£/hour] : £11 ± 7

- EV purchase

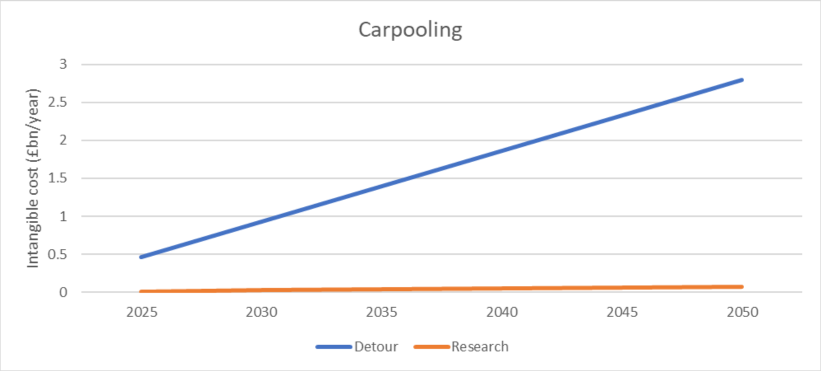
EV purchase intangible cost
(Range anxiety cost
[£/vehicle] : [0,1700]
+
Model availability cost
[£/vehicle] : [0,200])
x
Deployed BEVs
[M vehicles] : [0,44]

NB: Behaviours 4, 6 and 7 unquantified

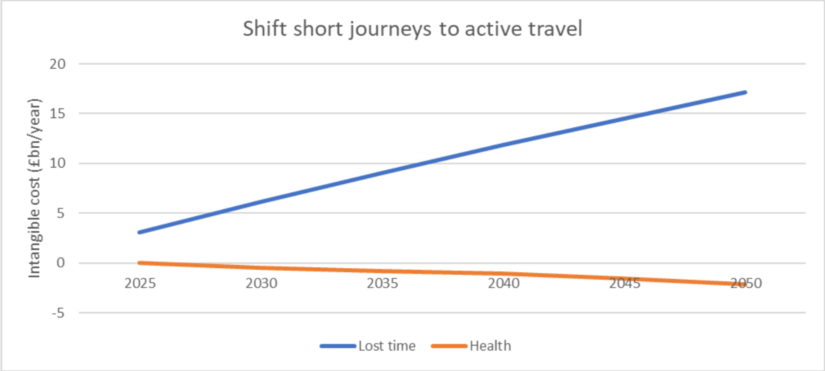
NB: VoT = £11.43 for commuting, £18.59 for business, £5.22 otherwise. Additional segmentation lift is VoT up for higher incomes
Values in red are ESC judgement. Values in blue are informed by literature, particularly [19] and [20]. Bracketed numbers indicate ranges

Quantification: initial estimates of intangible costs where feasible

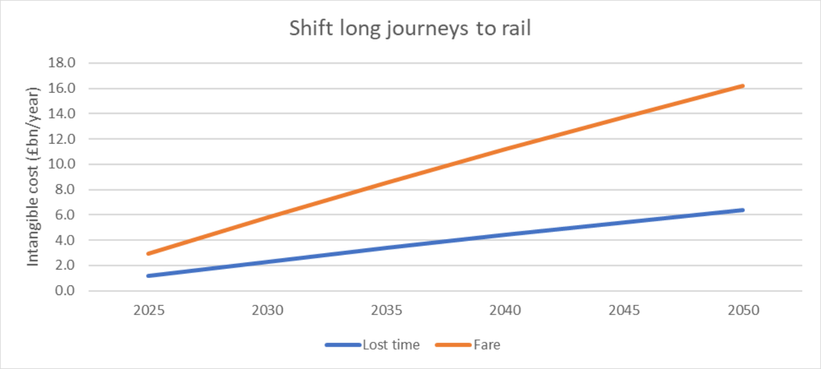
- Car pooling



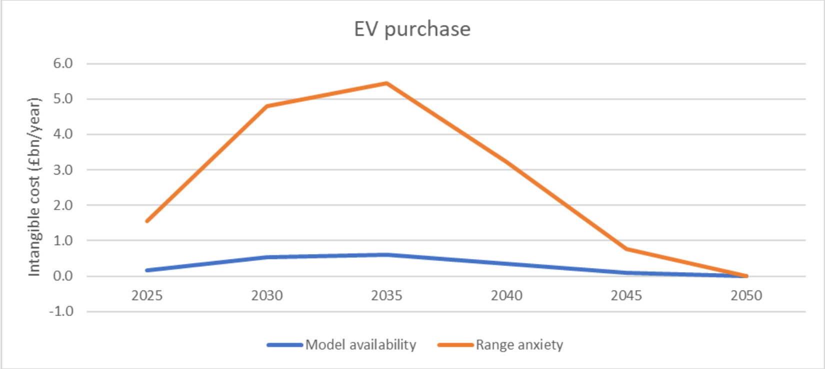
- Short journeys to active travel



- Long journeys to rail



- EV purchase



All trends are aligned to demand reduction cases modelled, i.e. intangible cost assumed to be net additional cost
Note that the range anxiety curve is a function of number of EVs on the road in the high behaviour change case (50% new car sales in 2025) vs. the medium case (30% new car sales EVs by 2025). With more EVs on the road in the mid-2030s, the cost associated with range anxiety is higher. By 2050, there are the same number of EVs on the road in both cases and so the cost associated with this is zero. Intuitively this could be mean that by 2050, EV ownership is so widespread that no one experiences range anxiety.

How can these elements be used to supplement energy system modelling?

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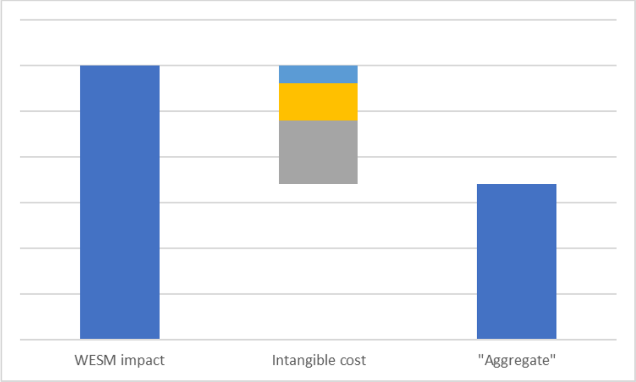
Qualitative

- Presentation of qualitative features of intangible costs alongside WESM costs
- Qualitative judgement applied to intangible costs (e.g. severity)
- Provides indicative view of challenges associated with behaviours

Behaviour	Model cost	Intangibles
Car pooling	£X bn	Dead time (low) Discomfort / freedom (high)
Active travel	£Y bn	Lost time (high) Health & wellbeing (high)
Overseas holidays	£Z bn	Loss of experience (high)

Quantitative, off-model

- Behavioural adjustments applied to model, and system costs calculated
- In parallel, equivalent intangible cost derived (where possible) based on model outputs
- Magnitudes of system and intangible costs compared: illustration of size of barriers to overcome for behavioural change



Quantitative, on-model

- Inclusion of intangible costs within WESM's optimisation, influencing "optimal pathway"
- Most appropriate analytical approach likely to be to unwind intangibles from WESM cost – intangibles adjust preferred solution, adding "behavioural realism", but cost definitions unchanged from convention WESM costs
- Natural to combine with other analytical methods discussed in WP3 – variable hurdle rates, elastic end-use demands etc

Several prominent gaps identified: limited exploration in time available

Behaviour	Gap/subjectivity
Car pooling	Disutility of space sharing Disutility of “commute matching” Assessment of consumer groups that preferentially carpool
Shift short journeys to active travel	Impact of accidents Intangible cost associated with travel conditions
Shift long journeys to public transport	Intangible cost associated with travel conditions Distribution of shifted journeys Perceived/actual fare premium
Shift domestic aviation to rail	Fare increment Mode comfort/discomfort
Purchase of EV	Inconvenience cost for on-road parking
Impact of smart charging	Perceived risk
Replace foreign holiday	Cost differential for “equivalent”
Cross-cutting	Distribution/disaggregation of intangible costs – breaking down average-based intangible costs using trip statistics (DfT support?) & HML/innovation status

Heat behaviour: energy systems modelling results

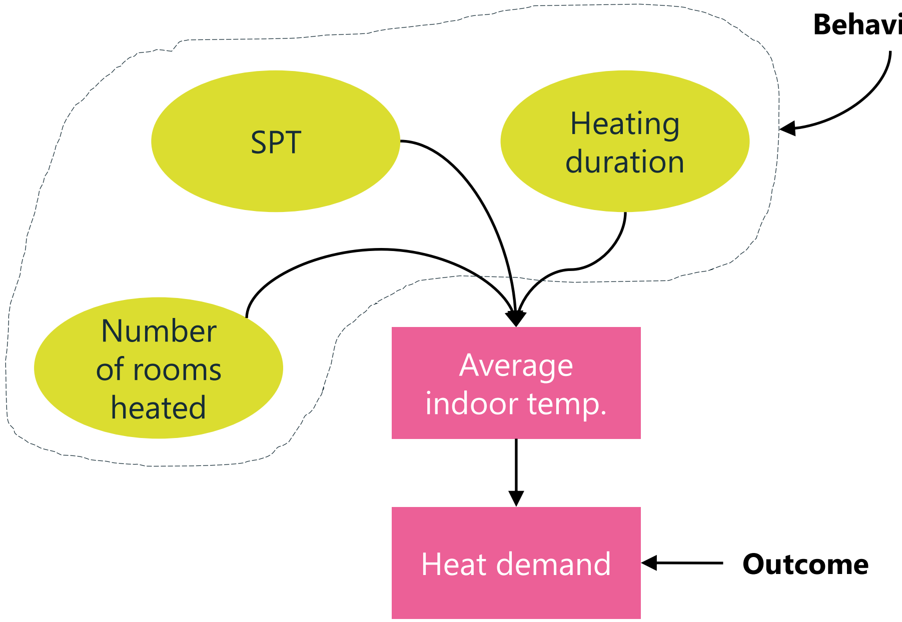
Heat behaviours modelled

Behaviour	High change	Medium change	Low change
Occupants are willing and able to limit the increase in average indoor temperatures	Occupants are willing and able to limit the increase in average indoor temperatures to 19°C by 2050 from 18.5 in 2010 Decrease in 2050 heat demand due to lower SPT, efficiency improvements and assumed increase in external temperature as a result of climate change	Occupants are willing and able to limit average indoor temperatures to 20°C by 2050 from 18.5 in 2010 Decrease in 2050 heat demand due to lower SPT, efficiency improvements and assumed increase in external temperature as a result of climate change	Occupants not willing/able to limit average indoor temperatures, which rise to 21°C by 2050 from 18.5 in 2010 (this is in line with the ESME Reference Case) Effects of increasing SPT roughly offset by increased thermal efficiency and rising external temperature due to climate change.
Occupants install whole-house retrofits	Engagement from homeowners consistent with that needed in the Reference Case energy system 10.8 million homes installing whole house retrofit packages by 2050	Installation rates are half those in the high behaviour change scenario with 5 million homes installing whole house retrofit packages by 2050. In 2017/18 an estimated 170,000 homes were renovated with significant energy efficiency improvements [22]	Installation rates of whole house retrofit packages is almost a quarter of those in the high behaviour change scenario with 2.5 million homes retrofitted by 2050. This is approximately 83,000 homes retrofitted each year from 2020.
Occupants install heat pumps	Deployment of HPs in domestic homes is in line with ESME Reference Case. Maximum deployment by 2050 is constrained by suitability of homes (thermal performance and space requirements). By 2050, heating is completely decarbonised with 60% of residential heat demand supplied by heat pumps (56% ASHP, 4% GSHP)	People install HPs but at a slower rate and delayed by 5 years Maximum deployment by 2050 is constrained by suitability of homes (thermal performance and space requirements). By 2050, heating is completely decarbonised with 60% of residential heat demand supplied by heat pumps (56% ASHP, 4% GSHP)	People are more resistant to installing HPs reflected by a slower deployment rate and 10 year delay Maximum deployment by 2050 is constrained by suitability of homes (thermal performance and space requirements). By 2050, heating is completely decarbonised with 60% of residential heat demand supplied by heat pumps (56% ASHP, 4% GSHP)
Occupants connect to district heat networks	Number of homes connected to DHNs is in line with ESME Reference Case. By 2050, almost 7 million homes are connected to DHN meeting 21% of heat demand	People connect to DHNs but at a slower rate and delayed by 5 years By 2050, almost 7 million homes are connected to DHN meeting 21% of heat demand	People are more resistant to connecting to DHNs reflected by a slower deployment rate and 10 year delay By 2050, almost 7 million homes are connected to DHN meeting 21% of heat demand

Reduce set point temperature

Behaviour being modelled
People are willing and able to reduce the thermostat temperature in their homes. This might lead to a loss of thermal comfort if no other measures are taken.

This is being modelled in ESME using a heat demand pre-processing tool. This generates heat demand for every dwelling typology (thermal performance and density) for each geographical region, daily time slice, season (including peak) and time period (2010-2050). The heat demand is influenced by SPT, internal gains and rising external temperatures due to climate change.



Behavioural outcome
The behavioural outcome of reducing SPT is ultimately a reduction in heat demand.

Reducing the SPT affects the average internal temperature of the home. All else being equal, a reduction in SPT will decrease the average internal temperature. This in turn decreases the heat transferred from the dwelling to the outside – this is equal to the heat demand.

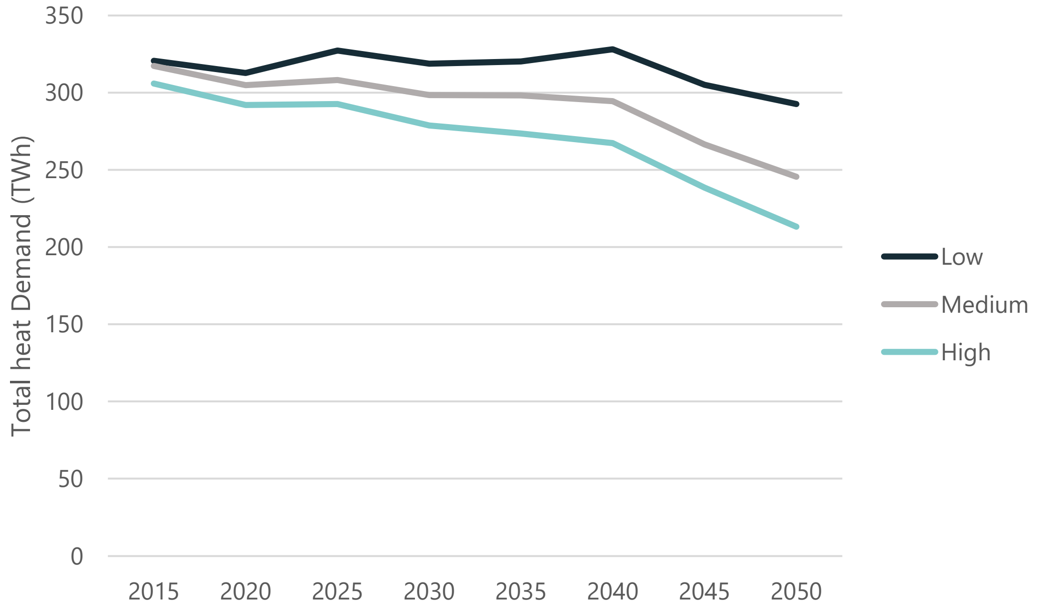
There may be other ways in which the average internal temperature of a dwelling can be reduced without changing the SPT: Changes to the heating pattern to reduce the duration of active heating and/or smart controls to limit heating to occupied rooms could both reduce the average indoor temperature and therefore heat demand.

Periods or rooms/spaces of lower temperature will impact on the thermal comfort of the occupants. However, minimising the heat losses by improving the thermal performance of the dwelling could achieve reductions in heat demand whilst minimising the effect on the average indoor temperature thus maintaining comfort levels.

How can SPT be reduced?
- Wear warm layers: brings thermal comfort to the individual

Reduce thermostat temperature

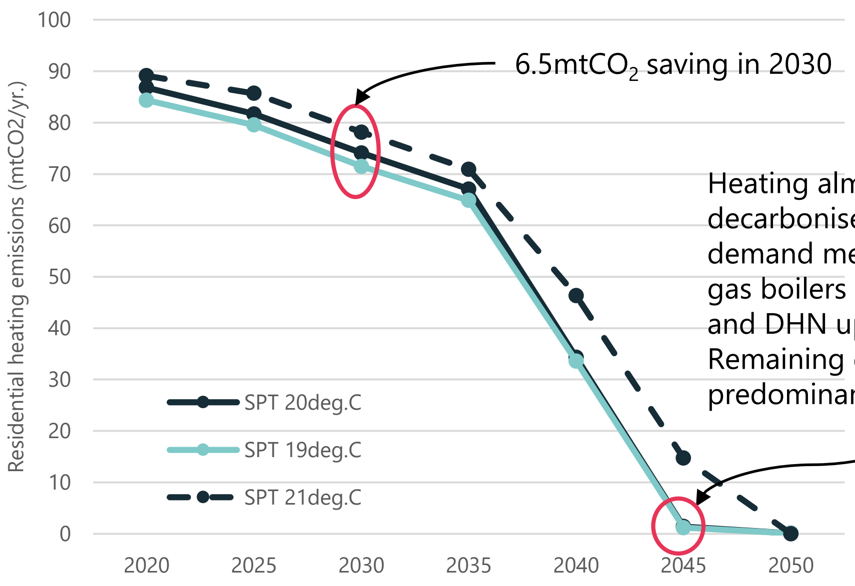
Heat behaviour	High	Medium	Low
Occupants are willing and able to limit the increase in average indoor temperatures	Occupants are willing and able to limit the increase in average indoor temperatures to 19°C by 2050 from 18.5 in 2010 Decrease in 2050 heat demand due to lower SPT, efficiency improvements and assumed increase in external temperature as a result of climate change	Occupants are willing and able to limit average indoor temperatures to 20°C by 2050 from 18.5 in 2010 Decrease in 2050 heat demand due to lower SPT, efficiency improvements and assumed increase in external temperature as a result of climate change	Occupants not willing/able to limit average indoor temperatures, which rise to 21°C by 2050 from 18.5 in 2010 (this is in line with the ESME Reference Case) Effects of increasing SPT roughly offset by increased thermal efficiency and rising external temperature due to climate change.



Illustrative impact of different SPT on total heat demand across all dwellings. Note that this assumes housing stock remains identical between scenarios. In reality, there are likely to be changes in housing stock in ESME e.g. a lower heat demand might reduce the number of retrofit measures installed.

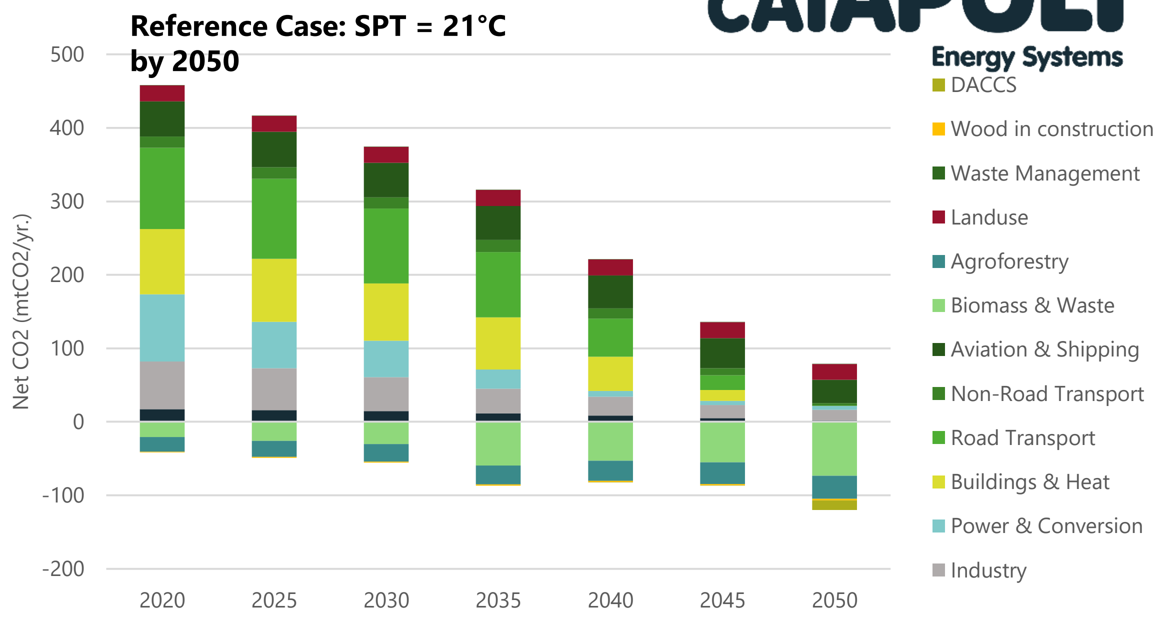
High behaviour change case results in reducing heat demand because of thermal efficiency improvements associated with retrofit measures and improved housing stock.

Reduce set point temperature: emissions



6.5mtCO_2 saving in 2030

Heating almost entirely decarbonised by 2045: lower heat demand means less reliance on gas boilers for base load as HP and DHN uptake increases. Remaining gas boilers are used predominantly in the peak period

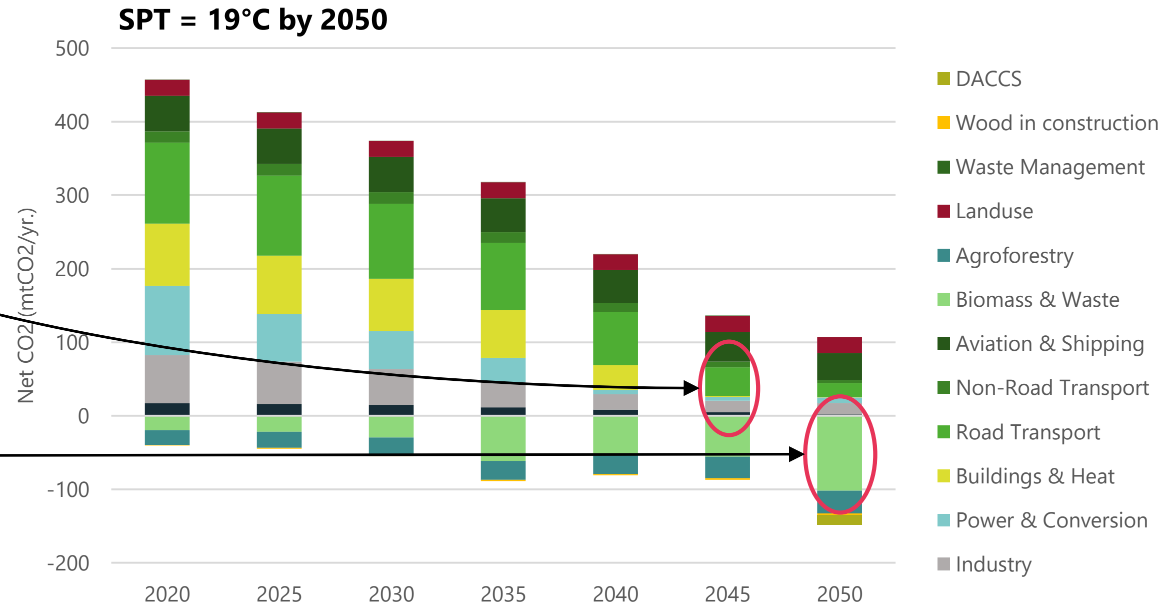


Reducing the SPT delivers emissions savings throughout entire pathway up to 2050 relative to the Reference Case. At 2050, the heating sector in all three cases is zero carbon. With a SPT of 19°C or 20°C, the heating sector is very close to being zero carbon in 2045. This is a result of lower heating demand reducing the reliance on gas to provide heat.

A SPT of 19°C achieves lower emissions than a SPT of 20°C up to around 2035. This is because fossil fuels, in particular gas, still provide the majority of heat during these time periods. Therefore, any reduction in heat demand will lead to a reduction in gas consumption and therefore emissions. Post-2035, the heating sector begins to decarbonise in both cases.

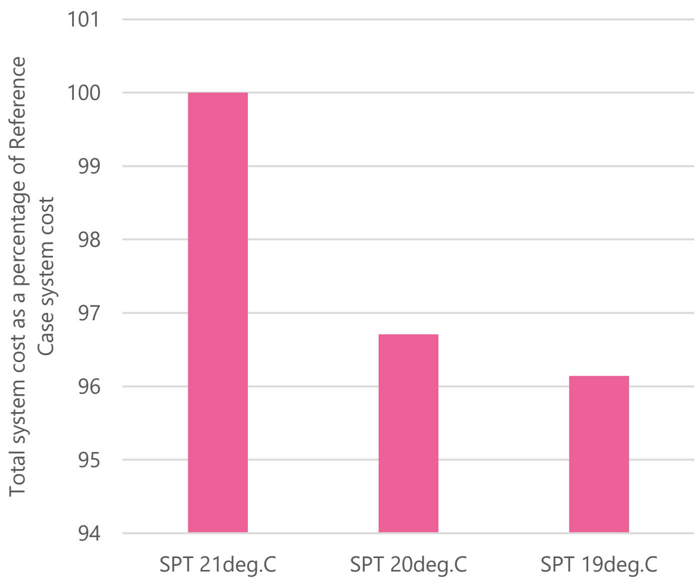
Emissions savings from heating sector are used by the transport sector.

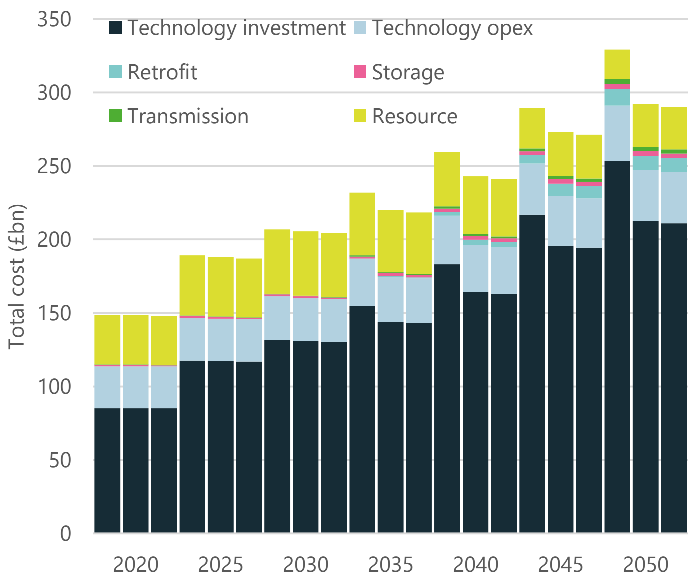
Increased biomass consumption to produce more hydrogen. With lower heating demand, hydrogen boilers are able to provide more baseload supplying approx. 1/3 of total heat demand



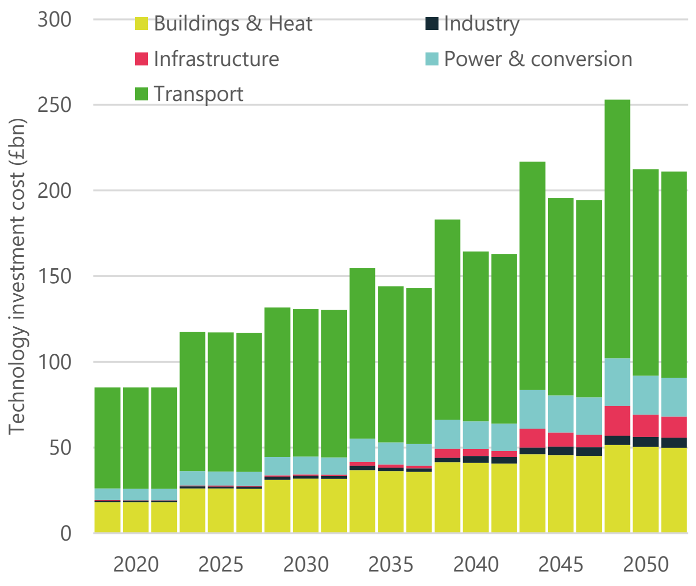
Reduce set point temperature: system costs

CATAPULT Energy Systems





Clustered chart shows 3 stacks per time period. From L-R: SPT21, SPT20, SPT19



A SPT of 19°C by 2050 (2°C lower than the Reference Case) achieves approximately 3.9% reduction in total system cost. This saving is largely due to lower technology investment costs appearing in the mid-2030s.

At SPT 20°C and below, heating demand is sufficiently low enough to allow zero carbon heating technologies to supply over 60% of heat in 2040 and almost all the heat from 2045. This generates emissions headroom which allows harder to decarbonise sectors such as some aspects of transport to continue to emit whilst still allowing the UK to meet carbon targets. In addition, having a lower demand for heat overall means less infrastructure, including electricity and hydrogen production, is needed to support a low carbon heating system. Both the creation of emissions headroom and a reduction in infrastructure requirements deliver a cost saving. Further analysis to test different SPTs would be needed to understand the response of the energy system to SPT. In particular this would help identify a possible critical SPT at which total heating demand is low enough to facilitate a majority supply of heat by zero carbon means, and allow system cost as a function of SPT to be plotted.

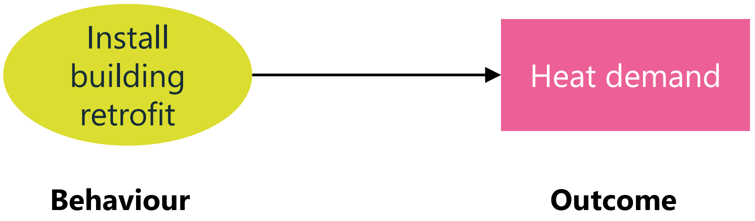
Savings in technology investment costs are mainly due to savings made in the transport and infrastructure sectors

Adopt building fabric changes

Behaviour being modelled
Homeowners/landlords install building retrofit measures to improve the thermal performance of their dwellings and reduce heat demand. This could be motivated by improved comfort/well-being, reduced energy bills, and/or concerns about the environment.

Three separate behaviours associated with building fabric changes were identified in WP1: installation of cavity wall insulation, solid wall insulation and double/triple glazing. In ESME, building fabric improvements are represented by two whole-house retrofit packages. These existing options in the model were used to consolidate the three separate behaviours into a single behaviour related to adopting building retrofits.

Three levels of behaviour were modelled reflecting three levels of willingness/ability of actors to adopt whole-house retrofit measures. The highest level of behaviour, which results in the highest number of whole-house retrofits is the ESME Reference Case. This is a least-cost optimum, which installs approx. 10.8 million retrofits by 2050. The two remaining levels model a reduction in the total number of retrofits installed in 2050 by reducing the rate of adoption.



Behavioural outcome
The behavioural outcome associated with retrofit adoption is a reduction in heat demand.

Installing building fabric improvements reduces the amount of active heating needed to achieve a desired SPT because less heat is lost through the fabric of the building and internal gains can contribute more to the warmth of the dwelling. Internal gains refer to heat produced within the dwelling by such things as occupants (people and animals) and appliances.

Reducing heat losses through the building fabric increases the thermal time constant (i.e. the time it takes for the building to cool down). This could enable occupants to shorten the duration of active heating (and prolong the time between heating periods). Improving thermal performance can also promote other heating behaviours such as reducing the flow temperature to radiators – this is useful when installing heat pumps which work more efficiently with low flow temperatures.

What affects building retrofit adoption?
There are a vast number of factors that need to be considered when making decisions about retrofitting both from the consumer's and supplier's perspective. These are related to costs, benefits, practical, considerations, risks and preferences.

There are several drivers that encourage consumers to adopt retrofit packages including comfort, health/well-being and savings on energy bills. However there are a number of barriers that make things difficult. Again, these barriers apply to both the consumer and the supplier.

Two types of whole house retrofit package in ESME: type 1, RetroFIX

- Wall insulation
- Loft insulation
- Floor edge insulation
- Draught-stripping
- Single room heat recovery
- A-rated boiler
- TRVs and zoned controls

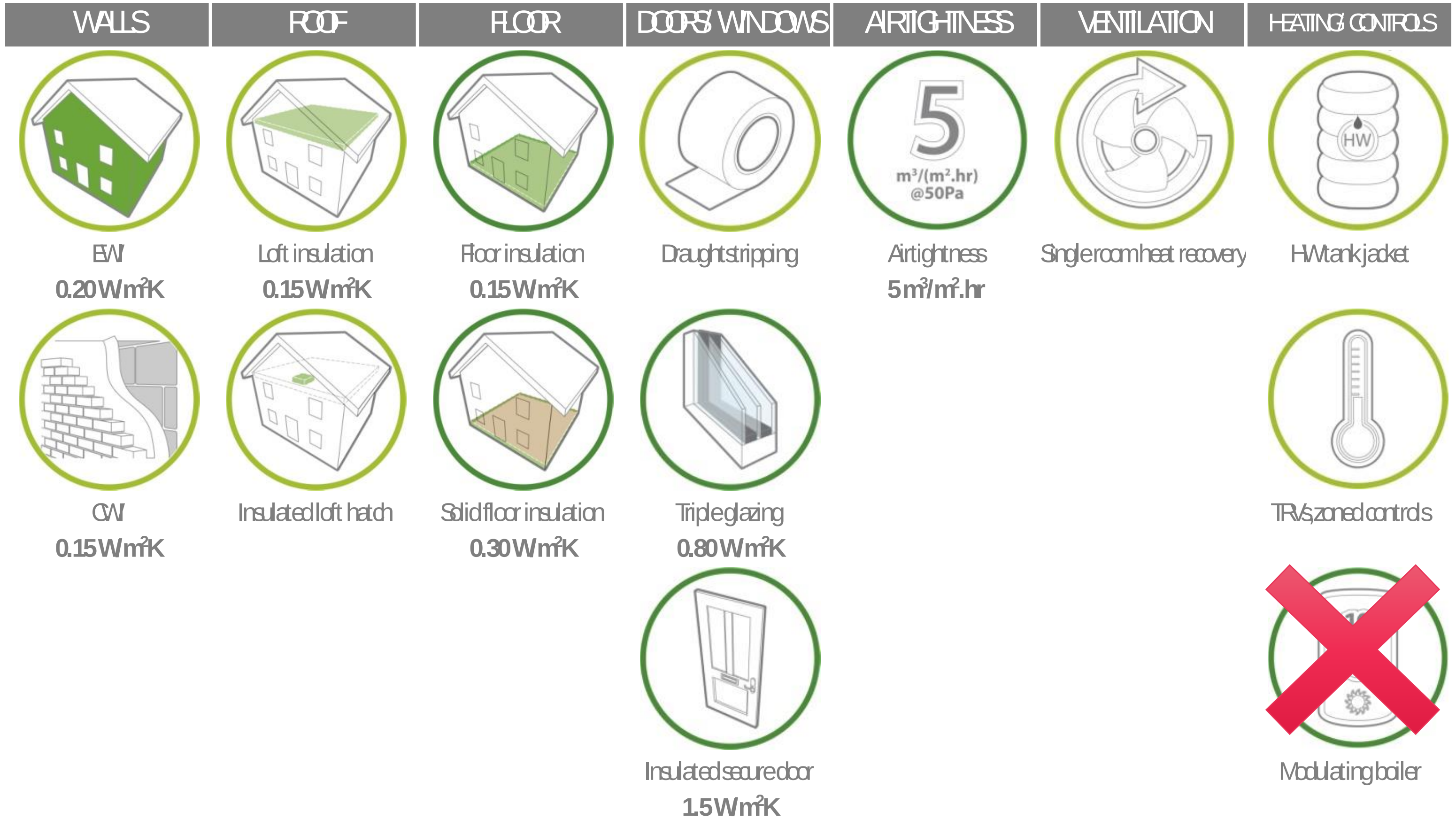
20-30% reduction in demand

£8-20k

Two types of whole house retrofit package in ESME: type 2, RetroPLUS

RetroFIX +:

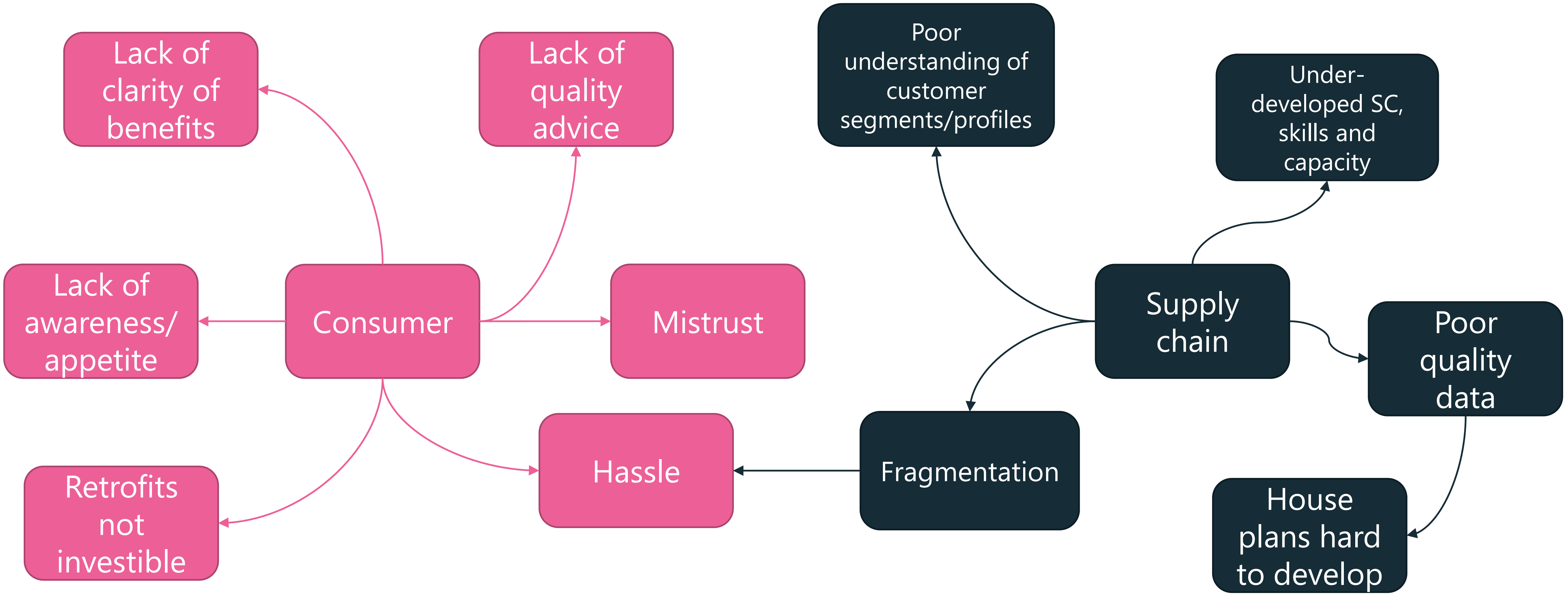
- Floor insulation
- Window replacement
- Door replacement
- Modulating boiler



35-45% reduction in demand

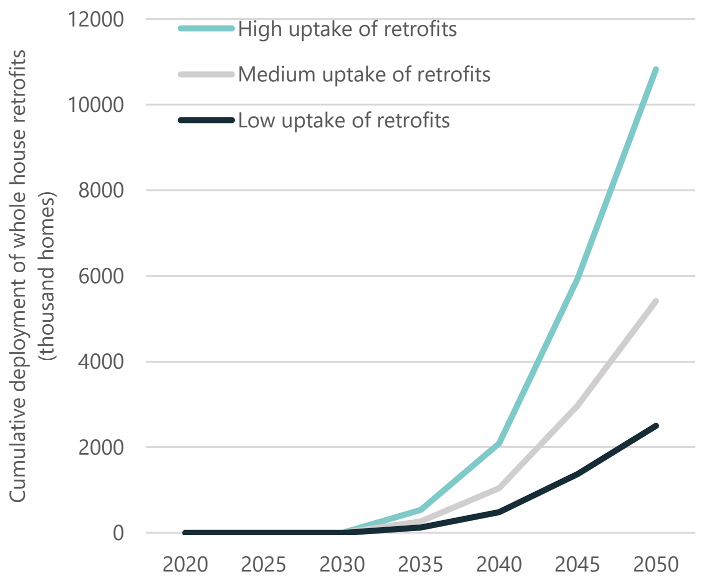
£15-25k

Key barriers to retrofit adoption (insights from ESC's Smart Systems and Heat (SSH) programme)



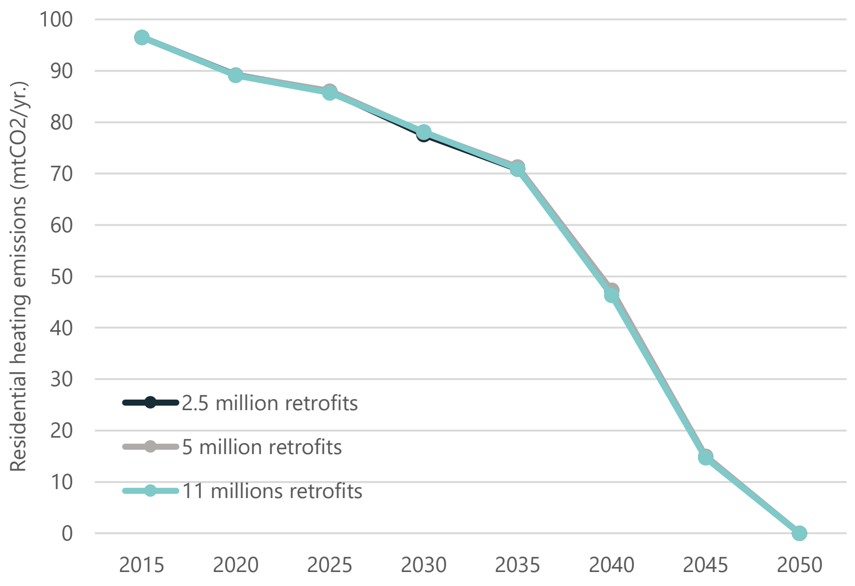
Adopt building fabric changes

Heat behaviour	High	Medium	Low
Occupants install whole-house retrofits	Engagement from homeowners consistent with that needed in the Reference Case energy system 10.8 million homes installing whole house retrofit packages by 2050	Installation rates are half those in the high behaviour change scenario with 5 million homes installing whole house retrofit packages by 2050. In 2017/18 an estimated 170,000 homes were renovated with significant energy efficiency improvements [22]	Installation rates of whole house retrofit packages is almost a quarter of those in the high behaviour change scenario with 2.5 million homes retrofitted by 2050. This is approximately 83,000 homes retrofitted each year from 2020.



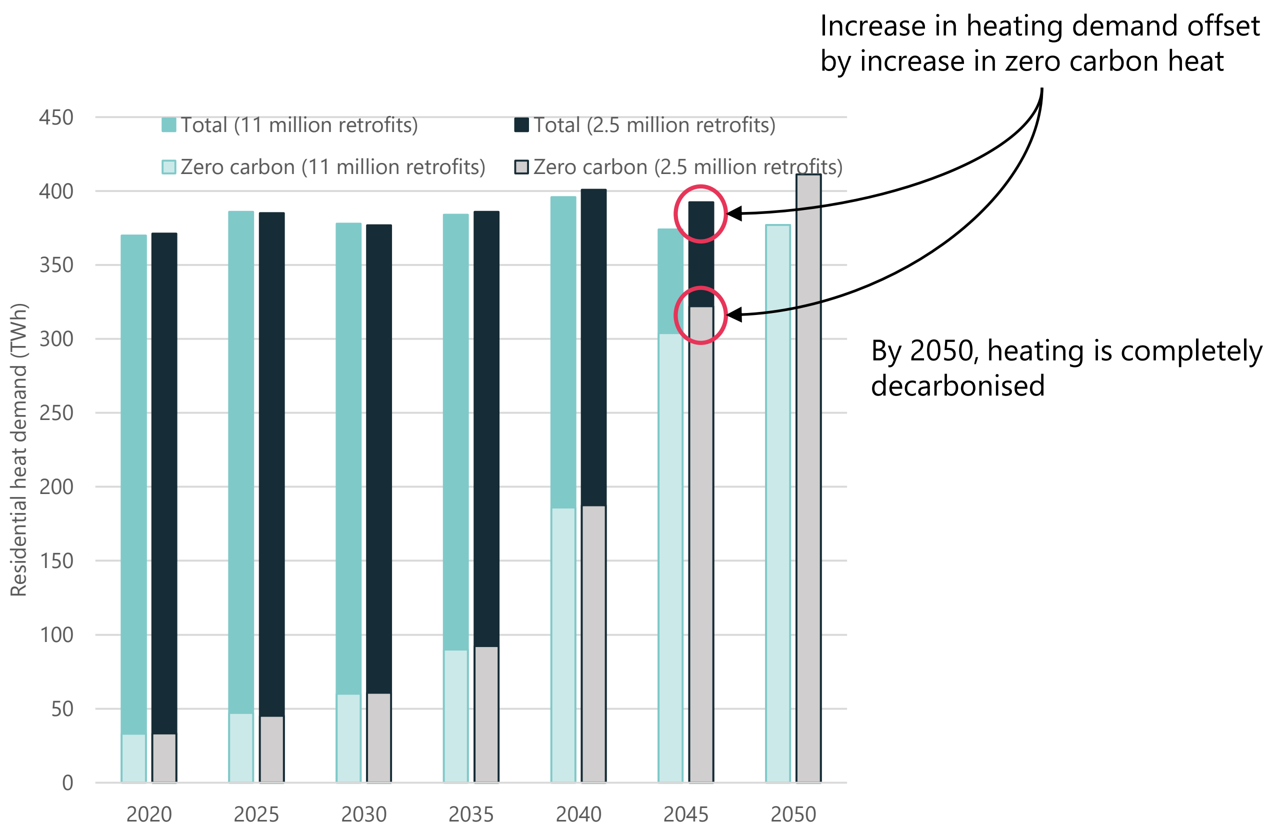
These are behavioural outcomes modelled in ESME associated with different levels of engagement homeowners have with installing whole house retrofit measures. Adopting these retrofit measures is the behaviour being tested.

Adopt building fabric changes: emissions

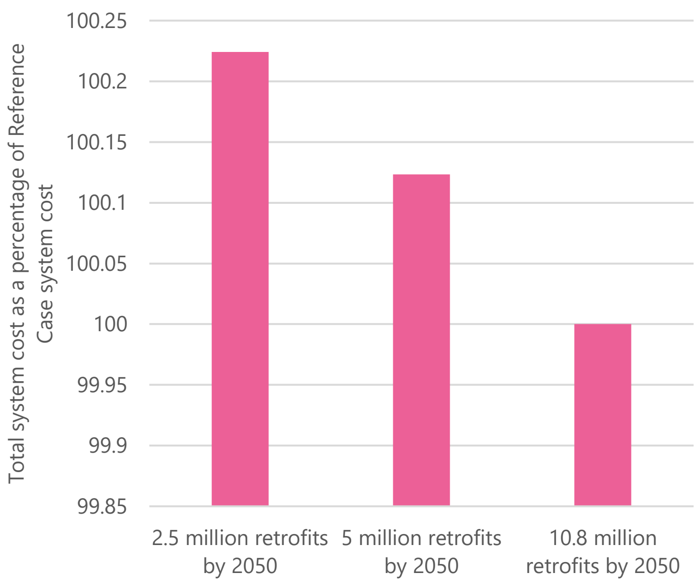


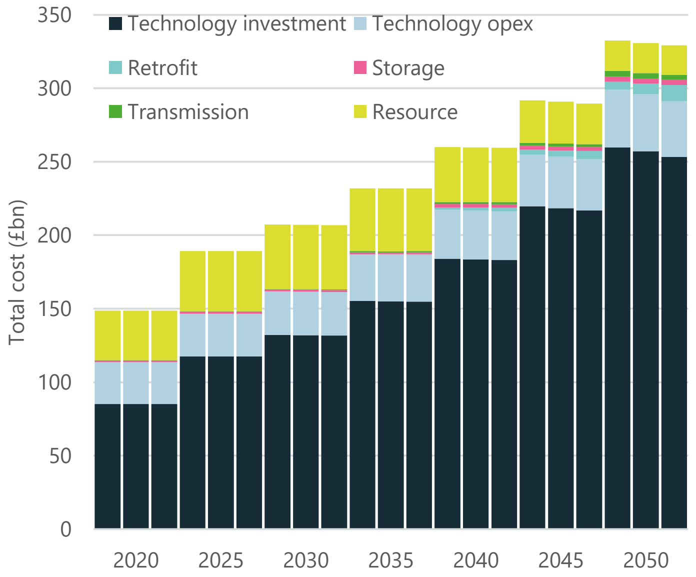
Negligible change in the emissions from residential heating between scenarios. Even though decreasing the number of retrofits does increase the heating demand, the effect of this is not noticeable until around 2040 because the number of retrofitted homes is quite small in all scenarios up until then. By this time, the low adoption scenario has 1.5 million fewer retrofitted homes out of a total stock of 32 million. Therefore the effect is quite small, leading to a 1mt increase in CO_2 in 2040 relative to the high adoption scenario.

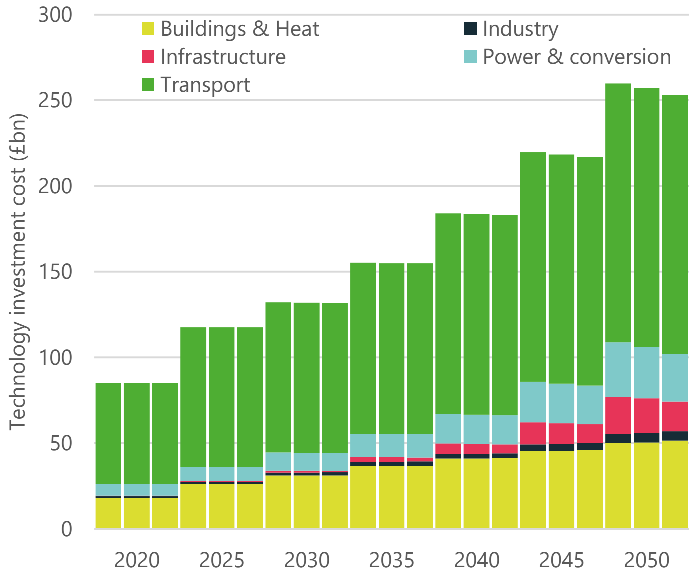
Post-2040, increases in heat demand as a result of fewer retrofits are offset by an increase in the capacity of zero carbon heating technologies (see right).



Adopt building fabric changes: system costs







Clustered chart shows 3 stacks per time period. From L-R: 2.5 million retrofits, 5 million retrofits, 10.8 million retrofits

A reduction in the number of retrofits installed leads to an increase in total system cost. The lowest adoption of retrofits scenario sees in an increase in the discounted total system cost of 0.23%. This cost is largely due to higher technology costs which outweigh any capex savings related to installing building retrofits. These costs are associated with the additional electricity and hydrogen needed to support higher heat demand (as a result of lower retrofit numbers) as well as the roll out of more DHNs.

There is a cost saving in buildings & heat sector because less is spent on retrofit packages.

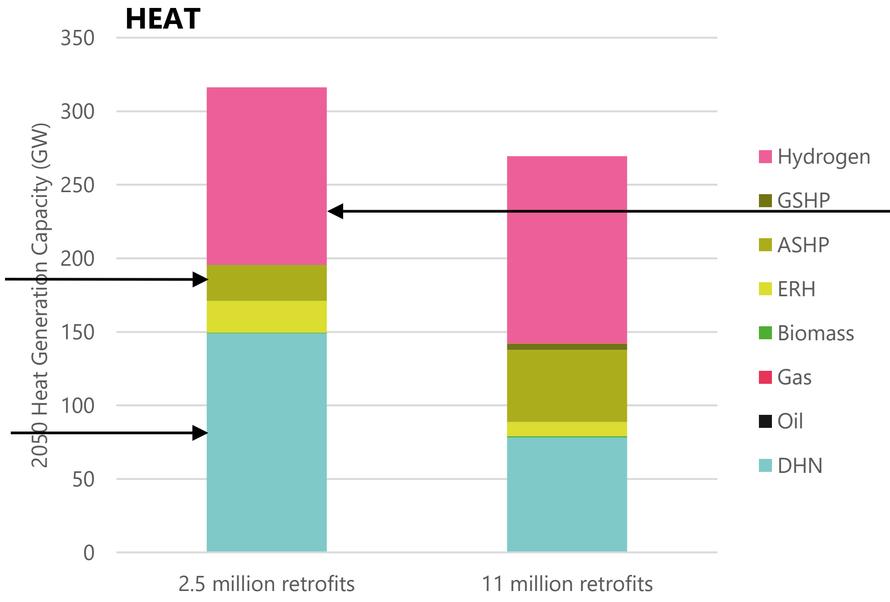
However, this is outweighed by increases in infrastructure and power & conversion costs:

- Hydrogen production and transmission
- Electricity production and transmission
- DHN infrastructure and network hot water production

Adopt building fabric changes: system design

Fewer retrofits means fewer homes suitable for heat pumps.

More homes connected to DHNs

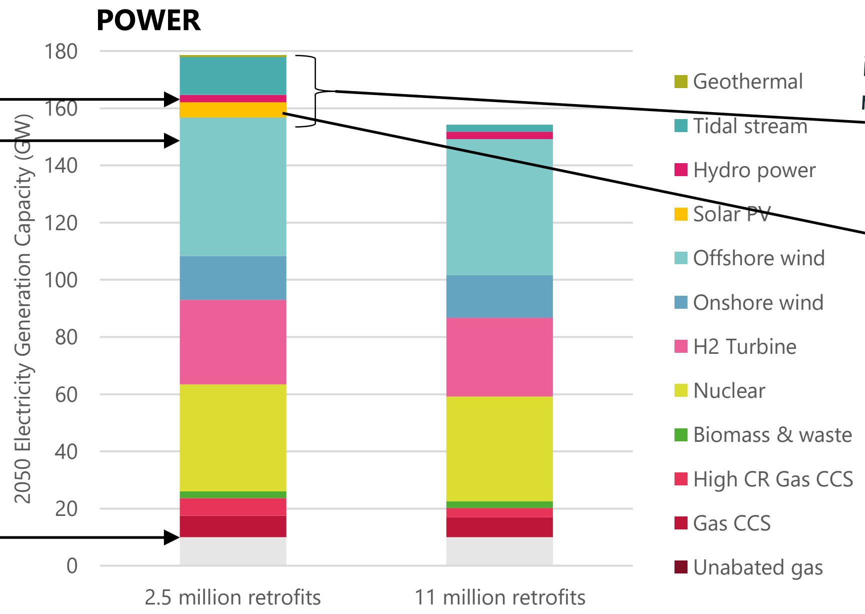


Capacity of H_2 boilers decreases by 7GW but supplies more heat (17.5% vs. 12%). Therefore more hydrogen produced by steam methane reformation with high capture rate CCS (189TWh vs. 161TWh)

Tidal stream

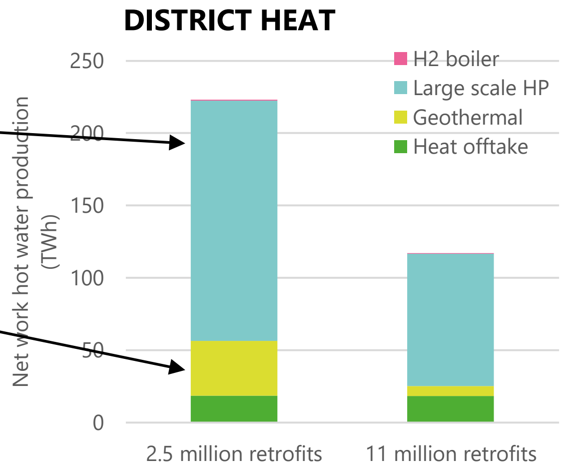
Geothermal

High capture rate CCGT with CCS



Increased generating capacity to support increase in large scale HPs for DHN and electric resistive heating

Geothermal capacity to supply additional electricity and heat to DHNs



Retrofit sensitivity to hurdle rate

Behaviour being modelled
Homeowners/landlords install building retrofit measures to improve the thermal performance of their dwellings and reduce heat demand. This could be motivated by improved comfort/well-being, reduced energy bills, and/or concerns about the environment.

This behaviour run builds upon the previous retrofit adoption behaviour. In the previous run, up to 10.8 million homes were retrofitted by 2050 in the high behaviour change case (Reference Case). To reflect a greater perception of the benefits of home retrofits by society, the discount rate associated with whole house retrofits has been reduce to 0% (from 8% in the Reference Case).

Behavioural outcome
As before, the behavioural outcome associated with retrofit adoption is a reduction in heat demand.

Installing building fabric improvements reduces the amount of active heating needed to achieve a desired set point temperature (SPT) because less heat is lost through the fabric of the building and internal gains can contribute more to the warmth of the dwelling. Internal gains refer to heat produced within the dwelling by such things as occupants (people and animals) and appliances.

Reducing heat losses through the building fabric increases the thermal time constant (i.e. the time it takes for the building to cool down). This could enable occupants to shorten the duration of active heating (and prolong the time between heating periods). Improving thermal performance can also promote other heating behaviours such as reducing the flow temperature to radiators – this is useful when installing heat pumps which work more efficiently with low flow temperatures.

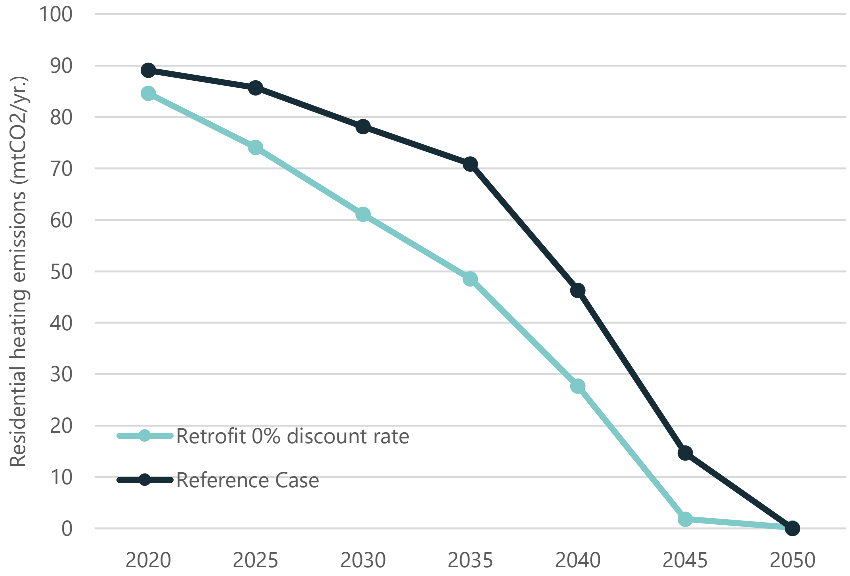
Discount rate in ESME
An investment discount rate of 8% (real) is assumed for the cost of capital for all technologies. This rate is used when annualising capital costs over the lifetime of a technology and when calculating the cost of interest during construction.

A social discount rate of 3.5% is used for all net present value (NPV) calculations in ESME, including the calculation of total energy system cost 2010-50.

What affects building retrofit adoption?
There are a vast number of factors that need to be considered when making decisions about retrofitting both from the consumer's and supplier's perspective. These are related to costs, benefits, practical, considerations, risks and preferences.

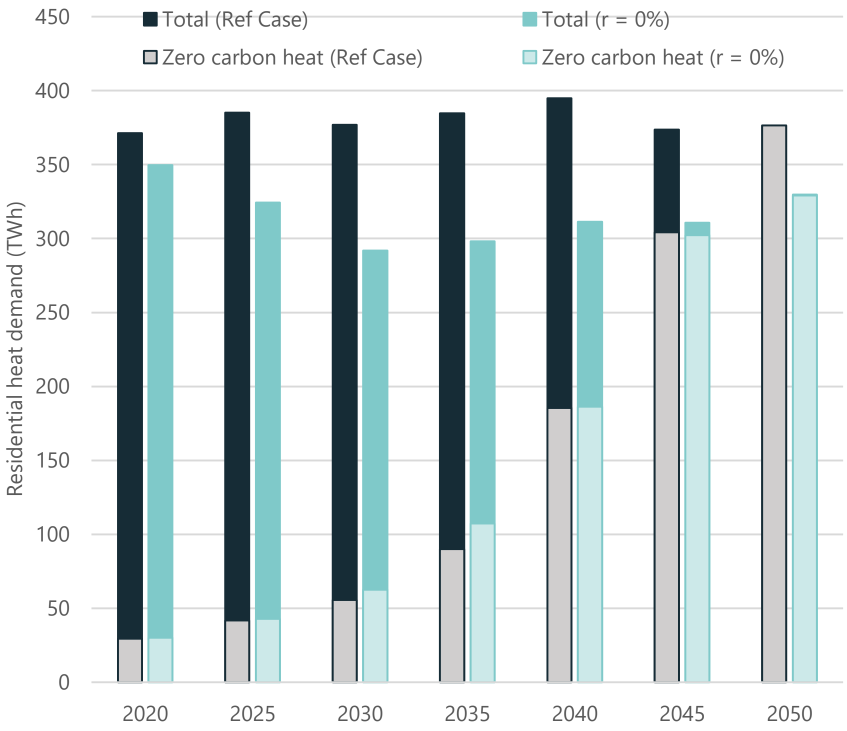
There are several drivers that encourage consumers to adopt retrofit packages including comfort, health/well-being and savings on energy bills. However there are a number of barriers that make things difficult. Again, these barriers apply to both the consumer and the supplier.

Retrofit hurdle rate 0%: emissions



Noticeable reduction in the emissions from residential heating between scenarios – peak savings made in 2035 (22.5mtCO_2/yr.).

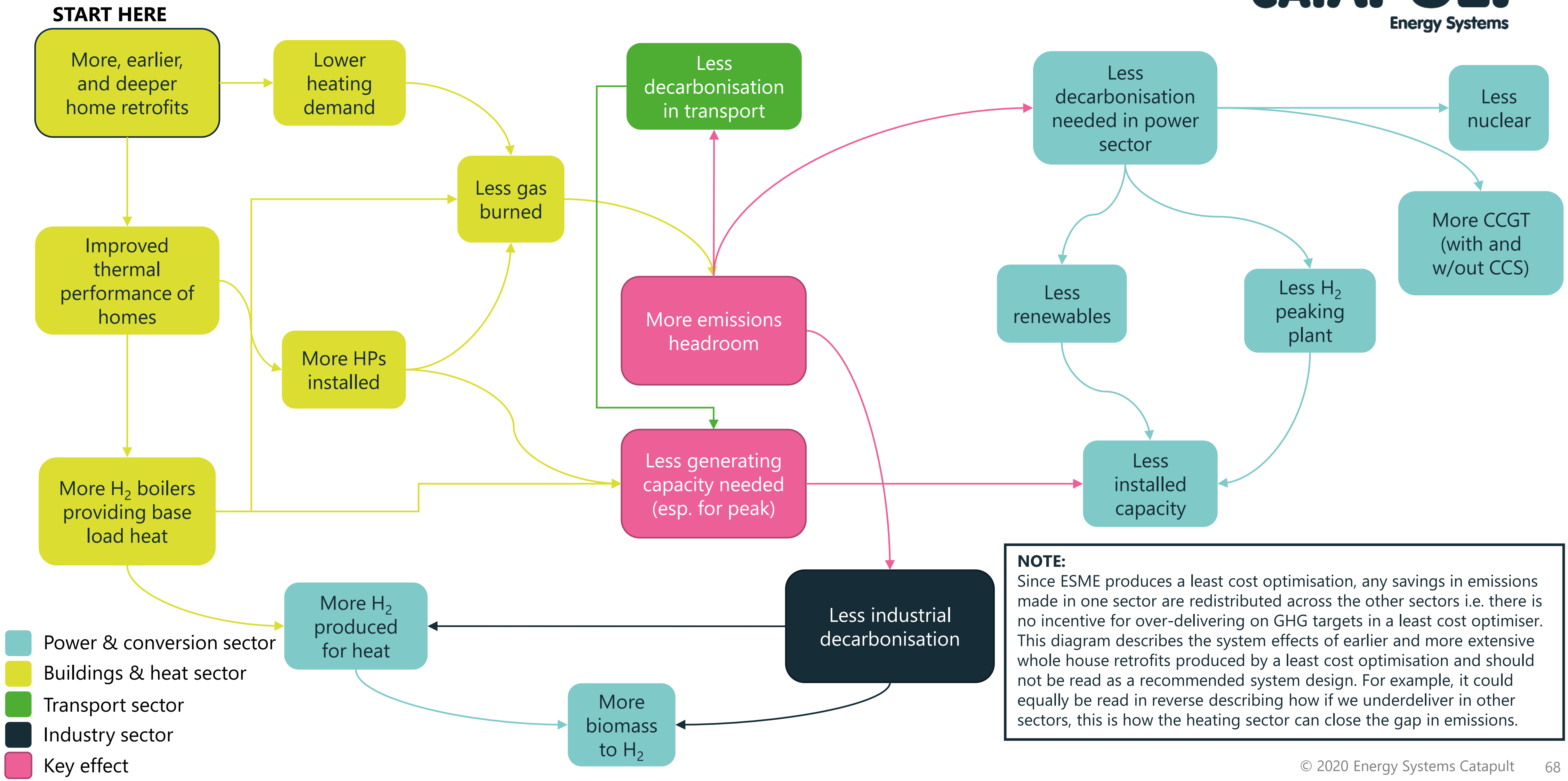
Emissions savings from the heating sector is a result of reduction is the demand for heat in the early-to-mid time periods. With a 0% hurdle rate, ESME brings forward the deployment of whole house retrofit. This means that the reduction in heating demand is being applied during time periods reliant on higher carbon forms of heating. Furthermore, the more favourable financial circumstance makes the more extensive Retroplus measure the preferred choice. This provides better improvements in thermal performance compared to the Retrofix option installed in the Reference Case.



Residential heat demand: A reduction in demand is evident from 2020. This continues to fall until 2025 then begins to plateau as improved thermal efficiency is balanced against more houses and increasing SPT.

The amount of heat delivered by zero carbon means is similar in both scenarios on a TWh basis. However, this is a higher proportion of total demand in the 0% hurdle rate on retrofits run.

Retrofit hurdle rate 0%: system design effects



NOTE:
Since ESME produces a least cost optimisation, any savings in emissions made in one sector are redistributed across the other sectors i.e. there is no incentive for over-delivering on GHG targets in a least cost optimiser. This diagram describes the system effects of earlier and more extensive whole house retrofits produced by a least cost optimisation and should not be read as a recommended system design. For example, it could equally be read in reverse describing how if we underdeliver in other sectors, this is how the heating sector can close the gap in emissions.

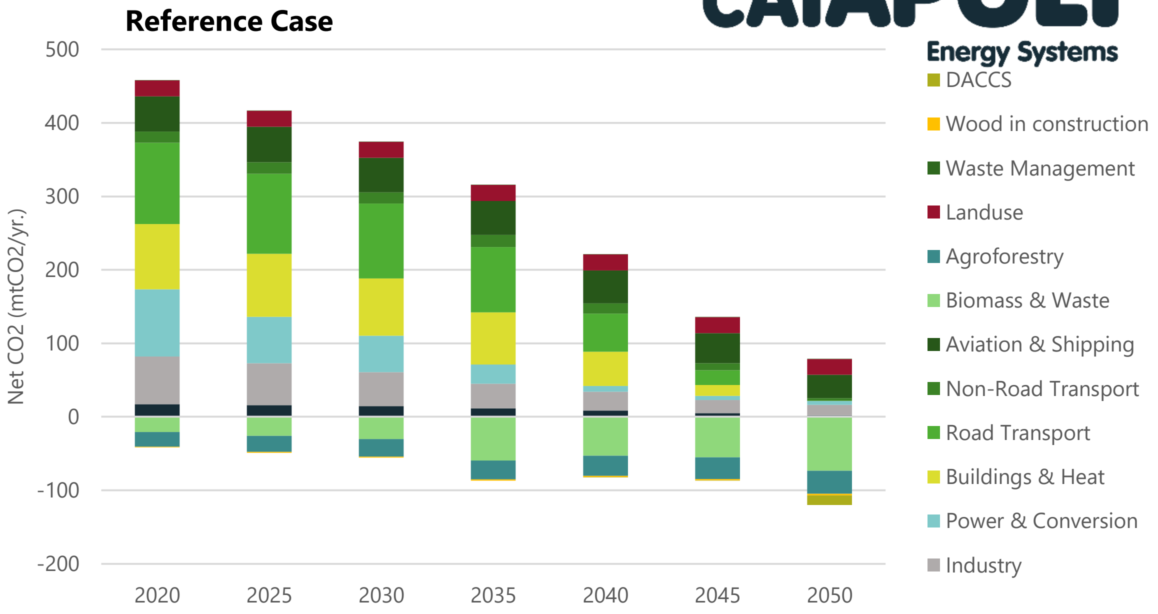
Retrofit hurdle rate 0%: whole system emissions

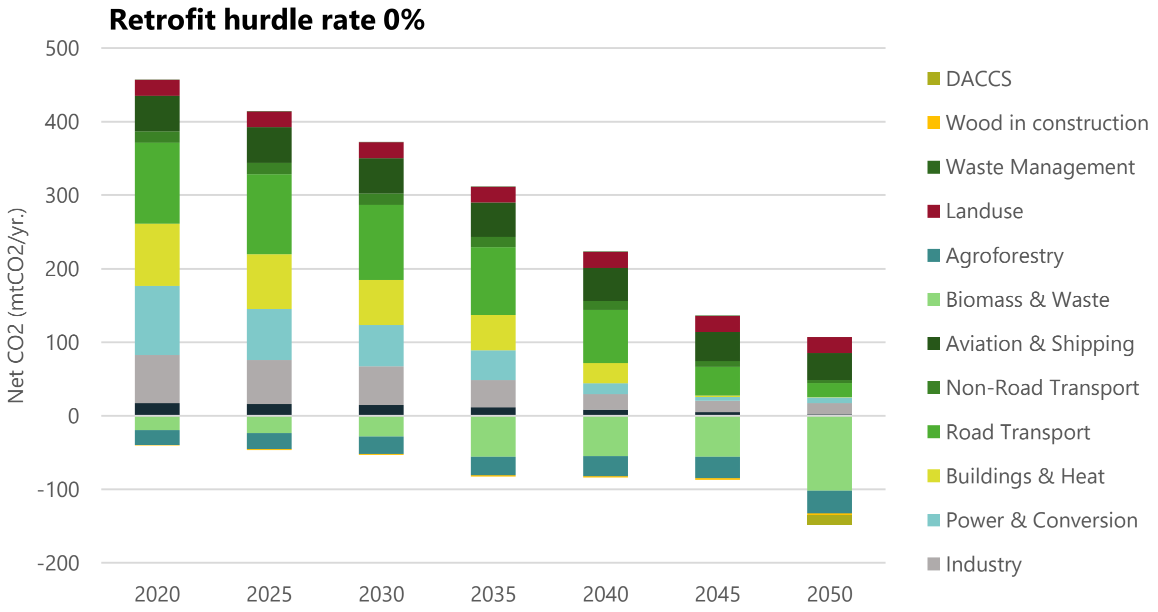
From 2025-2045 there is 10-20mtCO_2/yr. emissions headroom created by the installation of whole house retrofits. This headroom is consumed by the industry and power sectors up to 2040. From 2040 onwards, transport makes use of emissions savings in the heating sector.

In the near term (up to 2030), the power sector increases output from unabated CCGT plants and delays deployment of new generation III nuclear plant by 5 years (first appearance being 3GW installed in 2030).

Over the whole pathway, there is less reliance on nuclear and renewables as a result of the emissions headroom created by reduced heating demand. Overall there is also a reduction in the generating capacity installed as a direct result of lower heating demands.

In 2050, there is an increase the amount of biomass consumed, which delivers negative emissions (which the transport sector uses to reduce decarbonisation effort). The extra biomass is used in a gasification with CCS process to produce the additional hydrogen required to support an increased number of hydrogen boilers. These hydrogen boilers are also able to support more of the base load heat production (i.e. not just used in the peak period) as a result of a lower heating demand making this cost-effective.



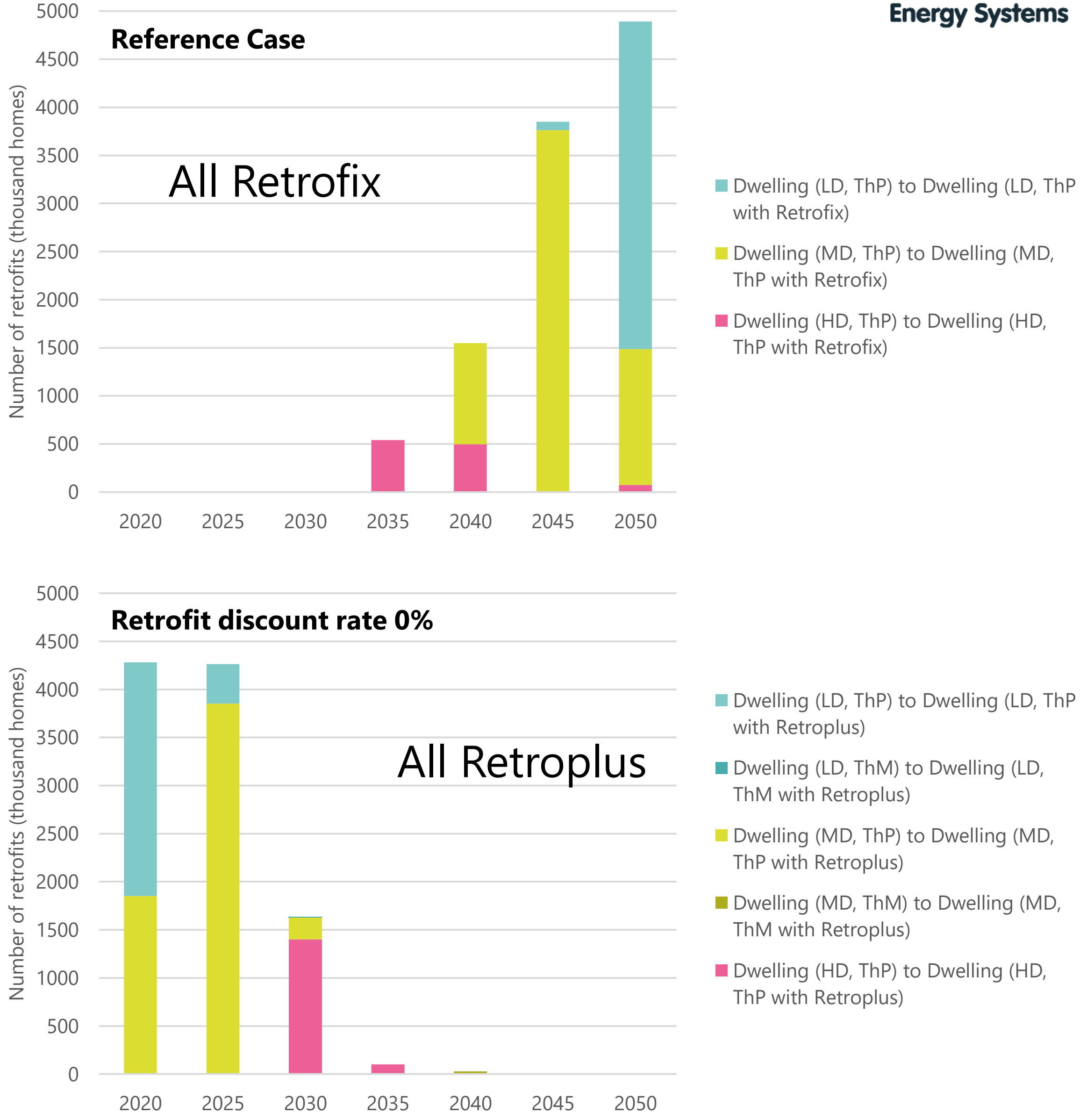


Retrofit hurdle rate 0%: retrofit deployment

In ESME, there are two whole house retrofit packages available: Retrofix and Retroplus. Whilst both are whole house packages, Retroplus is more extensive including floor insulation and triple glazed windows and comes at a higher cost.

In the Reference Case, where the discount rate on retrofits is 8%, retrofitting of homes does not begin until 2035. This is because ESME has perfect foresight of costs and therefore chooses to delay installation of such measures in order to take advantage of cost reductions assumed to occur with time. The net present value of later spending is also lower due to the social discount rate (assumed to be 3.5%) – this prompts spending in the later time periods if possible. All of the retrofit measures installed are of the less expensive, Retrofix type and applied only to thermally poor homes. By 2050, there are a total of 10.8 million homes retrofitted

Reducing the discount rate to 0% (to reflect higher engagement from home owners), leads to much earlier deployment – the aforementioned effect of the social discount rate (on encouraging later spending) still applies in this run but the system benefits of early deployment outweigh the higher costs. Retrofitting of homes in this scenario is well underway by 2020 and peters out by 2040. All of the retrofit packages installed are of the more extensive Retroplus type. By 2040, there are 11.8 million homes retrofitted.

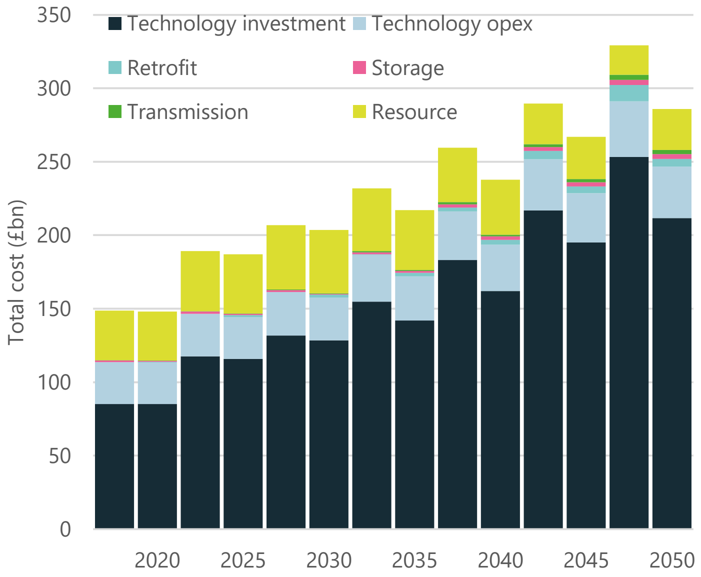


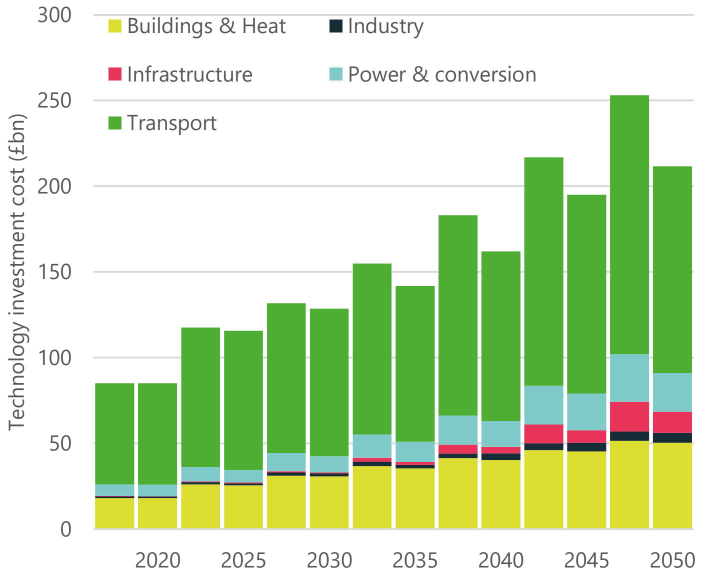
Retrofit hurdle rate 0%: system costs

Reducing the discount rate on retrofits to 0% saves 4.4% on the discounted total system cost for the full pathway.

Savings are made in technology investment costs as a result of less generating capacity being needed and less effort to decarbonise power, industry and transport sectors (less capex intensive, but more polluting technologies are installed in these sectors as a result of emissions headroom created by extensive retrofit installation).

It should be noted that all of the cost saving is a result of the low discount rate. The system design created here is non-optimal if the 8% discount rate is re-applied. Lower discount rates effectively make retrofits less expensive so they are deployed early on in ESME because it provides a very cheap way to decarbonise buildings. If the cost is increased deployment is delayed to take advantage of future cost reductions (which in the model are dependent on time not cumulative deployment).





Clustered chart shows 2 stacks per time period. From L-R: Reference Case, Retrofit discount rate 0%

Install a heat pump

Behaviour being modelled
Homeowners/landlords choose to install heat pumps (HP) to provide space heat and hot water.

Three levels of behaviour were modelled reflecting three levels of willingness/ability of actors to install heat pumps. The highest level of behaviour, which results in the highest number of heat pumps is the ESME Reference Case. This is a least-cost optimum, in which 60% of residential heat is supplied by HPs by 2050. The two remaining levels model delayed uptake and slower installation rates. However, the 2050 end point (i.e. approx. 60% heat supplied by HPs) is maintained.

In ESME, there are limits on the number of heat pumps that can be installed: HPs cannot be installed in thermally poor homes. To install in a thermally poor home, it must first be retrofitted to reduce the heat losses. In addition, ground source heat pumps (GSHP) can only be installed in houses deemed large enough to fulfil the space requirements.

Behavioural outcome
Installing a HP leads to a reduction in the use of natural gas for heating.

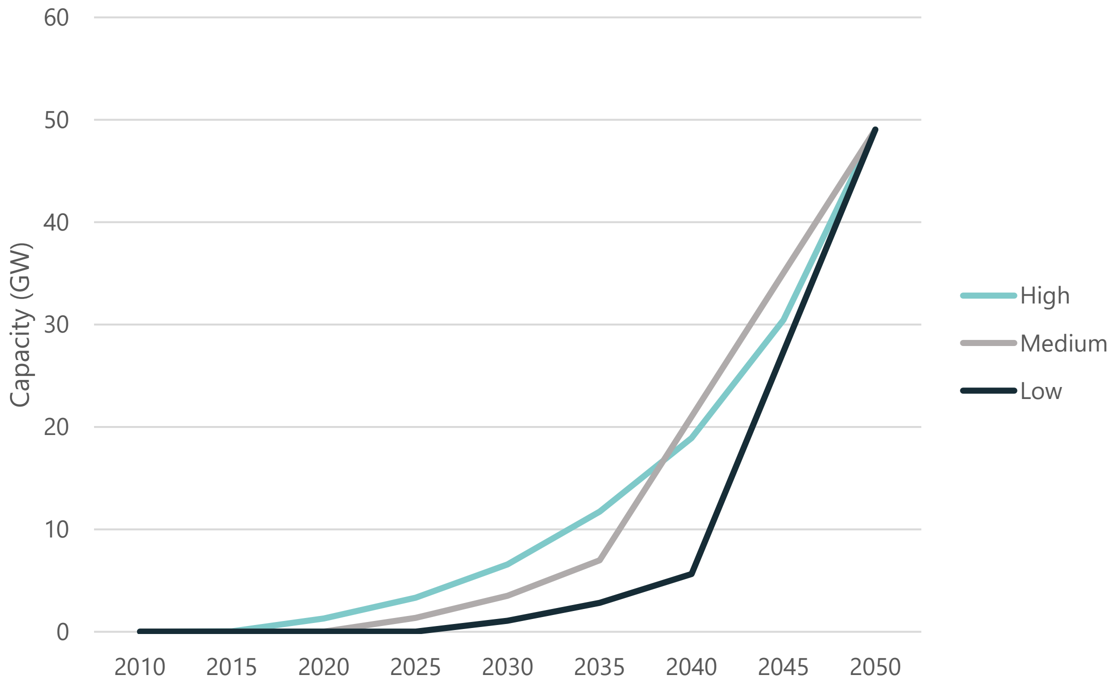
In some homes, a HP may be able to provide all of the space heat demands, with certain designs also able to provide hot water. In other homes, the retention of a back-up system, typically a gas boiler, is useful in supporting the HP during cold snaps and for provision of hot water – these are called hybrid systems. In both cases, the use of gas for heating decreases.

The advantages of hybrid systems are that HPs can be modestly sized because they are less relied up on to meet peak heat demands. This puts less strain on the electricity network in terms of supplying enough capacity and reinforcing the grid. Hybrids can also be controlled in such a way that maximises the efficiency of the HP, which decreases when the temperature difference between the sink and the source increases; for example, on cold days or supplying high temperatures such as is needed for hot water.

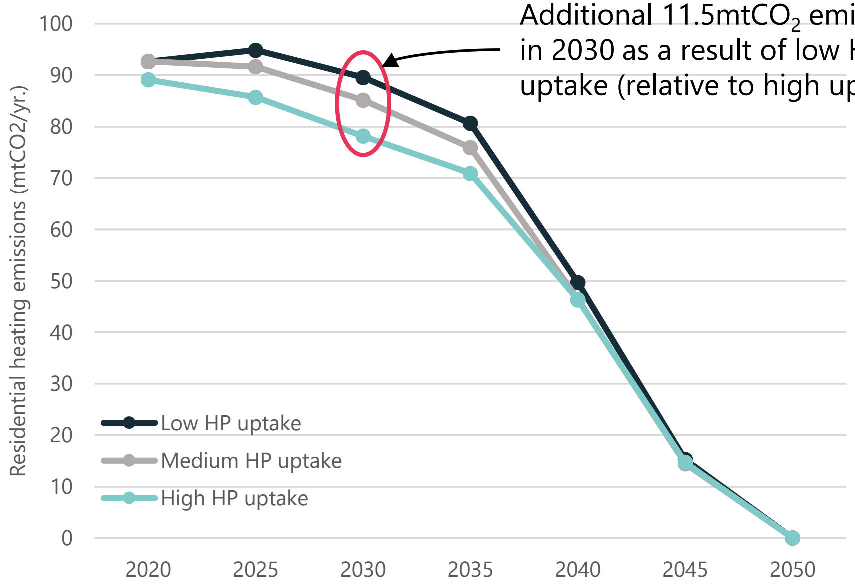
What affects HP uptake?
There are a number of technical and consumer related challenges facing the uptake of HPs. HP performance is maximised when the difference between the sink and source is minimised. This means low flow temperatures are advantageous. Low flow temperatures can be achieved by increasing the size of the radiator/installing underfloor heating and by reducing the heat losses of the home. These are additional costs/hassle to the consumer. Consumers tend to replace their heating system when it is too late (i.e. when the current system fails). Consequently, less time is spent on exploring the alternatives and inevitably a new gas boiler is installed. Some consumers prefer the feeling of high radiant heat (e.g. from a fireplace) as opposed to ambient heat supplied by some HP systems. HPs may appear expensive to run compared to gas boilers because of the current price of electricity vs. gas.

Install ASHP (away from boiler): indicative aggregate capacity

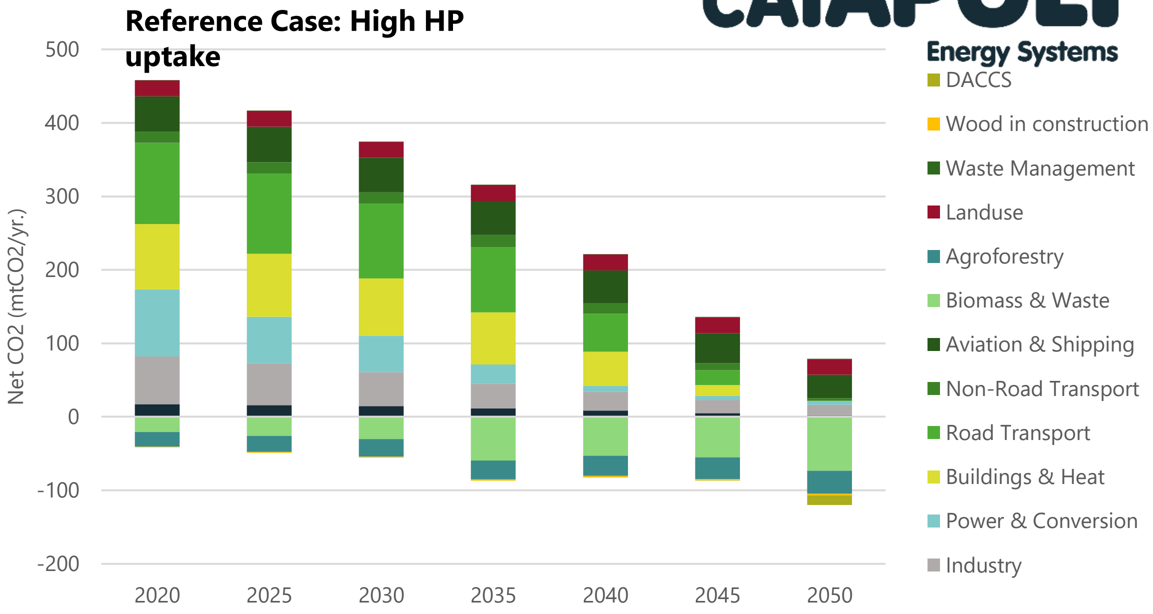
Heat behaviour	High	Medium	Low
Occupants install heat pumps	Deployment of HPs in domestic homes is in line with ESME Reference Case. Maximum deployment by 2050 is constrained by suitability of homes (thermal performance and space requirements). By 2050, heating is completely decarbonised with 60% of residential heat demand supplied by heat pumps (56% ASHP, 4% GSHP)	People install HPs but at a slower rate and delayed by 5 years Maximum deployment by 2050 is constrained by suitability of homes (thermal performance and space requirements). By 2050, heating is completely decarbonised with 60% of residential heat demand supplied by heat pumps (56% ASHP, 4% GSHP)	People are more resistant to installing HPs reflected by a slower deployment rate and 10 year delay Maximum deployment by 2050 is constrained by suitability of homes (thermal performance and space requirements). By 2050, heating is completely decarbonised with 60% of residential heat demand supplied by heat pumps (56% ASHP, 4% GSHP)

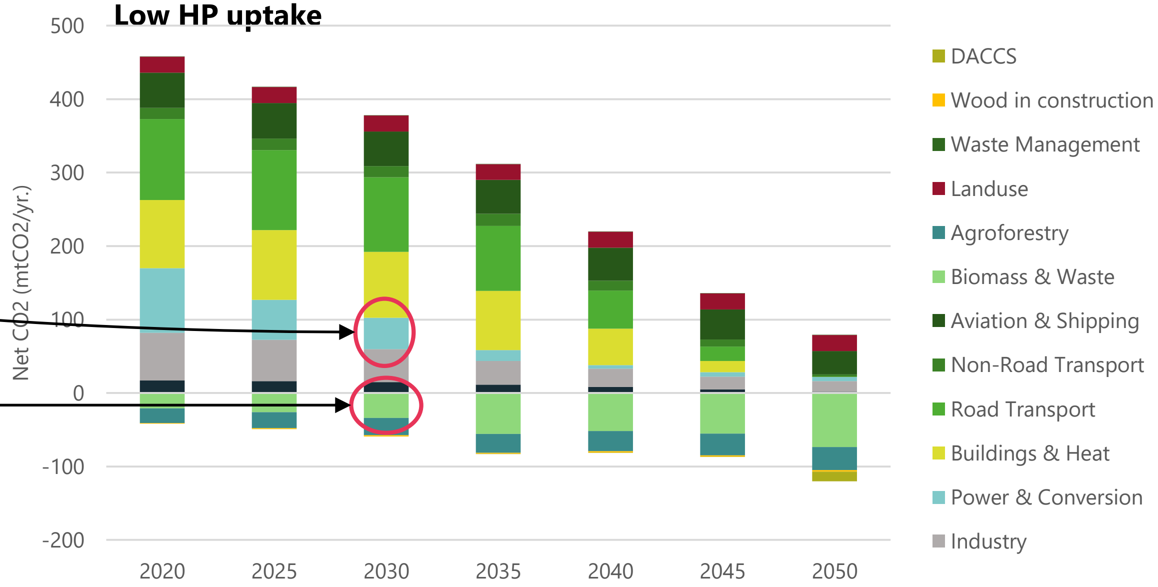


Install a heat pump: emissions



Additional 11.5mtCO_2 emitted in 2030 as a result of low HP uptake (relative to high uptake)

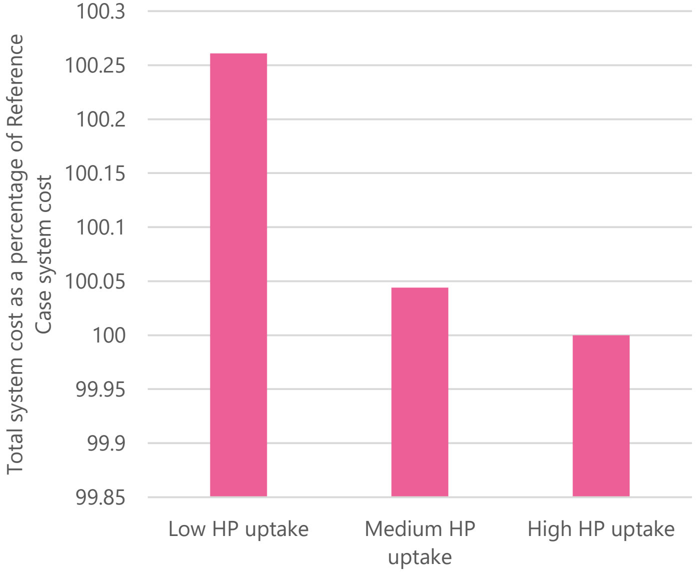


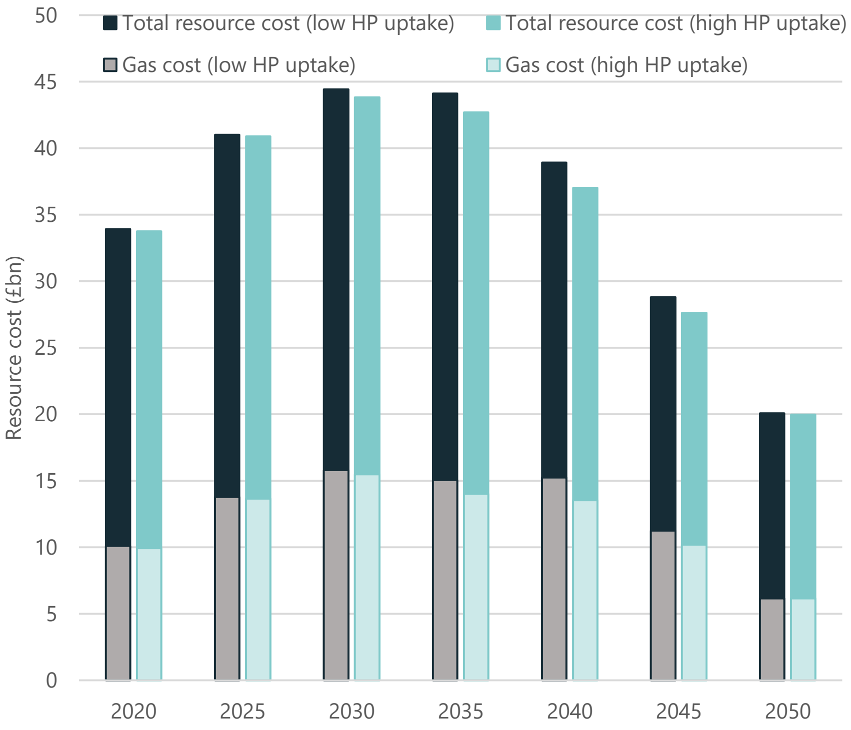


Emissions savings from power sector with a reduction in unabated gas capacity and output. There is no replacement of this capacity with zero carbon generators because electricity demands are lower as a result of continued gas boiler use in heating.

More emissions headroom delivered by an increase in biomass gasification with CCS to produce hydrogen. This additional hydrogen is used in industry and road freight providing further emissions savings in these sectors

Install a heat pump: system costs





Low uptake of HPs leads to an increase in total system cost. The lowest uptake of HPs scenario sees in an increase in the discounted total system cost of 0.28%.

This cost increase appears mid-pathway from 2030-45 as a result of increased gas consumption.

Connect to a district heat network

Behaviour being modelled
Homeowners/landlords choose to connect to a district heat network (DHN) to provide space heat and hot water.

Three levels of behaviour were modelled reflecting three levels of willingness/ability of actors to connect to DHNs. The highest level of behaviour, which results in the highest number of homes connected to DHNs is the ESME Reference Case. This is a least-cost optimum, in which 6.7 million homes are supplied by DHNs by 2050. The two remaining levels model delayed uptake and slower installation rates. However, the 2050 end point (i.e. 6.7 million homes connected to DHNs) is maintained.

In ESME, DHNs can supply space heat and hot water to homes of any thermal performance which is an advantage over HPs which are typically installed in buildings that are adequately efficient. In ESME, DHN costs and losses are a function of heat demand density and road density. Each MLSOA is grouped into one of three cost tranches, or, if the costs are very high, not included in any tranche. This places limits on the number of homes in each region that can connect to a DHN.

Behavioural outcome
Connecting to a DHN leads to a reduction in the use of natural gas for heating.

DHN provide zero carbon heat at point of use and can be fed by heat offtake from thermal generating plant such as CCGTs. As the energy system decarbonises the heat supplied by thermal plants decreases because these plants are used to respond to the short duration peak electricity demands. It is possible to recover heat from other generators such as small modular reactors. However in this analysis these plants have been prevented from supplying district heat due to the uncertainty around public acceptability of being in close proximity to these plants (necessary to supply DHNs). Remaining sources of network hot water include geothermal and large scale HPs, supported by large boilers burning gas or hydrogen to support peak periods.

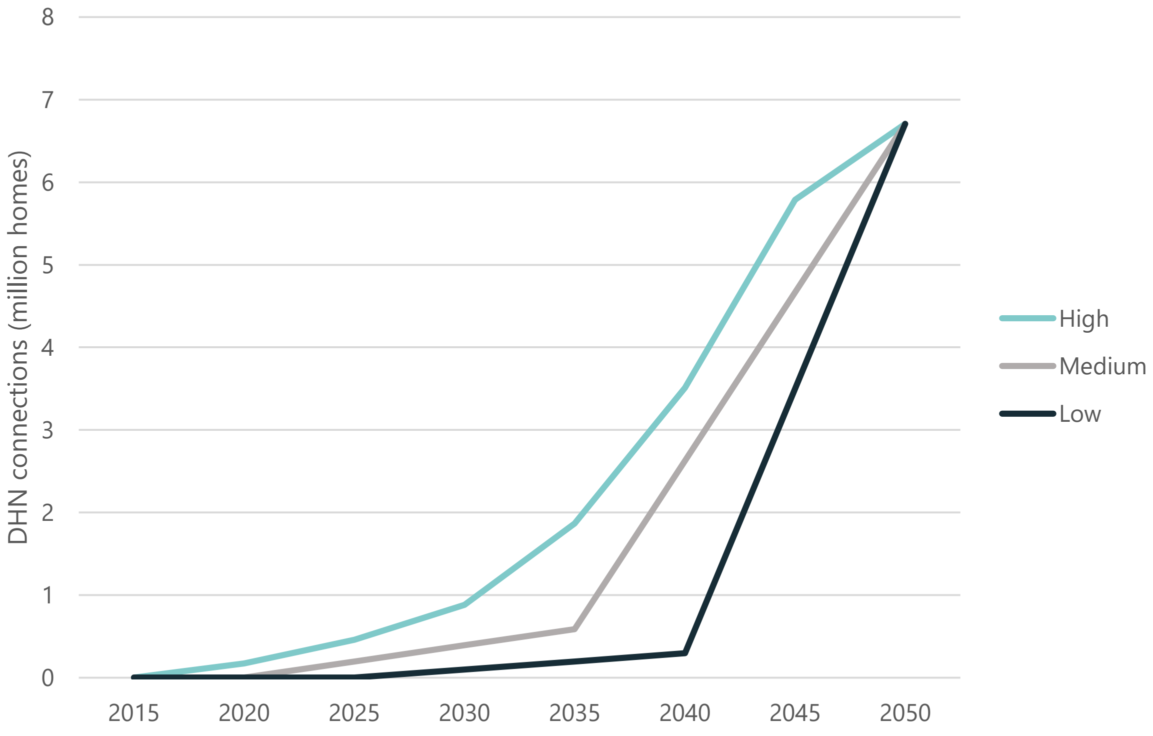
What affects DHN uptake?
There are around 2000 DHNs in the UK but these supply just 2% of UK heat demand. There are a whole range of technical and policy related issues which would need to be solved. These are difficult to address without industry and consumer demand for district heat.

Heat networks will provide most value to the energy system when they are large, connected and within existing urban areas. Low temperature heat networks within new developments with high thermal performance housing may be cost effective, but these are buildings that can be supplied by other means easily and cheaply.

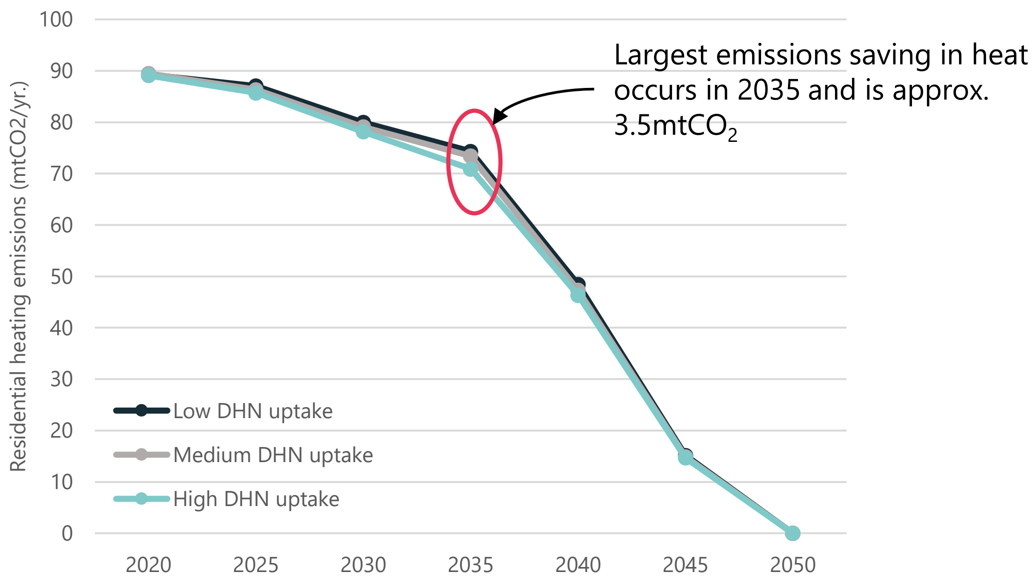
There is some work looking into heat sources for DHNs, including large marine source heat pump integration in Queens Quay [23] and a variety of collaborations across England Scotland and Wales into the utilisation of mine water.

Connect to DHN (away from boiler): indicative aggregate capacity

Heat behaviour	High	Medium	Low
Occupants connect to district heat networks	Number of homes connected to DHNs is in line with ESME Reference Case. By 2050, almost 7 million homes are connected to DHN meeting 21% of heat demand	People connect to DHNs but at a slower rate and delayed by 5 years By 2050, almost 7 million homes are connected to DHN meeting 21% of heat demand	People are more resistant to connecting to DHNs reflected by a slower deployment rate and 10 year delay By 2050, almost 7 million homes are connected to DHN meeting 21% of heat demand



Connect to a DHN: emissions

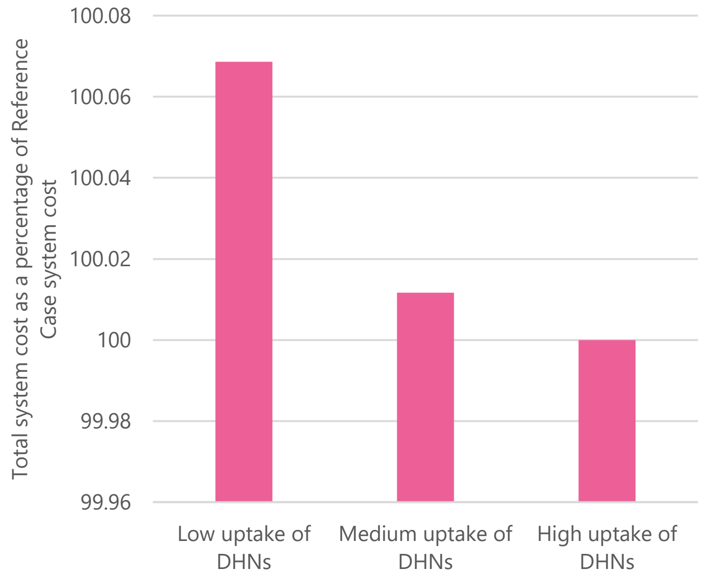


In the low uptake scenario, 3.5mtCO_2 more emissions are emitted in the heating sector in 2035 as a result of delayed DHN uptake. Gas boilers are used to supply heat at this time.

In 2040, the low uptake scenario sees an increase in the amount of heat supplied by H_2 boilers. H_2 boilers are likely to be a more suitable heating technology for thermally poor homes that are not suitable for HPs (in ESME). There is also an increase in GSHP capacity.

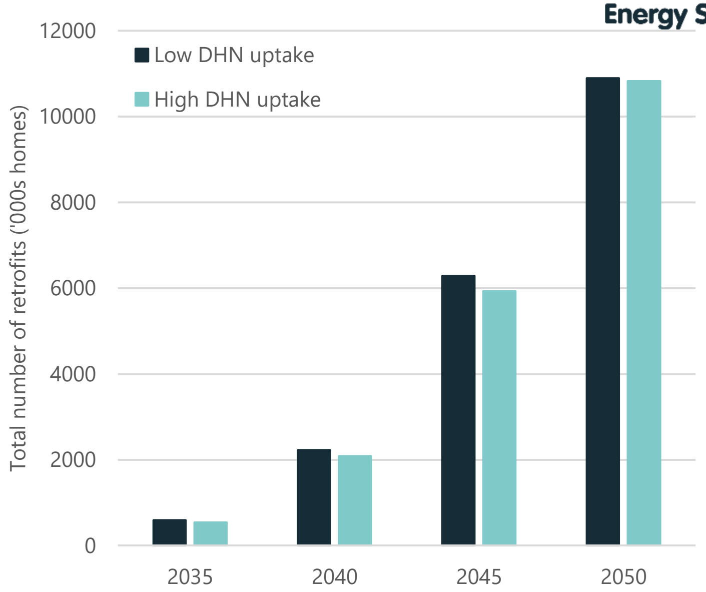
By 2050, the number of homes connected to DHNs is the same in all scenarios.

Connect to a DHN: system costs

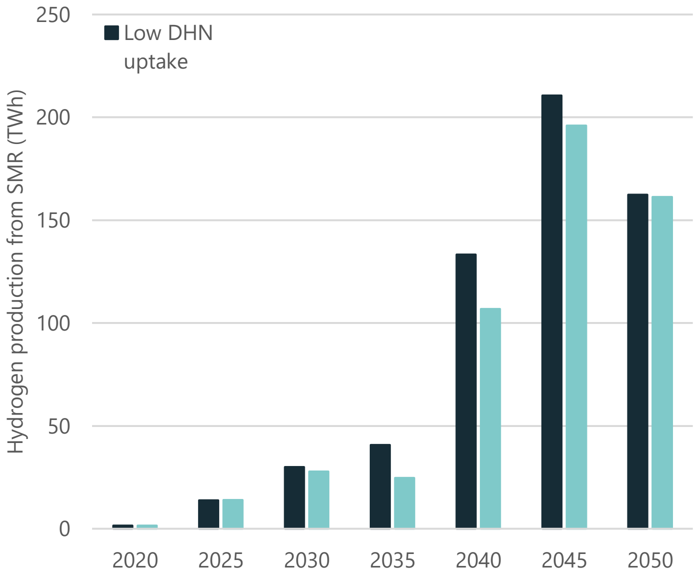


A reduction in the number of homes connected to DHNs leads to an increase in total system cost. The lowest uptake of DHNs scenario sees in an increase in the discounted total system cost of 0.09%.

Cost increase as a result of an increase in the number of homes that are retrofitted. This includes 53,000 homes adopting the highest level of retrofit package (Retroplus). This is to make more homes suitable for HPs (GSHPs) that would otherwise have connected to DHNs.



Additional costs associated with production of hydrogen from SMR with high capture rate CCS to supply increased demand from hydrogen boilers.



Heat behaviour: intangibles

Heat-related intangible costs: themes

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Value of time

- Time-related factors
  - Research time
  - Coordination time
  - Setup time

(Direct) Financial impacts

- Costs
  - (Unmodelled) infrastructure costs
  - Insurance
  - Supporting equipment costs
  - Taxes
  - Operating costs
  - Availability costs
  - Impact on value of home

Inconvenience / distress

- Insecurity
  - Accidents and emergencies
  - Energy vector availability
  - Thermal comfort anxiety
  - Heating reliability
- Discomfort
  - Thermal comfort
  - Convenience
  - Aesthetic impact
  - Loss of space (indoors)
  - Loss of space (outdoors)
  - Loss of preferred experience

Other impacts of adjusting heat behaviours

- Negative impacts
  - Health impacts
- Positive impacts
  - Neighbour effects
  - Health impacts

(adapted from [8])

Behaviour as proxy for others: Reduce thermostat setpoint

- 'Reduce thermostat setpoint' is investigated in the model as a proxy for behaviours which result in the reduction in overall heat demand. The other behaviours prioritised in WP1 which this relates to are:
    - Reduce number of rooms heated
    - Heat for fewer hours of the day

  Which are in some way facilitated by:
    - Install smart zonal heating controls
    - Install thermostatic radiator valves (TRVs)

- The relative impact of each of these in delivering a reduction in overall heating demand is outside the scope of this study. However, work carried in ESC's Home Energy Dynamics (HED) model suggests that there will be significant heterogeneity amongst homes [24].

- Further work is required to investigate the most appropriate approach to delivering an overall heat demand reduction, including the relative impact of each behaviour and their interaction.

Intangible costs relevant to behaviours

Reduce thermostat setpoint

- Control system interaction time

- Loss of preferred experience
- Reduced thermal comfort

Install retrofit measures

- Research time
- Coordination time

- Impact on value of home

- Loss of internal floor area (internal wall insulation)
- Loss of preferred architectural aesthetic (external wall insulation)
- Installation disruption

- Increased thermal comfort

Intangible costs relevant to behaviours

Install ASHP

- Research time
- Coordination time

- Impact on value of home
- Loss of external space
- Loss of internal space (hot water storage)
- Loss of preferred experience

- Installation disruption

Connect to DHN

- Research time
- Coordination time

- Loss of preferred experience
- Introduction of unknown technology

- Installation disruption (in-home)
- (Installation disruption (network))

Reduce thermostat setpoint

Literature summary: Little evidence discovered associated with the disutility cost associated to limiting the increase in internal temperature.

Theme	Commentary	Quantification approach
Control system interaction time	Associated with time taken to adjust thermostat or re-programme timer.	Assumed negligible
Loss of preferred experience	No useful data found	Unquantified
Reduced thermal comfort	No useful data found	Unquantified

Install retrofit measures

Literature summary: Discussed in [25] in relation to time (e.g. research) and financial costs not usually factored in (e.g. temporary accommodation, redecoration, etc.)

Theme	Commentary	Quantification approach
Research time	Time taken to research the options, potential installers, etc.	Research time x VoT
Coordination time	Time to coordinate installer, prepare for installation (clearing rooms, etc.), etc.	Coordination time x VoT
Impact on value of home	Retrofit measures could have a positive or negative impact on home value depending on perception of buyers/lenders, quality of work, etc.	Unquantified
Loss of internal floor area	For internal wall insulation, there is an impact on useable internal floor area	£6800 (2009) [26] (only applicable for internal wall insulation)
Loss of preferred architectural aesthetic	For external wall insulation, the appearance of the home is impacted, which in some cases will have an associated intangible cost. Linked to impact on value of home, above.	unquantified
Installation disruption	Restricted access to home during installation, possible temporary accommodation	unquantified
Increased thermal comfort	This is a potential intangible benefit of installation of retrofit measure, allowing greater thermal comfort	unquantified

Install ASHP

Literature summary: Discussed in [25], [26] and [27] in relation to time and hidden financial costs not usually factored in

Theme	Commentary	Quantification approach
Research time	Time taken to research the options, potential installers, etc.	Research time x VoT
Coordination time	Time to coordinate installer, prepare for installation (clearing rooms, etc.), etc.	Coordination time x VoT
Loss of external space	Space for external unit of ASHP. No useful data found	unquantified
Loss of internal space	Where the installation of additional thermal storage is required in addition to the ASHP, this constitutes a loss of internal space.	Thermal storage - £580 [28]
Loss of preferred experience	Switching from the incumbent gas boiler to an ASHP will constitute a shift away from the experience the household is used to. This will cause disruption.	unquantified
Installation disruption	Restricted access to home during installation, Loss of system function during installation	unquantified

Connect to district heat network (DHN)

Literature summary:

Theme	Commentary	Quantification approach
Research time	Time taken to research the options, potential installers, etc.	Research time x VoT
Coordination time	Time to coordinate installer, prepare for installation (clearing rooms, etc.), etc.	Coordination time x VoT
Loss of preferred experience	Switching from the incumbent gas boiler will constitute a shift away from the experience the household is used to. This will cause disruption.	unquantified
Introduction of unknown technology	Where the installation of additional thermal storage is required in addition to the ASHP, this constitutes a loss of internal space. No useful data found	unquantified
Installation disruption	Restricted access to home during installation, Loss of system function during installation. This will also extend outside the home for the installation of the network.	unquantified

Quantification: initial method / approximations of intangible costs where feasible

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- Install retrofit measures

Time-related intangible cost (one-off)

Research time
[hours] : [4,16]
x
VoT
[£/hour] : £5 ± 2

Loss of internal floor area (one-off)

Cost
[£ / home] : [6800]

- Install ASHP

Time-related intangible cost (one-off)

Research time
[hours] : [8,16]
x
VoT
[£/hour] : £5 ± 2

- Connect to DHN

Time-related intangible cost (one-off)

Research time
[hours] : [8,16]
x
VoT
[£/hour] : £5 ± 2

NB: VoT = £5.22 [9]. Additional segmentation lifts VoT up for higher incomes
Values in red are ESC judgement. Values in blue are informed by literature, particularly [25]

How can these elements be used to supplement energy system modelling?

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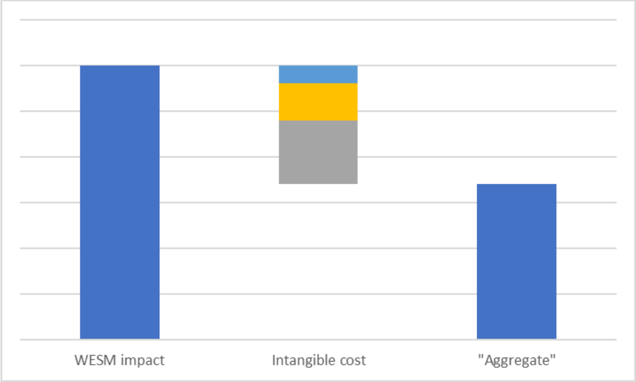
Qualitative

- Presentation of qualitative features of intangible costs alongside WESM costs
- Qualitative judgement applied to intangible costs (e.g. severity)
- Provides indicative view of challenges associated with behaviours

Behaviour	Model cost	Intangibles (e.g.)
Reduce thermostat setpoint	£X bn	Loss of preferred experience Reduced thermal comfort
Install retrofit measures	£Y bn	Lost of preferred aesthetic
Install ASHP/DHN	£Z bn	Loss of preferred experience

Quantitative, off-model

- Behavioural adjustments applied to model, and system costs calculated
- In parallel, equivalent intangible cost derived (where possible) based on model outputs
- Magnitudes of system and intangible costs compared: illustration of size of barriers to overcome for behavioural change



Quantitative, on-model

- Inclusion of intangible costs within WESM's optimisation, influencing "optimal pathway"
- Most appropriate analytical approach likely to be to unwind intangibles from WESM cost – intangibles adjust preferred solution, adding "behavioural realism", but cost definitions unchanged from convention WESM costs
- Natural to combine with other analytical methods discussed in WP3 – variable hurdle rates, elastic end-use demands etc

Several prominent gaps identified: limited exploration in time available

Behaviour	Gap/subjectivity
Reduce thermostat temperature	Disutility of reduced thermal comfort Disutility of loss of preferred experience
Install retrofit measures	Impact on value of home Intangible cost of disruption during installation Intangible benefit of increased thermal comfort
Install ASHP	Disutility of loss of external and internal space Intangible cost of disruption during installation Disutility of loss of preferred experience
Connect to DHN	Disutility of loss of preferred experience Intangible cost of disruption during installation
Cross-cutting	Health benefits Environmental benefits

Consumption & waste

Consumption & waste

Behaviours evaluated
There are two behaviours evaluated in this theme: reducing household food waste; and shifting to healthier diets that include more fruit and vegetables and less red meat.

Food waste
ESME is a whole systems model that focuses on the energy system and CO_2 (the predominant greenhouse gas emitted from the energy system). However, Net Zero means that non-CO_2 GHG emissions from non-energy sectors needs to be considered and are included in the model. The ESC is currently building up a base of evidence to help support a number of updates to ESME to provide more robust representations of non-energy sectors. Despite this, the complexity of food waste production, collection and management, as well as future policies on food waste, meant that accurately capturing the impacts of food waste behaviours on modelled systems was not possible in ESME as it stands. For this reason a different approach was taken for evaluating the effects on emissions of different food waste behaviours:

- Review of current food waste amounts including breakdown of waste
- Review of emissions impact of different types of household food waste
- Review of food waste reduction targets
- Evaluation of emissions savings achieved by meeting food waste per capita target
- Reasons for food waste and strategies to avoid it

Note that none of the calculations in the food waste section take into account the effect of increased food waste collection.

Shifts to healthier eating
Assumptions around diet related emissions, specifically emissions associated with the production of red meat and dairy are included in ESME. These are based on the CCC's Further Ambition position outlined in the Net Zero technical report and assumes a 20% reduction in red meat and dairy consumption by 2050. This is represented as a non-CO_2 emissions trajectory (CO_2e) which is accounted for by making adjustments to the CO_2 targets. ESME is unable to make decisions that affect the diet related emissions trajectory but it can make changes to the energy system to ensure that total GHG emissions meet Net Zero. Because of this, it is possible to model the impacts of different diet related behaviours on the energy system using ESME.

The Reference Case follows the CCC's Further Ambition (20% reduction in red meat and dairy consumption) assumption. This has been increased to 50% reduction in line with CCC's speculative position. The shift in diet away from red meat and dairy is assumed to reduce livestock numbers and the area of grassland needed for livestock rearing. The emissions savings assumed do not include emissions saved through changes in land use.

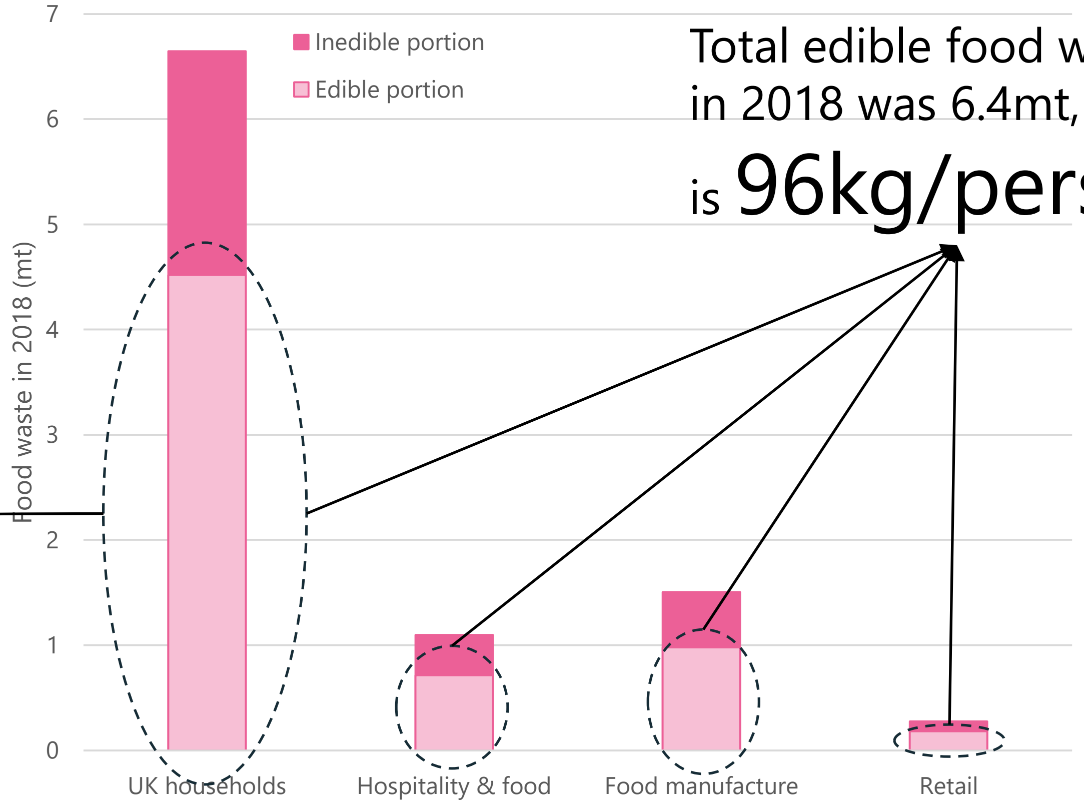
In addition to ESME modelling, the following activities were also undertaken:

- Review of current meat and dairy consumption in UK
- Review of emissions associated with meat and dairy products
- Evaluation of emissions savings achieved under different dietary assumptions

Food waste

UK households wasted 4.5mt of edible food in 2018

66.27 million people in the UK in 2018



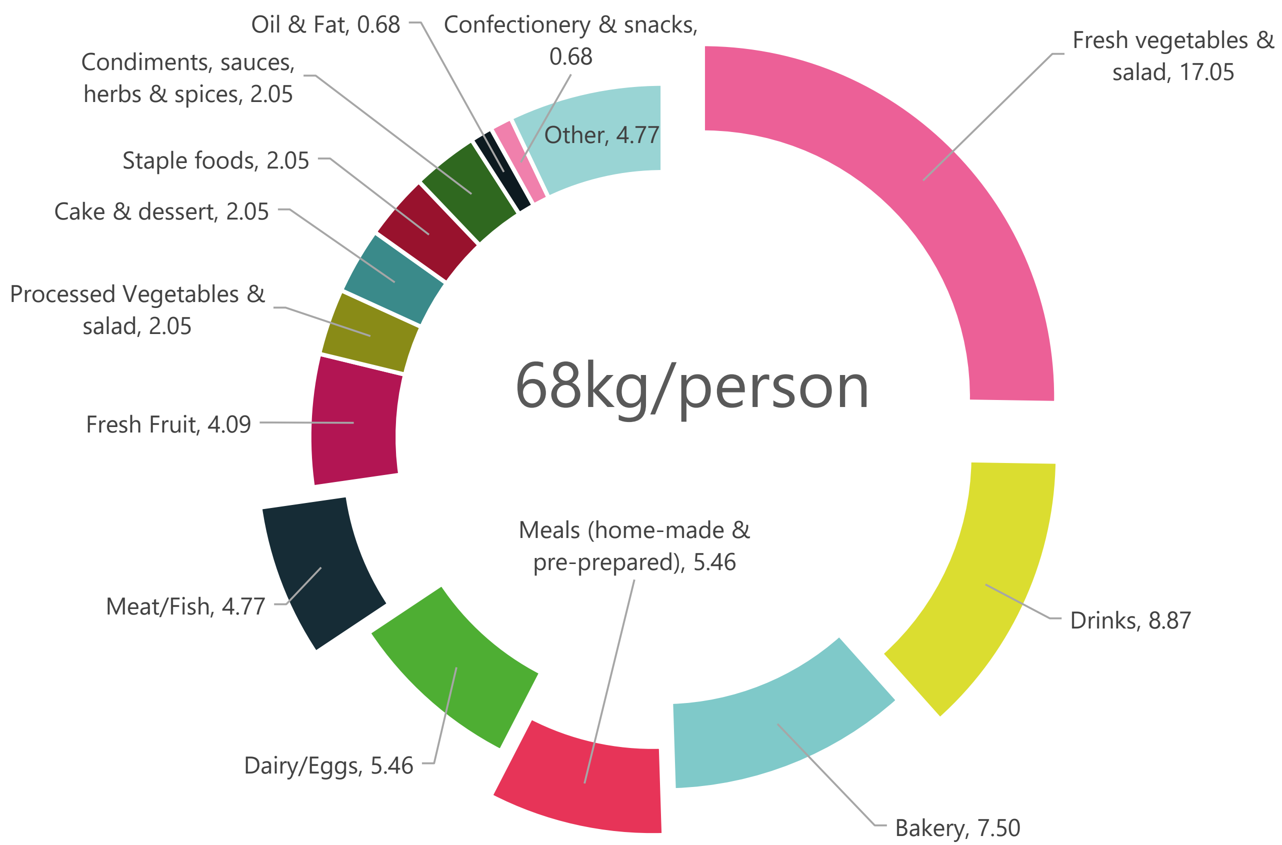
Total edible food waste in 2018 was 6.4mt, which is 96kg/person

68kg of edible household food wasted per person

21mtCO_2e associated with household waste – 14mt of this from edible portion [29]

211kgCO_2e per person

What did people waste*?



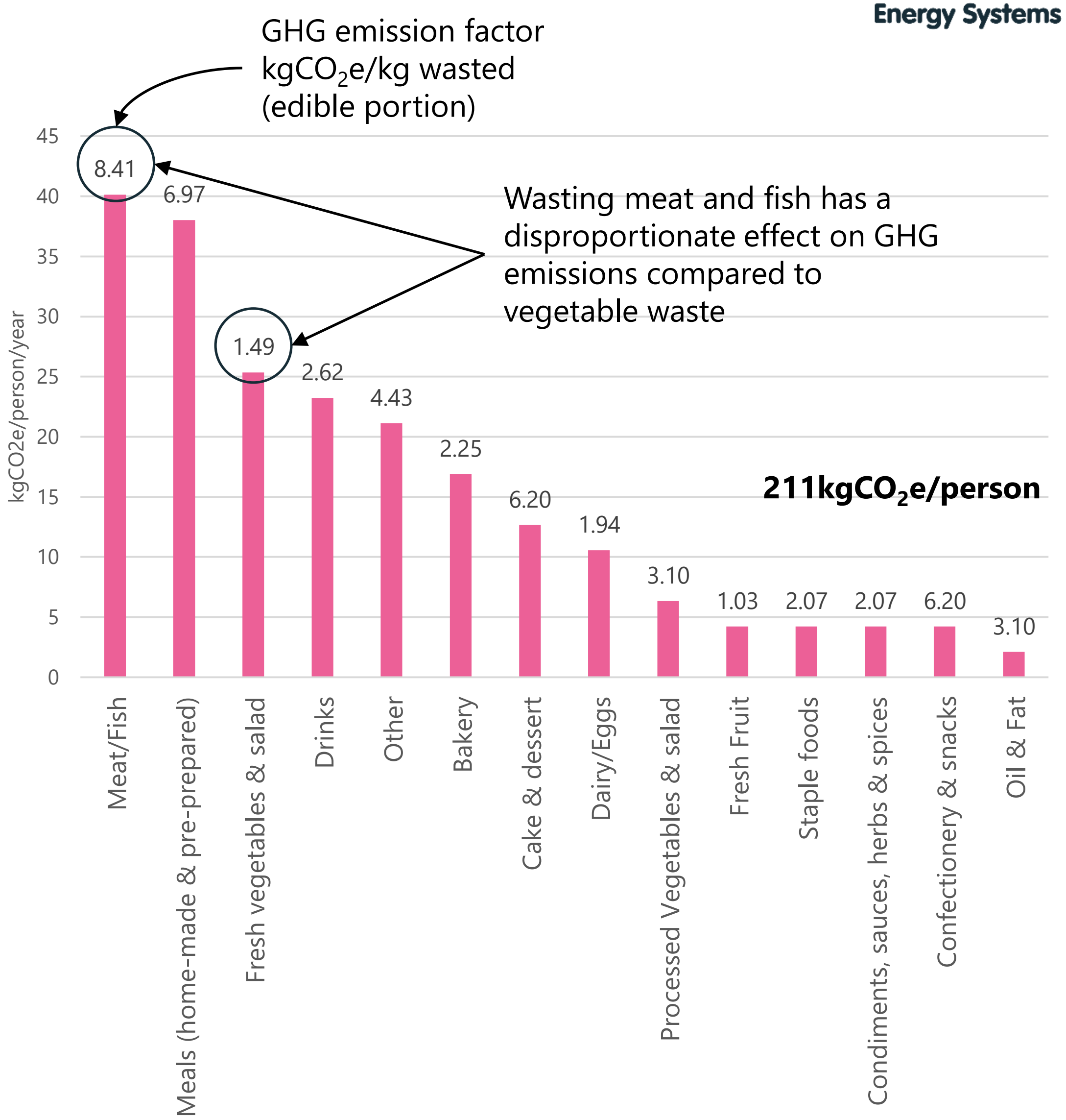
- Fresh vegetables, drinks, meals and meat/fish are in the top 6 wasted food groups and responsible for the highest contribution to GHG emissions
- >40 “nutrient days” wasted. A nutrient day is the complete micro/macro nutrient requirement (including calorific content) needed by a human being (benchmarked against daily RNIs and assumed average calorific intake of 2175kcal/day)

* Based on breakdown of food waste identified in [30]. Edible food waste in 2012 study was 5.4mt (85kg/person). Therefore, food waste per capita has decreased and so breakdown of food waste may well have changed but evidence of this is unavailable.

Not all wasted foods are equal

- Different food groups have different environmental impacts throughout their lifecycle.

- Food waste impacts include:
  - Greenhouse gas emissions
    - Especially during agricultural production of food, food preparation and disposal
  - Non-renewable resource depletion
    - E.g. fossil fuels extracted to generate electricity or for agricultural equipment
  - Eco-system quality
    - E.g. eco-toxicity; aquatic acidification; eutrophication
    - Almost entirely associated with agricultural production of food
  - Land use biodiversity
    - Almost entirely associated with agricultural production of food
  - Freshwater consumption scarcity
    - Almost entirely associated with agricultural production of food



Relative contribution per food group to overall environmental impact of edible UK household food waste [31]

Food group	Weight of edible food waste	Environmental impacts				
		Climate change	Non-renewable resource depletion	Eco-system quality	Land use biodiversity impacts	Freshwater Consumption Scarcity
Fresh vegetables & salad	25%	12%	13%	8%	3%	8%
Drinks	13%	11%	10%	18%	2%	22%
Bakery	11%	8%	9%	3%	3%	1%
Meals (home-made & pre-prepared)	8%	18%	17%	15%	10%	12%
Dairy/Eggs	8%	5%	3%	3%	2%	2%
Meat/Fish	7%	19%	16%	26%	53%	20%
Fresh Fruit	6%	2%	1%	2%	0%	7%
Processed Vegetables & salad	3%	3%	4%	3%	2%	2%
Cake & dessert	3%	6%	5%	3%	2%	4%
Staple foods	3%	2%	3%	2%	1%	3%
Condiments, sauces, herbs & spices	3%	2%	2%	2%	4%	4%
Oil & Fat	1%	1%	1%	2%	2%	1%
Confectionery & snacks	1%	2%	1%	1%	13%	3%
Processed Fruit	0%	0%	0%	0%	0%	2%
Other	7%	10%	13%	10%	2%	8%
Total	100%	100%	100%	100%	100%	100%

Impact mainly from volume of waste

Disposal of drinks into sewerage and fresh water used in manufacture/preparation

Disposal and preparation as well as meat/fish content

Waste of meat and fish has the highest environmental impact across all metrics

SDG12.3 target of 66kg of total edible food waste* per person by 2030

* Total edible means that from hospitality & food, food manufacture and retail sectors as well as household waste.

50% reduction in per capita edible food waste relative to 2007

96kg/person – the per capita total edible food waste in 2018

1.3mt – the reduction in household food waste needed to achieve 2030 target [32]

4.5mt – 1.3mt = 3.2mt edible household food waste in 2030

69.1 million people – the ONS projection of UK population in 2030

47kg edible household food waste/person in 2030

Impact on emissions depends on which food groups waste can be reduced in

- Reducing waste across all food groups gives a 65kgCO_2e/person saving = 4.6mtCO_2 in 2030 – this is equivalent to eliminating all vegetable and meat/fish waste
- Reducing waste from the biggest contributions by weight:
  - 68kg/person
    - -17kg vegetable waste
    - -4kg needed from drinks
  - GHG emissions from these food groups totals 36kgCO_2e/person saving = 2.5mtCO_2e in 2030
- Reducing waste from biggest contributions by total GHG emissions:
  - 68kg/person
    - -4.8kg meat and fish
    - -5.5kg meals
    - -10.7kg needed from vegetables
  - GHG emissions from these food groups totals 94kgCO_2e/person saving = 6.5mtCO_2e in 2030

Some observations – healthier eating: potential for 4.8mtCO_2e savings

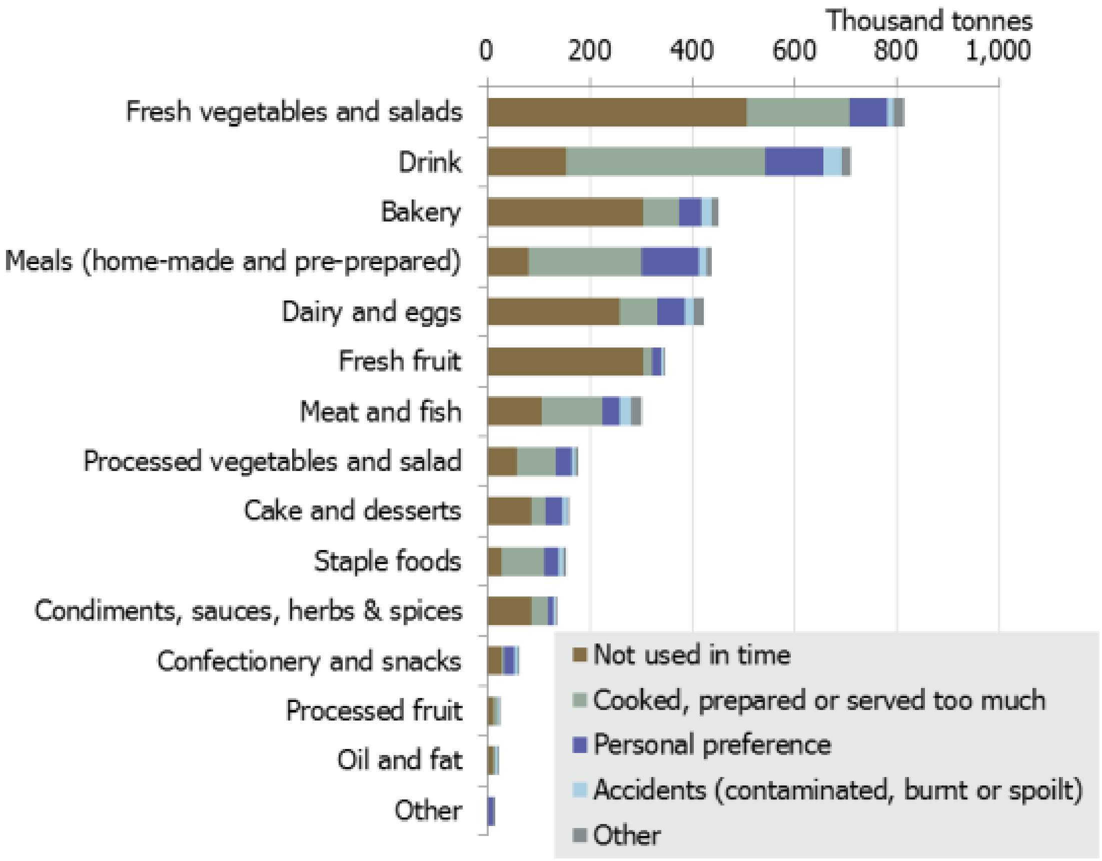
Fruit & veg.

- Fresh fruit and vegetable waste is estimated to total 264 portions per person per year (assuming 80g portion)
- Current estimates suggest only 1/3 of UK population achieves 5-a-day with average being 3.7 portions/person/day [33]
- Fruit and vegetable waste is almost equivalent to an additional portion suggesting that if people managed the 5-a-day target by consuming the produce they purchased, waste from this food group could be eliminated

Meat & fish

- Wasted meat and fish is equivalent to approx. 1 portion per week
- The UK on average consumes half the recommended 2 portions per week of fish [34]
- Waste from this group is equivalent to people consuming the recommended portions of fish for health, or reducing consumption of meat by one portion
- Reducing meat consumption would not only reduce emissions associated with wasted produce but would also have additional benefits associated with reductions in livestock farming

Why do people waste food? [30]

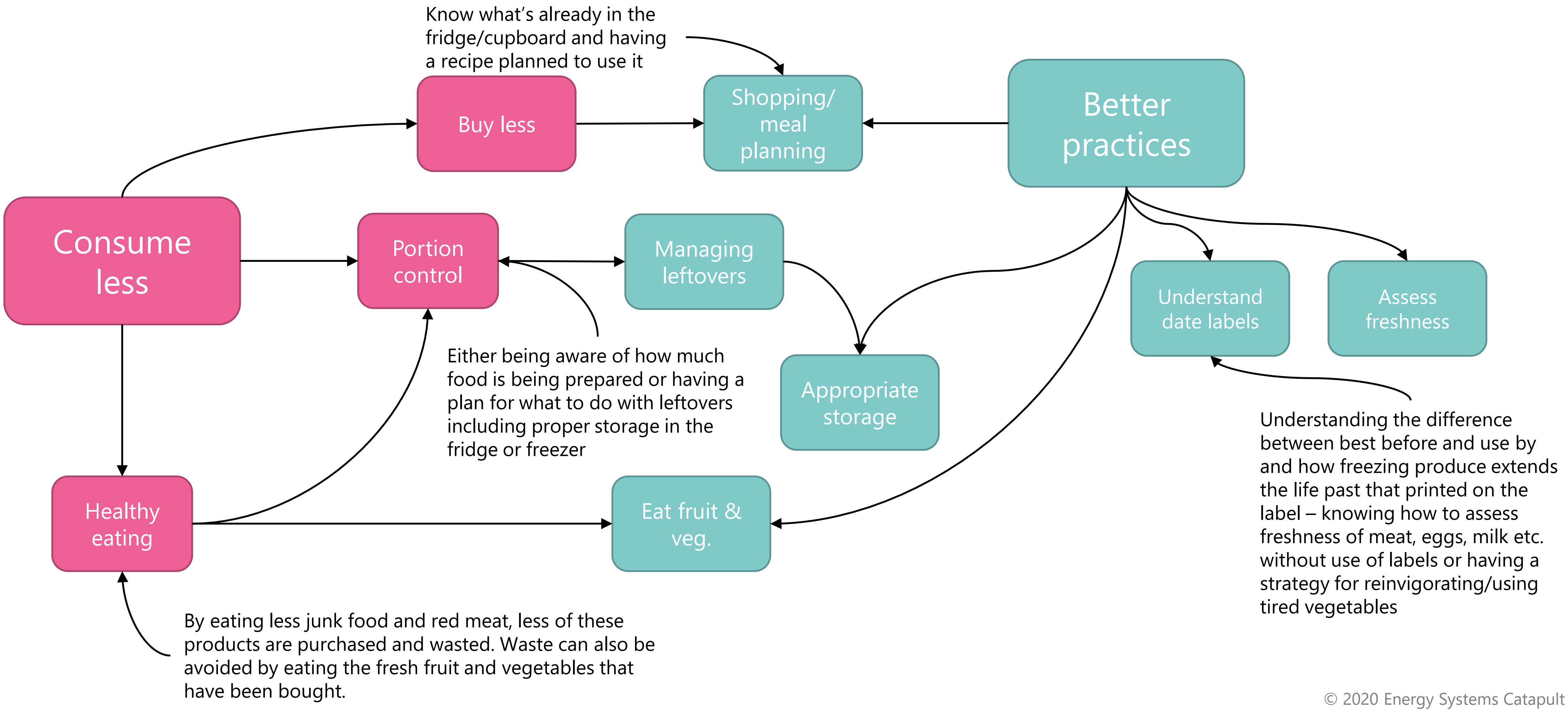


Reason for waste	Cause
Prepared too much	• Unable to judge portion sizes

Not used in time	• Bought too much
	  • Supermarket deals
	  • Size of packaging
	  • Not checking store cupboards before shopping
	  • Purchased for one recipe
	• Poor understanding of date labels
	  • Use by vs. best before
	  • No knowledge on how to assess freshness
	• Inappropriate storage
	  • Fridge temperature too high
	  • Could have frozen goods
	  • Better use of packaging
	• Simply not eating what's been bought

What can be done about it?

There might be different strategies to reduce waste for different food groups e.g. consuming less meat and/or fizzy drinks vs. better practices such as storing foods properly



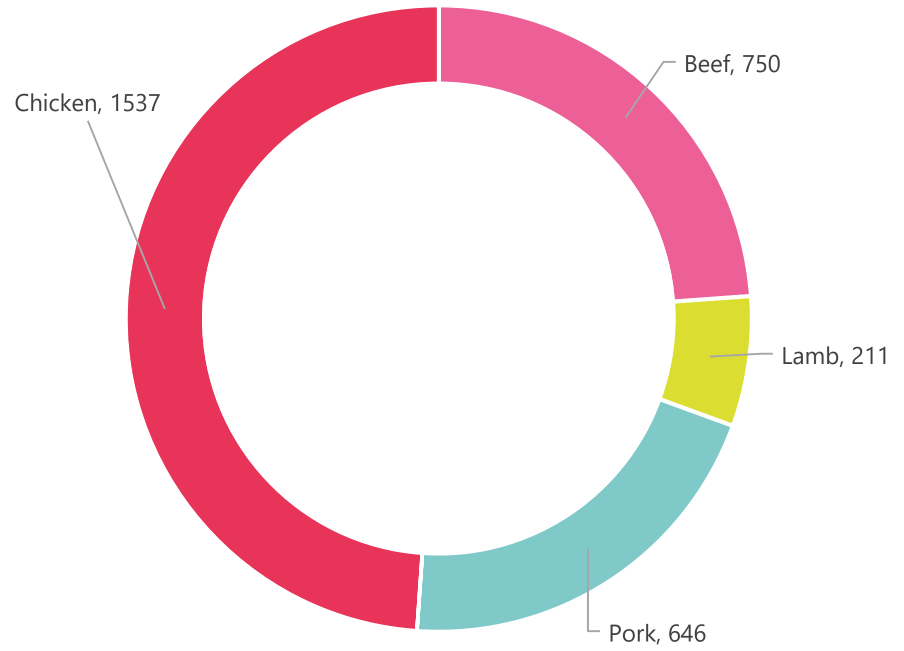
Diet

Meat & dairy consumption in the UK [35, 36]

- 66.7 million people in the UK in 2019
- The average person consumed:
    - 130g meat/day (70g of this is red meat including pork)
    - 257ml milk/day
    - 32g cheese/day (10g of which is UK produce)

Consumption of food in UK ~20% of UK GHG emissions [37] putting it in the order of 100mtCO_2e

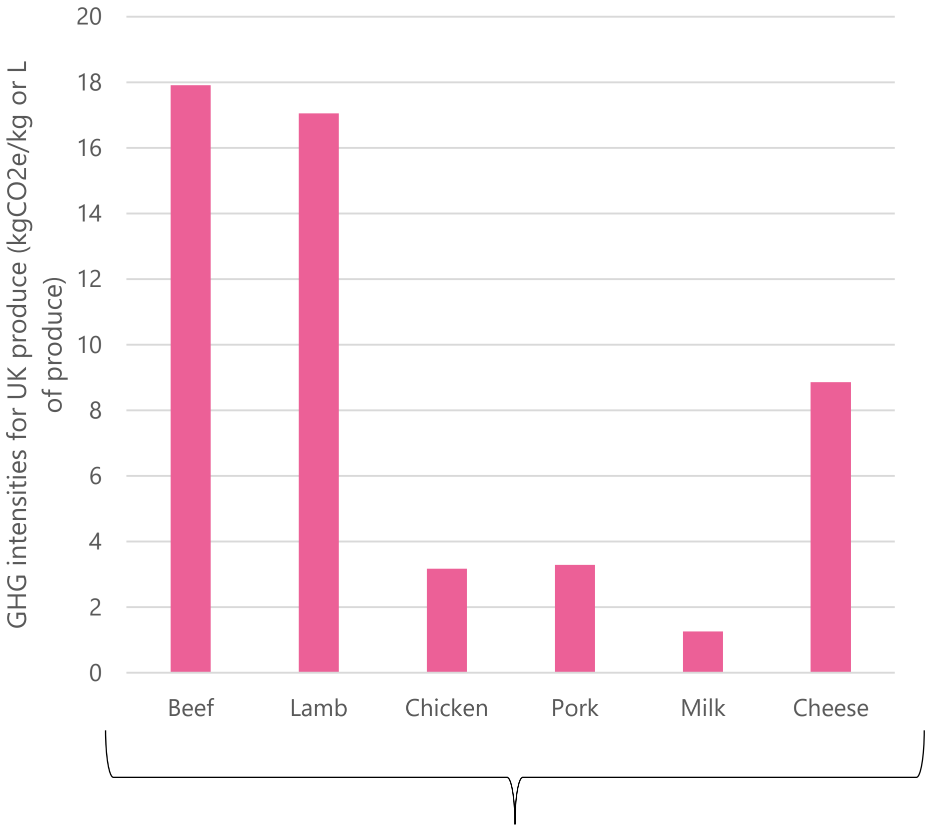
kt dressed carcass weight in 2019



6251 million L milk
254kt UK produced cheese

GHG intensities of meat and dairy products

System boundary for the life cycle analysis in [38]



UK mean values taken from tables 7 and 8 in [38]. These are given in $kgCO_2e$/kg bone free meat. A conversion from bone free meat to carcass weight was done using figures in table 1

*Not disposal in the home but waste produced during production

Meat-free Mondays and Veganuary

- There are already some commonly adopted initiatives in the UK related to reducing meat and dairy consumption for example "Meat-free Monday" and "Veganuary"

2.5mtCO_2e – GHG saving associated with UK adopting Meat-free Mondays*. This is 0.6% of UK total GHG emissions in 2018.

2.2mtCO_2e – GHG saving associated with UK adopting Veganuary**. This is 0.5% of UK total GHG emissions in 2018.

* Assumes reduction in consumption across all meat with a switch to a meat-free substitute
** Assumes reduction in consumption across all meat with a switch to a meat-free substitute. Cheese and yoghurt consumption is cut with no assumption about alternatives. Milk consumption is reduced and replaced with milk-free substitute
Assumes behaviour is taken up by whole UK population

GHG emissions savings by adopting shifts in diet

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Behavioural outcome	Motivation	GHG emissions saving in a year (relative to 2019)
People halve the amount of red meat (including pork) consumed by switching to chicken Milk/cheese consumption remains the same	Such a switch to chicken could be motivated by advice given by the NHS to limit red meat consumption including that of pork and opting for healthier alternatives such as chicken.	6.5mtCO_2e (1.4% of UK total GHG emissions in 2018)
People halve the amount of red meat (including pork) and chicken consumed by switching to meat free-substitutes Milk/cheese consumption remains the same	Motivated by health as above as well as increasing awareness of animal welfare	8.3mtCO_2e (1.8% of UK total GHG emissions in 2018)
People halve the amount of all meat consumed by switching to meat-free substitutes Milk/cheese consumption halves with milk substitutes being used	Motivated by health, animal welfare and impacts on the climate	12.7mtCO_2e (2.8% of UK total GHG emissions in 2018)

$$Total\ GHG\ emissions\ from\ consuming\ meat, dairy\ and\ meat\ alternatives = \sum_{p} (GHG\ intensity_p \times Daily\ per\ capita\ consumption_p \times Population)$$

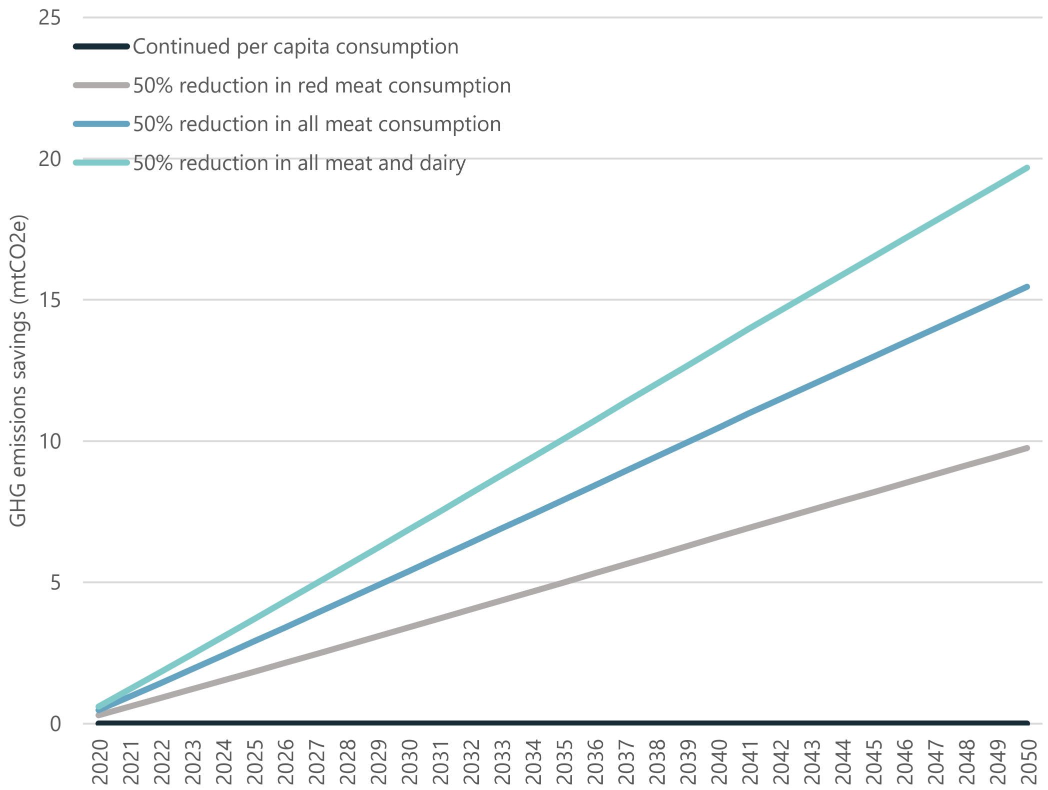
Where subscript *p* refers to the product being consumed (e.g. lamb or milk). The GHG savings presented in the table are calculated by subtracting the total GHG emissions from meat and dairy and meat alternative consumption for the diet shift scenario from the Reference Case (2019 consumption of meat and dairy).

Emissions savings to 2050

Emissions savings by adopting different dietary habits.

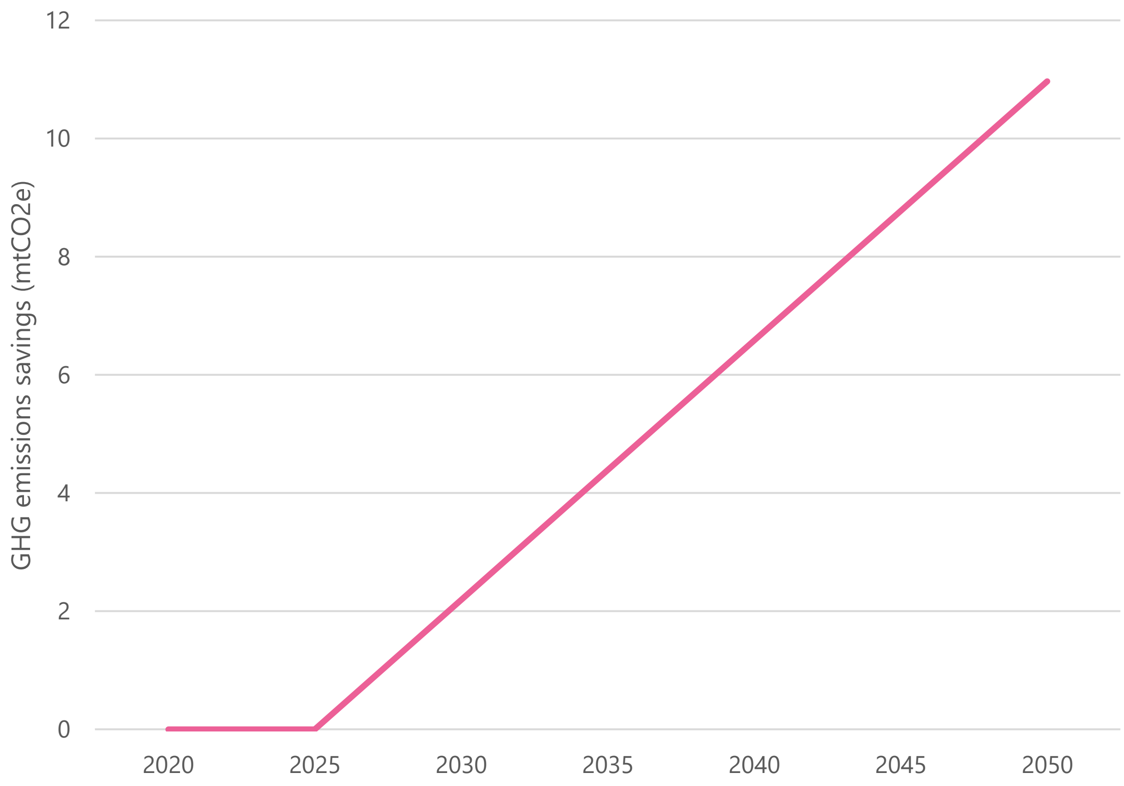
Savings are calculated by subtracting the emissions from the diet shift scenario from the Reference Case. The Reference Case assumes 2019 per capita consumption of meat and dairy products continues. Therefore consumption increases out to 2050 as a result of assumed increase in population. GHG intensities of these food products do not change. Total emissions therefore increase with total consumption. For the diet shift scenarios, a linear reduction in meat and dairy consumption from 2020 to a 50% reduction by 2050 is assumed. Again, per capita

- Additional savings could be made in the food waste sector assuming households waste less meat in line with lower consumption
- There are also other strategies to decarbonise livestock farming not included here



ESME modelling: 50% reduction in red meat and dairy consumption by 2050

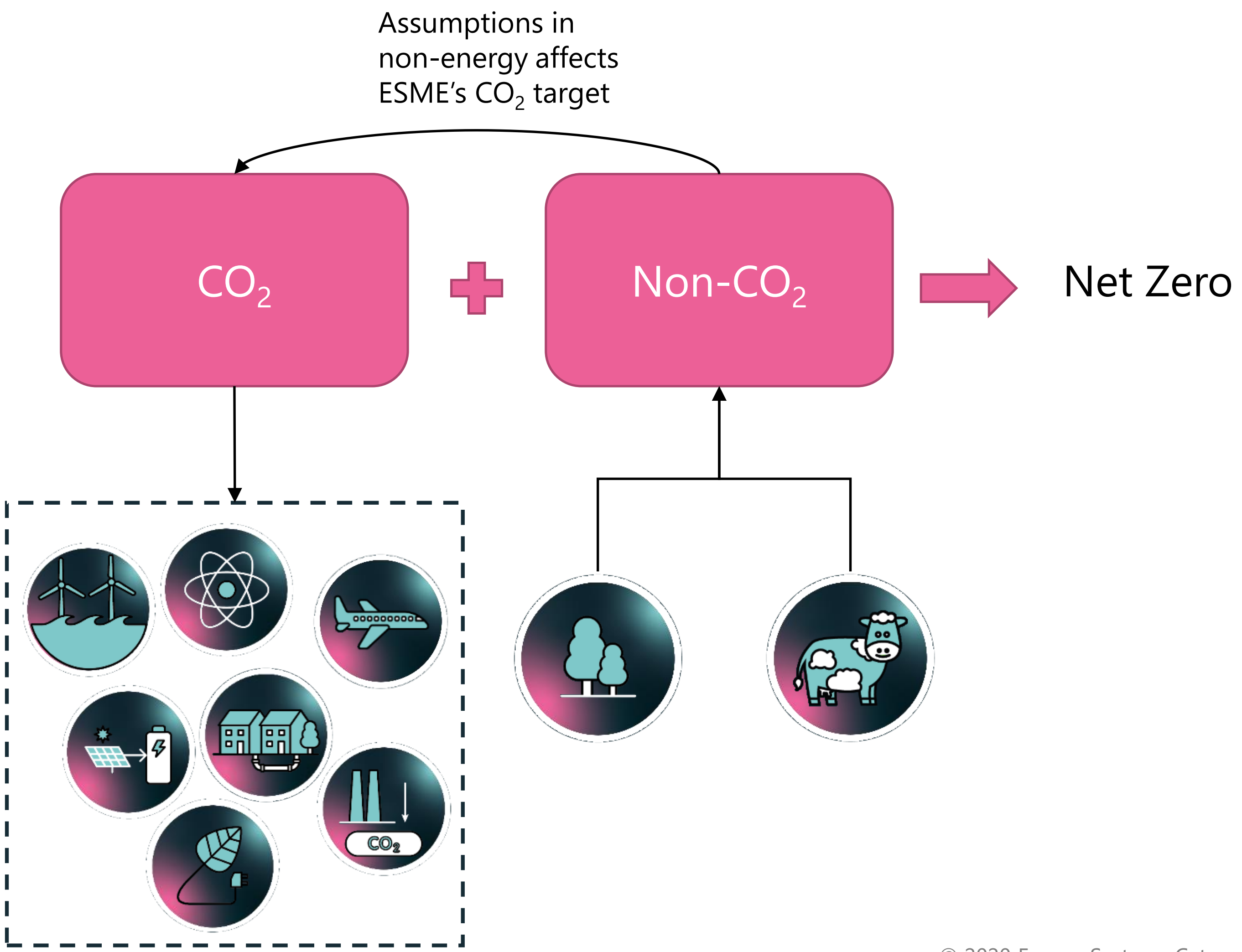
- Reference Case assumes 20% reduction in red meat and dairy consumption by 2050
- A further 30% decrease delivers an 11mtCO_2e saving relative to Reference Case by 2050. This is based on the CCC's speculative position which assumes the additional 30% reduction is achieved through shifting to alternative protein sources such as plant-based products or even lab-grown meat.
- It is assumed that reduction in UK consumption of meat and dairy products does not prompt an increase in exports. Likewise, decreased consumption of these products produced in the UK is not assumed to lead to an increase in imports.



Note that this emission saving projection is based on emissions in 2050 laid out in CCC's Net Zero report. Underlying assumptions and scope informing the CCC's speculative and further ambition positions for emissions associated with dietary change differ from those in this analysis. Therefore, savings presented here do not relate to those in the previous slide, which are based on bottom-up calculations completed for this analysis.

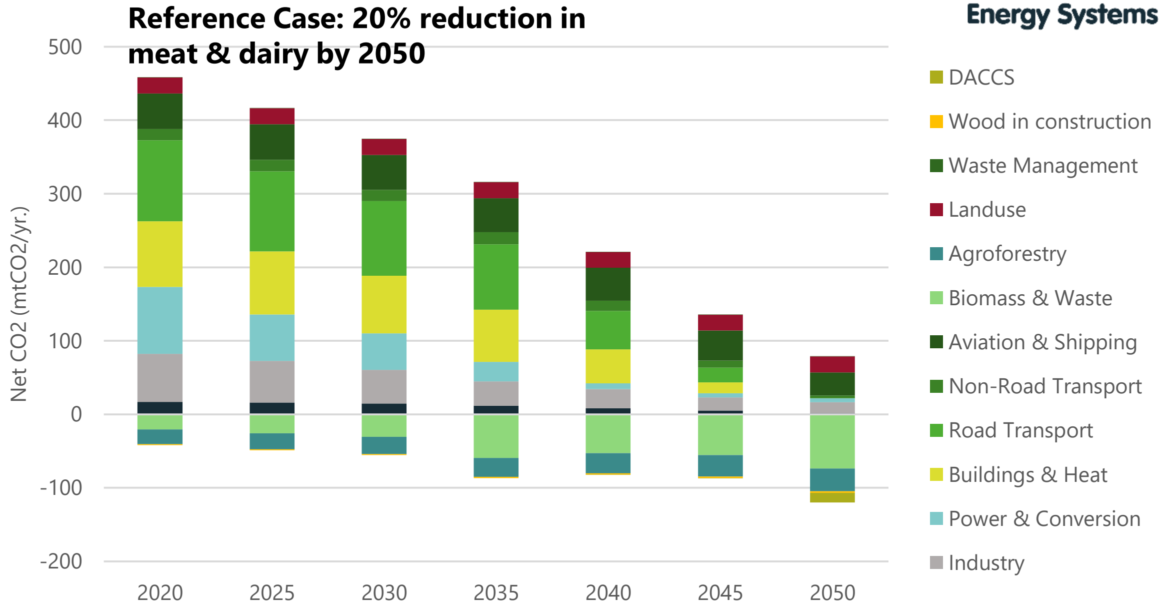
Effect of non-CO_2 emissions reductions in ESME

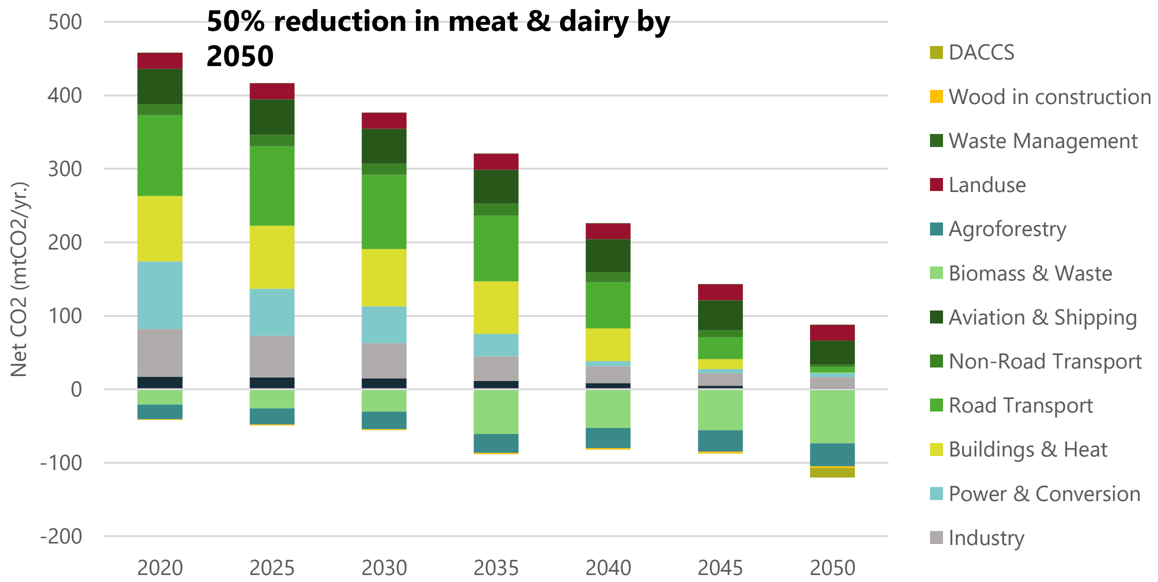
- Emissions target in ESME is made up of CO_2 and non-CO_2 components
- ESME is an energy systems model and designs the energy system subject to CO_2 constraints
- Changing the non-CO_2 constraints by making assumptions about diet causes changes to the CO_2 target – e.g. less emissions from meat = less non-CO_2 emissions and therefore less strict CO_2 target for the energy system



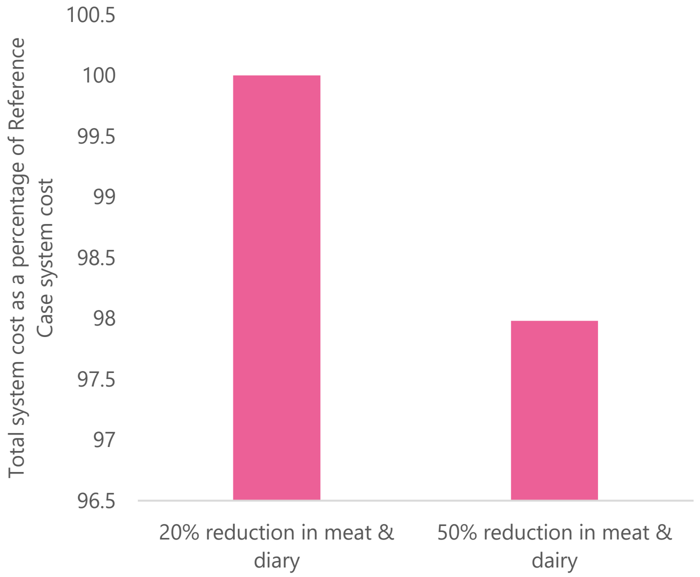
Reduction in red meat & dairy : emissions

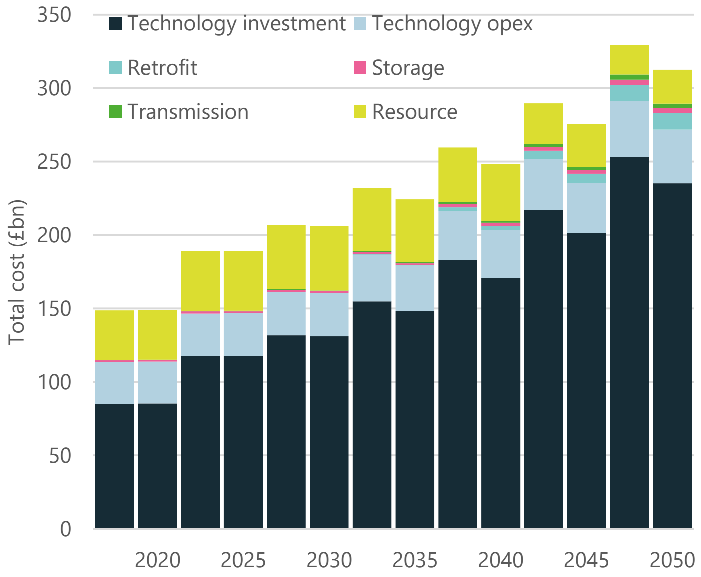
Up to 2035, emission headroom created by shifting to healthier diets allows decarbonisation in the power and conversion sector to be pulled back (more emissions from this sector in the 50% reduction run vs. reference Case). This sector is the first to begin deep decarbonisation and so is sensitive to headroom created in the early time periods. After 2035, transport takes advantage of the headroom created by reducing effort in the difficult to decarbonise aspects of this sector such as movement of freight. In the Reference case in 2050, it is seen that road transport is entirely decarbonised, whilst a 50% reduction in red meat and dairy means residual emissions in the order of 7.7mtCO_2 still allow the Net Zero target to be met.



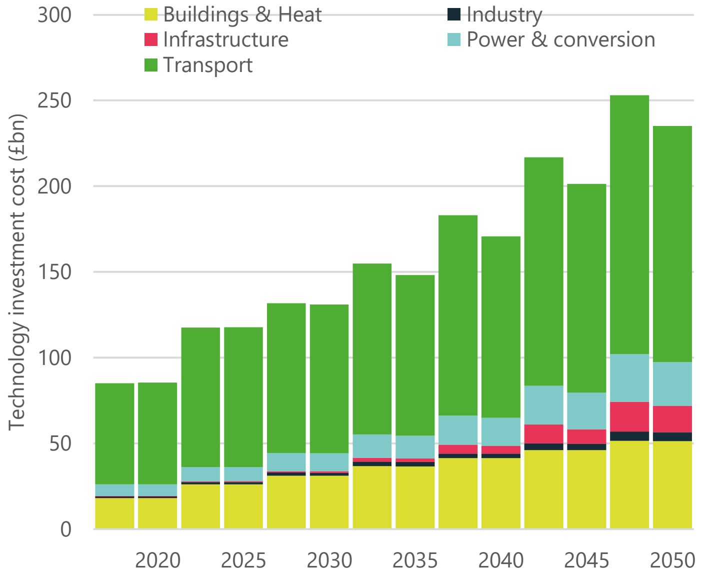


Reduction in red meat & dairy: system costs





Clustered chart shows 2 stacks per time period. From L-R: 20% reduction, 50% reduction



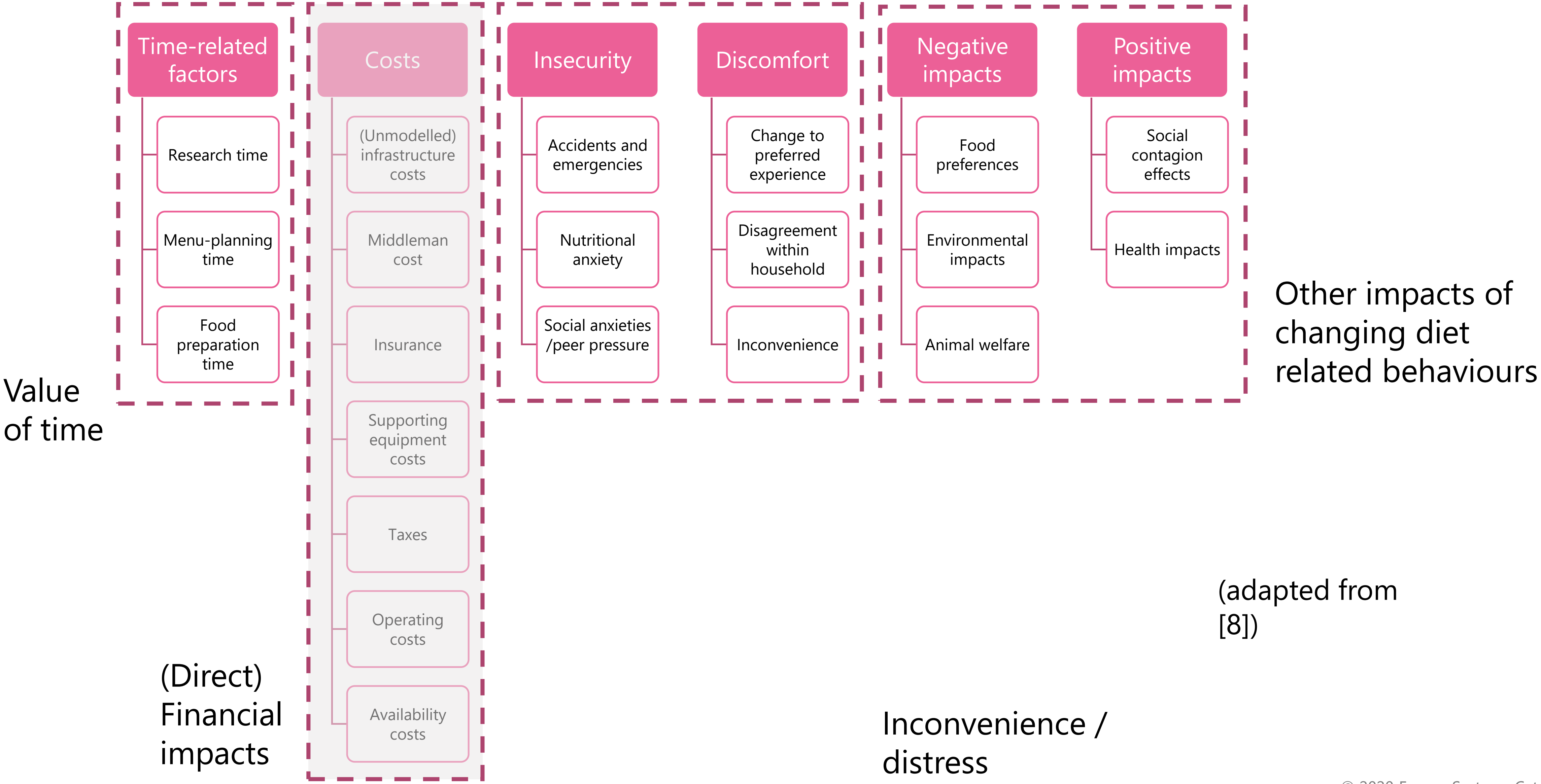
50% reduction in meat and dairy consumption by 2050 (30% lower than the Reference Case) achieves approximately 2% reduction in total system cost.

This saving is largely due to lower technology investment costs appearing in the mid-2030s

Savings in technology investment costs are mainly due to savings made in the transport sector

Diet & Waste behaviours: intangible costs

Diet-related intangible costs: themes



(adapted from [8])

Behaviours: costs and benefits

Theme	Commentary	Quantification approach
Research time	Currently awareness and availability of information on lower-carbon foods is low. Nutritional anxieties about dietary changes may also be seen as necessitating research.	Unquantified
Menu-planning/Food-preparation time	Changing diets may involve rethinking usual meal-planning and some new cooking skills (though many replacement products are easy to substitute). Learning new cooking skills may be seen as a benefit by some.	Unquantified
Loss of preferred experience	Swapping meat/dairy for alternatives may be seen as involving a reduced gustatory pleasure or a restricted choice of foods/take-aways/restaurants.	Unquantified
Disagreement/conflict within household	Potential for disagreements within the home about household food shopping/menu-planning (in some ways these are 'secondary effects', or knock-on effects, from other intangible effects given that food is often bought for/cooked for/shared with others)	Unquantified
Nutritional anxieties	While some consumers report beliefs that plant-based eating is healthier, some consumers report beliefs that animal foods are essential for good nutrition and may be concerned about how much they should reduce consumption of animal and remain healthy[1].	Unquantified
Social anxieties	The attitudes of others may be unsupportive or hostile to shifting to lower-carbon healthy diets. Peer pressure and negative attitudes can provoke anxieties or conflict in social situations or negative self-image[2].	Unquantified
Health benefits – weight loss, lower risk of disease/death	Ample evidence that there are health benefits for many/most consumers from: reduction in calorie intake; reducing consumption of meat and dairy; increasing consumption of plant-based foods/fruit/vegetables.	Unquantified (More quantifiable at public health level and savings to NHS).
Psychological wellbeing	Improved subjective wellbeing from physical health and self-image. Possible spillover into other healthier lifestyle choices beyond diet.	Unquantified

Dietary Behaviours - summary

NOTE:
- Behaviours may overlap (e.g. reduction and substitution)
- As food is an essential item, the most significant behavioural shifts are likely to be substitution of high carbon and animal-based foods for lower-carbon foods.

Diet-related Behaviours Group 1: food waste
- Reduce food thrown away (i.e., make food go further/last longer not eat more)
- Dispose of food waste by composting
- Dispose of food waste through local collection (for composting or animal feed)

Diet-related Behaviours Group 2: moderation
- Reduce calorie intake (buying less food and drink, especially discretionary products, including alcohol)
- Reduce portion sizes, especially of meat and other high-impact foods – likely combined with substitution
- Reduce frequency of meat consumption, esp. beef and lamb – likely combined with substitution

Diet-related Behaviours Group 3: substitution
- Swap to more local and seasonal foods
- Swap to lower-impact producers of same foodstuff (e.g., avoid the beefburger brand with highest carbon footprint)
- Swap meat/dairy for fruit and vegetables
- Swap beef and lamb for lower-carbon meats (e.g., chicken)
- Swap meat/dairy products for plant-based products
- Swap from meat products to lower-carbon blended animal products

Role of heterogeneity and temporality in intangible / disutility costs for diet

- As noted for other behaviours, there will be **heterogeneity in how impacts affect different individuals.** Individuals vary in predisposition to diet-related diseases, current diet, income, gender and social context (attitudes of household members and others; food outlet menu/clientele). The potential intangible costs (and benefits) from shifts in diet will differ accordingly.
- Anticipating a progressive societal change, there is also an important **temporal dimension** to both costs and intangible costs. As behaviours shift and become normalised, the context for low-carbon choices will be increasingly supportive [39] lowering some intangible costs such as anxieties about health or social identity/image management.
  - **The shifting of norms over time will be important for food-related behaviours**. This is because of social influences on food choices through both commensality (eating together) and the cultural meanings attached to food, e.g., meat and masculinity, tradition and negative stereotypes associated with food-avoidance [40-43].
  - Change over time also implies heterogeneity in impacts as **early adopters may pay more** for some plant-based protein products. In time, as costs fall, laggards (and everyone else) will enjoy cheaper prices.
  - It is also worth noting in connection to time that many **intangible costs could be reduced quickly through appropriate interventions** (these include information barriers to identifying lower-carbon foods and improving availability of more plant-based menu-options). There is, therefore, a risk of over-emphasising these intangible costs or presenting them as inevitable/inescapable.
  - Finally, once **new habits become embedded**, some intangible costs would reduce (effort, planning, research time, but also changing taste-preferences and conflict with household members)

Intangible costs relevant to diet-related behaviours
Group 1: food Waste

Reduce food thrown away (i.e., make food go further/last longer not eat more)

- Costs: effort (meal-planning)
- Loss of preferred experience?

- Benefits: savings on food shopping costs

Dispose of food waste by composting or through separate local collection

- Inconvenience (minor)

Intangible costs relevant to diet-related behaviours
Group 2: Moderation

Reduce calorie intake (buying less food and drink, especially discretionary products, including alcohol)

- Loss of preferred experience
- Possible disagreements within household
- Benefits:
  - Cost savings likely;
  - Health benefits for some

Reduce portion sizes, especially of meat and other high-impact foods

- Loss of preferred experience
- Possible disagreements within household
- Benefits:
  - cost savings likely;
  - health benefits for some[3]

Reduce frequency of consuming meat and other high-impact foods, esp. beef and lamb

- Loss of preferred experience
- Possible disagreements within household
- Time/effort: alternative meal planning
- Benefits:
  - Cost savings likely
  - Health[4]

Intangible costs relevant to diet-related behaviours
Group 3: Substitution

Swap meat/dairy for more fruit and vegetables
- Loss of preferred experience
- Possible disagreements within household
- Benefits: health[4]

Swap to more local and seasonal foods
- Loss of preferred experience
- Possible disagreements within household
- Time: menu-planning and awareness

Swap beef and lamb for lower-carbon meats (e.g., chicken)
- Loss of preferred experience
- Benefits: health[5]

Swap to lower-impact producers of same foodstuff
(NB. currently very difficult to obtain information)
- Loss of preferred experience (brand loyalty)

Swap from meat products to plant-based protein products
- Loss of preferred experience (reduced choice at home/take-away/restaurants)
- Possible disagreements within household
- Resisting peer pressure/conflict/reputational costs[1]
- Benefits: health[4]

Swap from meat products to blended meat products
- Benefits: health[6]

NOTES

- [1] The current social context, for most people, is not supportive of changing food choices. This is because of social influences on food choices through both commensality (eating together) and the cultural meanings attached to food, e.g., meat and masculinity, tradition and negative stereotypes associated with food-avoidance [40-43]. This peer pressure [39] makes shifting and maintaining new dietary behaviours more difficult [42].
- [2] Some consumers will have a degree of concern about the nutritional value of animal products and the health impacts of reducing or avoiding these foods. Measuring these 'attitudes' or 'beliefs' is not straightforward as pro-meat/dairy attitudes can also be seen as a 'cultural repertoire' used to justify current diets [41, 42].
- [3]. Food eaten in excess of calorific or nutritional requirements is a waste of resources and also has negative health consequences, notably obesity. The UK is the most overweight nation in Western Europe: approximately 29% of adults in England are obese [44] and these figures are set to climb to 60% of men and 50% of women by 2050. Twenty per cent of Year 6 children are obese [45]. It is estimated that obesity-related conditions in the UK are currently costing the NHS £6.1 billion per year [45]. Reducing overconsumption of calories is the topmost recommendation from the World Resources Institute report on a sustainable food future [46].
- [4] Much of the meat consumed in the UK is processed, contributing to over-consumption of saturated fat and salt in the diet. The UK population continues to consume too much saturated fat and not enough fruit, vegetables, and fibre [47]. The EAT-Lancet report advises a shift to unsaturated rather than saturated fats and a reduction in animal-based foods and added sugars [48].
- [5] Chicken is lower in saturated fat that beef and lamb. The UK population continues to consume too much saturated fat [47, 48].
- [6] Blended products exist now which substitute 30% of ground beef for mushroom or plant-based mince [46, 49].

Several prominent gaps identified: limited exploration in time available

Behaviour	Gap/subjectivity
Reducing/replacing meat/dairy with plant-based foods	Potential scope for dietary change to lead to conflict within the household.
Reducing/replacing meat/dairy with plant-based foods	Social anxiety from peer pressure and attitudes to adopting more sustainable healthy diets.
Reducing/replacing meat/dairy with plant-based foods	Nutritional concerns about reducing/eliminating animal products from diet. While animal products are widely considered to over-consumed, there will be some consumers who have concerns about loss of nutrition. As well as ambivalence and uncertainty in attitudes, it will be difficult to separate beliefs from justifications of current dietary choices that they may be reluctant to change.

In the time available, it appears that the above topics are gaps in current knowledge.

While important to highlight, there is the risk that these influences (intangible costs) may be overstated, especially given the heterogeneity in contexts and individual experiences. Any public statement about public attitudes and intangible costs should be aware that over-stating them could have the effect of reinforcing them.

Purchase of domestic solar photovoltaic systems

Behaviours modelled

Behaviour	High change	Medium change	Low change
Occupants are willing to install solar PV systems at home	People replace/re-energise their PV systems when they reach the end of life. There is also continued interest in installing PV systems leading to new capacity. 2050 capacity of domestic solar PV systems reached double that in 2020 (7.8GW)	People replace/re-energise their PV systems when they reach the end of life. PV capacity in 2050 remains the same as 2020 (3.9GW).	Once domestic PV systems reach end of life, capacity is not replaced. Most of this capacity leaves the energy systems after 2035. This is the cost-optimal solution seen in the Reference Case.

Install domestic solar PV systems

Behaviour being modelled
People are willing to install domestic scale solar photovoltaic systems.

This is being modelled in ESME by increasing the amount of domestic solar PV capacity installed.

There may be a range of reasons why people decide to install solar PV systems. Current capacity was driven mainly by policy mechanisms such as the Feed in Tariff.

Behavioural outcome
Behaviour that drives the decision to install solar PV systems is modelled as an increase in the domestic solar PV capacity relative to the Reference case.

The Reference Case delivers cost-optimal deployment of domestic PV systems. The amount of domestic PV installed is constrained in the 5-year time periods 2015 and 2020 to reflect the current installed capacity in the UK. The assumed technical lifetime of a PV system is 25 years which means by 2040, all of the existing capacity has reached its end of life (with most of this retiring after 2035). At this point the cost optimal solution is to not replace/re-energise that capacity.

The medium behaviour change case assumes that people will replace/re-energise the capacity that they have. In ESME this incurs the full cost of the system. In reality it might be only partial replacement of system components is necessary e.g. the inverter, which might be a cheaper option.

The high behaviour change case assumes that people replace retired capacity, and that additional systems are installed too. In this case, 2050 capacity is double the 2020 capacity.

Why do people install PV systems [50]?
The UK population seems to be interested in installing solar PV systems with 62% of respondents in a YouGov survey indicating they would like to install PV at home.

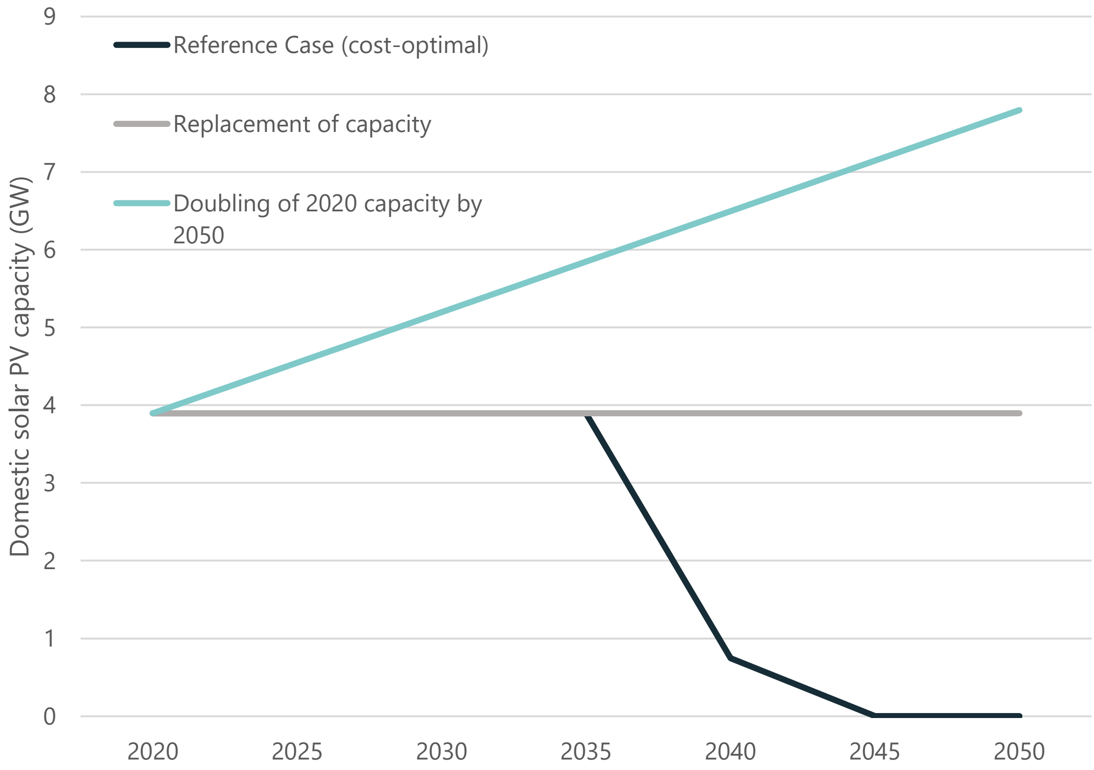
The Energy Saving Trust found that 11% of Scottish renewables customers said environmental impact was their primary motivation for installing PV. Only 3% suggested generating income from renewables was the main driver. However, over half of those customers with PV already installed would not have done so without the Feed in Tariff.

Other benefits of PV systems?
Installing PV systems on a roof is a visible sign of someone’s commitment to reducing their carbon footprint. This could prompt others to consider their own behaviours which might have negative impacts on the environment.

People who own PV systems may have a better understanding of their energy consumption and adopt other behaviours elsewhere in their lives that are consistent with achieving Net Zero.

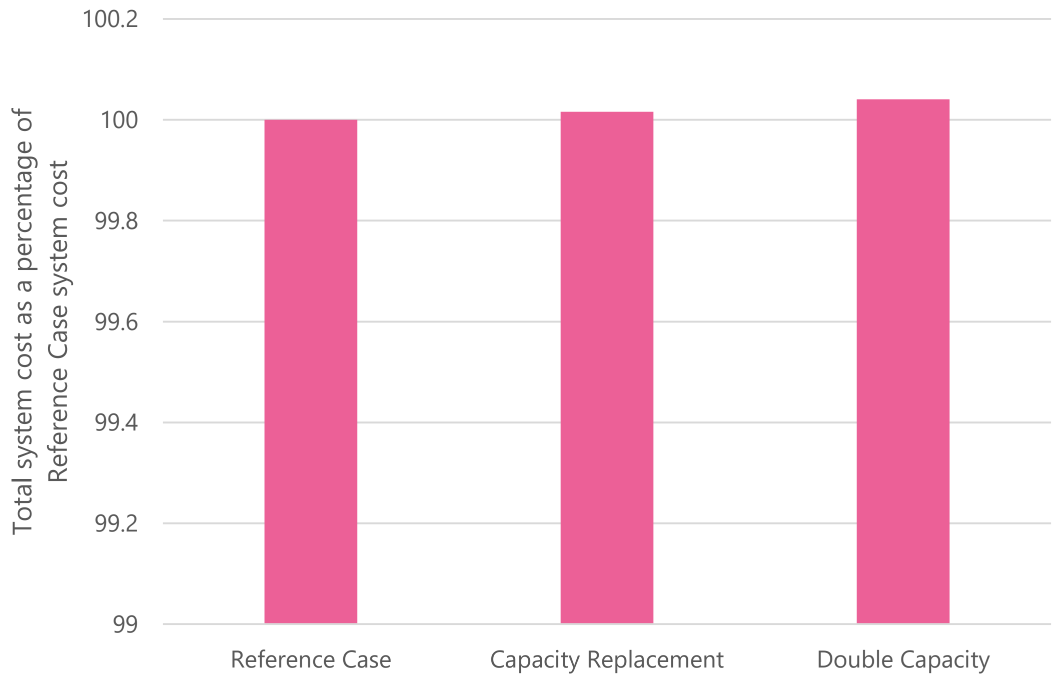
Install domestic PV systems

Behaviour	High	Medium	Low
Install domestic PV systems	2050 capacity double 2020 capacity (7.8GW)	Retire capacity is replaced (3.9GW in 2050)	Retired capacity is not replaced (0GW in 2050)



System cost

- Negligible impact on total system cost
- Negligible effect on the wider system because by 2040/2050 much of the energy system has been decarbonised/electrified. Therefore additional zero carbon generating capacity does little to reduce emissions further. No additional emissions headroom is created that can be used by harder to decarbonise end uses such as industry.
- The capacity factor of domestic solar PV is approx. 10%, therefore 7.8GW of capacity contributes 7TWh of electricity in 2050, which is around 1% of the total demand. This is not enough to prompt noticeable changes in the energy system
- 7.8GW of domestic solar PV causes the deployment of electrolysers to occur with 360MW installed by 2050 – these produce <1% of total hydrogen production. There is good synergy between electrolyser operation and PV generation profiles: electrolysers do not operate during peak periods (so as not to stress the electricity network), and PV systems output when demand is low (e.g. in the summer midday). Electrolysers can operate when demand is low and PV output is high to generate hydrogen for use in peak periods (e.g. by H_2 boilers or H_2 turbines).



Summary

- The capacities of solar PV modelled here are small enough to be absorbed by the energy system without noticeable changes to the design of the system. Therefore the effect on system cost and emissions is negligible.
- Higher PV capacities may well introduce further changes to the energy system particularly through an increased deployment of electrolysers to produce hydrogen owing to the synergy between electrolyser operation and PV generation profiles.
- In reality, installing PV systems at home might prompt certain changes in energy use behaviour (such as demand shifting) in occupants. This might limit the amount of PV generation that can be used by electrolysers. In large enough quantities, this kind of behaviour has the potential to reduce peak demand and could have a positive benefit on the electricity network. However, such behaviours and usage patterns cannot be tested in ESME and therefore the role additional solar can play in meeting Net Zero might be underestimated.
- Operating PV systems with home storage in order to maximise self consumption is also not tested

Energy efficient appliances

Energy efficient appliances

Energy labelling

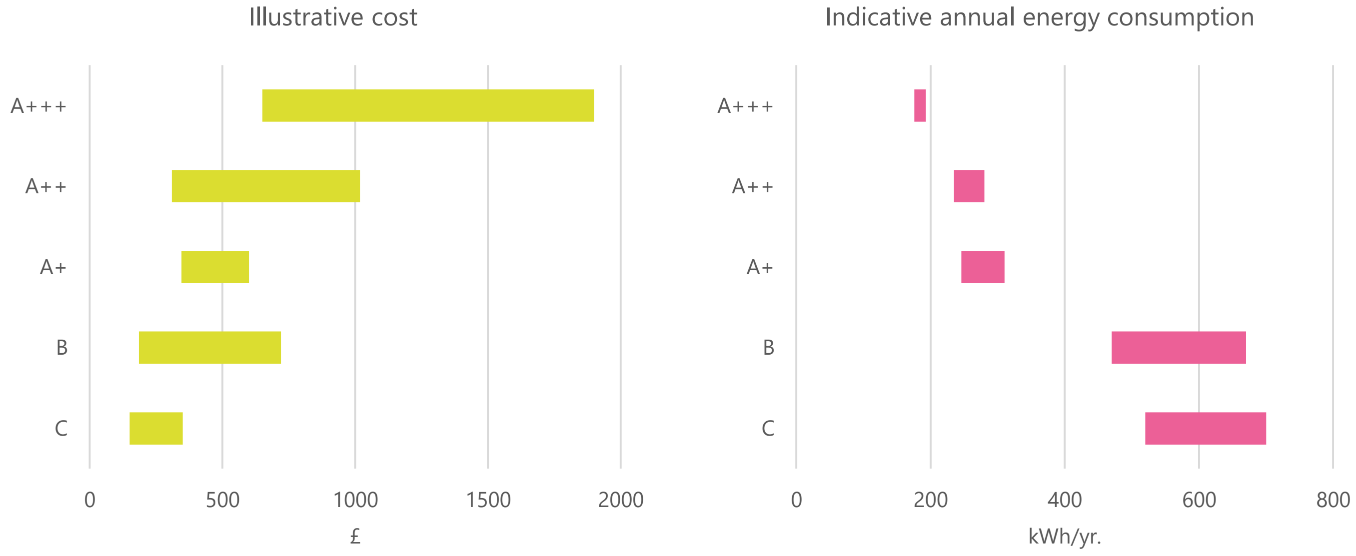
- Energy ratings from A+++ to G
- Many appliance are now in the top end of the scale (A+/A+++)
- Some appliances such as tumble driers still have a broader range of energy performance with the worst at a C rating (vented type) and the best (heat pump models) at A+++
- Rescaling A+++ to G scale to A to G in 2021: current A+++ will be around C-D in new scale to allow for continued innovation and improvement

Motivation behind new appliance purchases

Previous research [51] describes white goods such as washing machines and refrigerators as “work-horse” appliances. These face a lifetime of heavy usage and are typically **replaced only when they fail**.

Other appliances such as televisions are replaced more frequently in response to newer models having new features and improved technologies (e.g. 4k screens). The motivation is for the **latest technology** rather than as a “distress purchase” following failure of the appliance.

For white goods, a key decision making variable is the energy efficiency rating. This might be because consumers know they will be using these products regularly. It might also be a result of energy labelling successfully bringing energy efficiency to the attention of consumers.

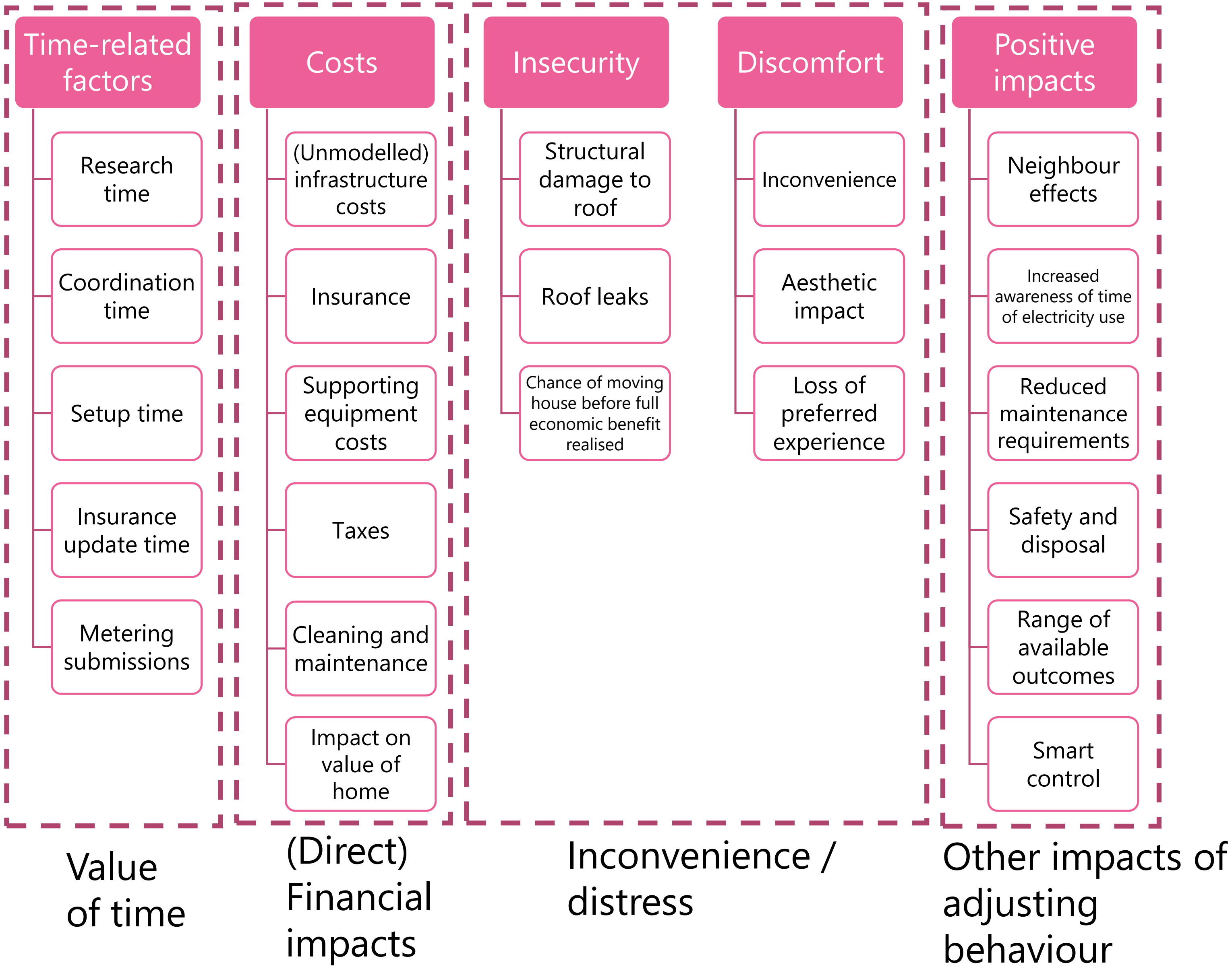


Efficiency vs. cost

- Ecodesign directive is pushing improvements in appliance efficiency with less efficient models being phased out over time
- Charts above show illustrative cost of different tumble driers (left) and annual energy consumption (right)
- Products with higher energy efficiencies typically cost more
- Consider potential distributional impacts of energy efficiency:
  - Poorer households more reliant on cheaper to purchase but expensive to run appliances, especially relevant for white goods which tend to be “distress purchases” i.e. perhaps unplanned
  - Future efficiency standards might be out of reach for some vulnerable consumers
  - Some consumers might also be unable to access flexibility services made possible by smart appliances (due to cost of appliances and other enabling tech such as fast Internet and smart devices)

Electricity behaviours: intangible costs

Electricity-related intangible costs: themes



(adapted from [8])

Intangible costs relevant to installing solar PV panels

- Research time
- Coordination time
- Setup time
- Insurance update time
- Metering submissions
- (Unmodelled) infrastructure costs
- Insurance
- Supporting equipment costs
- Cleaning and maintenance (may not be essential)
- Impact on value of home
- Taxes
- Structural damage to roof (only with substandard installations)
- Roof leaks (only with substandard installations)
- Change of moving house before full economic benefit realised
- Aesthetic impact
- Neighbour effects (neighbours motivated to install their own panels)
- Increased awareness of time of electricity use

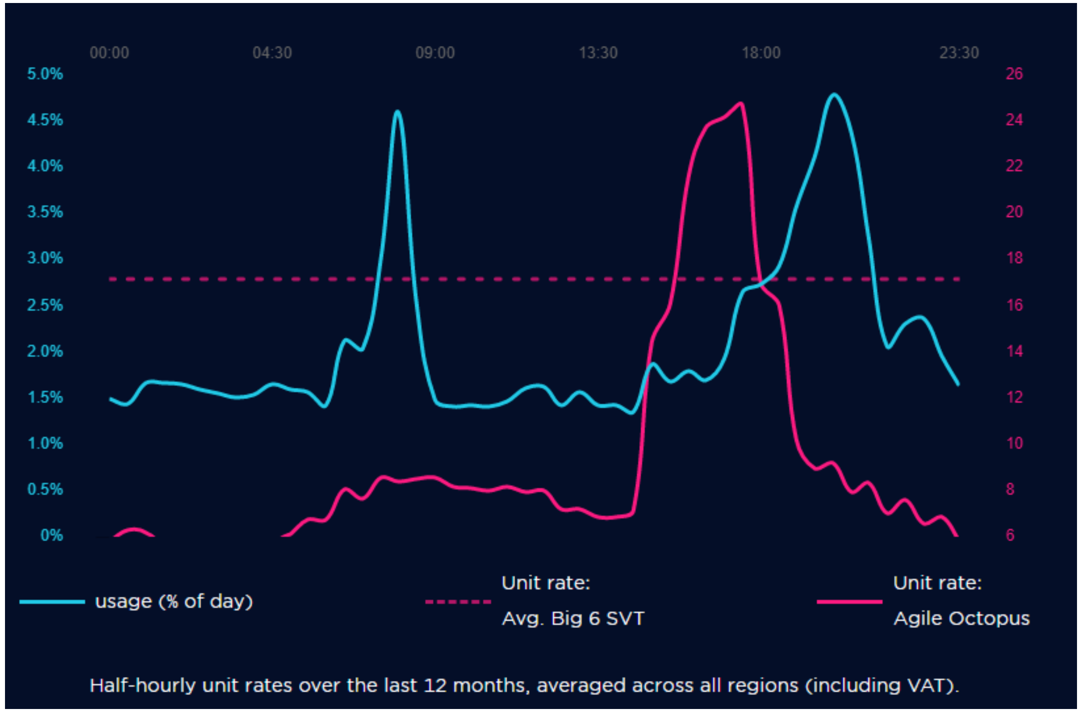
Behaviour 1: Install solar PV panels

	Theme	Commentary	Quantification approach
Time-related factors	Research time	Time taken to research the options, potential installers, etc.	Research time x VoT
	Coordination time	Time to coordinate installer, prepare for installation (clearing rooms, etc.), etc.	Coordination time x VoT
	Setup time	Time to configure the new system. No user setup required beyond installation, but time to learn how to use the monitoring equipment is advisable [53]	Setup time x VoT
	Insurance update time	Time taken to update home insurance policy to cover the value of the new panels	Update time x VoT
	Metering submissions	With the transition from feed-in tariffs to smart export guarantee and smart metering, metering submissions should no longer be required for new PV owners	Nil
Costs	Insurance	Change in insurance premium due to home alteration and additional property	Nil [54]
	Supporting equipment costs	Additional equipment required for the desired operation of the panels, e.g. inverter, meter, distribution boards	Assumed to be included in installation quote
	Cleaning and maintenance	Costs to routinely clean panel to maintain optimum performance – not typically required in rainy climate [55] Inverter replacement after approx. 10 years	Assumed nil £600-800 [56]
	Impact on value of home	Change to the overall value of the building – understood not to affect property value [57]	Assumed nil
	Taxes	VAT is charged at the reduced rate of 5% on solar panels for residential accommodation [58]	

Behaviour 1: Install solar PV panels (continued)

	Theme	Commentary	Quantification approach
Insecurity	Structural damage to roof	Due to increased weight, wind and snow loading – understood to be highly unlikely with professional installation [59]	Nil
	Roof leaks	Caused by the attachment of fixings – understood to be highly unlikely with professional installation [59]	Nil
	Chance of moving house before full economic benefit realised	Savings will accrue to the current occupants of the house, so will cease to benefit the household who installed the panels if they move	Not quantified. Average time between house move is 23 years. ROI for solar PV is around 20 years.
Discomfort	Aesthetic impact	Change in appearance of building roof	Assumed nil
Positive impacts	Neighbour effects	Neighbours may be motivated to install panels of their own	Positive externality, not quantified
	Increased awareness of time of electricity Use	The incentive to use electricity at times when solar resource is available may increase awareness of timing of energy use in general, which could be beneficial with increasing renewable penetration and time-of-use tariffs	Shifting electricity use to lower cost times could save £120 per year [60]

Interaction between behaviours:
Installing PV panels and switching to smart time-of-use tariffs



Example of variation of electricity price (solid pink) on ToU tariff against fixed tariff (dashed pink) [61]

Time-of-use electricity tariffs have a variable electricity price depending on the time of day, reflecting variations in wholesale energy and network costs. In the UK, this typically means that electricity is much more expensive than a flat rate tariff on weekday evenings between 4pm and 7pm, but cheaper than flat rate the rest of the time, particularly at night and during times of high renewable output.

Since the majority of solar PV generation occurs during the low price times, this suggests that the economic case for PV will be eroded by the transition to ToU tariffs, as the average cost of energy displaced by the PV generation will be lower.

Intangible costs relevant to purchasing high-efficiency appliances

- Research time
- Setup time
- Taxes
- Loss of preferred experience

Key findings

Choosing more efficient products can result in lower overall cost of ownership in some cases, despite higher upfront costs [62]. Increased consumer awareness of total cost of ownership (accounting for operational costs such as energy consumption), as widely adopted in business-to-business transactions, could help drive the purchase of more efficient appliances.

However, long payback periods make cost effectiveness a very weak driver in consumer choice (these can be under 10 years for fridges and freezers, but often longer than typical appliance lifetime for washing machines and cooking appliances [63]). In some cases, choosing the most efficient products available can result in higher overall lifetime costs, despite reduced running costs [51]. The higher purchase price of these products may be justified on the grounds of higher product quality and additional features though, implying that not all of the additional cost is paid purely for efficiency. Replacing appliances before the end of their life specifically for the efficiency improvement will further lengthen or eliminate any payback.

Gradual replacement of existing white good stock with the most efficient options available could reduce electricity demand by these appliances by 8% by 2035 from 2015 levels [63]. The reduction from particular appliance types is much higher (51% in the case of tumble dryers), but this is balanced out by an increase in number of appliances, partly due to growth in number of households.

EU minimum energy performance standards gradually increase the minimum efficiency required for appliances placed on the market, meaning the efficiency of appliances purchases will gradually increase without consumer action.

Behaviour 2: Purchase high-efficiency appliances

	Theme	Commentary	Quantification approach
Time-related factors	Research time	Time taken to research the options, etc.	Research time x VoT
	Setup time	Time to configure the new appliance. Where the appliance purchase is occurring for non-efficiency reasons, e.g. replacing a failed appliance, it is assumed that the behaviour of choosing a more efficient product does not impact the setup time.	Nil when appliance replaced for non-efficiency reason
Costs	Taxes	VAT will apply to appliances at the standard rate of 20%	No adjustment to model required
Discomfort	Loss of preferred experience	Since the volume of sales of the most efficient class of appliances tends to be lower than that of lower rated appliances, we would expect the product selection of the most efficient products to be more limited. This could have implications for the range of options, features and designs available to customers choosing the most efficient appliances, as well as a disproportionate impact on price.	Not quantified

Intangible costs relevant to installing LED lighting

- Research time
- Taxes
- Loss of preferred experience
- Reduced maintenance requirements
- Safety and disposal
- Range of available outcomes
- Smart control

Findings

The manufacture and sale of incandescent light bulbs for most general domestic lighting was phased out in September 2018 by EU directive, meaning that once existing stock has been sold by retailers, they will no longer be available for purchase [64].

Compact fluorescent lamps, the energy-saving predecessor to LEDs, will be phased out in September 2021 [65] as the next round of Ecodesign takes effect (it appears unlikely that this will be affected by Brexit [66]). In fact, CFLs have already disappeared from supermarket shelves [67, 68], perhaps owing to the superior start-up performance, energy efficiency and lifetime of LEDs for a similar purchase price, as well as the avoidance of hazardous mercury at disposal or when accidental breakage occurs.

Behaviour 3: Install LED lighting

	Theme	Commentary	Quantification approach
Time-related factors	Research time	Time taken to understand suitable replacement for previous lighting type. Supermarket purchases may require almost no additional time as selection of lumen outputs and colour temperatures is often limited to those closely mimicking incandescent predecessors, however online shopping or purchase from large retailers may require understanding of lumen output and colour temperature.	Research time x VoT
Costs	Taxes	VAT will apply to bulbs at the standard rate of 20%	
Discomfort	Loss of preferred experience	The most commonly available LED products for domestic use are incompatible with dimmer switches [67, 68] Dimmable products must specifically be purchased, often from a separate retailer from the supermarkets, and on occasion these can be incompatible with the particular dimmer switches in use as well. Colour rendering is slightly poorer than incandescent equivalent, though unlikely to be noticeable in most cases. Colour rendering of LEDs is similar to compact fluorescent lamps, so no change will be experienced by those who are already accustomed to the CFL predecessors. Greater variation in light quality by product, and wider selection of available colour temperatures, some of which don't match traditional incandescent colour, may produce unsatisfactory results	Cost to replace light switch (if dimmer switch incompatible) £75-145 [69] (probably lower end as range includes relocation). Number of dimmer switch replacements needed unknown Not quantified Time for repeat purchase if unsatisfactory product purchased x VoT (could also apply to dimmer issue)

Behaviour 3: Install LED lighting

	Theme	Commentary	Quantification approach
Positive impacts	Reduced maintenance requirements	LED lighting has a longer lifespan than its incandescent and fluorescent predecessors, meaning replacement and disposal is required less frequently.	Change in annual replacement time x VoT
	Safety and disposal	Unlike compact fluorescent predecessors, LED bulbs do not have fragile glass tubes which release hazardous materials if broken. The imperative to dispose of compact fluorescents separately from household waste does not apply as strongly to LEDs, though recycling is still preferable.	Not quantified – time to visit recycling centre could be relevant, though likely incorporated with disposal of other items. Time to clean and decontaminate if CFL broken – frequency of breakages unknown.
	Range of available outcomes	The availability of a range of colour temperatures, lumen outputs, and special effects such as colour changing and remote dimming increase the versatility of domestic lighting	Not quantified
	Smart control	The smart features available with some LED products may facilitate energy savings through improved control, as well as greater convenience and functionality. Note however the additional power requirements for standby.	Not quantified. Standby power up to 0.5 W per bulb.

Quantification: initial method / approximations of intangible costs where feasible

• Install solar PV panels **Time-related intangible cost (one-off)** *Research time [hours] : [8-16]* *Coordination time [hours]: [5.5-14]* *Leaning how to use monitoring equipment: [1-2]* *Update insurance: unquantified* *xVoT* *[£/hour] : £5 ± 2* *Inverter replacement: £600-800 after 10 years* *Shifting time of electricity use could save £120 per year*	• Purchase high-efficiency appliances **Time-related intangible cost (one-off)** *Research time [hours] : [1-2]* *x* *VoT* *[£/hour] : £5 ± 2*
• Install LED lighting **Time-related intangible cost (one-off)** *Research time [hours] : [0.5-1]* *x* *VoT* *[£/hour] : £5 ± 2* **Reduced maintenance (ongoing)** *Replacement time saving* *Assume 3 lamps used for 3h/day* *Gives 3285 lamp-hours/year* *LED life: 15,000h* *CFL life: 8,000h* *Halogen life: 2,000h* *Time to replace lamp: 0.17h* *1.64 halogen replacements/year* *0.41 CFL replacements/year* *0.22 LED replacements/year* *Saving of 1.42 replacements/year against halogen* *Avoiding 0.24 hours maintenance/year against halogen* *0.03 hours/year against CFLs* *x* *VoT* *[£/hour] : £5 ± 2*	

NB: VoT = £5.22 [9]. Additional segmentation lifts VoT up for higher incomes
Values in red are ESC judgement. Values in blue are informed by literature, particularly [25]

How can these elements be used to supplement energy system modelling?

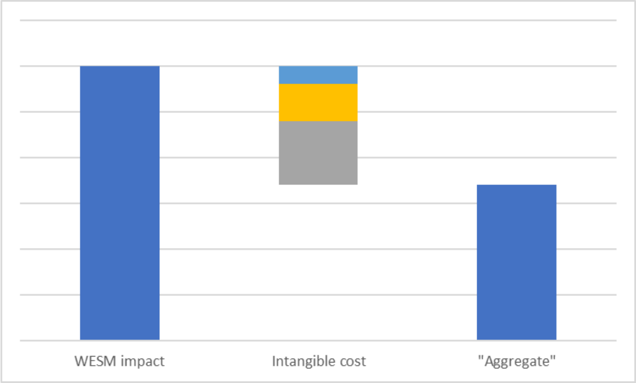
Qualitative

- Presentation of qualitative features of intangible costs alongside WESM costs
- Qualitative judgement applied to intangible costs (e.g. severity)
- Provides indicative view of challenges associated with behaviours

Behaviour	Model cost	Intangibles (e.g.)
Install solar PV panels	£X bn	Aesthetic impact, change of moving house before full economic benefit realised
Purchase high-efficiency appliances	£Y bn	Research time
Install LED lighting	£Z bn	Loss of preferred experience

Quantitative, off-model

- Behavioural adjustments applied to model, and system costs calculated
- In parallel, equivalent intangible cost derived (where possible) based on model outputs
- Magnitudes of system and intangible costs compared: illustration of size of barriers to overcome for behavioural change



Quantitative, on-model

- Inclusion of intangible costs within WESM's optimisation, influencing "optimal pathway"
- Most appropriate analytical approach likely to be to unwind intangibles from WESM cost – intangibles adjust preferred solution, adding "behavioural realism", but cost definitions unchanged from convention WESM costs
- Natural to combine with other analytical methods discussed in WP3 – variable hurdle rates, elastic end-use demands etc

Gaps identified: limited exploration in time available

Behaviour	Gap/subjectivity
Install LED lighting	Disutility of loss of preferred experience: how to quantify occurrence of unsatisfactory product purchase? How often are dimmer switch incompatibilities encountered? Number of dimmer switch replacements needed Avoided need to dispose of hazardous waste – what portion of households disposed correctly of CFLs previously? Did they make special trips for this purpose? Is it appropriate to assume LEDs can be disposed of in general waste?

Heat behaviour: energy systems modelling results

Working from home (WfH)

Behaviour being modelled
An additional 30% of the working population is willing and able to work from home an average of 2 days per week.

In 2019, 12.3% of the working population in the UK worked from home [70]. The recent COVID pandemic has increased this to 46.6% in 2020 [71] – this is taken to be the theoretical upper limit given that people have been strongly advised to work from home if they can. It should be noted that the COVID pandemic has meant that those currently working from home are likely to be doing so for a full working week. The modelled behaviour does not assume that this (lockdown) level of WfH will continue after lockdown restrictions have been lifted and instead assumes WfH occurs for 2 days per week on average.

The theoretical upper limit for those able to work from home would suggest an additional 34.3% of the working population do so. This has been tempered slightly so that the WfH assumption applies to an additional 30% (above 2019 levels). Therefore, in total 42.3% of the working population is assumed to work from home 2 days per week on average. In ESME, the increase in WfH applies from the 2025 time period which covers years 2021-2025.

In ESME, 2019 falls in the 2020 five-year time period (2016-2020). 2020 in ESME is also a "no COVID" year i.e. demand projections for 2020 were set before, and do not assume, the COVID pandemic. For these two reasons, it is an implicit assumption that the demand projections for 2020 account for the 12.3% of the population that worked from home in 2019.

Behavioural outcome
Two things have been adjusted in ESME to represent the WfH behaviour: a reduction in car travel demand; and an increase in residential heating demand. There is also likely to be a reduction in the number of passenger km travelled on public transport. However it is more difficult to determine what the effect of WfH is likely to be on the number of rail/bus services being provided i.e. trains may continue to run as usual but with fewer people on board. The COVID pandemic cannot as easily provide evidence on how WfH affects rail services because these have been restricted in order to minimise transmission of the virus as well as because of a reduced demand. No assumptions have been made about changes in energy demand (e.g. reduced heating, cooling, electricity) for commercial buildings that are no longer fully occupied by workers throughout the week.

Car travel demand reduction applies to the proportion of miles deemed to be for commuting, which is approx. 25% of miles driven [72]. Evidence suggests WfH 2 days/week increases residential heating demand by 7.1% [73]. This increase has been applied to the mid-day time-slice for the Winter season in ESME.

WfH: Car travel demand

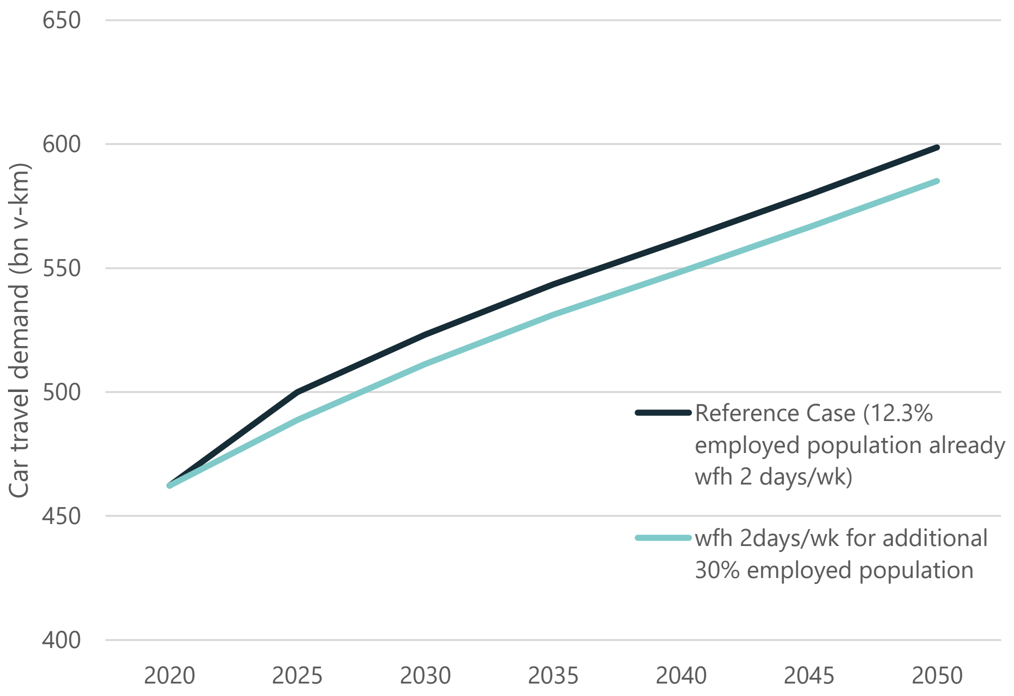
Methodology
Outlined below is the approach taken to estimate the updated car travel demand profile (resulting from 2 days/week WfH for additional 30% of working population) for use in ESME:

- Additional proportion of working population WfH = 30%
- Number of days WfH = 2 days per week (i.e. 40% working week)
- Proportion of total car travel demand assumed to be for commuting = 25%
- Rebound effect = 25% [74, 75]

Percentage reduction in total car travel demand = 0.3x0.4x0.25x(1-0.25) = 2.25%

Other assumptions
Car travel demand is assumed to increase out to 2050 but the proportion of this demand for commuting is assumed to remain fixed (i.e. 25%).

The UK population is assumed to increase out to 2050. The proportion of total population in employment is assumed to remain fixed (i.e. same as 2019 proportion of people in work approx. 49%). Proportion of this working population WfH is also assumed to remain fixed i.e. total 42.3% of working population WfH on average 2 days per week.



There is a relatively small reduction in car travel demand because this applies to a fraction of the UK workforce for a fraction of the miles travelled for 2 days per week. On top of this, a rebound effect is assumed which takes account of additional non-commuting miles travelled i.e. as people do not travel as much for work, they travel further for other reasons such as recreation and leisure [74, 75].

WfH: Heat demand

Methodology

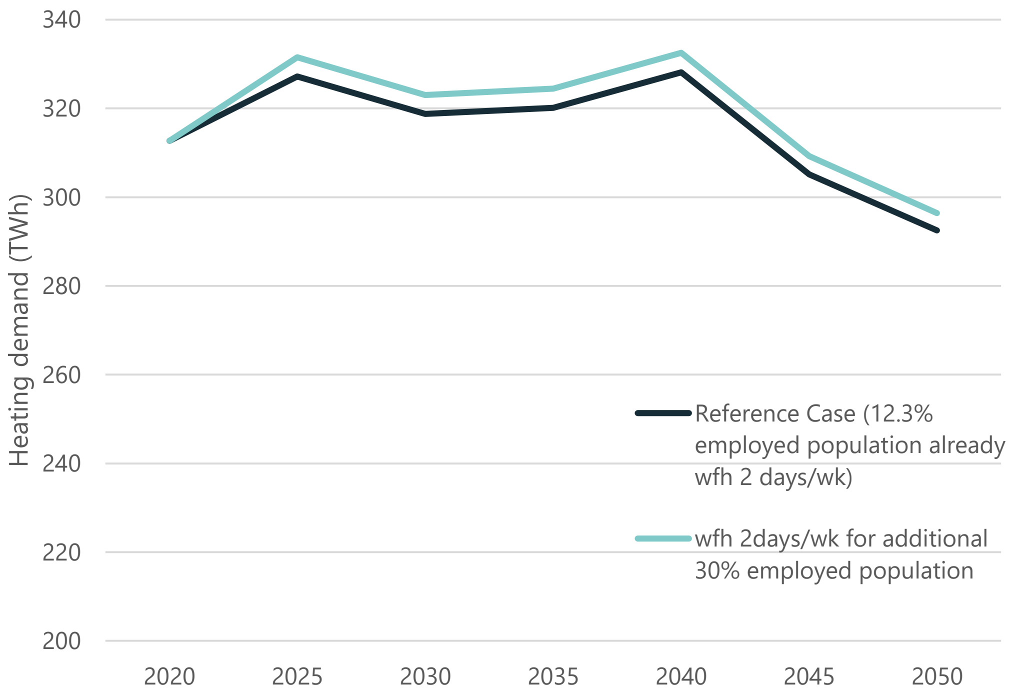
Heating demand as a result of WfH is assumed to increase by 7.1%. This needs to be applied to households with at least one person WfH. The number of households is estimated as follows:

- 12.5 million households in the UK with <u>all</u> occupants in employment
- 5.7 million households with at least one occupant in employment and one not in employment
- This gives 18.2 million households with at least one person in work[1]
- Assume 30% of these households will have someone working from home 2 days per week[2]
- Giving 5.46 million households with at least one person WfH experiencing a 7.1% increase in heating demand[3]

These 5.46 million homes cannot be treated separately in ESME. Therefore, to implement the demand increase, the 7.1% is spread over the entire housing stock. This becomes a 1.34% increase in heating demand for 29.9 million households assumed to be standing in the 2025 time period.

To account for the overall increase in heat demand, the appropriate increase in heating degree day for each house archetype modelled in ESME was necessary[4]. This was applied to the mid-day time slice for winter and peak seasons.

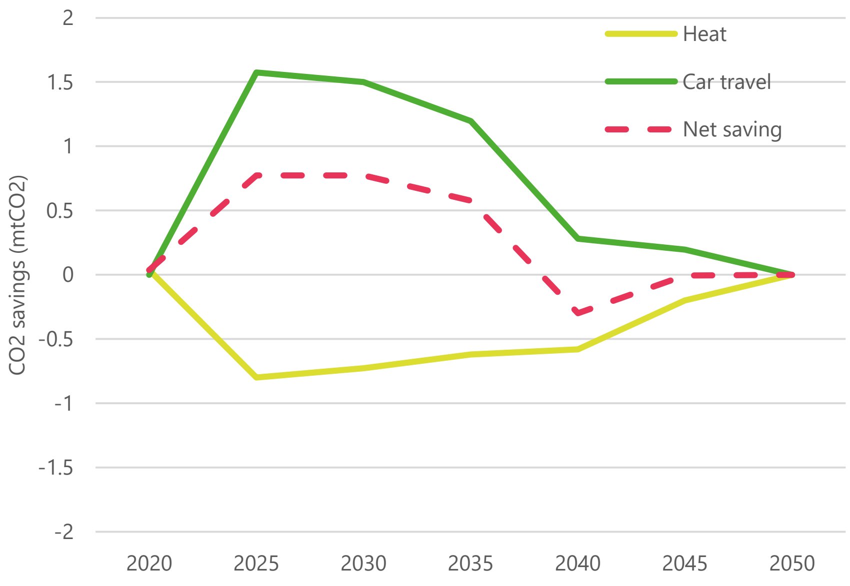
[1] This also includes those in part time work and therefore may be an overestimate. It excludes the 1.2 million people over 65 years of age also in employment.
[2] Some of these households might have multiple occupants WfH which means 30% is possibly an overestimate.
[3] If multiple occupants of a single household WfH for 2 days per week but on different days, then they would likely see an increase in heating demand greater than 7.1%. On the other hand, some households may have non-working occupants already at home during the day and a 7.1% increase in heating demand might be an overestimate for these homes.
[4] Heating degree days (HDD) are used to describe the heating needs of different house archetypes in different geographical regions and diurnal time slices out to 2050



Note that these heating demands are illustrative. They show the change in demand that would occur assuming the building stock remains identical to the Reference Case. In reality, ESME may well decide to make changes to the housing stock given the increase in heating demand (e.g. more retrofits).

Peaks in 2025 and 2040 are a result of the increased housing stock numbers and increasing set point temperature outweighing efficiency improvements.

WfH: travel and heating emissions

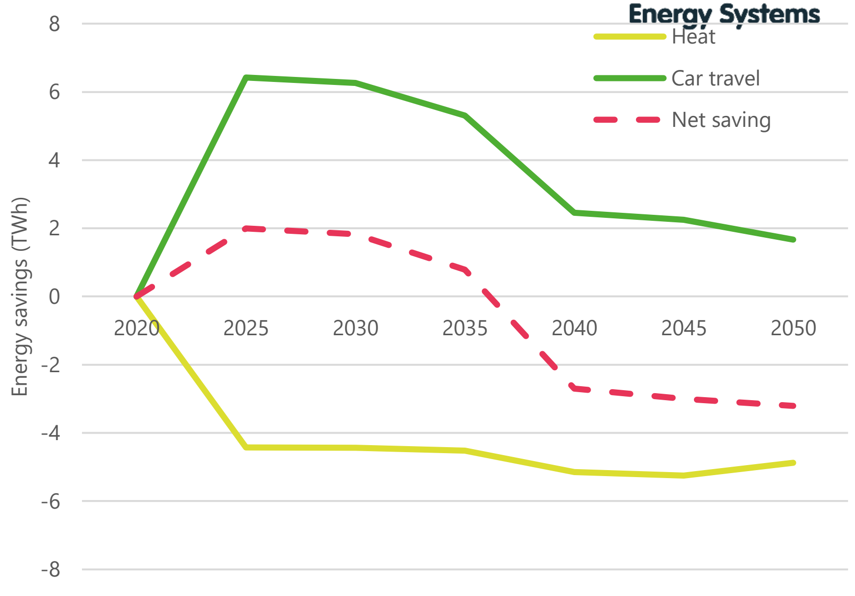


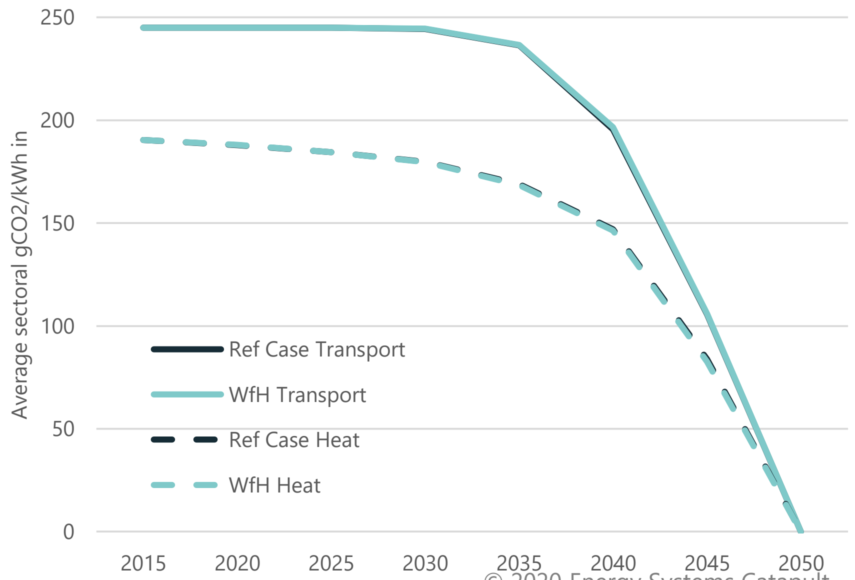
This chart shows the emissions saved from reduced car travel demand outweigh the increased emissions from higher heat demand as more people work from home relative to the Reference Case.

This net saving is in the order of 1-1.5mtCO_2/yr. from 2025 to 2035. Post-2035, the net saving diminishes as a result of a transition to zero carbon vehicles (ZCV). Once the entire car fleet is made up of ZCV, there are no direct CO_2 savings made by reducing car travel demand – this happens by 2050. By 2050, heating is also entirely decarbonised and so the increased heating demand does not cause an enduring increase in direct CO_2 emissions relative to the Reference Case. However, if increases to the heat demand are sufficient enough, this can have wider system effects as more electricity, hydrogen and district heat is needed to meet demand (or more building retrofits are installed to reduce thermal losses from homes).

The two charts to the right show why emissions savings associated with reduced car travel are higher than the increase from heating: Firstly, the amount of energy saved by reducing car travel is higher than the increased energy consumption to meet higher heat demands (top chart). Secondly, the average carbon intensity (measured in gCO2/kWh consumed) associated with car travel is higher than for heating (bottom chart). Therefore each kWh not put in the tank is associated with higher emissions savings than those gained from heating.

Lower car travel demand and increasing efficiency of EVs means that post-2035, more energy is consumed to meet additional heat demand than is saved by not commuting to work. However the overall impact on emissions is small because these sectors are decarbonising and the scale of demand change is relatively modest.





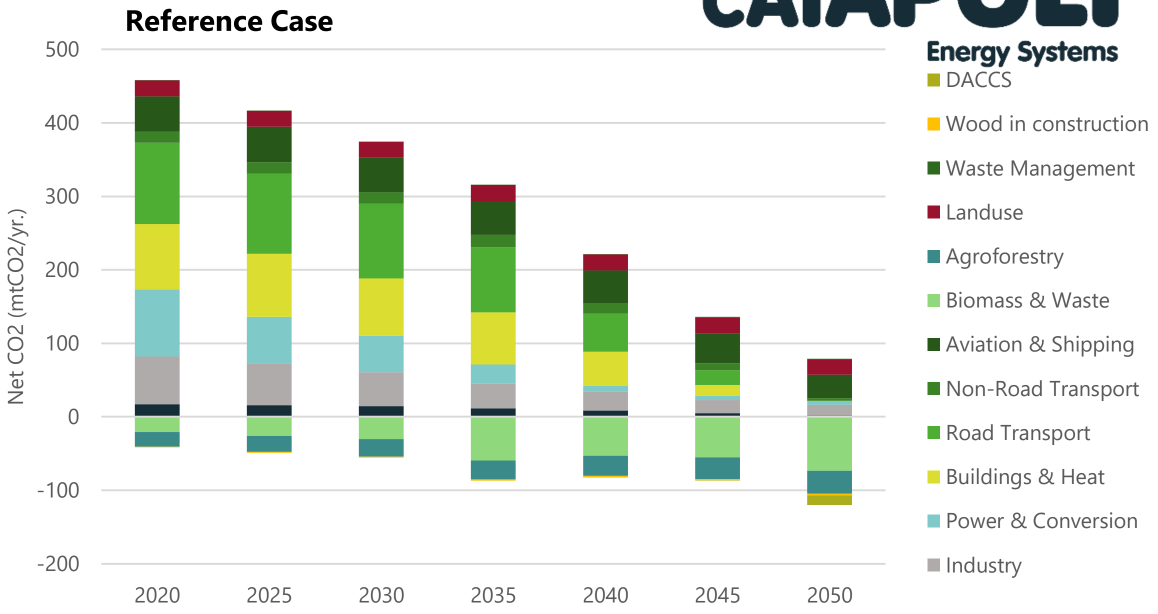
WfH: whole system emissions and costs

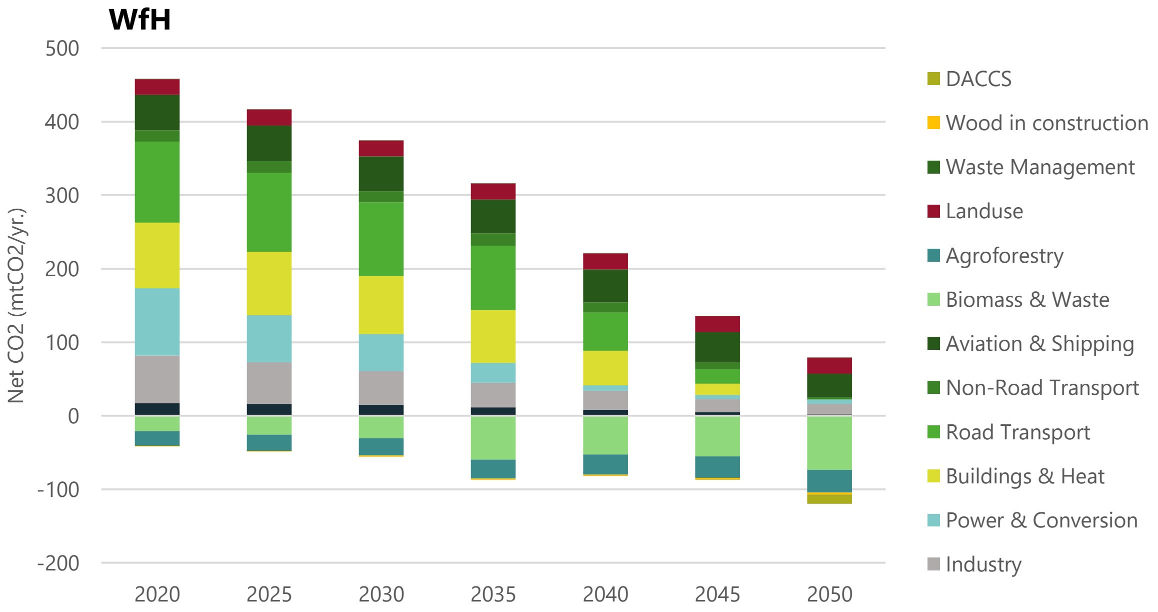
EMISSIONS
There is a relatively small saving in emissions from WfH behaviour. Approximately half of the emissions saved in the transport sector are offset by a increase in emissions from additional heating requirement. This leaves emissions headroom in the near-to-mid term in the order of 1-1.5mtCO_2/yr.

The emissions headroom is utilised by ESME in the power sector. The power sector generally sees the earliest and most rapid decarbonisation since this is a cost effective way to meet early carbon targets. Therefore emissions headroom generated in other sectors in the earlier time periods cause the model to pull back on decarbonisation in the power sector. In the WfH run, changes to the power sector are small amounting to a 2TWh increase in the output of combined cycle gas turbines (CCGT) in 2025 and 2030 – however, the installed capacity remains the same in both runs.

There are 56,000 fewer whole house retrofits overall by 2050. However, of the homes that have been retrofitted, 8,000 are of the more extensive, Retroplus option. It's worth noting that since ESME aggregates all heating demand in a region, it is not the right tool for assessing optimal decisions for individual homes. By 2050, 200,000 more homes are connected to district heat networks relative to the Reference Case, supported by large scale heat pumps.

COSTS
WfH achieves approximately £1.5bn reduction in total discounted system cost over the entire pathway. Typically, reducing car demand leads to greater savings in ESME because reducing demand leads to fewer vehicles on the road (therefore savings in capital and fixed costs associated with car ownership are made). In this model run, it is assumed that car ownership (and the associated costs) are unaffected by the WfH behaviour i.e. people continue to own cars – this reduces the system cost savings.





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