AGENT BASED MODELLING OF A HEAT MARKET

A report prepared for the National Infrastructure Commission

10 May 2021

CONTENTS

EXECUTIVE SUMMARY

Decarbonisation of the domestic heating sector will be a crucial part of the UK's pathway to net zero by 2050. The vast majority of homes are currently heated by gas boilers, and these will need to be replaced with low-carbon alternatives such as heat pumps or hydrogen-fired boilers.

Many models of this transition have been built. Often, these focus on the optimal pathway – i.e. the heating technologies which should be used in each year to minimise the overall cost of the system, while meeting various constraints (such as ensuring that demand can be met while respecting carbon targets). However in reality and in the absence of extremely restrictive policies, the decisions on which heating technologies to use are ultimately made by households. These decisions will be driven by a wide variety of factors that go beyond long-run cost minimisation – for example:

- influences from other people, such as neighbours or installers;
- non-monetary costs and benefits (e.g. the hassle of installing or running a specific technology);
- differences in the discount placed on the value of long-run benefits versus up-front costs and;
- differing attitudes to “green” technologies.

An agent-based model (ABM) simulates the interactions between autonomous entities, which can have differing properties and actions. In the context of the heat market, property owners can be modelled as agents, with rules defining how they make their choices of heating systems. The National Infrastructure Commission (NIC) has commissioned Frontier Economics to build such a model as a pilot project, to see whether ABMs can provide insights into questions such as how the heat market may develop, and to which factors the outcomes may be sensitive to. While this work is not intended to assess specific policies, it can show whether this type of modelling may be a useful tool for policymakers.

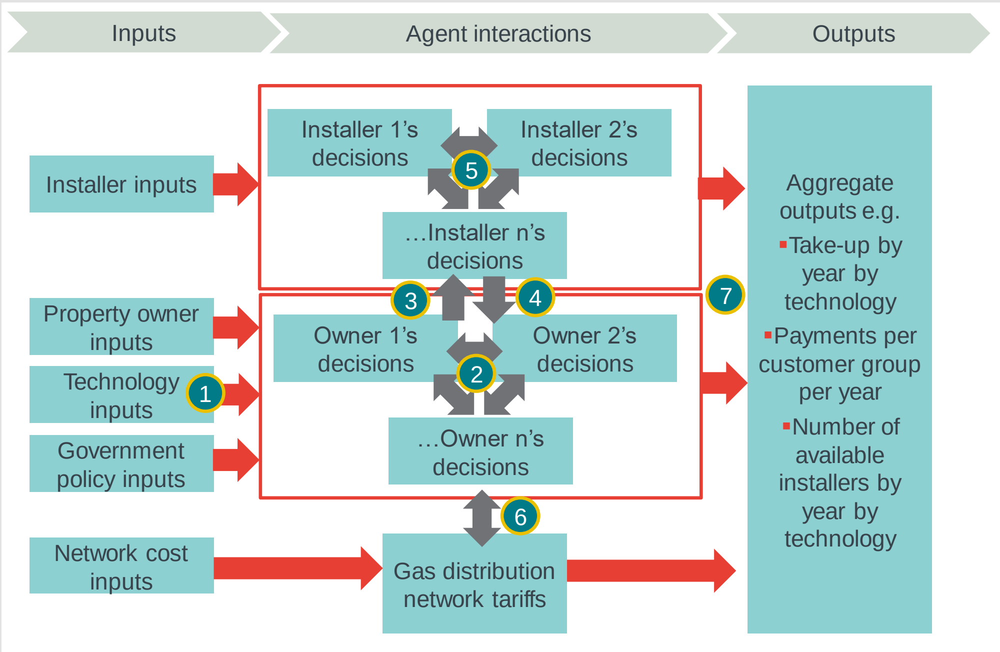
Model methodology

The model we have built is outlined in the box below. Property owners' decisions are the core of the model, and are modelled as being driven by the factors noted above. The parameters of the model have been set based on previous research into consumer choice, as well as ensuring that the model is able to broadly replicate historic take-up of heat pumps under the Renewable Heat Incentive (RHI).

In addition to property owners, the model considers the actions of installers and gas distribution networks (GDNs). As noted in the box below, the decisions taken by these entities influence one another. These interactions have the potential to lead to effects such as virtuous circles (where take-up of low carbon heating technologies by some owners results in greater take-up by others). Other dynamics may also be possible: for example the finite availability of installers could lead to take-up by some owners having an *adverse* effect on the take-up of others. By simulating these interactions, the ABM can illustrate the high-level outcomes that emerge as a result.

HIGH-LEVEL SUMMARY OF THE MODEL

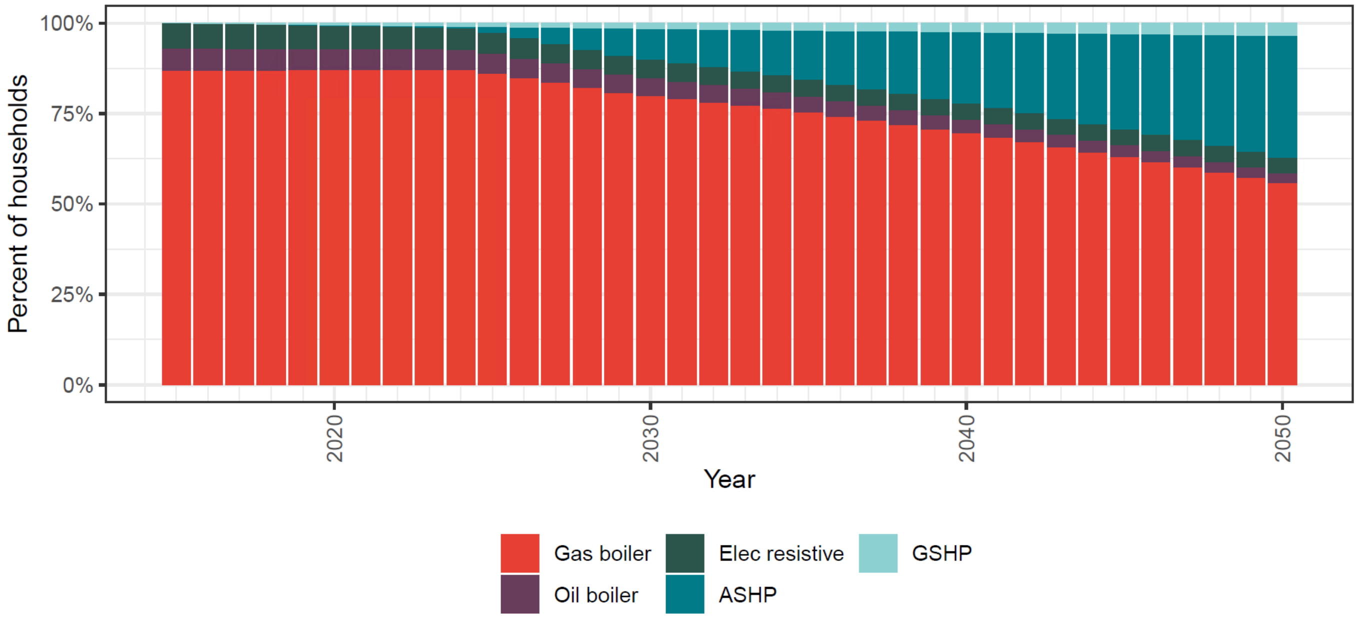
- **Owners of properties** are modelled as agents who decide which heating system to take up when their existing system reaches the end of its life. They make their decisions based on factors (1) such as the cost and perceived hassle of installing and running a given technology.
- They are also influenced by other nearby owners (2) – the more high quality heat pump installations there are locally, the more likely an owner will get one installed.
- Owners' decisions are influenced by **installers** (3), who are the second type of agent modelled. It is not possible to install a technology without a trained local installer, and installers may themselves recommend technologies they are more familiar with.
- Installers choose to enter and exit the market based on the demand for different technologies from property owners (4) and local supply from other installers (5).
- If property owners choose to stop using gas-fired heating, this leads to the **gas distribution network operator** setting greater network tariffs for other owners, which may in turn affect their decision (6).
- The model outputs the resulting aggregate take-up of heating technologies (7), as well as detailed outputs split by groups of agent.



Forecast take-up of low-carbon heating technologies in an scenario with no hydrogen transition

Figure 1 illustrates the high-level outputs of the model when a scenario is run where the only low-carbon source of heating comes from electrification (through the deployment of heat pumps). A carbon price has been applied to gas, based on the Green Book appraisal values, to act as an incentive for decarbonisation. Each stack of bars represents the technologies in use for a given year. It can be seen that, despite their increased running costs, gas boilers remain the dominant technology by 2050. This is due to the way in which customers are assumed to be making decisions, rather than the specific assumptions made regarding the installation and operating costs of the technologies. This can be seen by running the model with the same cost assumptions, but with customers making decisions on a purely cost-minimising basis (and with a low discount rate). In that case, the take-up of heat pumps is much higher, similar to the pathways produced by optimising models.

Figure 1 Take-up of heating technologies in electrification only scenario, 2015 - 2050



Source: Frontier Economics

The model is therefore able to quantify the impact of these barriers to take-up and the effect if they can be overcome. For example, with model inputs based on the results of previous consumer choice experiments, the high discount rates assumed for some types of homeowners (especially private landlords[1] and low-income owner-occupiers) are a much greater barrier than the monetary value that households are assumed to place on the hassle of installing and running a heat pump. This suggests that:

- Policies which lead to a significant increase in the cost of gas, without addressing the issue of up-front costs, may be insufficient to lead to a complete transition to low-carbon forms of heating.
- However, policies or business models which spread the up-front costs of renewable heating technologies (for example loans or lump-sum subsidies) could have a significant impact.
- And this may be the case even if it is not possible to reduce some of the "hassle" factors, which may be intrinsic to the technologies themselves and less amenable to policy intervention.

While these types of result are useful and illustrate that the model is functioning in a way that appears reasonable, they do not require a full ABM. Demonstrating the

[1] This may be the case if rental values do not fully reflect the costs of heating a property.

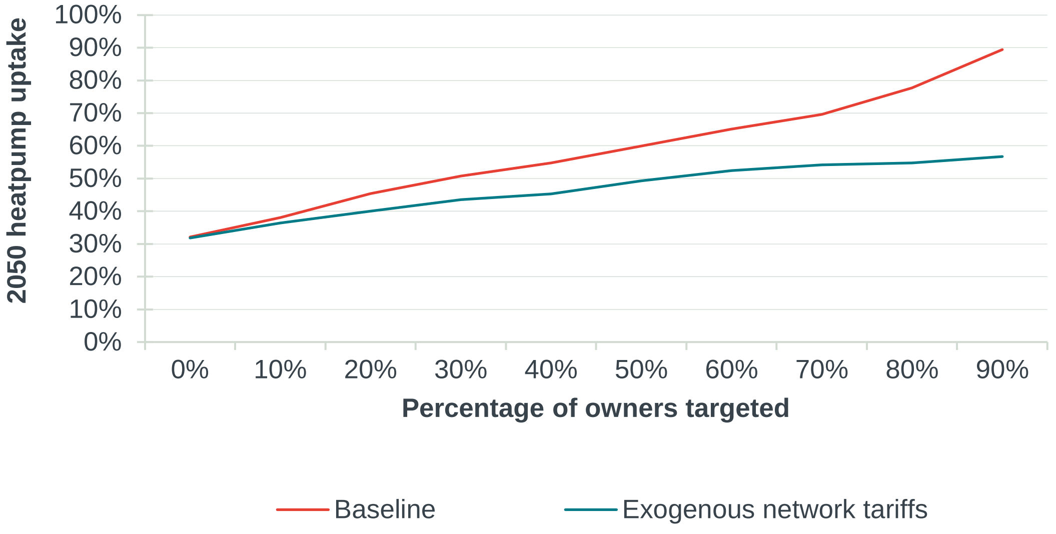
relative impact of different barriers to low-carbon heating could be carried out in a simulation where property owners were modelled as having different discount rates, aversions to hassle etc, without any interactions between them: The results are ultimately driven by the findings of the choice experiments used to calibrate the model. The real value of an ABM comes from being able to simulate the results when the actions of one agent can affect another. This can lead to an emergent outcome which could not be forecast when only considering agents individually.

Influence of interactions within the model

To determine if these interactions are material, a series of model runs were carried out where heat pumps were "forced" onto a varying proportion of households (many of whom would not have taken up a heat pump otherwise). This can be seen as representing a policy which is targeted at one subset of owners, while not affecting other owners (who are still free to purchase a heat pump if they wish).

The red line in Figure 2 plots the take-up of heat pumps by the owners who are *not* targeted. This demonstrates that there is a material spill-over impact on these owners – something that could not be captured within a model that considered them in isolation from one another and the wider system.

Figure 2 Impact of increasing the number of "green" owners on other owners' take-up decisions



Source: Frontier Economics

Some of this effect comes through network tariffs: If property owners take up heat pumps, they are assumed to disconnect from the gas network. The need to recover fixed costs from a smaller customer base is assumed to increase tariffs, leading to higher gas prices and a greater incentive for others to take up heat pumps. However even if this effect is removed from the model (as shown by the teal line above), the take-up by a subset of owners still has a positive influence on the remainder.

There is therefore a multiplier effect, where policies can have a wider impact other than on the group they are directly aimed at. Under our baseline scenario, we calculate that this multiplier may be as high as around 0.52 (i.e. for every one property that is directly “targeted” for a heat pump, a further 0.52 may be indirectly brought forward by 2050).

All else equal, policies which can exploit these types of multiplier effect will be more cost-effective. While this modelling has not been intended to assess specific policies, we have shown how the multiplier effect may be higher if other policies or business models are already in place that spread the up-front cost of technologies. However the multiplier effect may be dampened if the targeted group of owners is too clustered (e.g. a very large intervention in a single town may have less spillover effect than if it was spread out further).

These specific results will depend on the exact way in which property owners and installers interact: The model currently assumes that they influence one another within a set geographic radius, while in practice some channels of influence (for example media or social networks) might not be so defined geographically. However they demonstrate how, in principle, policies can be designed to better exploit these types of linkage.

A transition to hydrogen

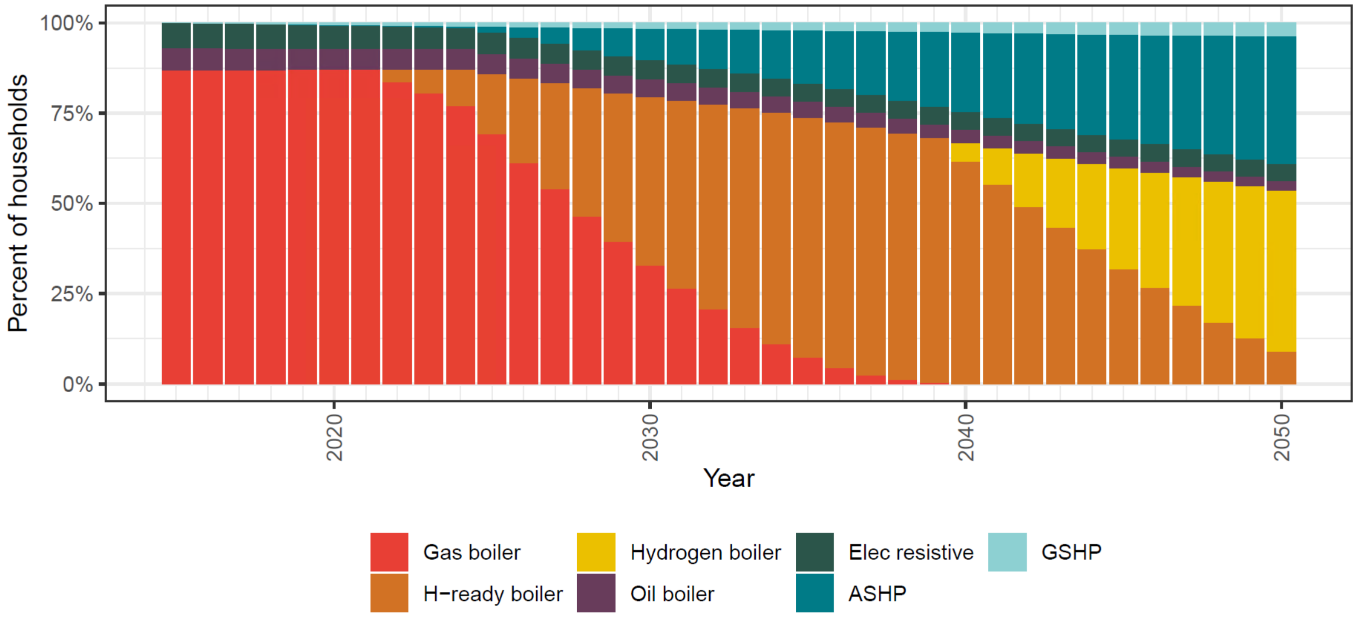
A move to hydrogen may be an alternative way of overcoming some of the barriers to decarbonisation of heat if (as assumed in our model) the costs and functionality of hydrogen boilers are assumed to be broadly similar to those of gas boilers. This would require the development of a hydrogen transmission network and conversion of the distribution networks, large costs which are not directly modelled here. However a significant degree of central co-ordination will also be required to guide consumer choices and ensure there is not a last minute need for many customers to switch their boilers.

We have modelled a transition to hydrogen which is defined by the following policies:

- In 2022, the hydrogen switch-over date is announced, and hydrogen-ready boilers (which can burn natural gas or hydrogen) become available.
- In 2025, hydrogen-ready boilers are mandated, with consumers unable to purchase natural gas boilers.
- In 2040, the switch to hydrogen for the region occurs.

Figure 3 shows the resulting take-up.

Figure 3 Take-up of heating technologies in hydrogen scenario, 2015 - 2050



Source: Frontier Economics

In this scenario, the mandation of hydrogen-ready boilers ensures a smooth transition, without promoting an unsustainable demand for installers. This is not the case for an alternative scenario where hydrogen-ready boilers become available in 2030 and are mandated only in 2035: A large number of gas boilers are still present in 2040,[2] and the demand for installers in the switch-over year exceeds supply.

Conclusions and next steps

This project has demonstrated that an ABM can produce useful insights regarding the heat market. Some of these insights could also be drawn from a simpler model which looked at consumers in isolation and modelled the drivers of their decisions. However such a model would overlook interactions between market participants which can mean policies have greater impacts than the sum of their impacts on individual customers. We have shown how such effects may be material, and that understanding them could help design cost-effective policies.

ABMs can include a vast number of parameters defining how agents interact, and it is therefore important to ground them in evidence on how consumers react in the real world. This model has been calibrated from two main sources: Past research on customer behaviour (generally from choice experiments), and observed behaviour under the RHI.

Consumers making decisions in real life may act differently to those in choice experiments, and those who have taken up the RHI to date are not representative of the wider population that will need to take up heat pumps in the future. It is

[2] In some cases, this is due to homeowners' heating systems not requiring replacement between 2030 and 2040. In other cases, homeowners with high discount rates will have purchased gas boilers in the period 2030-2035, due to their lower upfront costs.

therefore difficult at this stage determine the accuracy of the assumptions that the model has been populated with.

The model is more sensitive to changes in the costs of technologies (which are likely to be better understood) than the parameters relating to owner or installer behaviour. However the functional form that we have used to model property owners' and installers' decisions is one of many possibilities. Further research and calibration would therefore be necessary to produce an ABM which could produce a single forecast of this market with greater confidence.

The very structure of an ABM, where the behaviours of each agent is made explicit, provides a clear and objective framework around which to build the evidence base for consumer decision-making. The process of constructing an ABM requires codifying a wide variety of assumptions – for example, the factors that property owners and installers take into account when making decisions, and their relative importance. While there may be substantial uncertainties around these assumptions, documenting them formally can help subject-matter experts engage more deeply. And, as low-carbon heating systems become more mainstream, it will be possible to carry out further choice experiments and econometric exercises which can provide additional validation to the inputs. Future demonstrators and trials should be designed in a way which enables evidence to be gathered and used to build on a model like this one.

Even without additional research, this model is still be useful for policymakers as a powerful way of answering "what-if" questions. For example, say that a particular policy was proposed which was intended to increase the take-up of low carbon heating by a certain amount. The model could be used to verify if there are at least certain plausible conditions under which this could occur. If the policy requires particular conditions, targeted research could then be carried out to test if these hold.

1 INTRODUCTION

The UK is committed to bringing greenhouse gas emissions to net zero by 2050. Direct emissions from buildings[3] currently account for around 17% of UK emissions, with homes accounting for the vast majority (77%) of this.[4] Decarbonisation will require a radical shift in the technologies used by consumers, away from boilers burning fossil fuels (primarily gas) to low-carbon sources of heating. For example, the Prime Minister's recent Ten Point Plan includes a target for the installation of around 600,000 heat pumps per year by 2028,[5] approximately 20 times higher than the number installed in 2018.[6]

The choice of heating system for a property will typically be made by its owner. To make the transition to a low-carbon heating system, Government will need to make regulations and policies which incentivise and possibly constrain some of these choices.[7] However, unless *all* choice is taken away from *all* property owners, the way the transition occurs will still depend on the choices made by millions of individuals.

A considerable body of research, both within the context of the heating system and more widely, demonstrates that consumer choices are complex and influenced by factors such as "social proof" and prior attitudes. However many models of the decarbonisation of heating omit these factors. For example, optimisation models are frequently used which assume that consumers will pick the technologies that are optimal from the perspective of the energy system as a whole. If consumers do not act in the way implied by these models, their forecasts will be less applicable as predictions of what will actually happen.

An agent-based model (ABM) simulates the interactions between autonomous entities (which can have differing properties and actions). In the context of the heat market, property owners can be modelled as agents, with rules defining how they make their choices as heating systems. The National Infrastructure Commission (NIC) has commissioned Frontier Economics to build such a model as a pilot project. This model will show whether ABMs can provide insights into questions such as how the market may develop, and which factors the outcomes may be sensitive to.

The remainder of this introduction sets out the main options for a zero-carbon heating sector. We set out how these have often been modelled to date, and how these models do not account for potential issues that may arise during a transition which will be largely decentralised and dependent on consumer choice. We then describe why agent-based modelling can provide answers to some of these questions.

The rest of this report is structured as follows:

3 This measure excludes emissions from power stations used to generate the electricity used by buildings.

4 Committee On Climate Change (2020), *The Sixth Carbon Budget: Buildings* p6

5 https://www.gov.uk/government/news/pm-outlines-his-ten-point-plan-for-a-green-industrial-revolution-for-250000-jobs

6 https://committees.parliament.uk/committee/365/business-energy-and-industrial-strategy-committee/news/119747/committee-launch-decarbonising-heat-in-homes-inquiry/#_ftn4

7 For example, banning the use of a certain heating technology, as has already been done for non-condensing boilers.

- First, we describe in detail the model that we have developed and our assumptions (a mathematical specification of the model is included in the annex).
- We then present the results of our model when applied to a scenario where the only available path to decarbonisation of heating is electrification (through the use of heat pumps and electric resistive heating). We show how the modelled outcome varies as the parameters of the model are adjusted, and how the interactions between agents in the model affect the results.
- The following chapter presents the results of the model when applied to a scenario that includes the conversion of the gas grid to hydrogen.
- The final chapter summarises the potential next steps from this work, both in terms of implications for policy, and how this type of modelling could be developed further.

1.1 The path to a decarbonised heating sector

To reach net zero emissions, it will be necessary to move away entirely from fossil-fuel burning heating appliances (such as gas and oil boilers). The three main classes[8] of technology that could replace boilers are:

- electrically powered heating;
- the use of green gas or hydrogen in boilers; and
- heat networks.

1.1.1 Electrically powered heating

The power system is rapidly decarbonising with the Government aiming for a fully decarbonised power system by 2050.[9] Replacing fossil-fuel boilers with decarbonised electrical heating systems will therefore remove emissions from the heating sector.

Traditionally, the majority of electrical heating systems in use have been **electric resistive heating**, where electrical energy is directly converted into thermal energy. However heating a building in this way requires a substantial amount of electrical energy. This leads to both high fuel costs and, if many buildings in an area are converted from fossil fuel boilers to electric resistive heating, could lead to capacity on the local electricity networks being exceeded, with resulting reinforcement costs to increase their capacity.

These issues can be mitigated by using **night storage heaters**, where heat is produced during the night (when electrical demand is lowest and prices are lowest) and then released throughout the day. However these systems are currently less flexible,[10] and if deployed widely would still require a substantial increase in

[8] Solar thermal heating could also form a part of the heating technology mix, although will generally need to be deployed alongside other technologies.

[9] Energy White Paper p42.

[10] For example, if a storage heater has not been charged overnight, then it will not be able to provide heat without consuming expensive day-time electricity.

generation and network capacity (as large numbers of night storage heaters could result in the creation of a new peak in demand).

A heat pump uses electricity to transfer heat from outside a building into the building. It can therefore provide the same amount of heat using less electricity: While an electric resistive heater can convert 1kWh of electrical energy into 1kWh of heat energy, a heat pump might deliver 3-4kWh of heat energy[11] for the same input (with ground-source heat pumps typically being more efficient at providing space heat than air-source models). This greater efficiency mitigates (but does not eliminate) the problems caused by an increase in electrical demand.

Typically, a heat pump will be most efficient when outputting at a lower temperature output than a fossil-fuelled boiler. This may require changes to be made to a property such as installing additional insulation or under-floor heating before the heat pump can be installed. The heating may be less responsive than under a gas boiler,[12] and can take up a greater amount of space.

The heat pumps modelled within this report are high-temperature units which can be connected to a standard radiator system. However they do still require a minimum level of insulation to be installed if not already present.

Hybrid heat pumps are also possible, combing a heat pump with another technology such as a gas or hydrogen boiler which can provide heat during peaks of demand.

Heat pumps can also be categorised by the source of the heat they draw on. The two types of heat pumps most commonly used are:

- **Air-source heat pumps,** which transfer heat energy from the air surrounding a property; and
- **Ground-source heat pumps** which transfer heat energy from the ground surrounding a property.

Ground-source heat pumps can have lower running costs (as the temperature underground will generally be higher than the air temperature during winter). However they require the installation of a large amount of piping (a ground loop, which can either take the form of a horizontal trench or a vertical borehole). Installing this is only possible for properties with outside space, and means that the installation costs of a ground-source heat pump are higher. A single ground loop can potentially be shared among properties (for example flats within a building) each having their own heat pump.

1.1.2 The use of green gas or hydrogen in boilers

For homes on the gas network, instead of replacing gas boilers with an electrically powered heating system, a similar boiler could be used with a zero-carbon fuel, delivered through the existing gas distribution networks.

One option is **biomethane**. This is a form of gas produced from processes such as anaerobic digestion, which can be used as a substitute for natural gas.

[11] The efficiency of a heat pump will tend to be lowest when outside temperatures are lower. This seasonal effect is accounted for in the ESME dataset used in our modelling.

[12] I.e. if the heating is not kept on, it may take longer to reach the desired temperature.

Relatively small amounts of biomethane are already injected into the gas system, and do not require consumers to make any changes to their boilers. However there is unlikely to be sufficient supply of biomethane to entirely displace all current uses of natural gas.[13]

An alternative is to move away from natural gas to **hydrogen**. This could be produced by either:

- Using the steam methane reformation (SMR) process to extract hydrogen from natural gas, with carbon capture and storage (CCS) to sequester the resulting carbon; or
- carrying out electrolysis (splitting water into hydrogen and oxygen) using low-carbon electricity.

Once hydrogen is available (which would require significant investments in hydrogen production, transmission, and potentially CCS), sections of the local gas networks could be switched over from natural gas to hydrogen. Hydrogen-fuelled boilers are currently being trialled, and work in a very similar way to natural gas boilers from the consumers' perspective. However conventional natural gas boilers are not able to safely burn hydrogen. They would therefore need to be removed before any such switchover.

This transition may be eased by the use of "hydrogen ready" boilers, which can burn natural gas, but be swiftly changed over to burn hydrogen (perhaps by replacing the burner unit within the boiler).

1.1.3 Heat networks

The technologies described above all involve the generation of heat within a property. An alternative is to generate heat elsewhere, and use a system of pipes (a heat network) to transfer the heat to each property, where a hydraulic interface unit transfers the heat to the property's pipework. The network can be as small as a single building (e.g. a block of flats), or can cover a large area.

Many sources of heat can be used for such a network. For example, some current schemes use a combined heat and power (CHP) generator to produce both heat for the network as well as electricity. To reach net zero, the heat source would need to be zero emission, although a network could be built using a carbon-emitting heat source and later transitioned to a different heat source such as:

- large-scale heat pumps;
- large-scale boilers or CHP engines using fuels such as biogas or hydrogen; and
- waste heat from industrial facilities or power stations.

A key constraint on district heating is the density of properties. As pipes need to be laid to all the buildings on the network, such systems are most cost-effective in urban areas (or sites such as campuses) where there are a large number of buildings that can be connected to the network in close proximity.

[13] The CCC previously estimated that biomethane might be able to displace around 5% of natural gas by 2050. See CCC (2016) Biomethane Technical Note - https://www.theccc.org.uk/wp-content/uploads/2016/12/2016-PR-Biomethane-Technical-Note.pdf

1.2 Modelling heat decarbonisation

A variety of modelling approaches have previously been applied to determine what a transition to a decarbonised heating system may look like. This section provides a brief overview of two approaches: fully optimising models, and a model which starts from a 2050 endpoint and then builds a trajectory based on the types of policies which might be consistent with it.

1.2.1 Fully-optimising models

To date, much modelling of heat decarbonisation has focussed on the optimal roll-out of heating technologies as part of the wider energy system, under a variety of scenarios. A model can be developed which includes the costs and performance of a variety of technologies, such as:

- heating technologies (such as gas boilers or heat pumps, which convert fuels such as electricity or gas to usable heat);
- power generation technologies (which convert fuels to electricity); and
- transport technologies (such as petrol or electric vehicles, which convert fuels to usable transport).

These types of model, implemented as a mathematical optimisation, can determine the trajectory of take-up of each type of technology which minimises overall costs, subject to various constraints such as always ensuring demand for heat and demand for electricity is met. The imperative to take up low-carbon technologies can be simulated either through a further constraint (such as a cap on emissions), or by adding in a cost of emissions.

One such model is UK TIMES, used by BEIS in some of the modelling of the electricity sector for the Energy White Paper.[14] Another is the Energy Technology Institute's ESME model. Figure 4 and Figure 5 below show two scenarios which were informed by this model: A "Clockwork" scenario with well co-ordinated long-term investments, and a "Patchwork" scenario with a less centralised government intervention (for example no co-ordinated switchover from natural gas to hydrogen). Under both scenarios, heat pumps account for the majority of heating technologies by 2050, with some role for district heat and (in the "Clockwork" scenario) hydrogen.

[14] BEIS (December 2020), *Modelling 2050: Electricity System Analysis* p6

Figure 4. "Clockwork" scenario

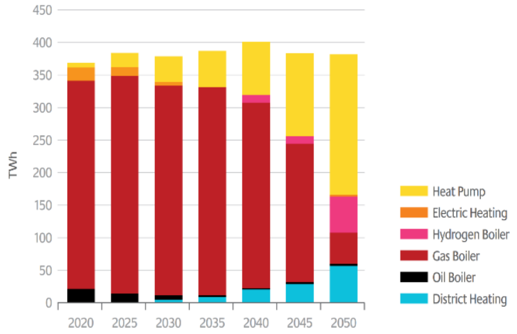
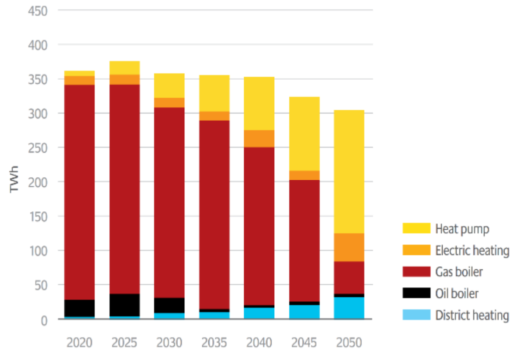


Figure 5. "Patchwork" scenario



Source: *Reproduced from ETI (2018), Options, Choices, Actions Updated*

Note: *These scenarios envisage the use of heat pumps alongside gas boilers (in a hybrid configuration to provide a supplementary heat source on cold days). When expressed in terms of installed capacity (as opposed to energy output as shown above) heat pumps are therefore a much lower proportion of the market. However, the vast majority of homes would still have a heat pump installed.*

These models are extremely useful in showing which pathways may be able to decarbonise the heating system at lowest cost, for a given scenario. However, unless there is an entirely "command-and-control" approach to the transition (with Government mandating the specific heating technologies that individual households must take up), the uptake of heating technologies will ultimately depend on the choices made by millions of individual consumers.[15] As noted in the ETI's commentary on these scenarios, "*transitioning to any of the alternatives portrayed here will require powerful consumer propositions that match, if not exceed, current experiences of energy provision in the home*."

The consumer psychology and behavioural economics literature makes it clear that consumers do not, in general, behave as perfectly informed and "rational" cost-minimisers. Consumers' choices may be affected by factors such as the perceived hassle of switching heating technology, or the extent to which they are familiar with one technology versus another. A significant amount of government intervention (for example, though building regulations, or subsidies and taxes) is therefore likely to be required to ensure that consumers take up technologies in a way that matches the "optimal" pathway set by these models.

1.2.2 Modelling a trajectory based on policies

Some models have sought to more directly account for the policy levers that may be required to move to a decarbonised heating system.

For the Sixth Carbon Budget, the CCC commissioned a range of scenarios for the deployment of energy efficiency, behavioural change, and technology adoption in the domestic heat sector.[16]

This modelling first calculated an end-state for 2050, based on the cost-effectiveness of interventions (on a net present value basis), wider benefits (for example more energy efficiency measures are assumed to be deployed to help

[15] These choices will still be subject to constraints. For example, if natural gas is phased out, then a gas boiler will not be an available option. However consumers may still be able to choose between a variety of technologies, such as electric resistive heating, heat pumps, and hydrogen boilers.

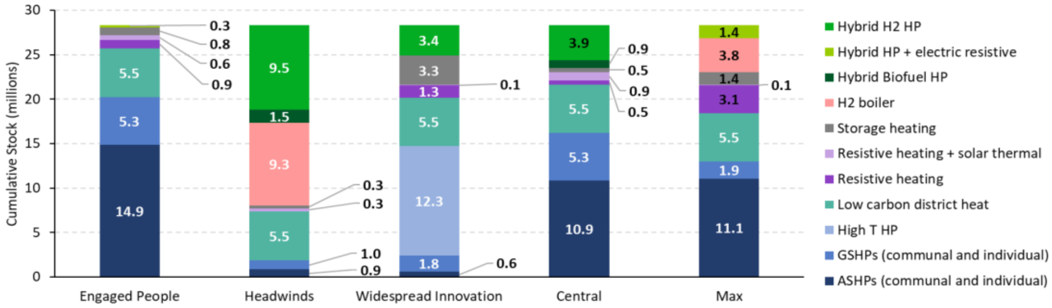
[16] A summary is provided on p100 of CCC (December 2020) *The Sixth Carbon Budget: Methodology Report.*

tackle fuel poverty) and consumer preferences (considering different mixes of intervention that would still reach net zero). Trajectories towards this end-state were then developed, based on:

- realistic regulatory levers (e.g. relating to the date from when all new heating technologies must be low carbon); and
- overall constraints on the maximum speed of roll-out of technologies.

Figure 6 shows the 2050 end-states of the five scenarios created as part of this modelling. All of them include a high number of heat pumps (whether conventional or hybrid units), although there are very significant differences in the technology mix. For example, one scenario ("Headwinds") includes a much higher proportion of hydrogen boilers than the others.

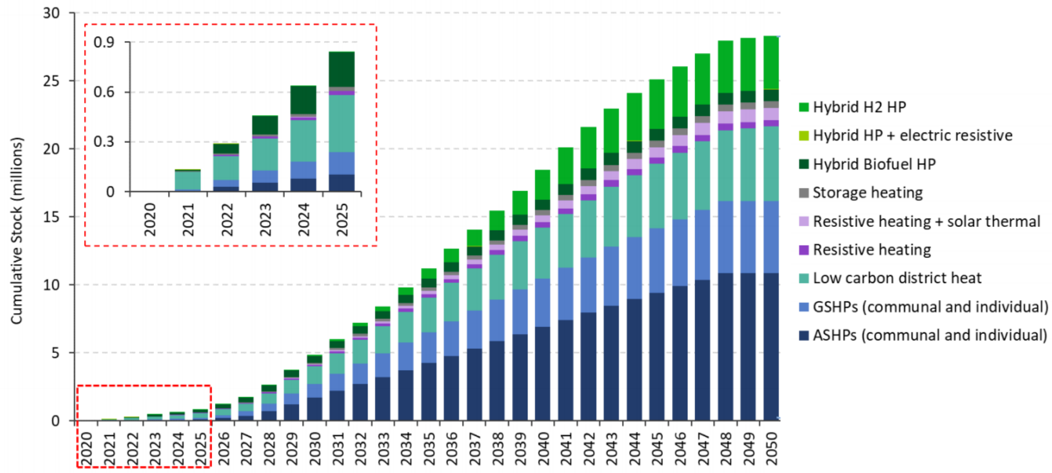
Figure 6 2050 uptake in modelling for Sixth Carbon Budget



Source: *Reproduced from Element Energy (December 2020), Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget, p30*

Figure 7 shows the cumulative take-up of heating technologies under the "central" scenario of the above modelling. It shows that there is a substantial uptake in low-carbon heating, with heat pumps being used by a large number of households by 2050.

Figure 7 Cumulative uptake of heat technologies for Sixth Carbon Budget, 2020 - 2050



Source: *Reproduced from Element Energy (December 2020), Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget, p29*

This type of modelling can help demonstrate that a particular pathway is attainable with the right set of policies. However, there is still no "bottom-up" modelling of the drivers of consumer choice. It is therefore difficult to understand the extent to which restrictive policies are *required* to obtain these outcomes, or whether, with the right incentives, consumer choices could be guided in a way which is consistent with reaching net zero.

1.3 Agent-based modelling

The modelling approaches described above are broadly "top-down". They start from the premise that consumers will behave in a way which is in line with the socially optimal pathway, or specific policies. However consumers do not necessarily behave in this way, and so it is not necessarily the case that the overall outcome of the market will follow this "optimal" trajectory.

By contrast, an agent-based model (ABM) is "bottom-up", and focusses on the individual decisions made by consumers. An ABM simulates the interactions of agents: autonomous entities, modelled as having their own properties and actions. These interactions can occur between agents, or between agents and the environment they populate.[17] The individual rules followed by agents are often very simple, but can lead to the emergence of complex behaviour which would not seem to intuitively follow from the individual rules.[18]

Some of the main differences between ABMs and more traditional economic modelling approaches include the following:

- **Consumer behaviour**: Consumers are often modelled as following rules which may appear very simple (e.g. picking the product with lowest expected costs), while nonetheless requiring consumers to calculate payoffs in a perfectly "rational" way (e.g. often assuming perfect foresight). For example, although the cost-optimisation models described in the preceding section do not explicitly model individual consumers, they take as a starting point that they minimise costs. By contrast, agents in an ABM can be imbued with a far richer set of decision-making rules – which need not correspond to common notions of what is "rational".
- **Consumer heterogeneity:** The models described in the preceding section group consumers into a small number of archetypes (many economic models go further an assume a single "representative agent"). ABMs often contain far more heterogeneity – for example, different consumers may have different decision-making rules.
- **Consumer interactions**: In many models, the decisions taken by one consumer may only affect others weakly. For example, in an optimisation model, the decision taken by one customer to choose a particular heating technology will often only impact others if it causes constraints such as carbon emissions to be breached. By contrast, the flexible nature of an ABM means

[17] Based on the definition provided in Wilensky, U and Rand, W., *An Introduction to Agent-Based Modelling*, MIT press 2014

[18] One well-known example within the social sciences is the Schelling Segregation model. This considers the behaviour of two different types of agents, who can change their location, and have a mild preference to live near to other agents of the same type (for example, agents will move if there are fewer than a third of their neighbours are of the same type). The apparently mild preferences of the agents, when repeated across all agents over time, leads to agents moving into entirely segregated regions containing only one type of agent. This shows how simple rules can lead to unexpected outcomes in an ABM.

that interactions can be much more complex, with the actions of one agent impacting others directly and indirectly.

In the context of modelling the transition to a low-carbon heating system, an ABM will allow the path of the overall transition to be determined by simple rules reflecting consumer interactions. This is in contrast to an optimisation model which assumes that the high-level result of these interactions will be an optimal transition, and then solves what this transition is.

ABMs are not without their issues. They can include a vast number of parameters defining how agents interact, and two related critiques that are sometimes made are that:[19]

- the behavioural rules for agents can be *ad hoc*; and
- the lack of relevant empirical data may make it difficult to calibrate and validate the ABM.

It is therefore important to ground ABMs in evidence on how consumers react in the real world.

Ours is not the first ABM of the heating market. Annex C provides a summary of some of the work that has been carried out previously.

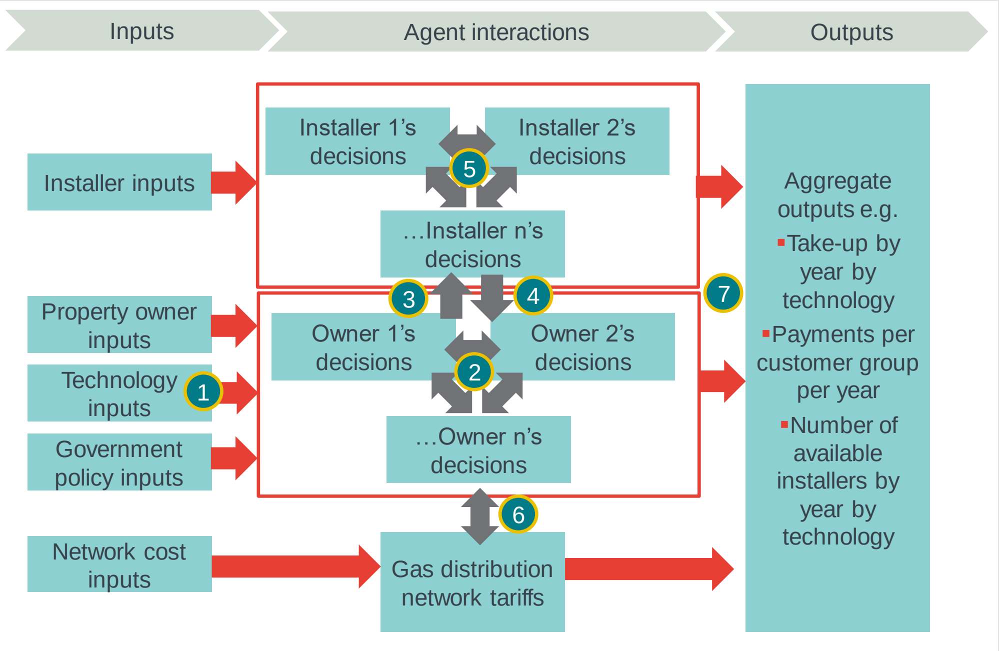
[19] Robinson, S and Rai, V (2015), *Agent-based modeling of energy technology adoption: Empirical integration of social, behavioral, economic, and environmental factors* in *Environmental Modelling & Software* 70

2 MODEL METHODOLOGY AND ASSUMPTIONS

We have built an agent-based model which simulates the take-up of domestic heating technologies between 2020 and 2050. The box below provides a high-level overview of the model.

HIGH-LEVEL SUMMARY OF THE MODEL

- **Owners of properties** are modelled as agents who decide which heating system to take up when their existing system reaches the end of its life. They make their decisions based on factors (1) such as the cost and perceived hassle of installing and running a given technology.
- They are also influenced by other nearby owners (2) – the more high quality heat pump installations there are locally, the more likely an owner will get one installed.
- Owners' decisions are influenced by **installers** (3), who are the second type of agent modelled. It is not possible to install a technology without a trained local installer, and installers may themselves recommend technologies they are more familiar with.
- Installers choose to enter and exit the market based on the demand for different technologies from property owners (4) and local supply from other installers (5).
- If property owners choose to stop using gas-fired heating, this leads to the **gas distribution network operator** setting greater network tariffs for other owners, which may in turn affect their decision (6).
- The model outputs the resulting aggregate take-up of heating technologies (7), as well as detailed outputs split by groups of agent.



In this section, we first describe the overall scope of the model. We then then describe the assumptions made for each type of agent in the model: Property owners, installers, and the gas distribution network. Finally, we describe how government policy and energy service companies have been implemented using simple exogenous rules (rather than as agents themselves).

2.1 Model scope

When modelling any system, it is necessary to determine the boundaries of the model: Which decisions and outcomes are decided endogenously within the model, and which are given as exogenous inputs?

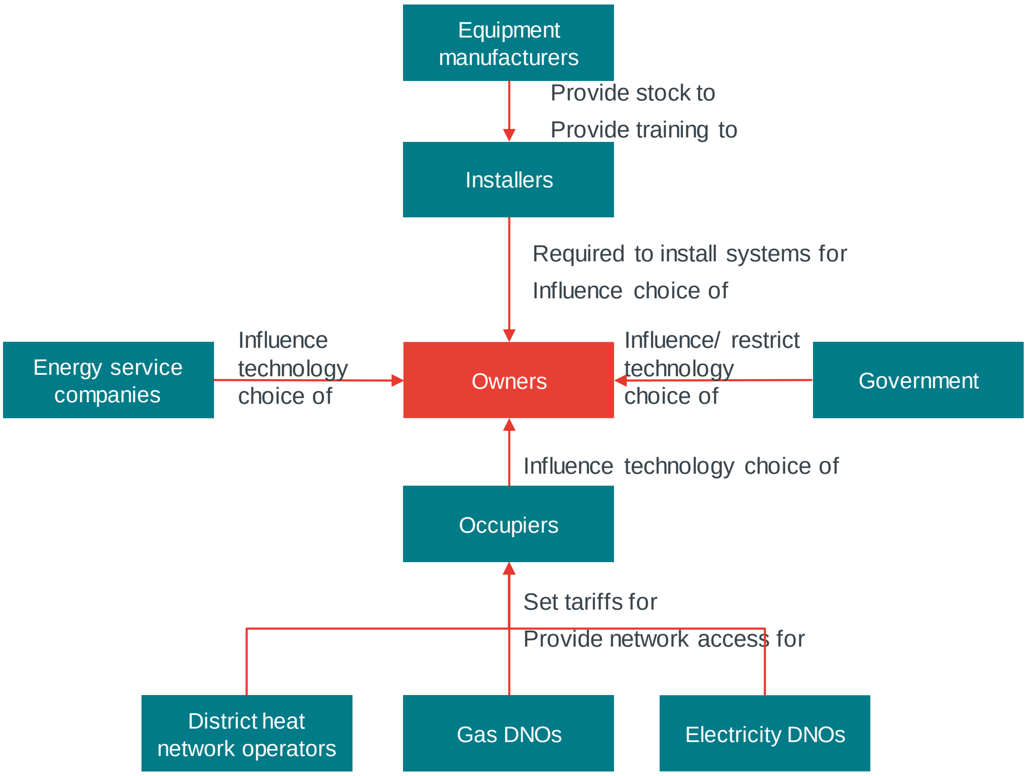
In this section, we first explore the wider scope of what could be modelled. We then describe how this has been narrowed for the purposes of this pilot model.

2.1.1 The potential scope of a heat market model

The decision on which heating technology to take up is generally made by the owner of the property. **The "core" of our model is therefore the decision-making process of property owners** (in the domestic market – the model does not cover non-domestic property owners) when choosing a new heating technology. Owners are represented in the model as agents.

The decisions made by owners will be influenced by the actions of many other types of agents in the system. Figure 8 illustrates at a high level some of the different agents that could be modelled and how they relate to the take-up decisions of property owners.

Figure 8 Other agents in the domestic heating market



Source: Frontier Economics

This is a highly simplified picture as it does not account for the interactions and interdependencies that may occur between agents. For example, the decision of installers to provide a technology may depend on the perceived demand from owners, and the network tariffs set by network operators will depend on the number of customers over which fixed costs can be spread.

The roles of the agents in Figure 8 include:

- **Property owners**: Including both landlords as well as owner-occupiers. In addition to owners of existing properties, developers of new properties will also be relevant. All of these agents select the heating technology to install within their property / properties, and may make other related investments such as additional insulation.
- **Property occupiers**: The occupiers will typically control the way in which the heating system is used – for example how often it is used and at which temperature it is set. Where the occupant is not the owner, they may still have some influence over the property owners' choice of heating system, either directly (e.g. through recommendations) or indirectly (if the choice of heating system affects the rental value of the property). In some circumstances, property occupiers may fund or co-fund some retrofit measures themselves.
- **Installers**: Install heating technologies in properties. Not all installers may be able to install all types of technology, and installers may invest in new skills and capacity if the market expands. Installers may also provide advice to property owners on which technologies to install.
- **Gas distribution networks (GDNs)**: GDNs set tariffs for access to the gas network (subject to regulatory rules). They may also be responsible for converting sections of the gas distribution network from natural gas to hydrogen, although this is likely to require central co-ordination from Government.
- **Electricity DNOs**: Like GDNs, the electricity DNOs set network tariffs (subject to regulatory rules). They can carry out reinforcement of the local networks to meet demand, or may commission demand-side response services (such as the use of hot water storage by consumers) to change the profile of demand.
- **District heat network operators**: These develop and extend district heat networks (including both heat sources and pipework). They also set tariffs for heat, subject to any regulatory rules.
- **Energy service companies**: These reflect a variety of possible business models that bundle heat technologies with the provision of energy, and may help drive the uptake of new technologies. These may include facilities management contracts, or retrofit schemes.[20] Based on consumer demand, these companies may adapt and change their offerings.
- **Equipment manufacturers**: They produce the equipment such as heat pumps and district heat piping. Equipment manufacturers may respond to consumer demand by changing the range of products that they provide, or altering production capacity.

[20] For example "*Energiesprong"* a whole house retrofit scheme, where a comprehensive set of improvements are funded via an "energy plan" – see https://www.energiesprong.uk/.

- **Government**: The Government (national or local) may set policies affecting the choices that owners can make. For example, Government may restrict the availability of certain technologies as has been done with non-condensing boilers, and might be done in the future by preventing the use of carbon intensive technologies for groups such as new build homes. Government may also provide incentives such as the Renewable Heat Incentive (RHI).

This list is not exhaustive – the decisions made by property owners regarding heating technologies may be influenced by other markets entirely. For example, an increase in the number of electric vehicles being used might affect wholesale (and ultimately retail) electricity prices, which could feed through to differing incentives for consumers to take up heat pumps.

While all of these influences are relevant, it would be impractical for a model (let alone one intended as a pilot) to include all of them. The following section describes the subset of this system which our model considers.

2.1.2 The scope of our model

For the purpose of this pilot model, we have concentrated on a subset of these agents. Three types of agent are modelled endogenously:

- **Owner-occupiers**. As described above, their choices are central to heating system take-up.
- **Installers**. The presence of installers could lead to a variety of "feedback loops" in the model, both positive and negative, which are of particular interest in an ABM. These are explained in Figure 9.

Figure 9 Feedback effects between property owners and installers

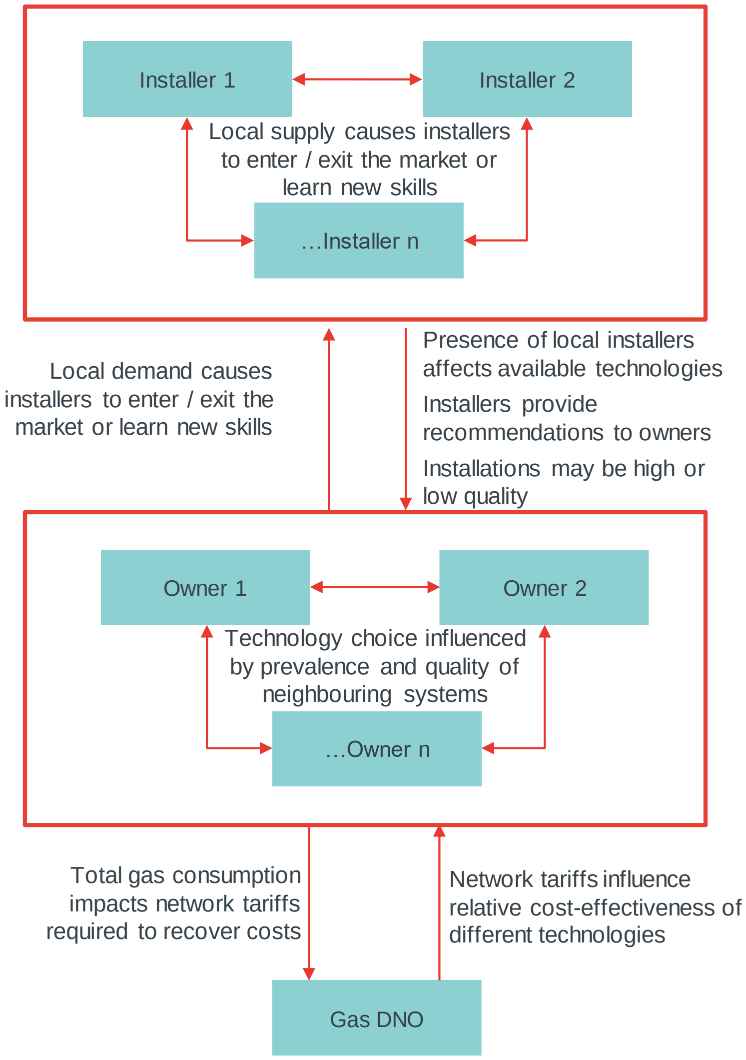
Positive feedback effects	Negative feedback effects
▪ In the long-run, installer capacity is flexible. So if one owner installs a low-carbon heating technology, this may incentivise the entry of new installers who can serve (and maybe promote) demand for low-carbon heating for other owners. ▪ As more low-carbon heating technologies are installed, installers will become more familiar with them. They may carry out higher quality installations (which may lead to positive recommendations from other owners) and may directly recommend low-carbon heating technologies.	▪ In the short-run, installer capacity is limited. So if one owner installs a low-carbon heating technology, this may reduce the remaining installer capacity available for its neighbours. ▪ If demand for low-carbon heating technologies causes a large number of inexperienced installers to enter the market, they may carry out low quality installations, which may lead to adverse recommendations.

Source: Frontier Economics

- **Gas distribution networks**. The tariff-setting role of GDNs may also be particularly important. This is since under a path to decarbonisation that involves full electrification, use of the gas network will fall significantly. If this were to result in significantly higher tariffs, this could have a significant impact on fuel costs, and therefore decisions made on heating technology take-up – an example of a negative feedback loop. We model a single GDN.

Figure 10 illustrates the relationship between these agents in more detail. The arrows show the different ways in which the agents influence one another.

Figure 10 Modelled agents



Source: Frontier Economics

A number of the other agents in Figure 8 are accounted for exogenously (we do not explicitly model their decision-making):

- **Property occupiers.** To simplify the model, we have combined the role of property owners and occupiers. While owners of rented properties will still be responsible for choosing the heating system, they will have somewhat different incentives. We describe how different tenure types have been modelled in the section on property owners.
- **Government policy** is modelled exogenously (the Government is not an agent). Policy will be an important driver of decarbonisation: given carbon emissions are a negative externality, some form of intervention is required to ensure consumer choices reflect these costs. However, it is not our intention to simulate the policy-making apparatus of government. Neither is this pilot model

intended to be used to assess specific policies. We have therefore included a small number of basic policies as exogenous inputs (i.e. specified by the user running the model, not determined within the model itself).

- **Energy service companies:** To the extent that energy service companies may affect the way in which owners choose heating technologies (for example providing access to finance) this is modelled as a scenario with different parameters for owners' decision-making (for example a lower discount rate on future benefits). We have not modelled ESCs as agents with their own behaviours.

All other agents are not modelled at present, although could be added to the model in the future. The agents that have been excluded (and what this implies for the modelling) are as follows:

- **Electricity DNOs**: The model assumes that sufficient network capacity can be provided for any owner that wishes to install an electrical heating system to do so. In practice there are likely to be significant costs of reinforcement, and a future version of the model could explore the extent to which these costs affect take-up.
- **District heat network operators**: District heat may be an important part of the overall path to a decarbonised heating system. However, unlike technologies such as heat pumps and hydrogen boilers, it is only likely to be cost-effective in the most densely populated areas of the country. Given the significant work required to fully implement district heating within the model, the current version has focussed on other heating technologies.
- **Equipment manufacturers**: The model assumes that the price of heating technologies does not change with the level of uptake, and that there are no restrictions on the availability of technologies. This can be seen as reflecting a global market for heating technologies where UK take-up has no impact on overall demand.

The remainder of this chapter describes the way in which the model simulates each type of agent. Further technical detail is available in Annex A.

2.2 Modelling property owners' decisions

The core of the model is the choice of heating technologies made by property owners when their existing system fails. The interaction between large numbers of heterogenous agents making individual decisions is ideally suited for an ABM. In this section, we describe:

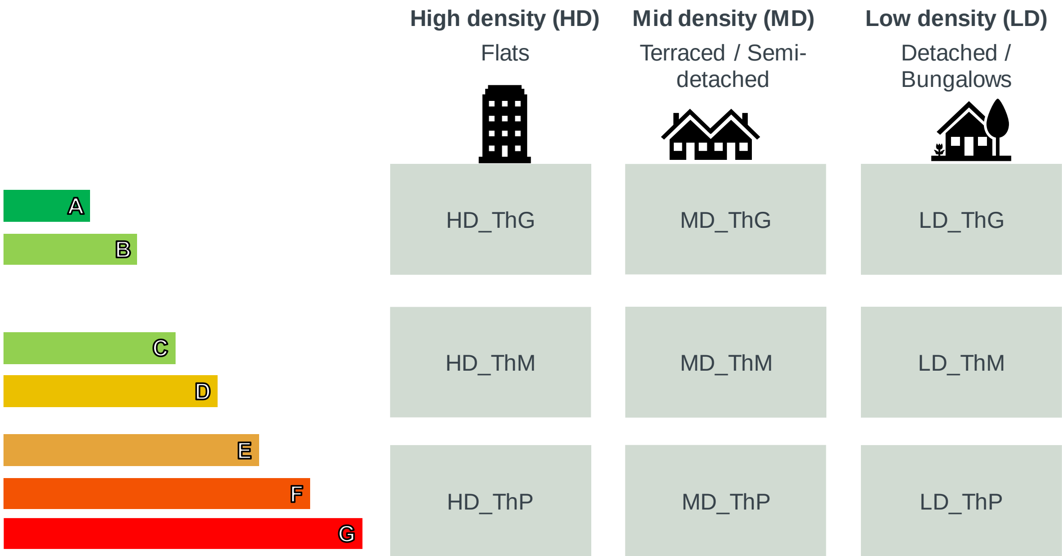
- The housing archetypes we model, and the heating technologies available to each one;
- the "trigger" for an owner to consider a new heating system;
- the way in which an owner is modelled as choosing between the heating system alternatives once they are "triggered";
- the additional forms of heterogeneity among owners that the model considers; and

- how we account for new build houses and energy efficiency retrofits to the existing stock.

2.2.1 Housing archetypes and available technologies

The housing stock has been split into archetypes, based on the ESME dataset originally developed by ETI. ESME divides the housing stock into groups based on density and thermal efficiency, as illustrated in Figure 11.

Figure 11 Housing categories used by ESME



Source: ESME 4.4

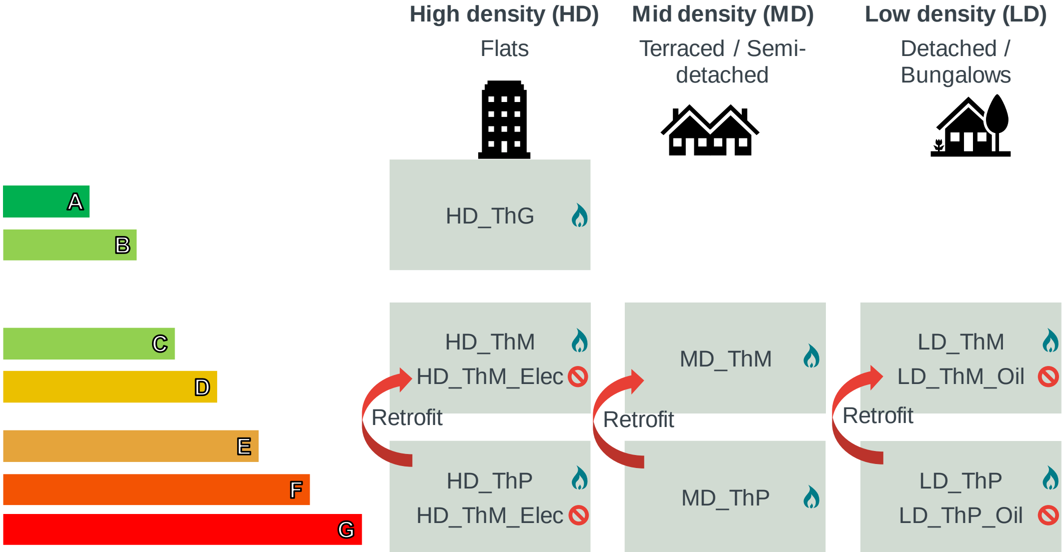
ESME also has an “Excellent” thermal rating, which corresponds to a space heat requirement of less than half of the “good” properties. However none of the existing housing stock is assume to meet this standard.

The final set of archetypes used in our model is a slightly modified version:

- All “good” thermal efficiency mid- and low-density houses have been removed, since according to ESME there is an insignificant number of these. These properties are still available as new builds (discussed in section 2.2.5).
- Four of the groups have been split to account for off gas grid households:
  - The “Elec” high density dwellings represent flats without a gas supply. The “good” thermal efficiency flats have not been split in this way as there are so few of them (1% of flats are “good” according to ESME).
  - The “Oil” low density dwellings represent off-grid rural properties.

Figure 12 illustrates the resulting set of archetypes (this also shows the changes in archetype mediated by retrofits, which are discussed shortly).

Figure 12 Modelled housing archetypes



Source: Frontier Economics

Within our model, each domestic consumer archetype is assumed to have an incumbent technology and a set of technologies available to them based on the density of their household and whether the property is connected to the gas grid. We assume that:

- Gas boilers (and potentially hydrogen and hydrogen-ready boilers) are available to all properties on the gas grid.
- Oil boilers are only available to those off-grid rural properties which already have them.
- Electric resistive heating (a tank with an immersion heater) is available for all high-density properties.
- Air-source heat pumps are only available for mid- and low-density properties.[21]
- Ground-source heat pumps are available for the off-grid low density properties (which represent rural properties which will tend to have more available space) and high-density properties (representing a shared ground loop system).[22]
- Houses with poor thermal performance are not able[23] to install a heat pump without an extensive retrofit that transforms them into a “medium” performance house.

Figure 13 lists each archetype and their available technologies.

[21] Carbon Trust (2020), *Heat pump retrofit in London* summarises the issues installing heat pumps in high density properties. While fully integrated air-source heat pumps (using a duct connection to outside) may be suitable for flats, these may be a less attractive option due to the amount of space taken up.

[22] As our model does not group individual households into larger buildings, we still simulate this technology as if individual dwellings can invest in a heat pump by themselves.

[23] The model therefore assumes that installers will correctly identify and advise the owners of properties which are unsuitable for heat pumps. Another possibility which is not modelled is that some homeowners may install heat pumps where they are not suitable, leading to unsatisfactory performance.

Figure 13 Technologies available to archetypes

	Gas / Hydrogen (ready) boiler	Oil boiler	Electric resistive	Air-source heat pump	Ground-source heat pump
HD_ThG	✓		✓		✓
HD_ThM	✓		✓		✓
HD_ThM_Elec			✓		✓
HD_ThP	✓		✓		Retrofit required
HD_ThP_Elec			✓		Retrofit required
MD_ThM	✓			✓	
MD_ThP	✓			Retrofit required	
LD_ThM	✓			✓	
LD_ThM_Oil		✓		✓	✓
LD_ThP	✓			Retrofit required	
LD_ThP_Oil		✓		Retrofit required	Retrofit required

Source: *Frontier Economics*

Note: *Hydrogen-ready boilers and hydrogen boilers are an available technology from 2022 and 2040 respectively, in the "high hydrogen" scenario*

As noted above, properties with "poor" thermal efficiency are assumed to be unable to upgrade to a heat pump unless an extensive retrofit is carried out. The relevant upgrades are marked in brackets above. The model uses the cost of the "RetroPlus" package of interventions from ESME.

Technology costs

Each technology has an associated capital cost (which includes the cost of installation), ongoing running costs (fuel) over its lifetime, and heating efficiency. The capital costs and heating efficiency of each technology, with the exception of hybrid and hydrogen-only boilers, are based on ETI's ESME dataset. ESME provides data on capex and heating efficiency of the different technologies for the years 2010 and 2050. We estimate the data points for the years in between through linear interpolation. Figure 14 shows the fuel source(s) and capital cost in 2050 for each technology.

Figure 14 Fuel and capital costs of technologies

Technology	Fuel	Capital Cost, 2010 (£)	Capital cost, 2050 (£)
Gas boiler	Gas	2,967	2,967
Oil boiler	Oil	3,323	3,323
Electric resistive	Electricity	3,109	3,109
Air source heat pump	Electricity	7,693	6,129
Ground source heat pump	Electricity	11,957	9,455
Hydrogen-ready boiler	Hydrogen or gas	-	3,561
Hydrogen boiler	Hydrogen	-	3,561

Sources: ESME 4.4

Notes: Figures shown as in real 2018 terms. It is assumed that boilers and electric resistive systems are sized to provide a heat output of 15kW, while heat pumps produce a heat output of 8kW. Heat pumps are assumed to be installed alongside a 11.5kWh storage tank.

The ESME figures do not include the installation of other elements of the central heating system, as it is assumed that the heat pumps are able to operate at a sufficiently high output temperature that a conventional wet radiator system can be used.[24]

For some of these technologies there may be a significant cost saving when installing a like-for-like replacement, compared to installing for the first time. We therefore assume[25] that:

- Replacing a ground-source heat pump like-for-like saves 50% of the capital costs; and
- replacing an air-source heat pump like-for-like saves 10% of the capital costs.

For hydrogen-ready and hydrogen-only boilers, our assumptions on the capital costs and efficiency are based on evidence in a study conducted by Element Energy (2018).[26] Hydrogen-only boilers are assumed to be as efficient as gas boilers. The study notes that a hydrogen-ready boiler running on natural gas will run with reduced efficiency. As such, we assume a hydrogen-ready boiler is 5% less heat efficient than either a gas boiler or hydrogen-only boiler.[27] The study assumes that, in the base case scenario, hydrogen boilers are roughly 20% more costly than gas boilers at 1,000,000 units produced per manufacturer per year.

Fuel prices are taken from the Treasury Green Book supplemental guidance. These projections will include the effect of a carbon price within the electricity price, but not the prices for gas and oil. While the model is not intended to assess specific

24 Energy Systems Catapult (2019), ESME Data References Book

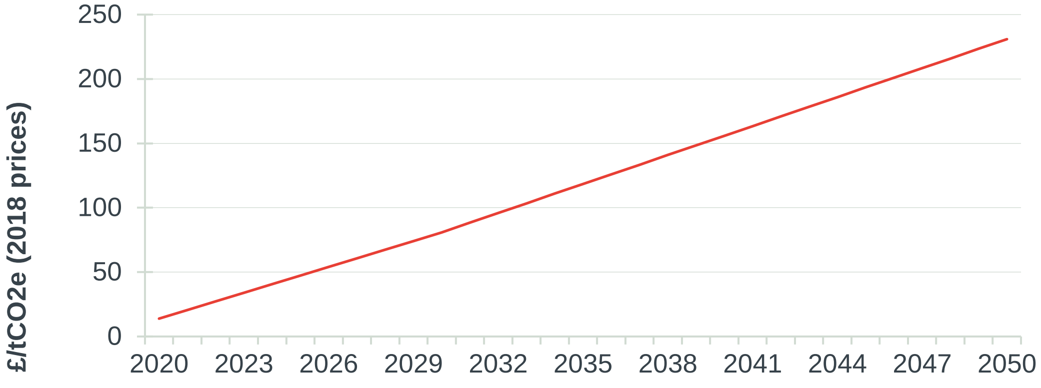
25 Based on assumptions from Pöyry and Faber Maunsell for DECC (2009), The potential and costs of district heating networks, which is the sourced cited for ESME's heat pump costs.

26 Walker, I., Madden, B., Tahir, F. (2018). Hydrogen Supply Chain Evidence Base; Element Energy Ltd.: Cambridge, UK.

27 We do not currently model the way in which the hydrogen-ready boiler's efficiency may increase when the switchover to gas occurs. However this cannot affect consumer decision-making in the model, since hydrogen-ready boilers are assumed to only be available before the switchover.

policies, some way of internalising the externality of carbon emissions is required to drive the take-up of low carbon heating technologies. The model therefore considers the RHI (when simulating historic years), but for future years applies a cost of carbon to gas (which does not currently have such a cost when combusted in a domestic setting). The carbon cost used is the central traded value from the Green Book, which rises from £14/tonne in 2018 to £231/tonne in 2050, as shown in Figure 15.

Figure 15 Carbon price applied to gas



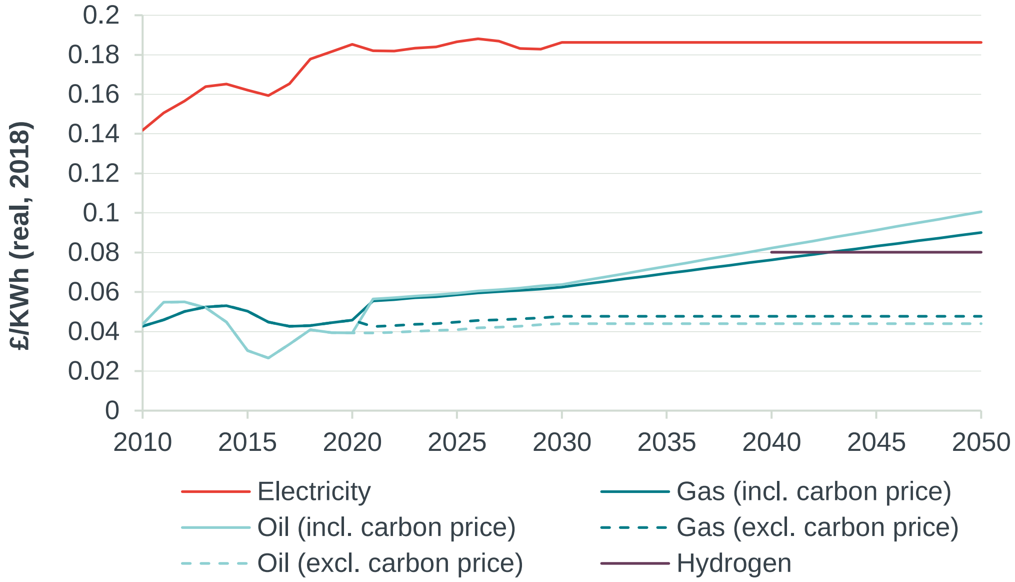
Source: Green Book Supplemental Guidance

As the model is focussed on consumer decisions, it does not attempt to identify the infrastructure costs of a hydrogen transition (e.g. the new transmission network that will be required). Retail fuel prices for hydrogen are an area of significant uncertainty (and we have carried out sensitivity tests as part of the modelling). However, as a baseline assumption, we have used the approximately 8p/kWh central figure used in the CCC's sixth carbon budget.[28]

Figure 16 plots a time series of fuel prices used in the model.

[28] Element Energy for CCC (2020), *Development of trajectories or residential heat decarbonisation to inform the sixth carbon budget*, databook

Figure 16 Fuel prices including and excluding assumed carbon price



Source: Treasury Green Book Supplementary Guidance; Frontier Economics calculations

2.2.2 Triggers for heating system change

Research suggests that the decision to take up a new heating technology is generally caused by one of a small number of "triggers", predominantly a system breaking down or otherwise coming toward the end of its life and not working effectively.[29] We therefore take the failure rate of a heating system to be our driver of heating system change.[30]

Each period the model takes a random draw to determine which heating systems fail, and requires those owners to invest in a new system. Figure 17 shows the process of the model per owner, per year.

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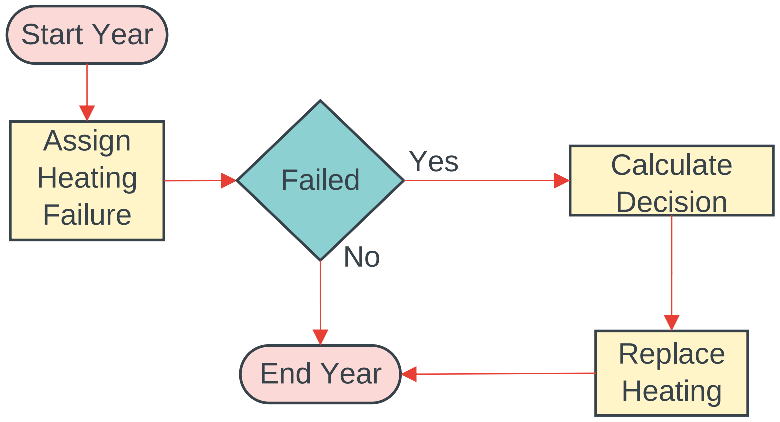
[29] Frontier Economics for BEIS (2017) *RHI Evaluation: synthesis*, available at https://www.gov.uk/government/publications/rhi-evaluation-synthesis-report

DECC (2013), *Home owners' willingness to take up more efficient heating systems*.

[30] The model therefore does not consider triggers for change such as extensive renovations, or pro-active upgrades due to a technology becoming particularly cost-effective or popular.

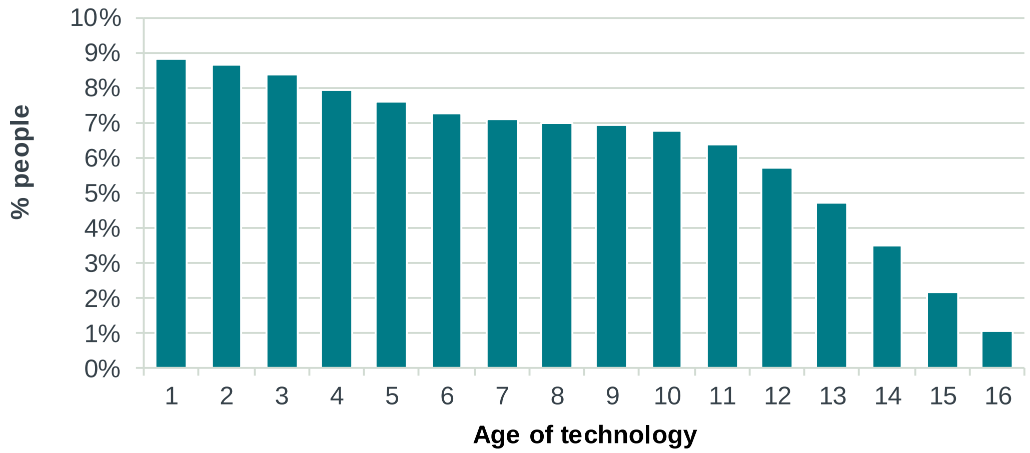
Figure 17 Trigger for heating system change for an owner



Source: Frontier Economics

The rate of failure is dependent on the age of a technology and its expected lifetime – a system is more likely to fail the older it is. These failure rates have been chosen so that, when applied over many years to reach a "steady state", the spread of ages[31] broadly matches the observed ages of boilers.[32] An example of the age distribution resulting from these failure rates, can be seen in Figure 18. Upon exceeding its overall technical lifetime the model will ensure a technology fails with certainty.

Figure 18 Spread of ages for resulting from choice of failure rates



Source: Frontier Economics

Note: The above is for a technology with a lifetime of 15 years. Those that are 16 years old will fail with 100 % certainty.

In the hydrogen switchover scenario heating system change is additionally triggered at the date of switchover: Any owners of gas-only boilers must change their heating system at this point. This affects the lifetime of gas technologies in

[31] We assume that, for the given failure rates, the spread of ages has reached a steady state at the initial year. This steady state is derived by simulating several years of failures after starting with just new technologies.

[32] DECC (2013), *Home owners' willingness to take up more efficient heating systems*. We excluded customers reporting that they had never changed the heating system in their current home.

regards cost but not in regards reliability – a 5 year old gas boiler one year before switchover is just as reliable as the same boiler if no switchover were to occur. Therefore the failure rates are unaffected.

2.2.3 Drivers of heating system choice

When a heating system fails, the owner must choose a replacement from the set of alternatives described in Figure 13. The model accounts for the following broad drivers of owners' choice of heating system.[33]

Figure 19 Description of factors affecting heating system choice

Decision factor	Description
Monetary cost	▪ All else equal, a property owner is more likely to select a technology that has lower installation and running costs. ▪ Agents in the model calculate the discounted present value of each heating system choice over its lifetime. While consumers do not in practice tend to use discount rates in this way, doing so provides a straightforward way of adjusting the weight placed on future costs and benefits. ▪ The model then calculates the relative cost of each technology, compared to the consumers' previous technology.
Awareness and information	▪ Consumers are generally unfamiliar with the use of renewable heating technologies. Their technology decisions often driven by recommendations by friends, installers, or other sources.
Non-monetary costs ("hassle")	▪ Low-carbon heating technologies are often perceived as having non-monetary barriers, such as hassle, noise, or space requirements. ▪ This term reflects these "hassle" costs.
"Green" attitudes	▪ A subset of owners may value the environmentally-friendly credentials of some heating technologies.

Source: Frontier Economics

For a given owner considering a specific technology, the model calculates a "utility function" based on a weighted sum of the factors above. The higher the utility of a specific technology, the more likely a consumer is to adopt it.

The weights on each factor indicate their relative importance for decision-making. We have set the four weights based on the following conditions:

- We have imposed a constraint that the sum of all four weights should add up to one.
- A choice experiment[34] found that the disruption of installing a hot water cylinder was valued by participants at £600. We have assumed that the inconvenience of installing and running a high-temperature air-source heat pump (compared to a gas boiler) is similar to this.[35] We have therefore calibrated our model such

[33] These drivers are frequently cited in reports (e.g. *BEIS (2018), Clean Growth – Transforming Heating*) and used in other ABMs (e.g. Snape, Boait, and Rylatt (2015), *Will domestic consumers take up the renewable heat incentive? An analysis of the barriers to heat pump adoption using agent-based modelling* in Energy Policy 85.

[34] Element Energy (2008), *The growth Potential for Microgeneration in England, Wales and Scotland*

[35] Installing and running a heat pump may have non-monetary costs greater than those of installing a water cylinder – e.g. additional noise, and the external space required. However another paper (Scarpa and Willis

that, if an air source heat pump was identical to a gas boiler but £600 cheaper, a typical owner (mid density, medium thermal efficiency, middle income level) would be indifferent between the two choices. This tells us the relative weight on the hassle and cost factors.

- The same choice experiment showed that the combined benefit of recommendations from friends and tradesmen was valued at £1700. We have therefore calibrated the model that an owner would be indifferent between a technology that is not used by any of their neighbours (or recommended by any installers), and a technology that is in use by around 50% of their neighbours, and recommended by 50% of installers, but costs £1700 more. This tells us the relative weight on the social and cost factors.

These constraints are not enough to uniquely identify a set of choice weights (there are four weights to set, but only three equations relating them to one another). We have therefore run, for the period 2015 to 2020, for different values of the hassle weight (the other weights will change accordingly) seeking a set of values which broadly replicate the uptake of heat pumps on the RHI. This is shown in Figure 23.

While this model of consumer choice is more complex than one that just includes monetary factors, it is not intended to describe *how* consumers actually make their decisions (in reality they will not explicitly weigh up the utility of alternative options in this way). However this is a simple model which accounts for some of the key drivers of choice, and lends itself well to exploration by varying parameters such as the weight on each driver of choice. While more complex models[36] might better represent consumer behaviour, they can involve a much more detailed set of parameters, which can make it harder to understand what is driving the results. As illustrated in Annex B, users of our model are able to look at the drivers of decisions of individual agents in the model, which helps develop an intuitive understanding.

The following sections outline how each component of the utility function has been calculated.

Monetary cost

The cost factor is calculated as the relative cost saving of a technology over the previously used heating technology. Costs are calculated on an equivalent annual basis. This requires a discount rate, which determines how much weight a property owner places on the costs of a technology in its first year (i.e. the upfront installation cost and the first year of fuel), compared to the fuel costs in future years.

Choice experiments conducted in the study by Element Energy (2008) [37] found that consumers are willing to pay £2.91 in up-front costs to reduce their annual fuel bills by £1. Given that the expected lifetime of a boiler is 15 years, we have calculated that the discount rate for a typical consumer is about 50%.[38] This discount rate can

(2010), *Willingness-to-pay for renewable energy: Primary and discretionary choice of British households' for micro-generation technologies* in Energy Economics (32)) found a much lower perceived cost of a hot water tank (£221). £600 therefore seems a reasonable value for the non-monetary costs of heat pump, albeit one that is subject to very significant uncertainty.

36 For example the “Hot Coherence” model used in Wolf, Scröder, Neumann and de Haan (2015), *Changing minds about electric cars: An empirically grounded agent-based modelling approach* in Technological Forecasting and Social Change Vol 94

37 Element Energy,2008. The growth Potential for Microgeneration in England, Wales and Scotland

38 A stream of £1 savings over 15 years, discounted at 50%, is approximately equal to £2.91.

be seen as representing a number of effects, such as the time value of money, and the way in which property owners might not expect the full value of energy-saving technologies to be reflected in property resale values.

As described in the following section on customer heterogeneity, we apply different discount rates for low and high income owners, as well as owners of privately and socially rented homes.

Awareness and information

This consists of two components. First, the recommendations of installers. Previous research carried out by IPSOS Mori indicates that owners are more likely to take advice from installers than from other people (such as neighbours).[39] The section on installer agents describes how these recommendations are formed in the model.

Second, recommendations from neighbours within a geographic radius. An agent in the model will be more likely to take up a technology that has more high-quality installations nearby. We have used a 1km value for this radius, based on running the model for different values of parameters and determining which combination gives a representation of historic (2015 – 2020) heat pump take up equivalent to RHI historic take up.

Non-monetary costs

The "hassle factor" proxies for non-monetary costs of a given technology such as the hassle of installation, or the space taken up or noise produced by a technology once it is installed. We have taken as a starting point the values used in a previous agent-based model,[40] which assumed that a ground source heat pump had higher non-monetary costs than an air-source heat pump, which in turn had higher non-monetary costs than an oil boiler, with gas boilers having the least hassle. We have added electric resistive heating, and increased the hassle associated with the installation of heat pumps in higher density buildings, to reflect the greater difficulties finding space for ground loops or the external units of an air-source heat pump.

When a heat pumps is installed "like-for-like", we assume a significantly reduced hassle factor (the same as an electric resistive heater). This accounts for both the way in which the consumer may have become more used to the way in which the technology operates, as well as reduced hassle during the installation itself.

Figure 20 summarises the hassle costs used in the model.

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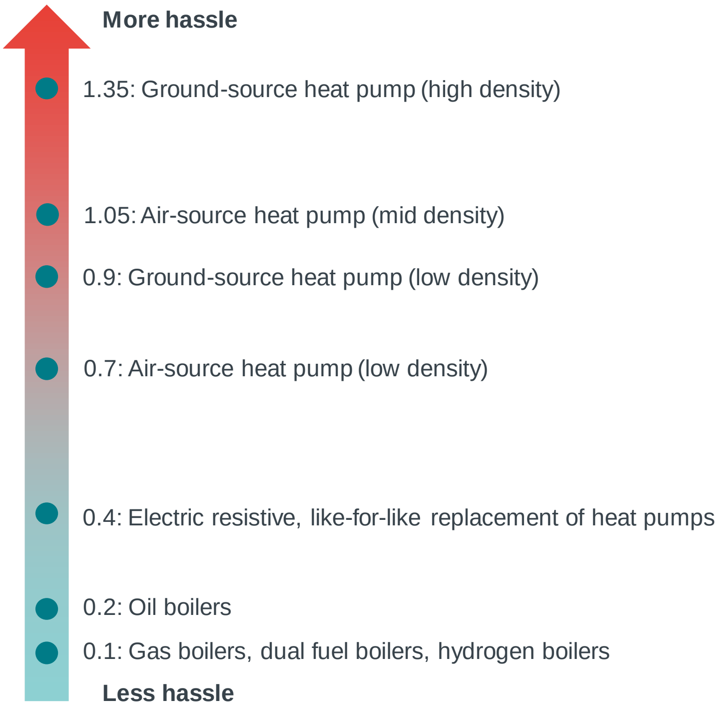
[39] Ipsos Mori for DECC (2013), *Homeowners' Willingness To Take Up More Efficient Heating Systems*

[40] Snape, Boait, and Rylatt (2015), *Will domestic consumers take up the renewable heat incentive? An analysis of the barriers to heat pump adoption using agent-based modelling* in *Energy Policy* 85

Figure 20 Hassle costs



Source: Frontier Economics

"Green" attitudes

As described in the following section, some owners in the model are assumed to have a preference to take-up low carbon technologies (heat pumps, and hydrogen boilers (but not hybrid boilers burning natural gas). For these agents there is a further "boost" to the utility function for these technologies.

2.2.4 Modelling customer heterogeneity

One of the benefits of an ABM is that it allows for great heterogeneity in respect of the agents modelled. It is important that the model contains a sufficient amount of heterogeneity, as otherwise the modelled transition may be unrealistically rapid (if all households are identical, then as soon a renewable heat technology is *just* optional for one household, all others will wish to take it up as well).

Our model accounts for the following types of heterogeneity:

- demand for heat and available choices of technology;
- income levels;
- tenure type;
- attitudes towards "green" technologies"; and
- unobserved sources of heterogeneity.

Differing demands for heat and technology choices

As described in Figure 12 we have applied a range of housing archetypes. These vary both in terms of their heat demand, and the choices of technology available to them.

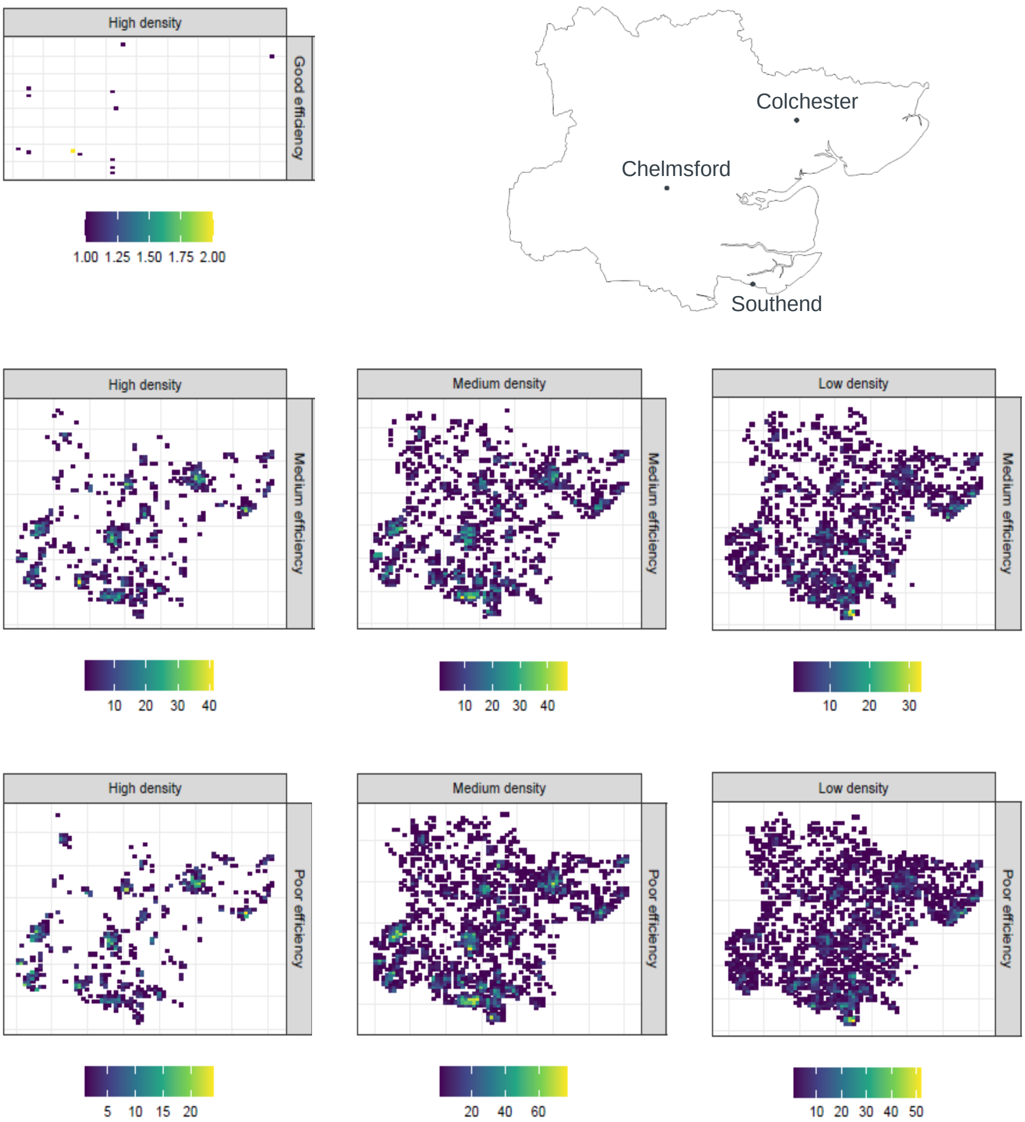
As our model has a social component (the take-up of heating technologies is affected by the take-up of neighbours), we need realistic locations of these archetypes to reflect the way in which similar types of property will tend to cluster together.

We have done this by using 2011 Census data to estimate the distribution of properties for a real geographic region. Currently, we are modelling 5% of all properties in the county of Essex. Any geographic area can be used for the simulation, however Essex is an example of a country with both a number of large towns and more outlying rural areas (some of which will be off the gas grid), which means that there is a good variety of property types to simulate. There are also no very large cities in the area – this is an advantage for our purposes as the model does not simulate the use of district heat, which is likely to be more applicable to the most built-up areas. The model has been run for other regions,[41] and the broad results described in this report are robust to the choice of region.

Figure 21 shows the location of modelled households by archetype. It can be seen how the higher density archetypes are particularly clustered in town centres.

[41] For example, a scenario was run using data from Cumbria rather than Essex. The higher average income in Essex means that fewer customers are modelled as being credit constrained, which increases uptake. However the general trends are very similar.

Figure 21 Location of households



Source: Frontier Economics

Within each of these archetypes, we have added further variations in heat demand for each property. To do this, each property's heat demand is drawn from a distribution centred on the value from ESME.[42]

[42] The heat demand from ESME is multiplied by a random number drawn from a normal distribution with mean 1 and standard deviation 0.05. While this adds some randomness to the level of heat demand, 95% of properties will have a heat demand within 10% of the central value.

Differing income levels

We have used census data to classify each property into one of three income groups. Several studies including Hausmann (1979)[43] and Meyer (2014)[44] have found evidence that the implied discount rate used by consumers to make choices is inversely related to income. This makes intuitive sense – if low-income customers are more likely to face credit constraints, then they may need to pick technologies with lower up-front costs, even if the lifetime costs are higher. Figure 22 shows the discount rates used for each income group.

Figure 22 Income groups

Income group	Definition	Assumed discount rate
High	Disposable income above middle third of the country	0%
Medium	Disposable income in middle third	50%
Low	Disposable income below lower third of the country	1000%

Source: *Frontier Economics analysis of ONS net annual income after housing cost data*

Note: *Census data income is "Net annual income"*

As described in the section on owners' choices, the discount rate for the middle income group of customers has been based on a choice experiment. The rates for high and low income consumers are more illustrative, to demonstrate the impact of placing a high and low weight respectively on future savings.

Different tenure types

We have also used census data to distinguish between three forms of property:

- **Owner-occupied properties** are modelled as described above.
- **Private landlords** are observed[45] to install fewer energy-efficiency measures in their properties than in their own homes, as they do not directly face the costs and benefits of running a heating system (but do pay the upfront costs).
  - We apply a discount rate of 1000% to simulate the incentive private landlords have to consider the up-front cost of technologies in preference to ongoing savings (we do not split rented properties by the income of the tenant, as it is not the tenant paying for the heating system).
  - We halve the weight on the "hassle" factor, to illustrate the way in which landlords will not themselves experience any non-monetary costs of the heating system (but may still be influenced by their tenants' preferences)
  - The weight on "green" attitudes has been removed.
- **Social landlords** frequently have social and charitable objectives that are focussed on providing decent and affordable housing to those that need it.

[43] Hausman, J.A. (1979). "Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables." The Bell Journal of Economics 10 (1), 33–54.

[44] Enzler, H.B., Diekman, A., Meyer, R. (2014). "Subjective Discount Rates in the General Population and their Predictive Power for Energy Saving Behaviour." Energy Policy, 65, 524-540.

[45] Element Energy (2008), *The growth Potential for Microgeneration in England, Wales and Scotland*

These institutions will tend to weight the upfront and maintenance costs of a system as well as the costs to the tenant of running the system.

- We apply a discount rate of 2.5%. This is based on data from Element Energy (2008) which indicated that the median surveyed social landlord would be wiling po pay £5,000 to reduce bills by around £400 per year.
- The weight on "green" attitudes has been removed, although we acknowledge that some social landlords may wish to choose a low-carbon technology for its own sake, and this assumption could be flexed if evidence is found for this.

Differing attitudes to "green" technologies

We assume that a set proportion of owner-occupiers place a weight on taking up technologies which are "green". For example, these owners may be more inclined to take up a heat pump because they are less carbon intensive.[46] In our baseline model runs, it is assumed that a random 10% of owner-occupiers have "green" attitudes.

The assumption for the value of this parameter is loosely founded on research commissioned by the Department of Energy & Climate Change (DECC)[47] into the take up of more efficient heat systems and consumer attitudes towards heat technologies. In response to the survey question: *"Which, if any, of the following do you personally think is the most important factor for heating system in general?"*, 2% of respondents' **main** reason for considering replacing their heating system was due to environmental reasons. We assume a higher value of 10% to account for owners who may be impacted by green issues, but it may not be the primary focus of their decision making. This also enables us to broadly replicate the take-up of heat pumps under the RHI, as described in the section on model calibration.

Unobserved heterogeneity

In our model, the higher the modelled utility, the more likely an owner is to take up a technology. The simplest way to implement this would be to assume that an owner will always take up the option with the highest utility. For example, even if a heat pump has only very marginal benefits over a gas boiler for a specific owner, the owner would pick the heat pump.

However, this would omit two sources of uncertainty.

- First, in real life there will be other factors affecting decisions other than those present in the model's utility function. For example, an owner with a particularly constricted space may place a greater weight on the space requirements of a heat pump than accounted for in the hassle term in our model, and so not take up a heat pump even through the model predicts that action. From the point of view of the model, this is an unobserved source of heterogeneity.

[46] This could also relate to the "conspicuous consumption" of green technologies. Although heating technologies (unlike, for example, electric vehicles or solar panels) are typically inconspicuous, and so this effect may not be material in practice.

[47] UK DECC. 2013. "Home owners' willingness to take up more efficient heating systems." London, UK: Department of Energy and Climate Change.

- Second, owners may not have full availability of information, or confidence in the information that they do have. If two technologies are extremely similar in terms of their costs and benefits, many owners may therefore choose the technology that is slightly “worse”.

We account for this by using a functional form[48] that allows some uncertainty in choice:

- If the utility of one technology is greatly in excess of all others, then the owner will choose it with a probability that approaches certainty.
- If the utility of two technologies are closer, then owners will be most likely to choose the technology with the higher utility – but may still choose the one with lower utility.
- If the owner is choosing between technologies that have identical levels of utility, the owner will choose each technology with an identical probability.

The functional form is described in mathematical terms in Annex A. It includes a single parameter, “*I*”, which determines how much more likely an agent is to pick a technology with a marginally higher utility. For very high values of the heterogeneity parameter, agents will almost certainly pick the technology with the highest utility. If the parameter is zero then agents will always pick a technology entirely at random, no matter what the utilities are.

The value of this parameter was based on carrying out multiple model runs with differing values of the heterogeneity parameter[49] (along with different social radiuses and differing weights on the hassle factor). A set of parameters was picked which allows the model to broadly reproduce the aggregate level of heat pump take-up under the RHI for the period 2015 – 2019 (see the top half of Figure 23).

The bottom half of Figure 23 breaks down the modelled and simulated take-up by technology and property type. At this level, the model results do not match historic take-up as closely (in particular, the model underestimates the take-up of ground source heat pumps for low density properties, and overestimates for high density properties). While it would be possible to manually “tweak” many more parameters in the model to obtain a closer fit, we have avoided doing so as the reasons why people have taken up the RHI in the past are likely to be very different to how heating decisions are made by the majority of the population in the future.

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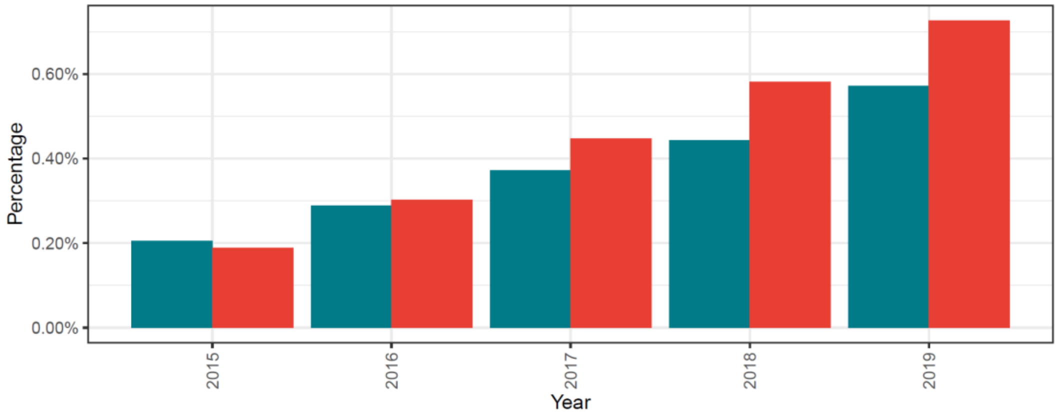
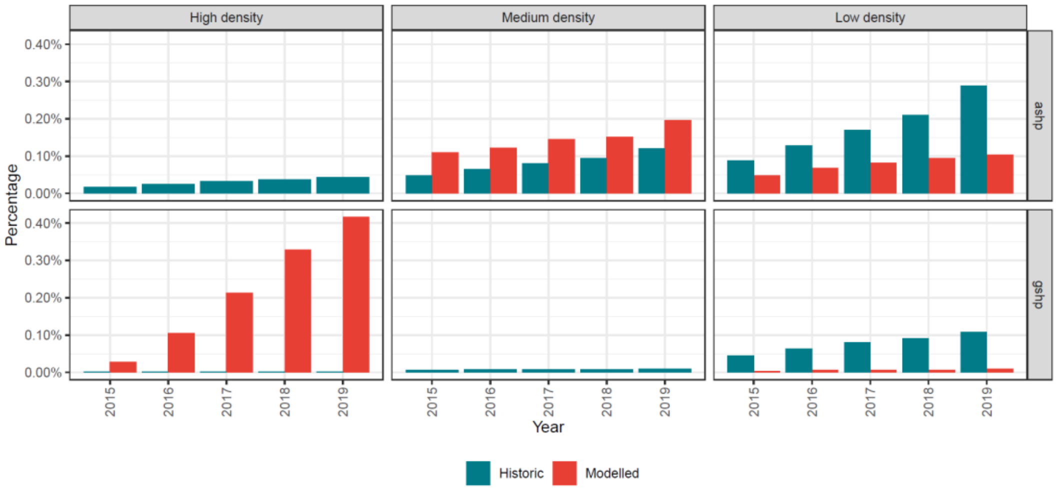
48 Derived from Allen, P.M. and McGlade, J.M. (1986), *Dynamics of discovery and exploitation: the case of the Scotian Shelf Groundshelf Fisheries* in Canadian Jounal of Fisheries and Aquatic Sciences.

49 We have also confirmed that the resulting parameter leads to “reasonable” consumer behaviour – we are expecting a sufficient amount of heterogeneity to allow for some early adopters, while ensuring that the vast majority of owners are carrying out decisions in line with what the model suggests is right given their cost, social, hassle and green factors).

Figure 23 Simulated and observed historic take up of heat pumps, 2015 – 2019





Note: *In the model, ground source heat pumps are not able to be taken up by medium density (MD) properties.*

The impact of random variation on the model

Many of the sources of heterogeneity described above (in addition to the probabilistic nature of elements of the model including heating system failure) result in an element of randomness. A powerful feature of ABMs are their capacity to incorporate any number of such random components. However, these can often lead to very different outcomes in the model when run multiple times,[50] and so it is important to be sure that the results from a single run of an ABM are representative.

In order to test the robustness of the results to this randomness, we have re-ran the model multiple times, observing the aggregate take-up of different heating technologies over time. There is almost no spread: the model is producing consistent results each time.

50 Our model uses a "seed" (a specific number inputted into the model) to ensure the results can be replicated. The model will always produce identical results if it is run with the same seed (the "random" numbers that are drawn will be the same each time). However, running the model with a different "seed" will give different results, and it is important to verify that the results we obtain are not very sensitive to the exact seed we happened to choose. If the system was chaotic in this sense (where small differences in inputs can lead to significant differences in the overall output), it would be difficult to provide forecasts with any certainty.

This consistency will to a large extent be due to the large number of agents in the model. The results below are based on approximately 30,000 agents. This is considerably higher than some similar ABMs.[51]

Given this, and for ease of comparison across scenarios, the results in following sections focus on the mean rather than the spread of model results. In each instance we have checked that the spread is neither significant nor important in interpreting the results.

2.2.5 New builds and retrofits

The housing stock will not be static between now and 2050:

- **New build houses will be constructed**. These are likely to be built to a higher standard of thermal efficiency and may have renewable heating technologies installed, leading to an exogenous increase in the take-up of these technologies. New builds in the model may also indirectly impact the take-up of heating technologies by owners of other properties – for example:
  - Installation of renewable heating technologies for new builds may in the short term constrain the number of installers available for existing properties. In the long run, the demand created by new builds may spur entry of installers who can serve other properties – although at least initially these new entrants may not always carry out high-quality installations.
  - The presence of nearby installations of renewable heating technologies may increase the propensity of other property owners to take up these technologies, through the "social" element of their decision-making.
- **Existing properties will be retrofitted**. Measures such as wall insulation will be carried out, either initiated by property owners themselves, by government policies, or a combination of the two.

This section sets out how the model accounts for these changes.

New builds

Every year, a number of new properties are added to the model. The nationwide number of new builds each year is based on the assumptions in ESME (which splits new-builds into the same low, medium and high density archetypes used within our modelling). For the period 2025 to 2030, the total number of new builds has been increased to 300,000 per year, to correspond to the commitment made by the government in October 2018.[52]

As the model simulates an area of the UK, it assumes that the number of new build houses to be built in that area are proportionate to the area's share of total population.

[51] By comparison, Snape, Boit and Ryulatt (2015), *Will domestic consumers take up the renewable heating incentive? An analysis of the barriers to heat pump adoption using agent-based modelling* in Energy Policy Vol 85 p32-38 used 4,000 agents, and Sopha, Klöckner, and Hertwick (2011*), Exploring policy options for a transition to sustainable heating system diffusion using an agent-based simulation* in Energy Policy Vol 39, p2722-2729 (2011) used 270 agents.

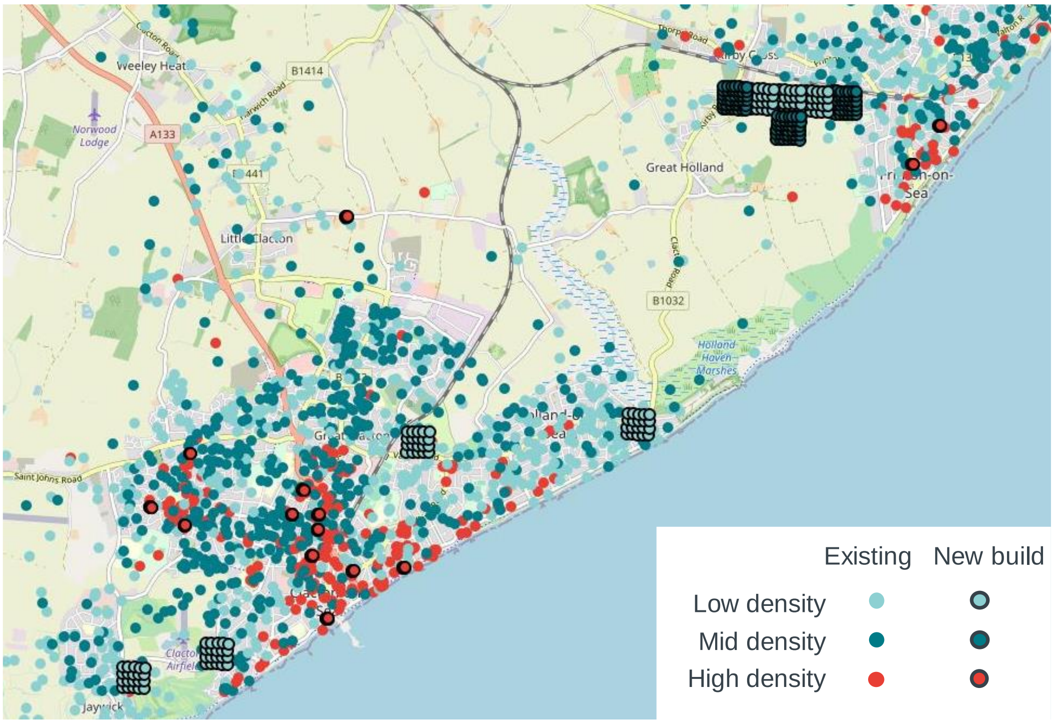
[52] https://www.gov.uk/government/news/government-announces-new-housing-measures

Simple heuristics are used to determine where new build properties are placed on the map. These are not intended to be accurate – for example, the resulting developments may be placed on green belt land or even water features. However the pattern of development is broadly similar to that observed in reality, and is sufficient for this model.

- High density new builds are added as a highly clustered groups of 120 properties, representing a development of flats. These are added to the map by choosing a random existing high-density development and building the new builds adjacent to this. This will generally simulate the building of flats in town and city centres.
- Mid- and low-density new builds are built as individual "estates", of 840 or 400 properties respectively, spaced regularly within 300m x 300m squares. The model adds these to the map by looking for areas where there is currently no housing, but that are near to existing urban areas.

Figure 24 shows an example of how the model places new build developments.

Figure 24 Example of new build placement



Source: Frontier Economics

New builds added before 2025 are assumed to have the same incumbent heating technologies as set out in Figure 13. From 2025, onwards, all new builds are assumed to have an air-source heat pump (to account for the Future Homes Standard).

All new builds are assumed to be built to the ESME "good" thermal rating – i.e. a SAP rating of A or B.

Retrofits

The government's Clean Growth Strategy[53] indicates that all fuel poor homes should be upgraded to EPC band C by 2030, and gives an aspiration for as many homes as possible to be EPC band C by 2035, where practical, cost-effective and affordable.

EPC band C corresponds to the "medium thermal efficiency" archetype in our model. We have therefore assumed that, every year, a proportion of the remaining thermally poor households are converted to meet this standard. As the remaining number of thermally poor houses decreases, the absolute number of retrofits will fall, which simulates the impact of those properties increasingly being hard to treat.

As an illustrative example, the model is currently set such that 5% of the remaining stock of "poor" houses are retrofitted each year. This implies that:

- By 2030, approximately 40% of the current stock of thermally "poor" houses will have been retrofitted to a "medium" standard;
- by 2040 65% of the current stock will have been retrofitted; and
- By 2050 81% will have been retrofitted.

These exogenous retrofits are in addition to the endogenous modelling of retrofits described in section 2.2.1 (when a poor thermal efficiency household wishes to install a heat pump). Unlike those endogenous retrofits, the model does not consider the costs of exogenous retrofits when considering the payments made by property owners. The exogenous retrofits are therefore assumed to be paid for in some other way – e.g. by the Government, or through supplier obligations like ECO.

2.3 Modelling installers' decisions

As summarised in Figure 10, installers both affect the choices made by property owners, and are in turn affected by those choices. These interactions occur across three stages of the model, which repeat for every simulated year:

- First, while property owners are carrying out any replacements to their heating system, they will engage with installers. This interaction takes two forms:
  - Installers provide recommendations which may influence the technology chosen by an owner. When a boiler starts to behave erratically, a property owner may consult a number of installers for advice. An installer who has carried out a lot of successful heat pump installations may suggest this to a property owner – although the owners' ultimate choice of technology will also depend on other factors as described in section 2.2.3.
  - An installer with available capacity is also required to install a technology once it has been chosen.
- Second, after all property owners have carried out any necessary upgrades, the existing installers in the market are assumed to react to market conditions. Installers that are insufficiently utilised may react by either "upskilling" to be

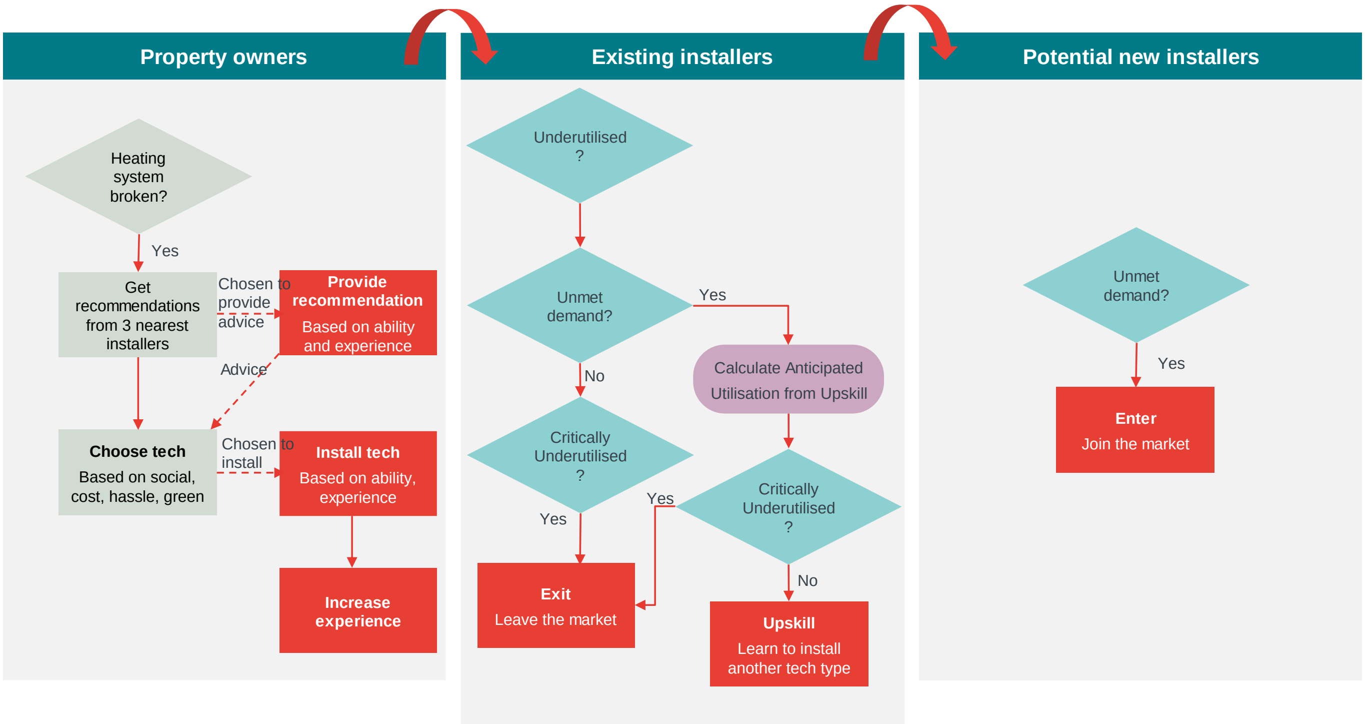
[53] HM Government (2017), *The Clean Growth Strategy*

able to install another type of technology (and choose to offer it to their customers), or otherwise exiting the market.

- Finally, if there is excess demand within the year that cannot be met by existing installers, new installers are modelled as entering the market.

Figure 25 summarises the different roles of installers in each stage of the model.

Figure 25 Involvement of installer agents for each modelled year



Source: Frontier Economics

In the remainder of this section, we first set out how the model characterises installers, and the data used to populate the simulated world with installers at the start of the model. We then describe each of the stages of the model from Figure 25.

2.3.1 Characterising the current market for installers

The model is initialised with a set of installers intended to represent the current market. Each installer in the model is represented by the following parameters:

- **A geographic location**. We have assumed that installers are distributed in proportion to households – i.e. there will be more installers in more densely populated areas. Figures from the Gas Safe Register and MCS register have been used to approximate the average number of installers per household.
- **A capacity** (in terms of person-hours) available to carry out installs. We have determined an average capacity by considering the number of installations currently carried out by installers.
- **A set of capabilities** which determines whether they are able to install different families of technology. The two technology families are as follows. These are not exclusive – for example, some (but not all) heat pump installers will also be

capable and willing to install gas boilers. We have populated the simulated world with a number of installers of each type which is sufficient to meet present demand:

  - Heat pumps (both air-source and ground source);
  - boilers (whether oil, natural gas, hydrogen, or hydrogen-ready) and electric restive heating.

- **The hours of experience** for each of these technology families. This is the number of hours that the installer has spent on installing the technology. This is set at a high level for existing installers.

2.3.2 The influence of installers on property owners

Property owners are assumed to obtain recommendations from their three closest installers regarding which technology they should install. The section on property owners explains how these recommendations feed into their decisions, which will also depend on the cost-effectiveness, local uptake, perceived hassle, and potentially "greenness" of the technology.[54]

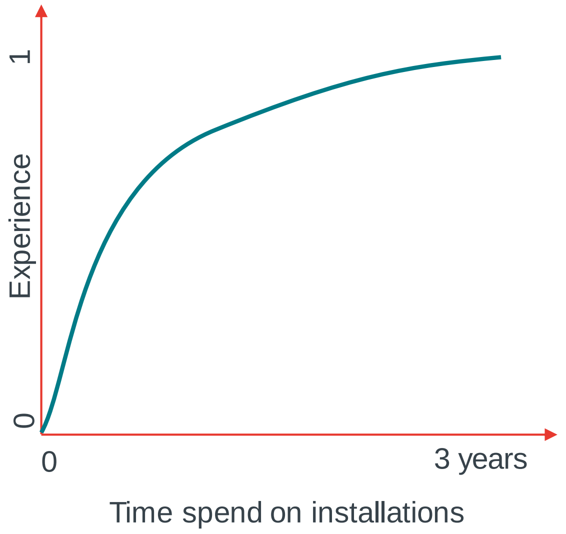
It is assumed that installers will be most likely to recommend the technology that they have most experience installing. This is consistent with past qualitative research suggesting that installers tend to offer technologies that are more familiar with them and are sceptical of the risk of unfamiliar products.[55] An installer's "experience" is a variable between zero and one, where zero corresponds to an installer who has never installed the given type of technology, and one to an installer who is as experienced as it is possible to get.

The model assumes that this experience increases most rapidly for installers with little experience, and then levels off. By a time an installer has spent the equivalent of three full years installing a given technology, we assume that their experience does not continue to increase (this is based on the three years the MCS Competency Criteria Guidance requires to demonstrate suitable experience without a qualification). Figure 26 Illustrates this relationship.

[54] The majority of heat pump installers surveyed as part of BEIS's RHI review reported that "some" or "a lot" of potential customers did not go on to install renewable heating technology after an enquiry, demonstrating that installer recommendations may often be overruled by other concerns. See BEIS (2016), MCS Renewable heat Technology Installers Survey.

[55] Wade, F., Hitchens, R. and Shipworth, M. (2016), *Understanding the missing middlemen of domestic heating: Installers as a community of professional practice in the United Kingdom in Energy Research & Social Science* 19

Figure 26 Installer learning curve (illustrative)



Source: Frontier Economics

Once an owner chooses to install a given technology, it will do so from one of the three nearest installers. If none of these installers have sufficient time available to install the technology, then the owner will need to install an alternative, and there will be unmet demand (see below for how installers respond to this).

2.3.3 The decisions made by existing installers

The model does not explicitly assess the profitability of installers and attempt to calculate their profit-maximising strategies. Rather, a series of simple heuristics are used to determine whether an existing installer chooses to exit the market, or to “upskill” and learn to install (and offer) a new type of technology.

These heuristics are intended to account for the way in which an installer might make decisions in real-life. Although installers are not modelled as strict profit-maximisers, these heuristics the way in which they face a large fixed cost (their wages) and will therefore need to maintain an acceptable utilisation in order to cover these costs.

The heuristics are also backward-looking: Installers are assumed to make these decisions based only on the activities of the previous year, not a forecast of what may occur in the future. While a significant simplification, this is also likely to capture how many installers may behave. Making forecasts of demand years into the future would be extremely difficult for an installer: As illustrated by our model, this is a complex problem. And even if installers could make better forecasts, they are unlikely to be able to sustain a loss for a long time in anticipation of future profitability.

However, we have not undertaken research to validate or calibrate this model – this is therefore an area of uncertainty which future quantitative research into installers’ behaviour could shed further light on.

The installers are modelled as behaving in the following way:

- The installers in our model first ask **whether there is local unmet demand for a technology**. If a property owner is unable to install their preferred heating technology due to a lack of installer capacity, this is considered "unmet demand" for that technology. Each installer observes whether, out of any of the property owners that contacted them for recommendations, any of these owners had unmet demand.
  - If there is no unmet demand, then the installer calculates their **utilisation**. This is the proportion of the installer's total available person-hours that were spent installing heating systems in the previous year. If utilisation is below a given low threshold, the installer **exits the market**.
  - If there is unmet demand for a technology, then the installer calculates their **anticipated utilisation** were they to upskill to be able to install that technology. This is equal to their previous year's utilisation, plus a share of the unmet demand that they would be expected to capture.
    - If this anticipated utilisation is below a low threshold, then the installer **exits the market**.
    - If this anticipated utilisation is above the low threshold (but not so high as to lead to over-utilisation) then the installer **upskills**.

Installers are not explicitly modelled as leaving the market once they reach retirement age (in a 2019 survey,[56] 22% of heating installers were aged 60 or over and so will retire relatively soon). The model is therefore consistent with a world where retiring installers are replaced by new trainees with the same skillset.

2.3.4 The decisions made by new installers

If existing installers are over-utilised, then the model assumes that a sufficient number of new installers will enter the market to ensure that the average utilisation of all installers lies midway between the upper and lower utilisation thresholds.

The calculation of whether existing installers are over-utilised is carried out after any exits and upskilling takes place. For example, consider the case if there was previously only one heat pump installer, who was over-utilised, but that a gas boiler installer had decided to upskill so it can also install heat pumps. The average utilisation would be calculated as if the workload from the previous year had been split between both of these installers.

The model uses a weighted K-means clustering algorithm to place new installers in those areas where existing over-utilised installers are most concentrated. For example, if there was sufficient demand for two new installers to enter, the model would divide the existing over-utilised installers into two geographically distinct groups, and position the new installers in the centre of these two groups.

The combined impact of installer exit, upskilling, and entry will be to ensure that in the long-run all installers have a moderate level of utilisation and can serve the market's demand. However, if there are sudden increases in demand, this may lead to temporary shortages of installers.

[56] Sustainable Energy Association (2019), *Installer Survey Results – October 2019*

2.4 Gas distribution networks

Within the model, the role of gas distribution networks is to set the network tariffs faced by owners. Sufficiently high network tariffs (which feed through into the retail costs of gas) may disincentivise the selection of technologies that use the gas network.

If the number of owners using the gas networks decreases, then the fixed costs of these networks will need to be spread among a smaller number of owners, increasing bills, and potentially incentivising further switching away from gas. If this effect is sufficiently large, it could result in a "death spiral" where costs continue to rise and customer numbers fall.

Frontier's previous modelling for the CCC found that, under a "low gas" scenario, gas volumes might fall by 83% between 2017 and 2050.[57] However the impact on network tariffs would be counteracted by a reduction in allowed revenue, as previous investments (particularly those relating to the replacement of iron gas mains) are recovered and removed from the regulatory asset base (RAB). This might result in an increase of combined distribution and transmission tariffs from 0.8p/kWh to 2.6p/kWh.

To incorporate these effects in the model, it will be necessary to calculate network tariffs based on customer volumes, and pass these through to customer bills (which will in turn affect take-up).

Since our previous work indicated that this effect may be relatively modest, rather than building a complex "bottom-up" model of allowed revenues, we have assumed that the total allowed revenue for gas networks remains constant. Total allowed revenue has been derived by estimating the total gas distribution tariffs payable by customers for our modelled region, at 2020 tariffs. For each year, we then divide this figure by the total kWh of gas or hydrogen consumed in the region to obtain a new network tariff for the following year.

As we are not modelling the decreases in allowed revenue that may follow if the RAB decreases, the model may overstate the impact of reduced gas volumes on network tariffs. However there are significant uncertainties – for example, Ofgem might ultimately choose to "smooth out" some of these changes in the RAB through accelerated depreciation, or additional policy costs may be loaded onto gas through policies like the green gas levy, offsetting an reduction in the RAB. We therefore carry out sensitivity tests on the allowed revenue assumption.

2.5 Government policy

The ABM we have built is not intended to assess specific government policies. However, as carbon emissions represent a negative externality (the climate change caused by one individual's emissions will adversely affect others), some form of government intervention is necessary to promote the uptake of zero carbon heating technologies. We therefore simulate a small number of basic policies.

[57] Frontier (2016), *Future Regulation of the Gas Grid*

While the government policies are an important part of the model, they are specified exogenously. The government is therefore not an "active" agent in the model – we do not attempt to model the government's decision-making process.

The model includes two broad types of government policy:

- taxes and subsidies on fuels; and
- policies that affect the availability of different technologies.

2.5.1 Fuel taxes and subsidies

As explained previously the model applies two types of taxes and subsidies to the fuel used by heating technologies.

- For the period 2015 to 2020 inclusive, we model the Renewable Heat Incentive (RHI). This is a subsidy paid to owners of renewable heating technologies (heat pumps, within our model), based on the deemed amount of heat they produce. This is included within the model so its results can better be calibrated to the actual take-up of heat pumps under the RHI.
- For the period 2021 onwards, we do not model the RHI. Instead, we assume that a carbon tax, based on the forecasts of traded carbon prices from the Green Book, is applied to all fuels used by households.[58] This is intended to act as a proxy for any forms of incentive that could be applied to encourage the take-up of low carbon heating technologies.

2.5.2 Policies affecting the availability of different technologies

Product policies have been used in the past to encourage the take-up of more efficient heating systems. For example, since 2005 all new gas boilers installed in domestic properties have been required to be high-efficiency condensing boilers.

The model has the flexibility to include these types of product policy, by changing the available set of technologies for different types of consumers in different years. We have used this functionality to model the interventions that may be required to transition away from natural gas to hydrogen. Due to the shared nature of the gas distribution networks it is not possible for some consumers to receive natural gas from the network and others on the same network to receive hydrogen. Some degree of central co-ordination will be required to ensure any transition to hydrogen is smooth.

This intervention will be required both during a transition phase, and for the switchover itself. Figure 27 summarises the dates we have assumed for each of these actions and how they have been modelled. These dates are assumed on the basis of key outcomes stated in the CCC's Sixth Carbon Budget.[59] Note that a transition to hydrogen could involve the conversion of different regions within the country at different times, however this model only considers a single region at a time.

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[58] The price of electricity also includes a carbon cost, since generators are required to purchase emissions permits. This cost will already be embedded within the retail electricity price projections we use.

[59] A summary is provided in table 1.1 of CCC (December 2020) *Policies for the Sixth Carbon Budget and Net Zero.*

Figure 27 Assumed timeline for hydrogen switchover

Date	Actions	Modelling
2022	**Announcement date** Consumers are made aware that natural gas will become unavailable from 2040, but that hydrogen-ready boilers will continue to function.	The assumed lifetime of gas boilers (used by owners when calculating the cost-effectiveness of a technology) is reduced accordingly.
2022	**Availability of hydrogen-ready boilers** Hydrogen-ready boilers become available as a choice for consumers on the gas network.	Hydrogen-ready boilers are added to the choice set of all owners on the gas network.
2025	**Mandation of hydrogen-ready boilers** Consumers are not able to purchase natural gas only boilers from this year onwards	Natural gas only boilers are removed from the choice set of all owners on the gas network.
2040	**Switchover date** Any remaining natural gas boilers must be replaced. Hydrogen-ready boilers burn hydrogen, rather than natural gas. Hydrogen-ready boilers are withdrawn from the marketplace and replaced with hydrogen-only boilers.	All remaining natural gas only boilers expire – these owners are forced to choose a new technology. Hydrogen-only boilers are made available to owners on the gas network and hydrogen-ready boilers are removed from the choice set.

Source: Frontier Economics

2.6 Energy service companies

The buildings modelling commissioned for the CCC's Sixth Carbon Budget included a number of scenarios where a "heat as a service" business model was assumed to be widespread. This had the following impact on the models' inputs:

- The cost of capital was changed to 7.5%, presumably to account for the cost of capital of the service company, which would be responsible for purchasing heating technologies.
- A 5% increase in heat demand was assumed. This may account for the way that customers no longer paying for each kWh of gas or electricity may face less incentive to carry out energy efficient behaviours.
- A 3% financial saving was modelled. This may account for cost savings from integrating the wider value chain (e.g. energy suppliers, heating technology suppliers, installation).
- A 15% increase in heat pump efficiency was modelled, which may account for the way a heat as a service company could, using automated controls and data gathered from other properties, optimise the use of a heating system.

We have simulated a scenario that considers energy service companies, and applies these assumptions (with the exception of the 3% financial saving, since we are not explicitly modelling energy suppliers).

Since our ABM considers non-monetary drivers of choice, we have also considered how these may be affected:

- We have removed the “social” factor. The assumption is that the energy service company itself chooses the technology it will install, and can provide a guarantee to the property owner that its performance will be satisfactory. This may reduce the impact of recommendations from other owners or from installers (who, in this scenario, would not be contracting directly with the property owner).
- We have maintained the assumptions around the “hassle” factor. Regardless of whether a heating technology is commissioned by an energy service company or by the owner themselves, the occupant of the property will still be impacted by its installation and running, and it seems reasonable that energy service companies would have to offset these non-monetary costs with lower prices.
- We have maintained the assumptions around the “green” factor. The presence of “green” energy tariffs demonstrates that some customers are willing to pay extra for a low-carbon product, even if they are not directly involved in choosing the underlying asset.

3 MODEL RESULTS: ELECTRIFICATION ONLY SCENARIOS

We have used the model described in the previous chapter to simulate the take-up of heating technologies by property owners in the period from 2020 to 2050.

To explore the results of this model, we have first considered a scenario where the only low-carbon sources of heating are electrically powered (air-source heat pumps, ground source heat pumps, and electric resistive heating). This allows us to understand the dynamics of the system before a transition from natural gas to hydrogen is introduced in the following chapter. Figure 28 illustrates the technologies available for each property archetype.

Figure 28 Technologies available to archetypes in "electrification only" scenarios

	Gas boiler	Oil boiler	Electric resistive	Air-source heat pump	Ground-source heat pump
HD_ThG	✓		✓		✓
HD_ThM	✓		✓		✓
HD_ThM_Elec			✓		✓
HD_ThP	✓		✓		Retrofit required
HD_ThP_Elec			✓		Retrofit required
MD_ThM	✓			✓	
MD_ThP	✓			Retrofit required	
LD_ThM	✓			✓	
LD_ThM_Oil		✓		✓	✓
LD_ThP	✓			Retrofit required	
LD_ThP_Oil		✓		Retrofit required	Retrofit required

Source: Frontier Economics

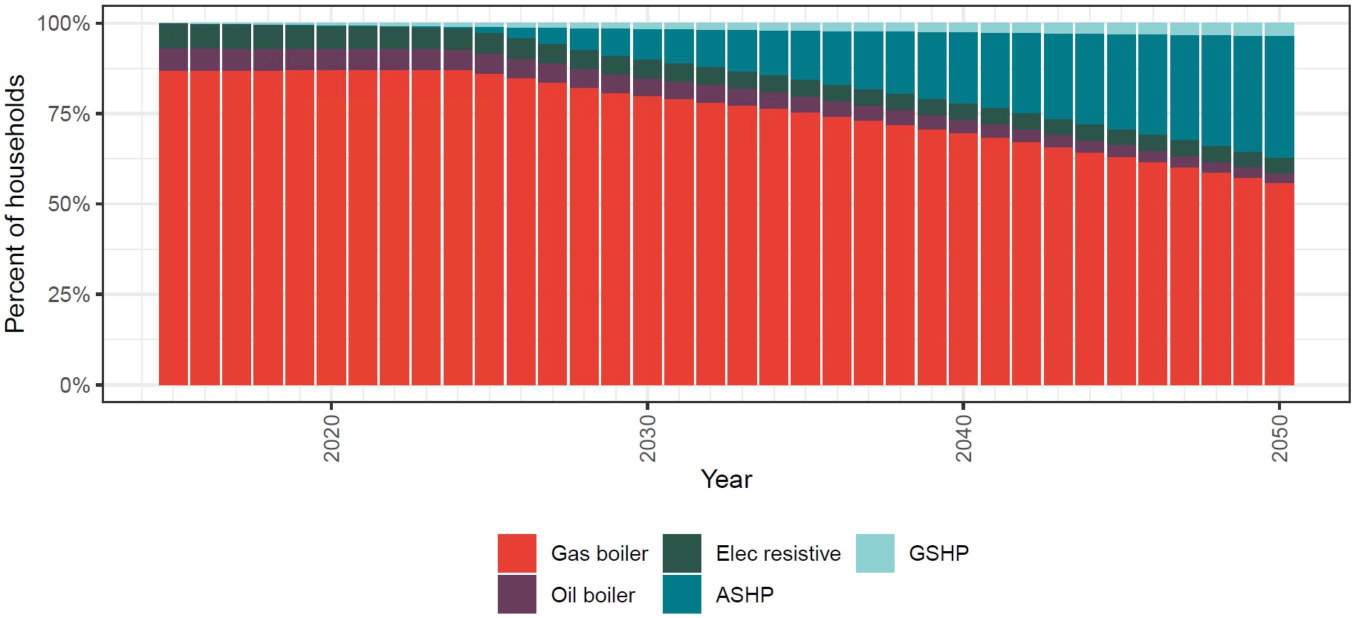
This chapter is structured as follows:

- First, we present the high-level results of the model when run with our base case assumptions (described in the previous chapter). The model outputs show the overall take-up of technologies and how this breaks down by archetype. We have also explored the distributional impacts of the modelled transition: Which types of owners does the model suggest will benefit more from the transition to a low-carbon heating system, and why?
- Although these results are intuitive, the uptake is much slower than the modelling carried out by the CCC and ETI shown in Figure 4, Figure 5, and Figure 6. To determine whether this result is driven by the model methodology or input assumptions, we have adapted the model to simulate owners that choose their heating technologies purely based on cost (and without high discounting of future benefits). This leads to a much higher take-up of heat pumps, closer to the CCC and ETI forecasts. This result demonstrates that the addition of non-monetary factors can lead to very different results in a model of this type.
- The following section shows the sensitivity of the modelled results to the carbon price, which is the main incentive for decarbonisation in the model.
- We then carry out a number of additional model runs which illustrate the way in which the links between different owners' decisions leads to a "multiplier effect" in the model – an exogenous increase in heat pump uptake by one group can lead to increased uptake by others.

3.1 Take-up of heating technologies under our base-case assumptions

Figure 29 shows the modelled overall take up of various heating technologies. Each vertical bar represents the technologies in use at the end of a given year.

Figure 29 Take-up of heating technologies in electrification only scenario, 2015 - 2050



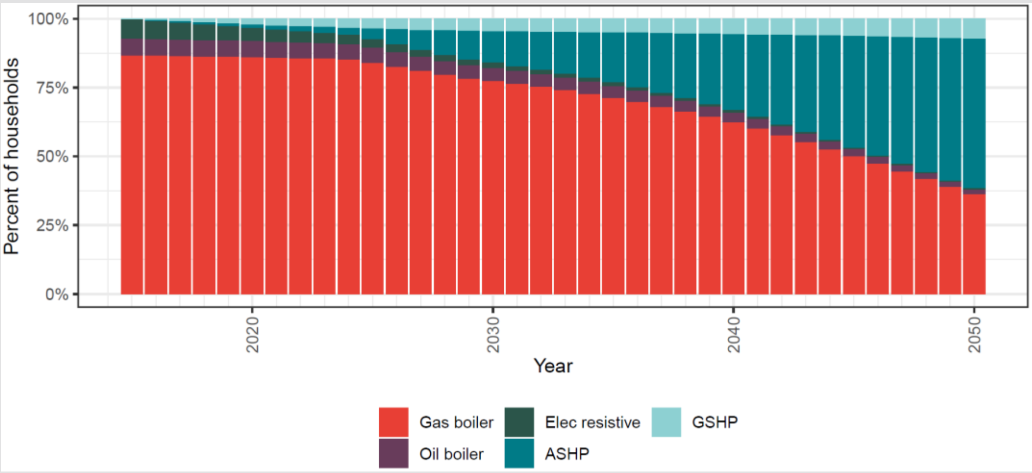
Source: Frontier Economics

Under our base-case assumptions in this electrification only scenario, gas boilers remain the dominant heating technology with just over half of households using this technology by 2050 – down from about 82% in 2015. While a greater proportion of off-grid customers using oil boilers move to heat pumps, the transition to heat pumps is not complete for this group either. Although we do see a slow increase in the take-up of air source heat pumps, ground source heat pumps still remain an unpopular choice of heating technology.

These results differ from the CCC projections shown in Figure 6 (and the ETI scenarios in Figure 4 and Figure 5), which show a significant take up of heat pumps, and an entirely low-carbon set of technologies by 2050. As described in section 3.2, the presence of non-monetary drivers of choice means that the aggregate take-up does not match what might be considered "optimal" for the system as a whole.

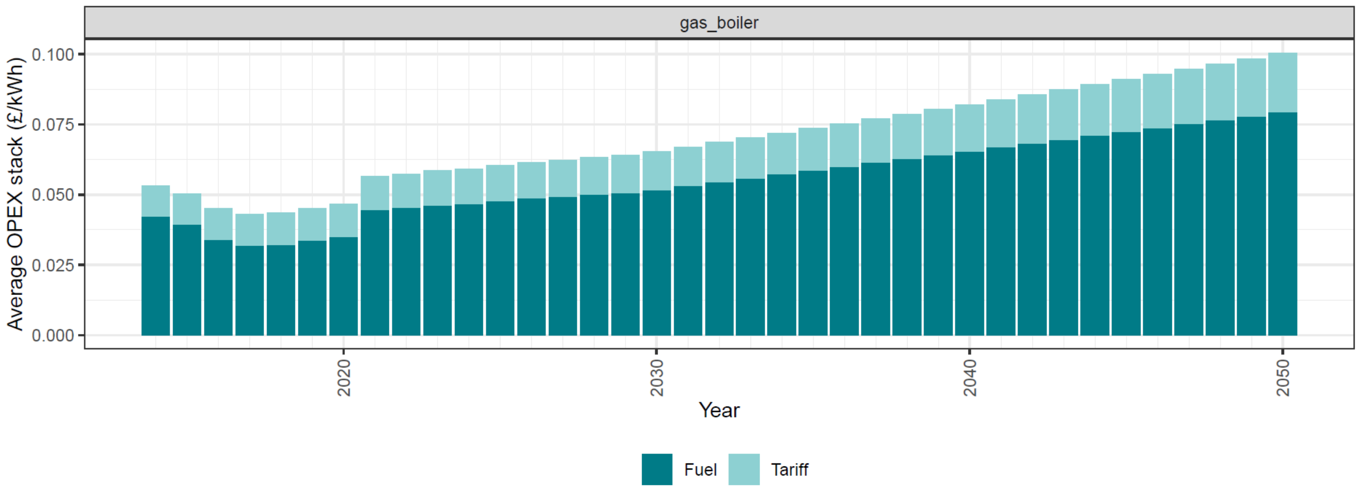
IMPACT OF ENERGY SERVICE COMPANIES

As described in section 2.6, we have also simulated the widespread rollout an “energy service company” model. The simulated results are shown below, and show a significant increase in heat pump uptake compared to the baseline. This is primarily due to the low discount rate assumed for the company, which allows all customer groups to access heat pumps once they are cost-effective, despite their high upfront costs. This demonstrates the potential impact of business models or policies which can overcome the aversion of some consumer groups to capital-intensive technologies.



Due to the move away from gas boilers, gas network tariffs increase over time, as shown in Figure 30. However this increase is relatively small compared to the overall level of the bill (which includes a carbon price charged on gas). There is therefore no substantial “death spiral” effect where increasing network charges lead to an ever accelerating move away from the gas network.

Figure 30 Gas prices including network tariffs

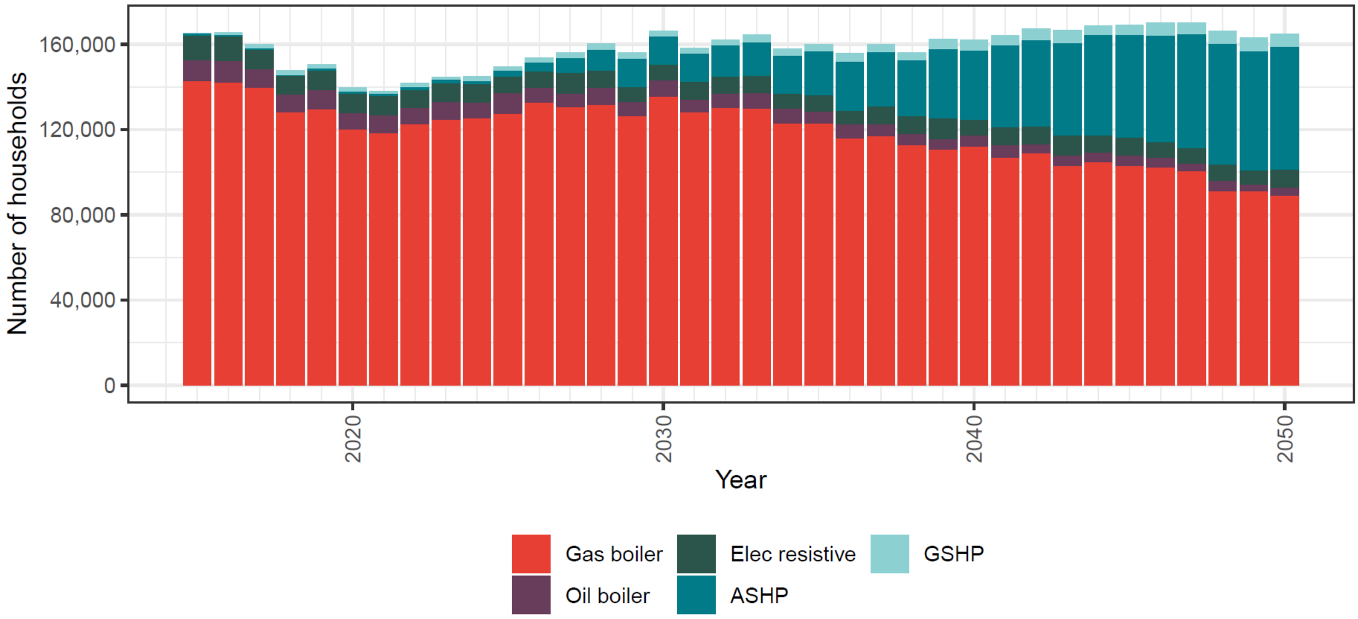


Source: Frontier Economics

Note: The discontinuity after 2020 is due to the addition of a carbon price to the gas price

Figure 31 shows the year-by-year number of installations, by technology. The yearly totals are broadly constant over time. As consumers are assumed to change their heating system once the existing system reaches the end of its life, the overall number of installations reaches a steady-state. The proportion of installations which are heat pumps gradually increases, particularly from the mid-2030s onwards. However even by 2050, heat pumps constitute fewer than half of all new installs.

Figure 31 Year-by-year installations of heating technologies in electrification only scenario, 2015 - 2050



Source: Frontier Economics

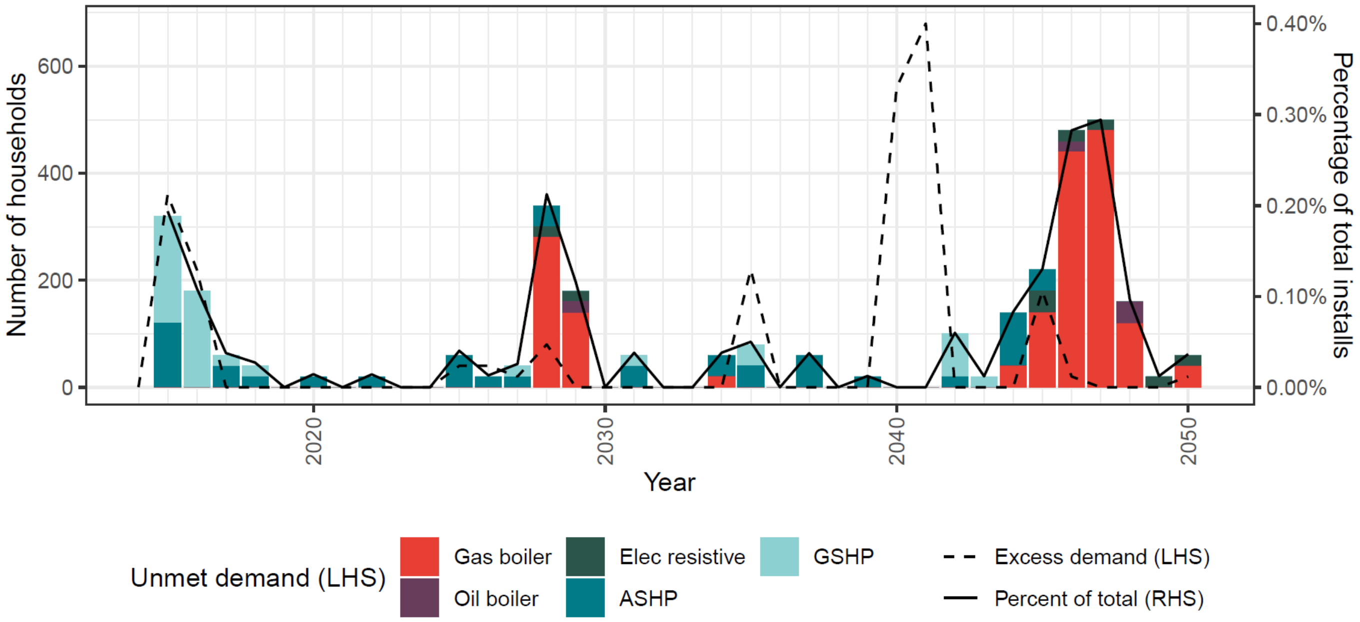
Figure 32 shows the amount of unmet demand of households by technology- i.e. the proportion of installations where an owner wished to install one technology, but could not do so due to a lack of available installers. This graph is interpreted as follows:

- The dotted line shows the absolute number of households which could not obtain a heating technology at all,[60] which is extremely low.
- The solid line shows the proportion of all installations where a household wanted one technology, but had to settle for another due to a lack of supply.
- The coloured bars show the technologies for which this occurred.

Before the mid-2040s, it is generally heat pumps for which demand cannot be met by installers. However, the proportion of total installations for which demand is unmet is typically below 0.15% of total installations, which indicates that the capacity of installers is not a material constraint for the take-up of heat pumps.

[60] In the model, all households must have some form of heating technology, and so one will be chosen for these households. However if this figure is high, it suggests that the market will have insufficient capacity to serve demand.

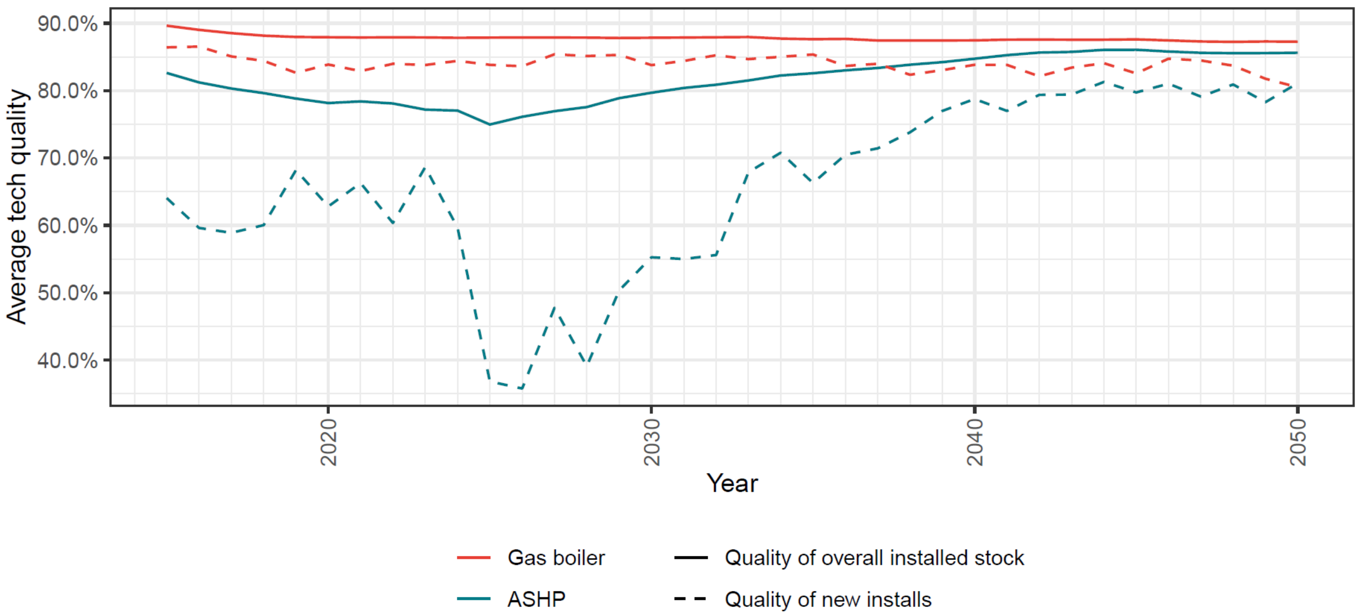
Figure 32 Year-by-year unmet demand of households by technology, 2015 - 2050



Source: Frontier Economics

In order to meet the demand, a large number of installers who had not previously installed heat pumps are required to enter the market. This glut of relatively inexperienced installers is particularly notable in the mid-to-late 2020s and, given the assumptions made in the model (described in section 2.3.2) leads to the average quality of heat pumps being installed falling, as shown in Figure 33. While the "quality" figure itself is difficult to interpret,[61] this clearly illustrates the risks associated with large-scale entry.

Figure 33 Installation quality by technology



Source: Frontier Economics

[61] The "quality" figure simply relates to the average experience of an installer, where 100% relates to an installation carried out by an installer with the equivalent of 3 years experience. We have not carried out research to quantify the link between this experience and an objective measure of install quality.

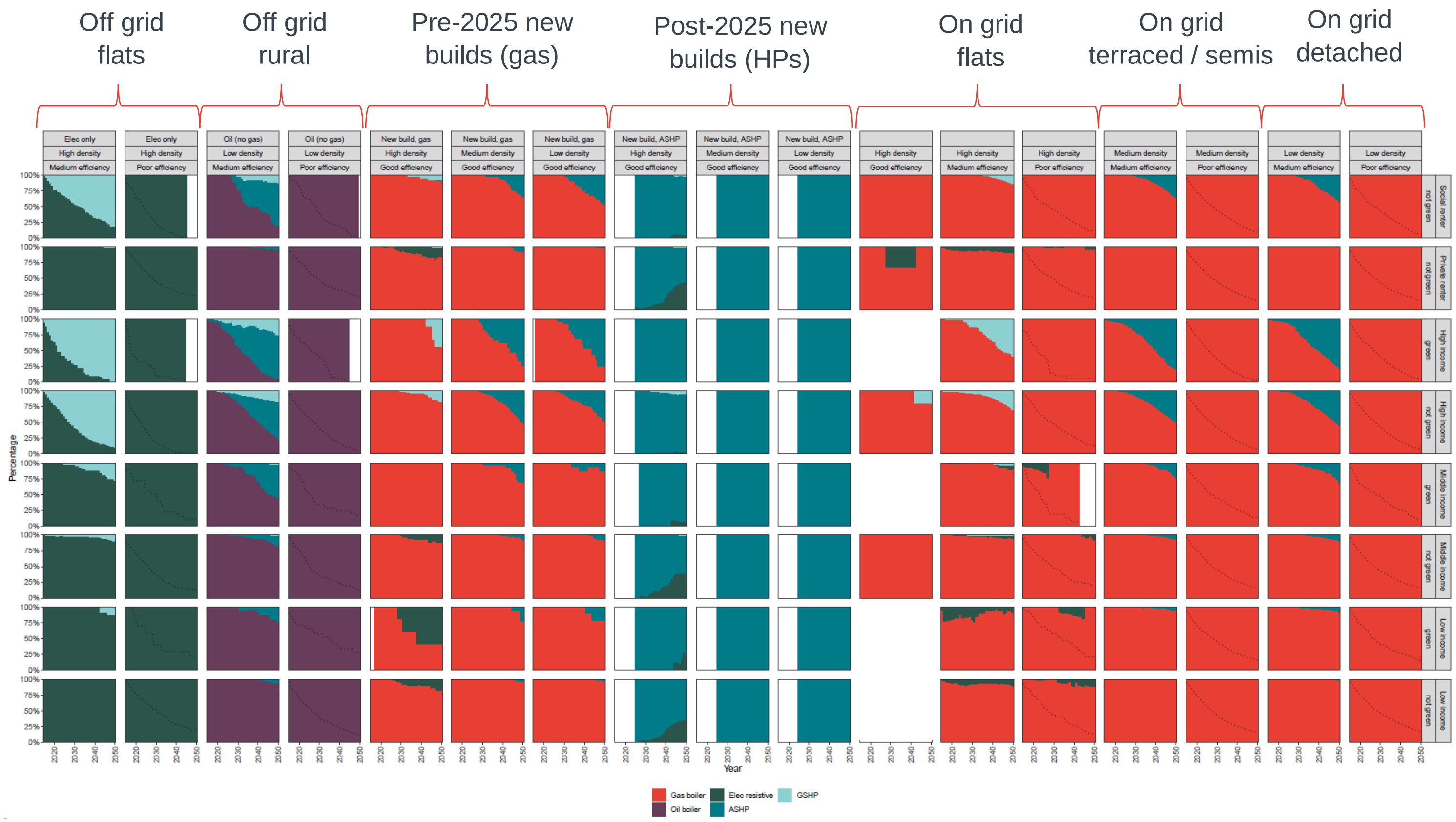
3.1.1 Results by archetype

Each column in Figure 34 shows the take-up for a particular archetype, defined by the type of property, presence of a gas grid connection, thermal performance. The archetypes are also split by income-group, tenure type, and whether the owners are "green" or not – this is shown in the different rows.

Each stacked area chart shows, for that archetype, the proportion of households using each heating technology in each year. If the chart is white, this is because there are no households of that type in that year.

The three "poor thermal efficiency" archetypes also have a dotted line. As described in section 2.2.1, these archetypes can upgrade their insulation to become "medium thermal efficiency" (this is required to install a heat pump). The dotted line shows the proportion of the original group remaining that has not upgraded.

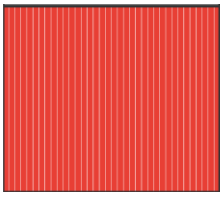
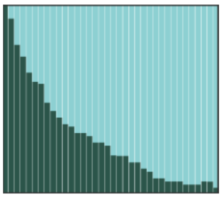
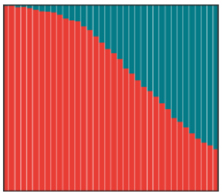
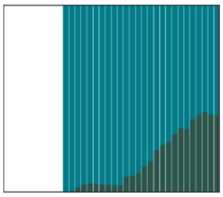
Figure 34 Take-up of heating technologies by archetype in electrification only scenario



Source: Frontier Economics

The different archetypes demonstrate a variety of patterns, which are summarised in Figure 35.

Figure 35 Different patterns of decarbonisation

Example	Description
	**No decarbonisation** Apart from the groups noted below, the majority of archetypes continue to replace their heating system like-for-like (i.e. with a gas, oil, or electric resistive system). With our baseline set of assumptions, a heat pump is modelled as having a higher lifetime cost, greater hassle, and (due to the majority of other property owners having gas boilers) less social pressure than the incumbent technologies, even by 2050.
	**Rapid decarbonisation** Some groups (notably high density, mid thermal performance, off-grid dwellings occupied by social tenants or high-income owner-occupiers) move to low-carbon heating systems quickly. Even though a ground source heat pump has additional capital costs and hassle, the resulting energy savings (it is assumed to use less than a third of the electricity) overcome this for these groups which have low discount rates.
	**Steady decarbonisation** A few groups display a steady move away from the incumbent technology to heat pumps, generally from the mid-2030s. These groups are primarily high income groups or social renters (who are assumed to have low discount rates). Take-up is somewhat higher among “green” households.
	**Air source heat pump to electric resistive** Many low- and mid-income owners (or private landlords) of new build flats, who are assumed to come already fitted with air-source heat pumps, are modelled as replacing them with electric resistive heating once they reach the end of their life. While counterintuitive (replacing a heat pump like-for-like is modelled as having no greater hassle than replacing with electric resistive), this is due to the much lower capital costs of electric resistive heating, which makes it more attractive to these groups.

Source: Frontier Economics

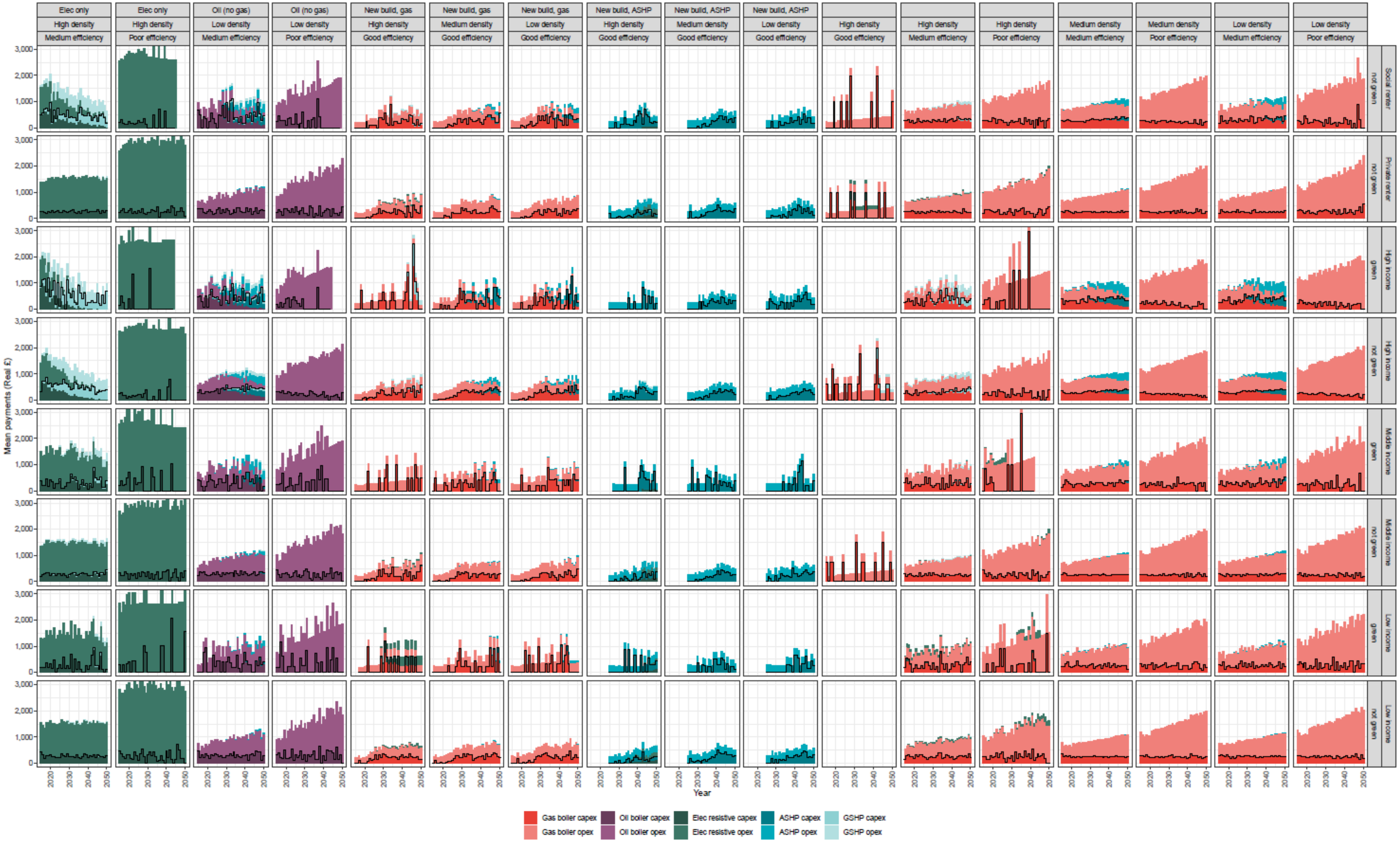
We now turn to some of the distributional impacts of the modelled transition.

3.1.2 Distributional Impacts

By looking at the average heating bill of the various archetypes, we can analyse the distributional impacts in the model to understand how the different income groups will be affected. Figure 36 shows the average yearly cost of heating for each archetype. This consists of:

- the initial capital expenditure required when a new heating system is purchased; and
- ongoing running costs (i.e. those elements of consumers’ energy bills relating to heating).

Figure 36 Archetype average payments by year – all archetypes



Source: Frontier Economics

Note : Light shaded areas above the black line are ongoing running costs, dark shaded areas below the black line are capital expenditure.

We can see that, by the end of the modelled period, for many groups:

- "Green" customers end up with slightly lower bills relative to non-"green" customers. This seems unintuitive, as one might assume that customers with "green" attitudes would be prepared to pay a premium for a "green" technology. However, by 2050, a heat pump is more cost-effective than a gas boiler (due to the significant increases in the cost of natural gas in this scenario) – it is the "social" and "hassle" factors (as well as the high discount rate of some groups) which prevent greater take-up. The "green" factor helps counteract these, and therefore leads to lower costs.
- High-income customers end up with lower bills relative to middle- and low-income customers. This is due to their lower discount rate, which means they pick technologies which are lower-cost in the long term. This has important distributional implications, as it suggests that the customers that may incur least costs from the transition to low-carbon heating are those that already have the most wealth.

All of the results described above seem reasonable, and provide confirmation that the model is working as we would expect. What is less clear is why the model is producing a much slower (and incomplete) transition to a decarbonised heating system than the types of model discussed in section 1, and whether this is due to the agent-based nature of the model. The following section explores this question further.

3.2 Impact of non-monetary drivers of choice

We wish to understand whether the slow transition to a decarbonised heating system in our model is due to the nature of the model (which captures many drivers of consumer choice and interactions that other models do not), or is simply the result of the assumptions that we have used (for example regarding the cost of the different technologies).

Below, we report the results of two sensitivities: The first amends the model to more closely correspond to a system optimisation model, and demonstrates that the lower uptake of heat pumps in our model is due to drivers of consumer choice other than cost. The second examines in more detail two of the factors which reduce consumer uptake (high discount rates, and the "hassle" factor).

3.2.1 Impact of non-monetary factors in aggregate

As described in the introduction, many models of the heating system transition focus on the mixture of technologies that minimise overall system cost. While the ABM described in this report is not a cost-minimisation model, it is possible to amend its parameters to more closely resemble such a model. By doing so, we can determine to what extent the non-cost factors included in the modelling are, together, driving results.

To carry out this exercise, we have amended the model inputs as follows:

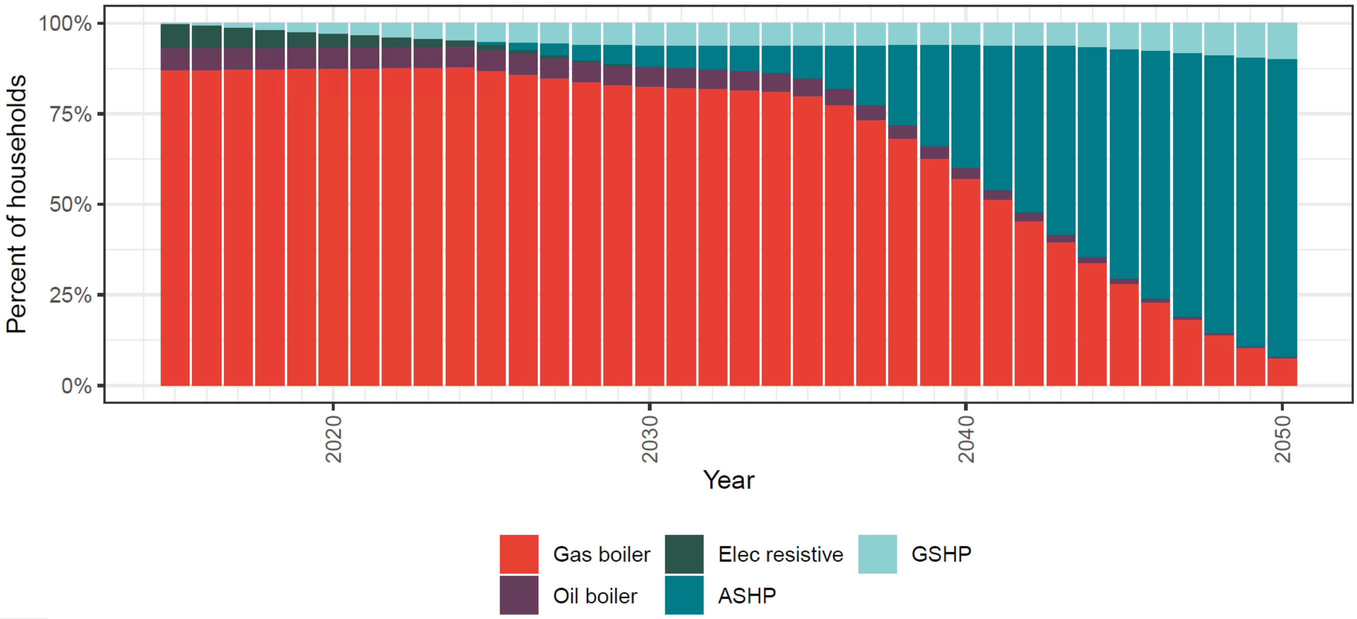
- We have set the weights assigned to the non-cost components (the "social", "hassle", and "green" elements of the utility function) to zero. Consumers will therefore only take into account the costs of purchasing and running a heating system.

- We have set the discount rate for all owners of 3.5% (the social discount rate used in the Treasury's Green Book).
- The heterogeneity parameter is set at a high enough value such that owners choose the most attractive option with a very high probability.

Since we have removed the "green" factor and set the discount rate to 3.5% for all agents, there is no longer any distinction between "green" and "non-green" owners, or different tenure types (owners-occupiers, private renters and social renters).

Figure 37 shows the aggregate take-up of heating technologies in the model driven by monetary cost. We can see that there is little change in the distribution of take-up among agents until the mid-2030s, at which point the increasing carbon price means that the annuitised cost of taking up a heat pump is lower than that of taking-up a gas (or oil) boiler for most consumers so we start to see mass switching to heat pumps.

Figure 37 Aggregate take-up of heating technologies in a model with no non-monetary drivers of choice, 2015 - 2050



Source: Frontier Economics

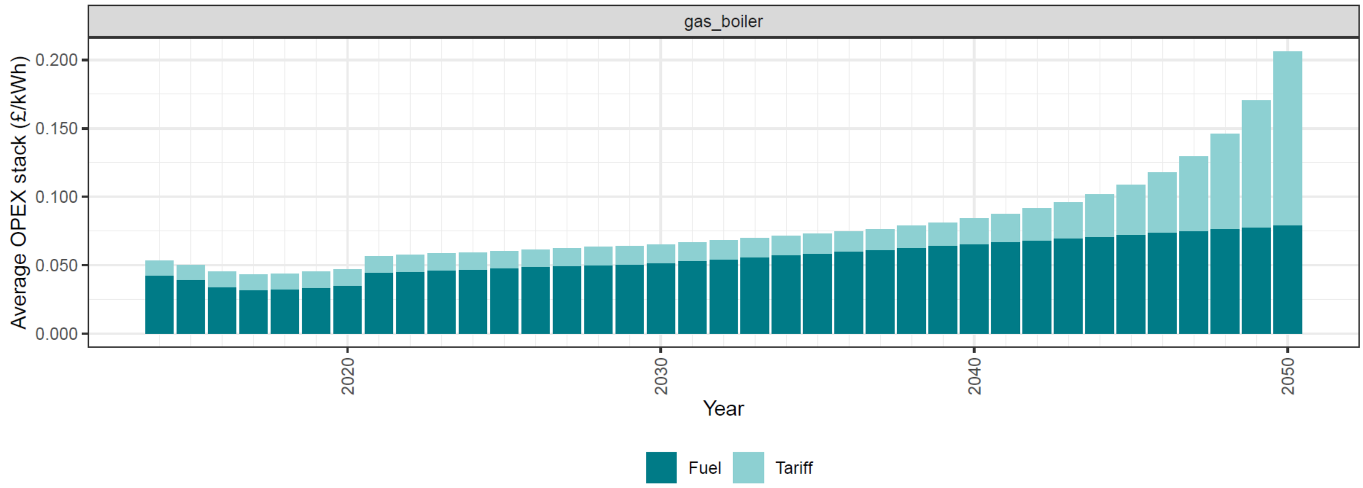
These results are broadly similar to the trajectories from the models described in chapter 1.[62] This suggests that **the low take-up in our model is driven not by the assumptions we have made regarding costs, efficiencies etc, but by the addition of factors such as hassle, high discount rates, and social influence**.

Even in this configuration, the model allows some indirect interactions between agents' decision-making to take place. However the overall impact of these now appears to be *increasing* the rate of heat pump uptake above what it would otherwise be:

[62] The transition occur within a faster period than the central CCC scenario shown in Figure 6. This is likely due to the way our model does not include a constraint on the rate of installation of heat pumps.

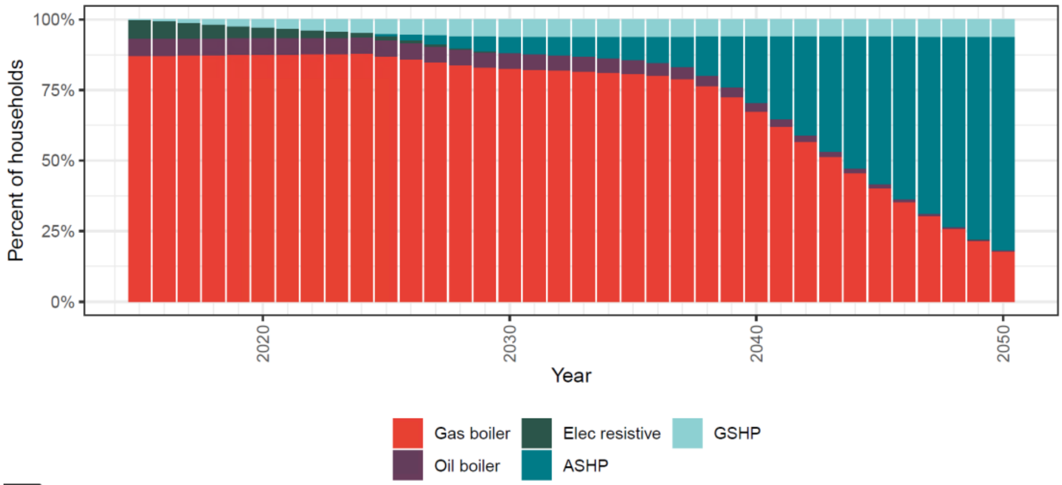
- As owners move away from the gas grid, **network tariffs** will rise which could **increase** the speed of the rollout. Figure 38 shows that there are substantial increases in network tariffs in this scenario. Figure 39 plots the overall take-up of technologies in a model without endogenous network costs, and shows how take-up of heat pumps by 2050 would be somewhat lower. While this network cost effect is also present in the baseline scenario, as shown in Figure 30, the lower levels of heat pump uptake in that scenario are insufficient to cause a substantial change in network tariffs.
- Heat pump installations may still be constrained by **installer availability**. However, the ramp-up of heat pump installs is sufficiently gradual that this is not a material constraint: Unmet demand is highest in the mid-2030s, but each year fewer than 0.5% of households wishing to install a heat pump are unable to do so due to a lack of installers.

Figure 38 Full electrification network costs in cost-driven model



Source: Frontier Economics

Figure 39 Full electrification technology uptake in monetary driven model, without endogenous network costs



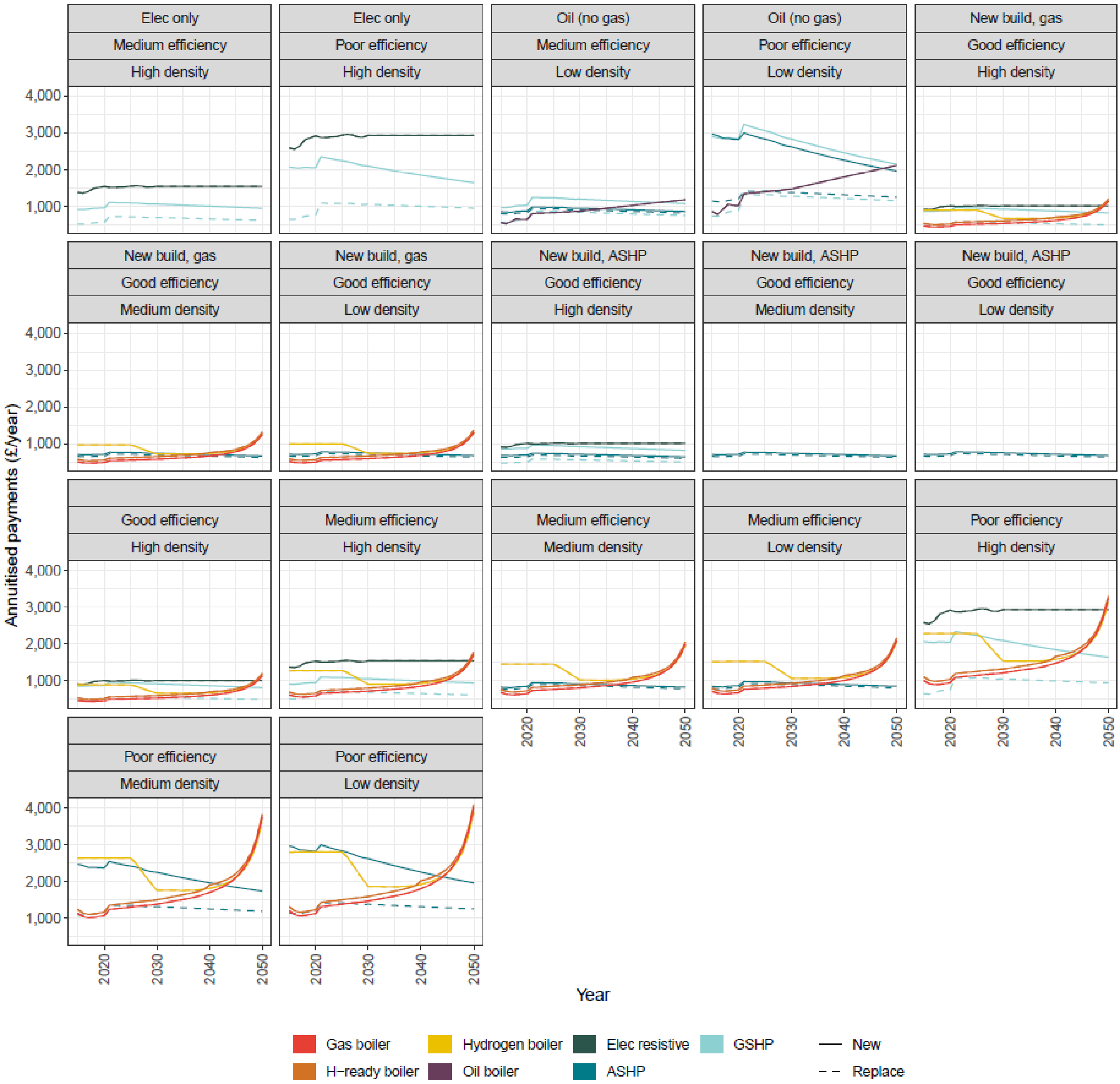
Source: Frontier Economics

Figure 40 breaks down the results by archetype. This shows how the transition to a low-carbon heating system starts at a slightly different time for the different groups. This reflects differences in the year when heat pumps become cheaper (on an annualised basis) than boilers, shown in Figure 41.

Figure 40 Archetype-by-archetype results in cost-driven model

Source: Frontier Economics

Figure 41 Annuitised payments for each technology, 2015 – 2050



Source: Frontier Economics

3.2.2 Which non-monetary factors are most important?

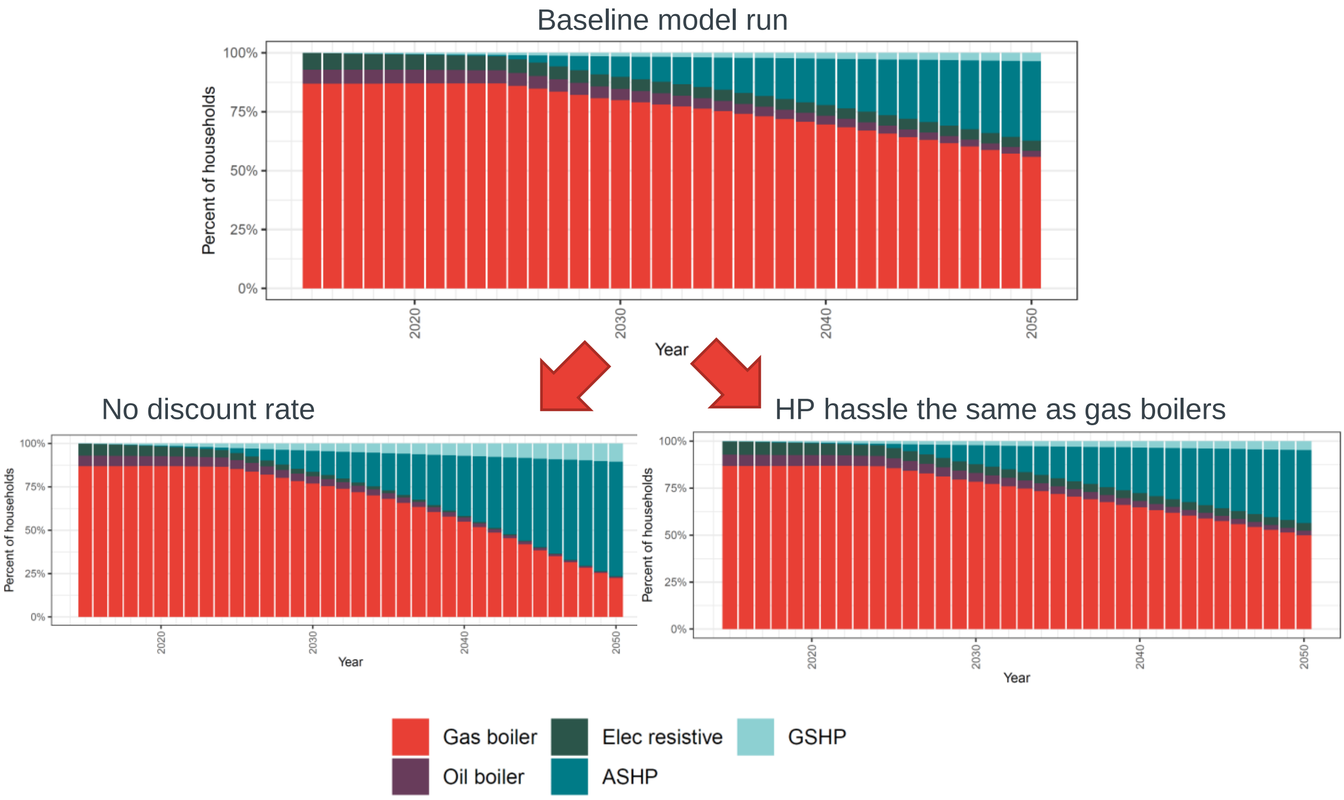
To understand what the most important barrier to heat pump uptake may be in the baseline model, we have run two further scenarios which isolate the impact of the "hassle" factor, and the heavy discounting applied by certain customer groups.

- In the first sensitivity, we have reduced the discount rate for all customers to zero (so all customers will place the same value on future bill savings as on up-front costs).

- In the second, we have reduced the hassle value for heat pumps to the same level as gas boilers.

Figure 42 compares the results of both scenarios to the baseline scenario shown in Figure 29.

Figure 42 Impact of hassle and discounting



Source: Frontier Economics

It is clear that the high discount rates assumed for some types of owners are a much greater barrier to modelled heat pump take-up than the impact of the "hassle" factor, even though the latter applies to all types of owner. This result follows from monetary value of hassle used in the model (which as explained in section 2.2.3 is derived from a previous choice experiment). Although the willingness to pay to avoid hassle is relatively high (£600), this is much smaller than the differences in capital cost of the technologies. For property owners who do not consider (or heavily discount) the future running costs of technologies, the capital cost will therefore tend to dominate.

If this result holds in practice,[63] then it suggests that policies and business models aimed at lowering the up-front costs of renewable heating technologies (for example loans or lump-sum subsidies) could have a significant impact. This could be the case even if it is not possible to reduce some of the "hassle" factors, which may be intrinsic to the technology and less amenable to policy intervention.

[63] As noted elsewhere in this report, this model has been calibrated to past choice experiments (which have not involved customers actually purchasing heating technologies) and the experience under the RHI (which so far has not appealed to the mass market). As the market becomes more mature, further consumer research and data analysis could help to validate the assumptions around consumer choice.

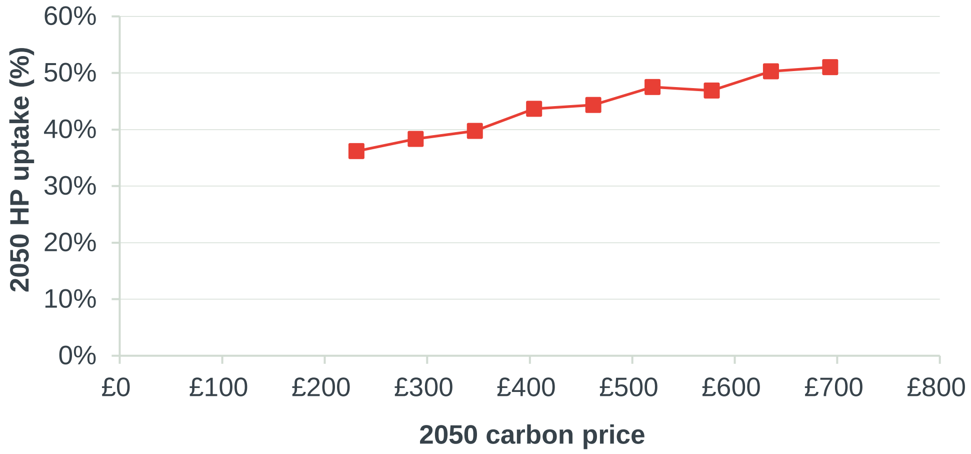
3.3 Carbon price sensitivity

In this section, we present the results of a model sensitivity where the carbon price applied to gas (the decarbonisation policy lever assumed in our model) is increased. A wider range of sensitivity tests have been applied to the model scenario which includes hydrogen, which are shown in section 4.4.

As shown in Figure 29, the carbon price we have applied to gas (based on the Green Book forecast value) is insufficient to lead to a mass switchover from gas to electricity. We have therefore carried out further runs of the model to determine whether a higher carbon price (as a proxy for policies which increase the running costs of gas boilers) could lead to a materially higher take-up.

Figure 43 shows the results of these sensitivities. The X-axis shows the carbon price in 2050 (applied to gas), which ranges from the Green Book value (£231/tCO2e) to a value three time that. We modelled a carbon price which increases linearly from current values to this level, so the uplift will be lower in earlier years. The Y-axis shows the total take-up of heat pumps in 2050.

Figure 43 Impact of carbon price (on gas) on heat pump uptake



Source: Frontier Economics

While a higher carbon price applied to gas does increase heat pump uptake, the effect is relatively gradual – even an increase of three times only increases the 2050 heat pump uptake from around a third to a half of all households. The impact is also relatively linear: The “feedback effects” discussed above are insufficient to lead to a critical mass of households taking up heat pumps.

3.4 Impact of interactions between agents

The results in the previous section demonstrate how incorporating drivers of consumer decision-making besides up-front and running costs can lead to very different outcomes. However, including high discount rates or including a non-monetary “hassle” parameter does not in itself require an agent-based model where the decisions of owners or installers affect one another. We have therefore carried out model runs designed to ascertain the impact of feedback effects between owners.

Below, we first demonstrate that there is a material effect whereby take-up by one property owner can spur take-up by other owners. We then consider the implications of this for policies – how might policies be designed that best take advantage of these effects?

3.4.1 Quantifying the feedback from owners' decisions

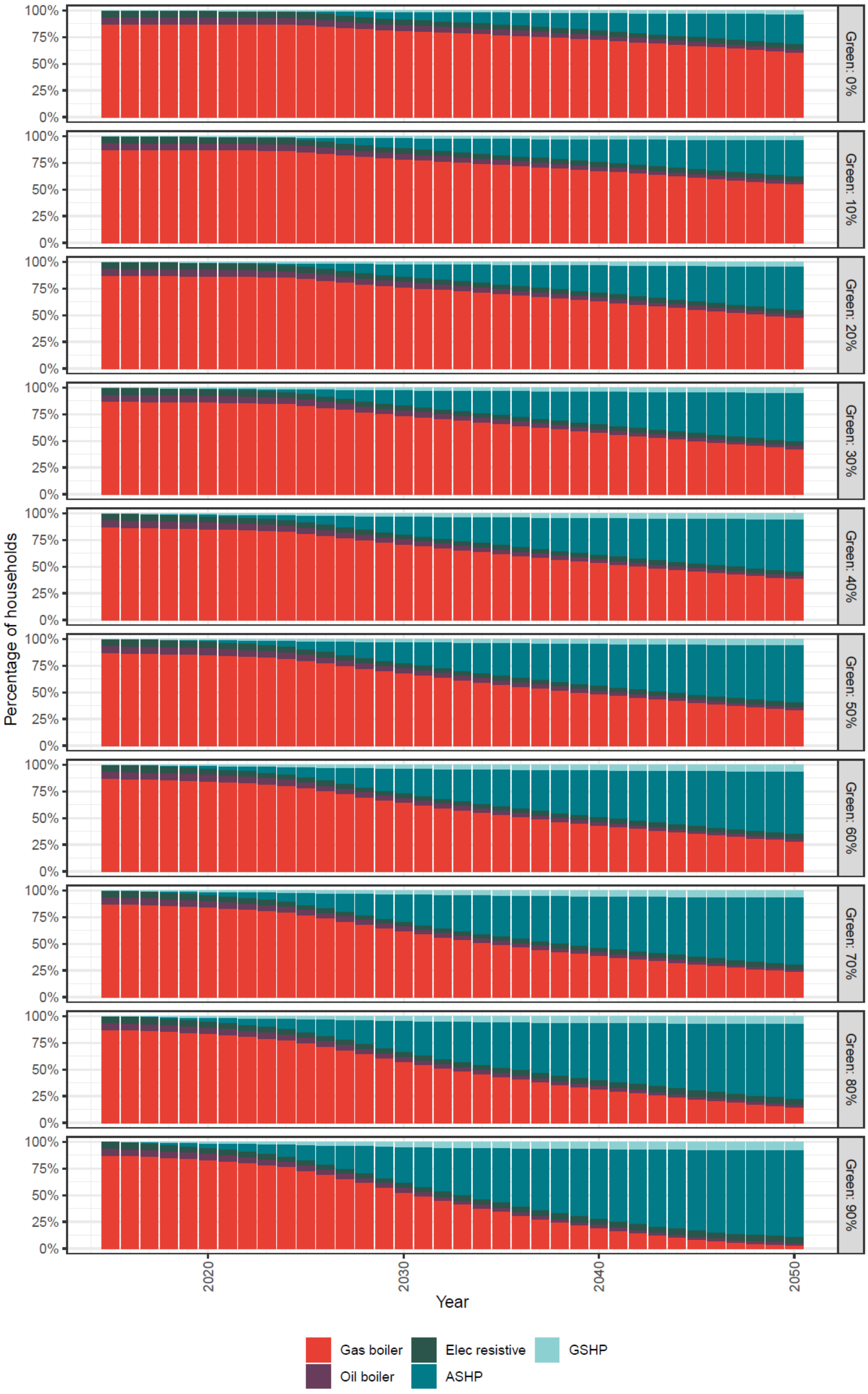
As illustrated in Figure 10, there are a variety of channels through which behaviour by one owner can impact the decision taken by another owner. To test the extent to which this impacts the results, we have carried out a number of model runs where we exogenously "force" on additional heat pumps, and then look to see if this has an effect on other owners' decisions.

To do this, we have repurposed the "green" agents within the model:

- The impact of the "green" boost to agent take-up has been increased by a very large amount, so that "green" agents will always take up a heat pump if one is available.
- We have then varied the proportion of "green" agents, from 0% to 90%, and examined the mix of technologies for non-"green" agents.

Figure 44 plots the resulting take-up. The top graph in this figure shows the take-up of technologies in each year *by non-green owners* when there are zero "green" owners (the technologies taken up by the "green" owners themselves are not included in these graphs). The bottom graph shows the take-up when 90% of owners are "green". It is clear that there is a substantial "spill-over", where take-up by the "green" owners hastens the take-up by others.

Figure 44 Impact of increasing the number of "green" owners on other owners' take-up decisions

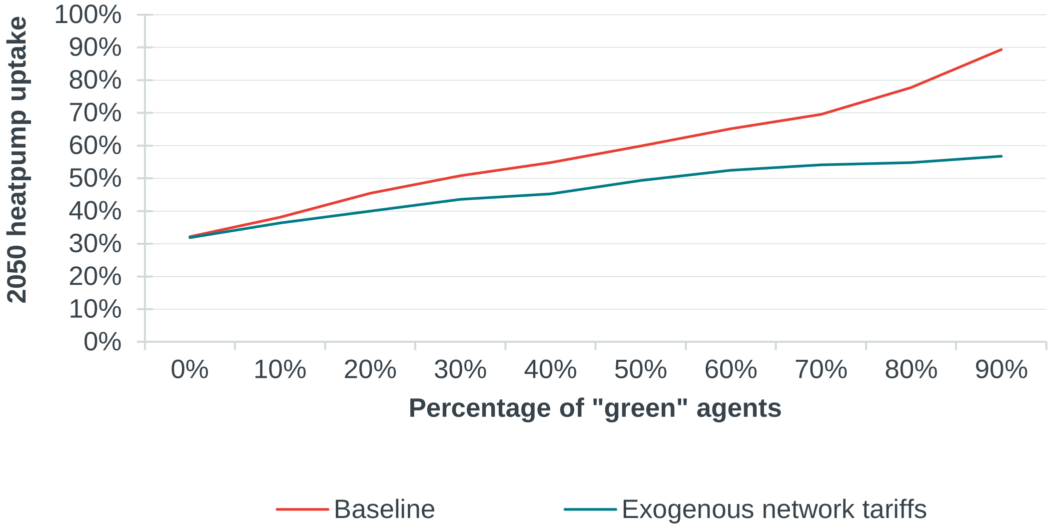


Source: Frontier Economics

This impact could be due to a variety of mechanisms. In addition to the interactions between property owners and installers, there may be an impact of network tariffs (which will increase as the use of the gas network decreases, further incentivising take-up of heat pumps).

While the impact of network tariffs is important to capture, doing so would not require a full agent-based model. We have therefore carried out a sensitivity where network tariffs are exogenous, to determine how much of the effect seen in Figure 44 is due to interactions between owners and installers. Figure 45 summarises the output. Rather than graphing the profile of take-up for every year, this graph plots the percentage of non-“green” owners modelled as taking up heat pumps by 2050.

Figure 45 2050 heat pump uptake by percentage of “green” owners



Source: Frontier Economics

Both lines slope upwards, showing how even in the absence of the network tariff effect, there is a material spillover from “green” agents to others.

3.4.2 Exploiting the multiplier effect

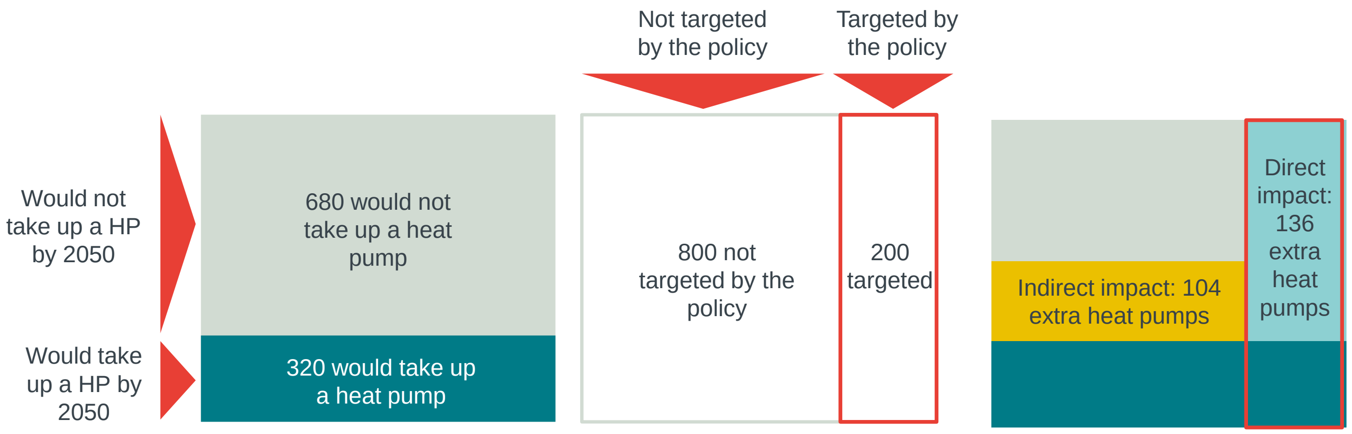
Quantifying this effect can be useful to help design cost-effective policies. Consider the decisions made when designing a scheme which increases heat pump uptake for particular targeted groups (for example, targeted subsidies, or a demonstrator programme that directly installs heat pumps). Such a programme would be most cost-effective if:

1. The cost per targeted owner is smaller;
2. the percentage of targeted owners who take up a heat pump is larger;
3. the percentage of these owners who would *not* have taken up a heat pump in the absence of the policy is higher; and
4. the spillover impact (where the heat pump take-up by targeted owners leads to greater take-up by others) is higher.

We can use the ABM to calculate a “multiplier effect” which shows, for every owner directly targeted, the number of additional heat pumps taken up by owners that were not directly targeted. This is illustrated in Figure 46 (the figures in this example relate to the model runs above where the percentage of “green agents” – those targeted by the policy – is increased from 0% to 20%).

- The left hand square illustrates a situation where there are 1,000 property owners. Of these, without any extra intervention, 320 would take up a heat pump by 2050, while 680 would not.
- The centre square illustrates a policy which targets 20% of owners at random. Therefore 200 owners are targeted (some of which would have taken up a heat pump anywhere).
- The right square shows the direct impact of the policy on targeted owners (for whom it is assumed the policy leads to 100% take-up) and also shows the indirect spillover on those that were not targeted: a further 104 heat pumps were brought forward from this group.
- So for every 200 owners that the policy targeted, there was an indirect increase in take-up of 104 heat pumps. **That can be expressed as a multiplier of 0.52 extra heat pumps per targeted owner.**

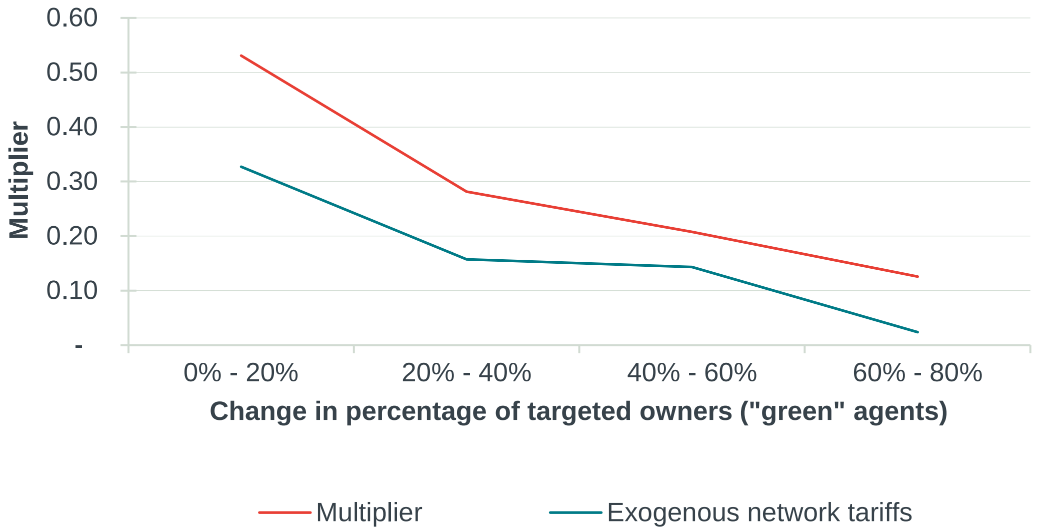
Figure 46 Calculating a multiplier effect



Source: Frontier Economics

The chart below plots this multiplier effect for the two scenarios in Figure 45. At relatively low levels of uptake, each additional heat pump that is added to the system leads to a further 0.53 heat pumps (as explained above, and if network tariffs are modelled endogenously), or 0.33 if they are not.

Figure 47 Multiplier effect of an intervention



Source: Frontier Economics

The multiplier effect falls as the number of targeted (i.e. “green”) owners rise: There are diminishing marginal returns to interventions which force more heat pumps onto the system. The more owners there are that are already taking up a heat pump due to an intervention, the fewer other owners there are for them to impact.

With very high proportions of “green” owners, most of the effect is driven by network tariffs. Network tariffs will become more significant as the overall number of heat pumps increases and the fixed costs of the network are spread across a smaller and smaller group of customers. For example, moving from 100% of properties being on the gas network to 90% would only increase network tariffs by 11%, while moving from 20% to 10% would increase them by 100%.

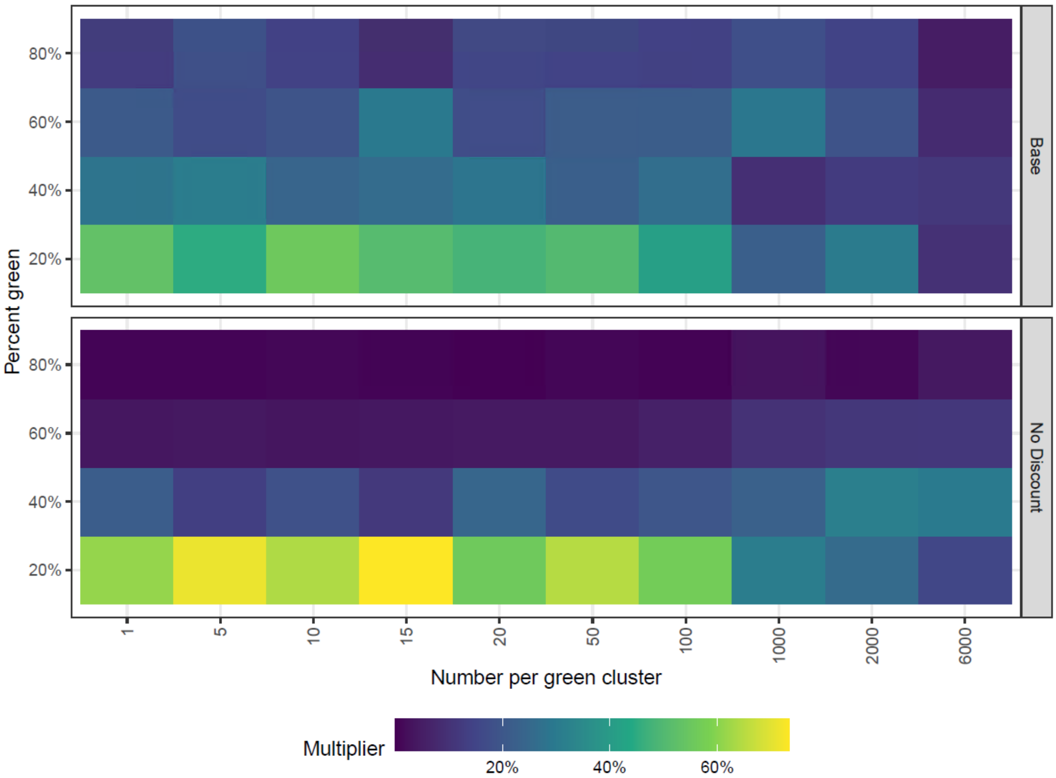
Government policies which take advantage of multiplier effects will, all else equal, be more cost-effective. While this work has not been intended to assess specific policies, as an example we have briefly assessed two factors which may increase the multiplier effect.

- First, the role of owners’ discount rates. As described in section 3.2.2, the high discount rates we have assumed many property owners place on future benefits are a significant barrier to take-up. They may dampen the multiplier effect, by reducing the impact that social influence from neighbours can have. We have therefore looked at what would happen to the multiplier effect if some other policy or business model had the effect of reducing discount rates for all groups of owners to zero, as in Figure 42.
- Second, the extent to which the properties targeted by the policy are geographically clustered. It is possible that a cluster of heat pumps (for example from a demonstrator programme) could have more of an impact than the same number of heat pumps spread evenly across the region.

Figure 48 summarises the results of these scenarios. Each square in the graph is coloured to indicate the size of the multiplier effect, ranging from dark blue for no impact, to light yellow for a high impact. The top figure shows the effects under our baseline scenario, while the lower figure shows the effects in a scenario with zero discounting. Going from left to right, the columns increase the extent to which the targeted “green” owners are clustered: from 1 on the left (where, as in the results above, green agents are chosen at random) to 6,000 on the right (where the targeted owners are clustered in a smaller number of groups of 6,000 properties).

Going from bottom to top, the figure shows the marginal multiplier effect if the policy targets more owners.

Figure 48 Multiplier effect by scenario



Source: Frontier Economics

This analysis shows that if other policies or business models are already in place which spread the up-front cost of technologies, the multiplier effect of a policy can be much greater than if customers apply the high discount rates in our baseline.

It is more difficult to observe a systematic impact of clustering. However, at least for the bottom row of the figures (which shows the multiplier associated with a policy which moves from targeting no owners to targeting 20%), very high levels of clustering appear to *dampen* the multiplier effect. When the intervention is concentrated in one small area, it affects fewer owners who are not already targeted.

The impact of clustering becomes less clear when looking at the incremental impact of interventions which target more customers. This may be due to the way that, as shown in Figure 47, at higher levels of uptake the effect is driven by network tariffs, which in the model are assumed to be the same across the entire region.

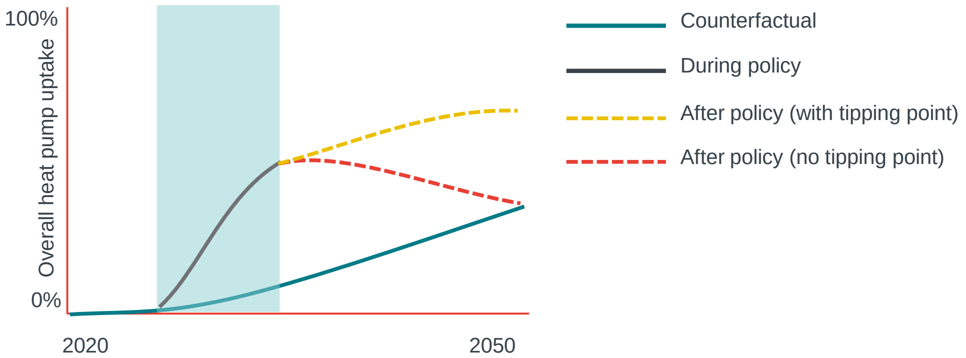
3.4.3 The persistence of policies

In all of the examples discussed in this section, the “green” owners we have used to proxy for policies are in place for the entire duration of the modelled period. Some of them will replace their heating system multiple times, and the policy is assumed to incentivise them to take up a heat pump every time.

A further question we have not investigated (but which could be examined with further development to the model) is the extent to which a policy which is only active for a limited period could have a long-run impact on the heating technologies in use. Figure 49 provides two illustrative example of what might happen if a policy was only in effect for a limited period (shown by the blue shading):

- A tipping point may be reached, which ensures that the additional heat pumps brought about by the policy persist, and continue to bring about increased uptake even after the policy is finished. This is shown by the yellow dotted line.
- Alternatively, if such a tipping point is not reached, the extra households that have taken a heat pump may gradually revert over time, such that in the long run the policy has no effect.

Figure 49 Illustrative example of a tipping point



Source: Frontier Economics

There are a variety of mechanisms in the model (and in the real world) which may mean that the impact of a policy continues after it has ceased. These include the feedback effects discussed above, where the greater level of uptake increases incentives to take up a heat pump, even once the policy ceases. The lower cost and hassle of replacing a heating technology like-for-like will also produce a ratchet effect, where owners who have overcome the initial barriers to switching will find it easier to keep the same technology in future.

However, we have also seen from this modelling that the initial cost of low-carbon heating systems can be a very high barrier for some groups. If this barrier is greater than the effects describe above, then it is plausible that some owners may revert to heating technologies with lower upfront costs if they are available. This can be observed in Figure 35 where a material proportion number of new-build customers with heat pumps ultimately reverted to electric resistive heating once they had the choice, despite being part of new-build estates which would all have heat pumps.

If ABMs are used to simulate specific policies, then they will be able to shed light on the likely dynamics of what will happen after the policy is removed.

4 MODEL RESULTS: HYDROGEN SCENARIOS

The model has been used to simulate a transition of the gas network to deliver hydrogen (assuming that hydrogen production and transmission infrastructure has been built). Figure 50 indicates the technologies that are now available to each archetype.

Figure 50 Technologies available to archetypes in hydrogen scenarios

	Gas boiler	Hydrogen / gas boiler	Hydrogen boiler	Oil boiler	Electric resistive	Air-source heat pump	Ground-source heat pump
HD_ThG A B	Until 2024	2025 - 2039	2040 onwards		✔		✔
HD_ThM C D	Until 2024	2025 - 2039	2040 onwards		✔		✔
HD_ThM_Elec C D					✔		✔
HD_ThP E F G	Until 2024	2025 - 2039	2040 onwards		✔		Retrofit required
HD_ThP_Elec E F G					✔		Retrofit required
MD_ThM C D	Until 2024	2025 - 2039	2040 onwards			✔	
MD_ThP E F G	Until 2024	2025 - 2039	2040 onwards			Retrofit required	
LD_ThM C D	Until 2024	2025 - 2039	2040 onwards			✔	
LD_ThM_Oil C D				✔		✔	✔
LD_ThP E F G	Until 2024	2025 - 2039	2040 onwards			Retrofit required	
LD_ThP_Oil E F G				✔		Retrofit required	Retrofit required

Source: Frontier Economics

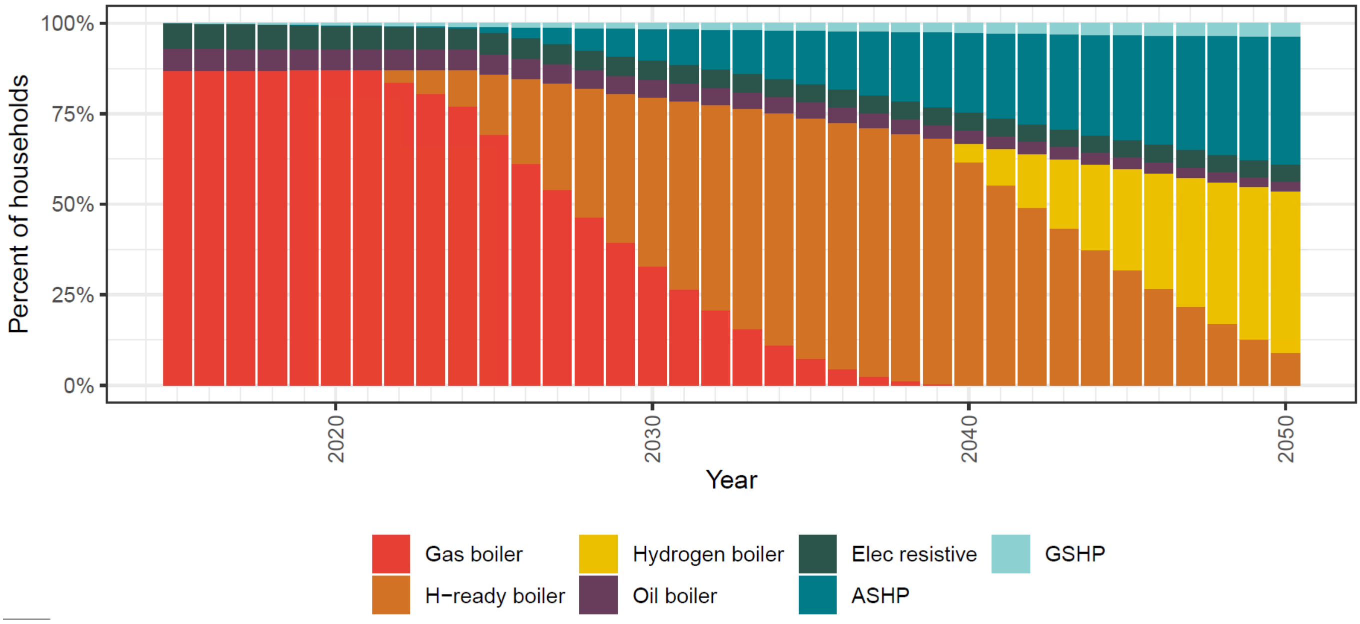
This chapter is structured as follows:

- First, we present the high-level results of the model. Under our baseline assumptions, hydrogen boilers have a similar cost (and functionality) to gas boilers. With a sufficient transition period, the results are therefore very similar to those discussed in the previous chapter, albeit with hydrogen boilers taking the place of gas boilers.
- We then explore scenarios where insufficient time is given for the hydrogen transition, and where the costs of purchasing and running hydrogen boilers are higher.
- Finally, we present a variety of sensitivity tests to examine the impact of the model to different assumptions.

4.1 Take-up of heating technologies under our base-case assumptions

Figure 51 shows the overall take-up of heating technologies modelled in the scenario where hydrogen and hydrogen-ready boilers are available. Broadly, the pattern is very similar to Figure 29, but with hydrogen-ready and hydrogen-only boilers taking over from gas boilers once they are mandated. The assumptions we are using suggest that from a household's perspective these technologies are very similar to gas boilers (including a similar fuel price). It is therefore unsurprising that the overall profile of technology take-up is similar to a scenario where boilers continue to burn natural gas.

Figure 51 Take-up of heating technologies in hydrogen scenario, 2015 - 2050

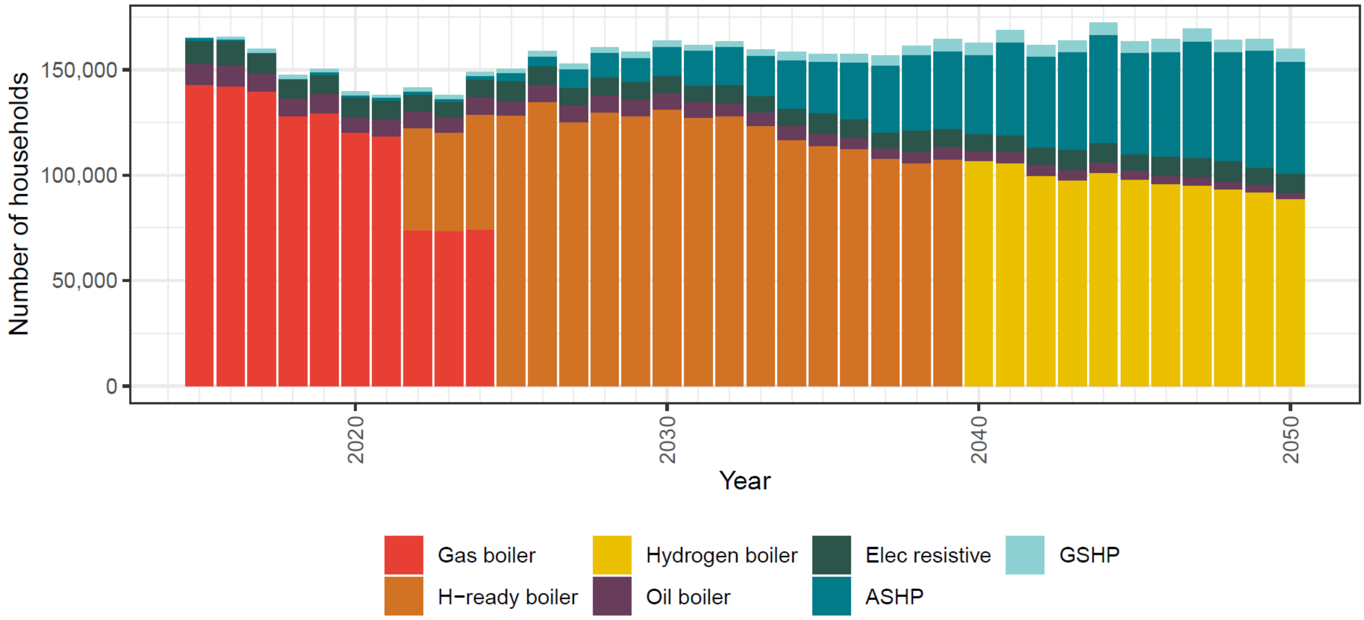


Source: Frontier Economics

As the majority of properties continue to use the gas network (which by 2040 is delivering hydrogen rather than gas), there is relatively little impact on modelled network tariffs, which in turn do not have a significant impact on uptake.

Figure 52 shows the number of technologies of each type installed per year. Due to the early mandation of hydrogen-ready boilers, there are no remaining natural gas boilers to replace in 2040. This means that there is no sudden requirement for installations upon switchover.

Figure 52 Year-by-year installations of heating technologies in hydrogen scenario, 2015 - 2050

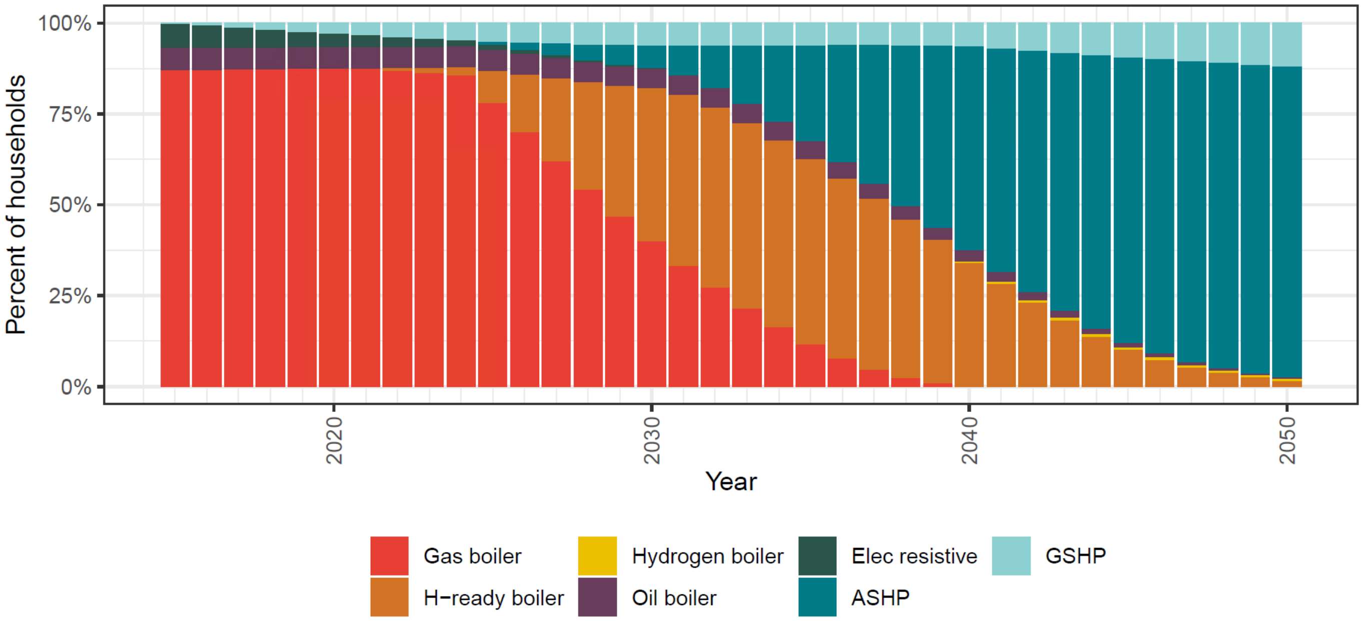


Source: Frontier Economics

The distributional consequences of this scenario are very similar to those shown in Figure 36, owing to the similar cost and behaviour of hydrogen boilers to their gas-fired counterparts.

As in the full electrification scenario, we have also tested a variant of the model with no non-cost factors affecting take-up. The resulting take-up is shown in Figure 53. As hydrogen has a similar cost to gas, it is again “optimal” in the long-run for boilers to be replaced with heat pumps, and so (in this specific model which does not explicitly account for electricity distribution network costs) hydrogen is not the optimal long-run solution.

Figure 53 Aggregate take-up of heating technologies in a model with no non-monetary drivers of choice in hydrogen scenario, 2015 - 2050

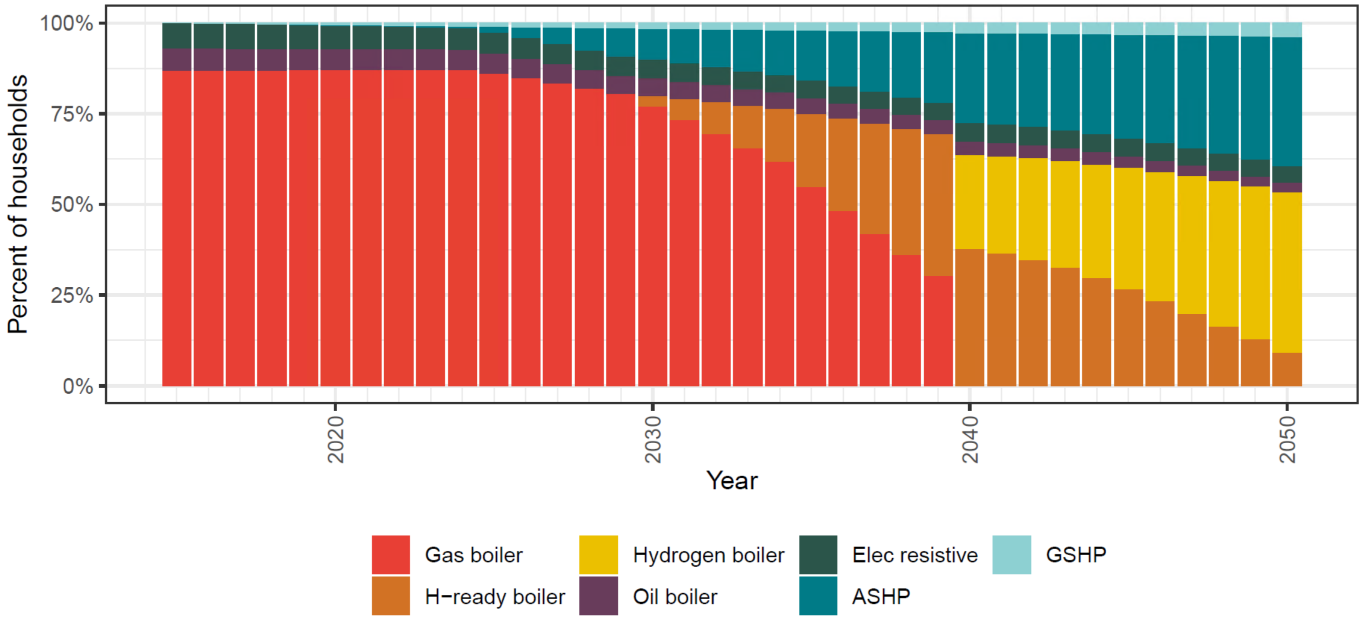


Source: Frontier Economics

4.2 "Rushed transition" sensitivity

In the scenario described above, gas-only boilers are phased out in sufficient time that none will still be active by the time of the switchover to hydrogen. As a sensitivity, we have considered a scenario where there is insufficient time for this to be the case: Property owners in the model will still be aware of the limited lifespan of gas-only boilers when they are purchased, but may still purchase them (due to the slightly lower capital cost). Dual fuel boilers are assumed to become available in 2030 and are mandated in 2035, only five years before the switch-over. Figure 54 plots the resulting mix of technologies each year, which shows the sizable proportion of gas boilers remaining in 2039.

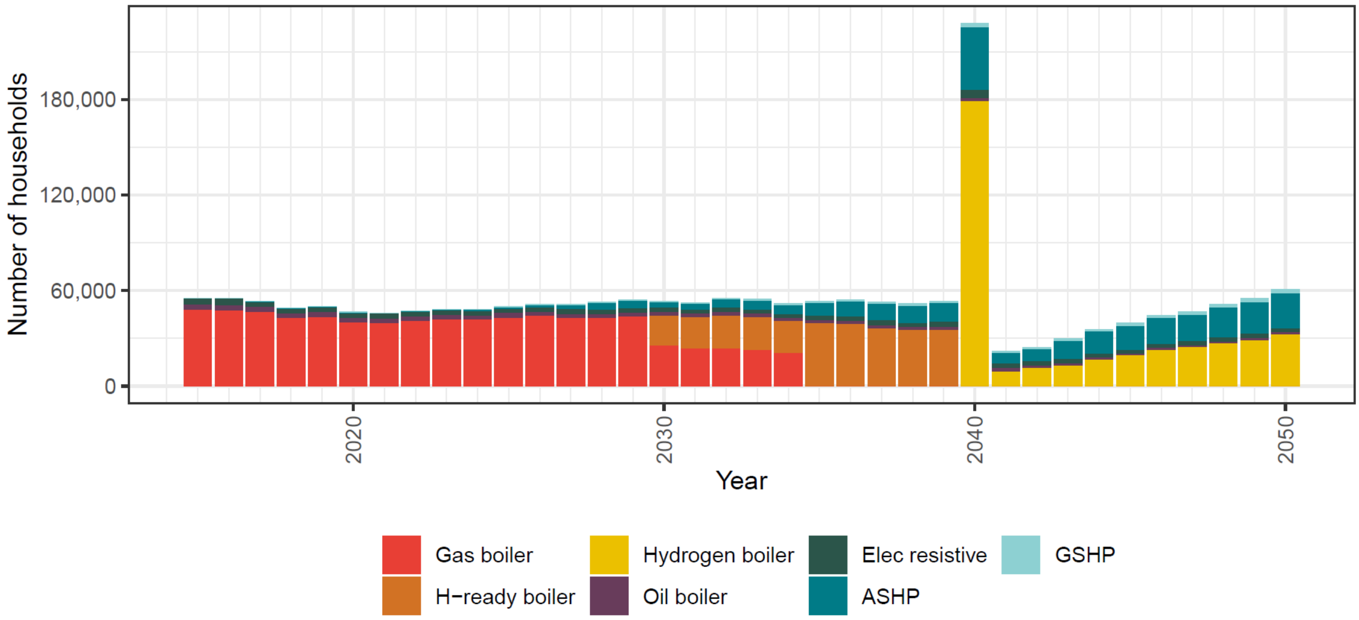
Figure 54 Take-up of heating technologies in "rushed transition" hydrogen scenario, 2015 - 2050



Source: Frontier Economics

Figure 55 shows the resulting number of installations of each technology per year. There is a very material spike of installations of hydrogen boilers in 2040, as well as air-source heat pumps (due to some owners of gas boilers being unable to find a hydrogen boiler installable, and so obtaining a heat pump instead).

Figure 55 Year-by-year installations of heating technologies in "rushed transition" hydrogen scenario, 2015 - 2050



Source: Frontier Economics

The utilisation of installers peaks to over 150%. The installers present (which are not modelled as having any foresight and so do not increase capacity in advance) are incapable of meeting this demand, and some households in this scenario are left without a heating system altogether, although that is not an outcome that the model is able to simulate.

4.3 "High cost hydrogen" sensitivity

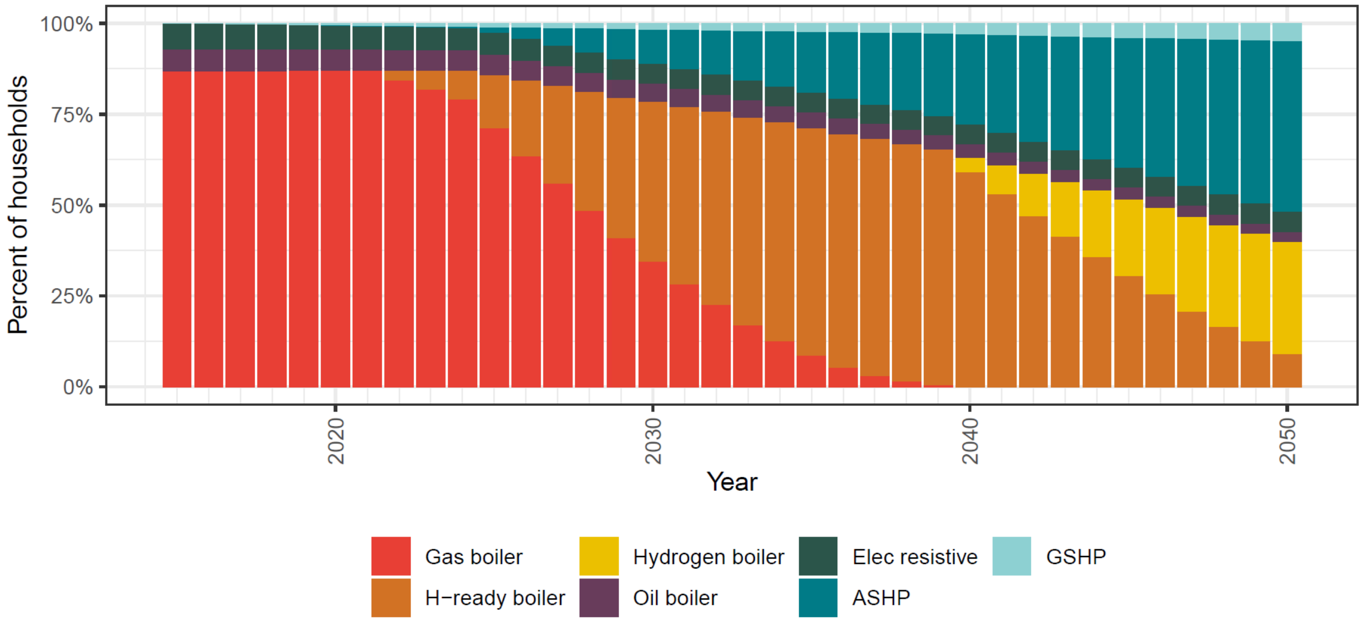
The results of our hydrogen scenario are so similar to the baseline scenario because the costs and non-cost characteristics of hydrogen and hydrogen-ready boilers are assumed to be similar (in many cases identical) to their gas counterparts.

The economics of hydrogen are still extremely uncertain, and so we can use the model to understand how sensitive the results are to other plausible scenarios. In the results below we have made the following changes:

- An additional cost of £500 has been added to the initial installation of a hydrogen or hydrogen-ready boiler, reflecting costs which may be incurred in upgrading the pipework within the house to carry hydrogen.
- The hassle of hydrogen or hydrogen-ready boilers (when not replacing a unit of the same type) has been increased to the same level as electric resistive heating, to proxy for the hassle of having pipework changed.
- The cost of hydrogen has been increased from the CCC price (which remains at 8p/kWh from 2040 to 2050) to 12p/kWh.

As shown in Figure 56, the higher costs and hassle do lead to an increased move away from hydrogen boilers towards air-source heat pumps from 2040 onwards, with the market evenly divided between the two technologies.

Figure 56 Overall take-up in higher cost hydrogen scenario



Source: Frontier Economics

Given the feedback effects within the model, it is possible that there is a lower level of hydrogen uptake, below which the use of hydrogen is unsustainable: Below this critical level, more and more customers would move to heat pumps, increasing network costs and reducing the social incentives for those remaining on the hydrogen network to continue to do so). However, Figure 56 shows that, at least until 2050, this is not the case: An even split between hydrogen and electrification appears to be sustainable under these conditions. Further model runs could be used to test under which scenarios this split would not be stable.

4.4 Other sensitivity tests

To assess the robustness of these results and inform the assumption log which accompanies the model, we have carried out a number of other sensitivity tests. Key model parameters have been increased by 50% and decreased by 50%. The tornado chart in Figure 57 summarises the impact of these changes on overall heat pump take up in 2050 (which, as shown in Figure 51, is approximately 40%).

The red bars show the change in take-up (in percentage points) if the parameter is increased, while the teal bars show the change in take-up if the parameter is decreased. In some cases, both sensitivities cause a change in the same direction, in which case the overlapping portion of the bars are shown as a darker colour.

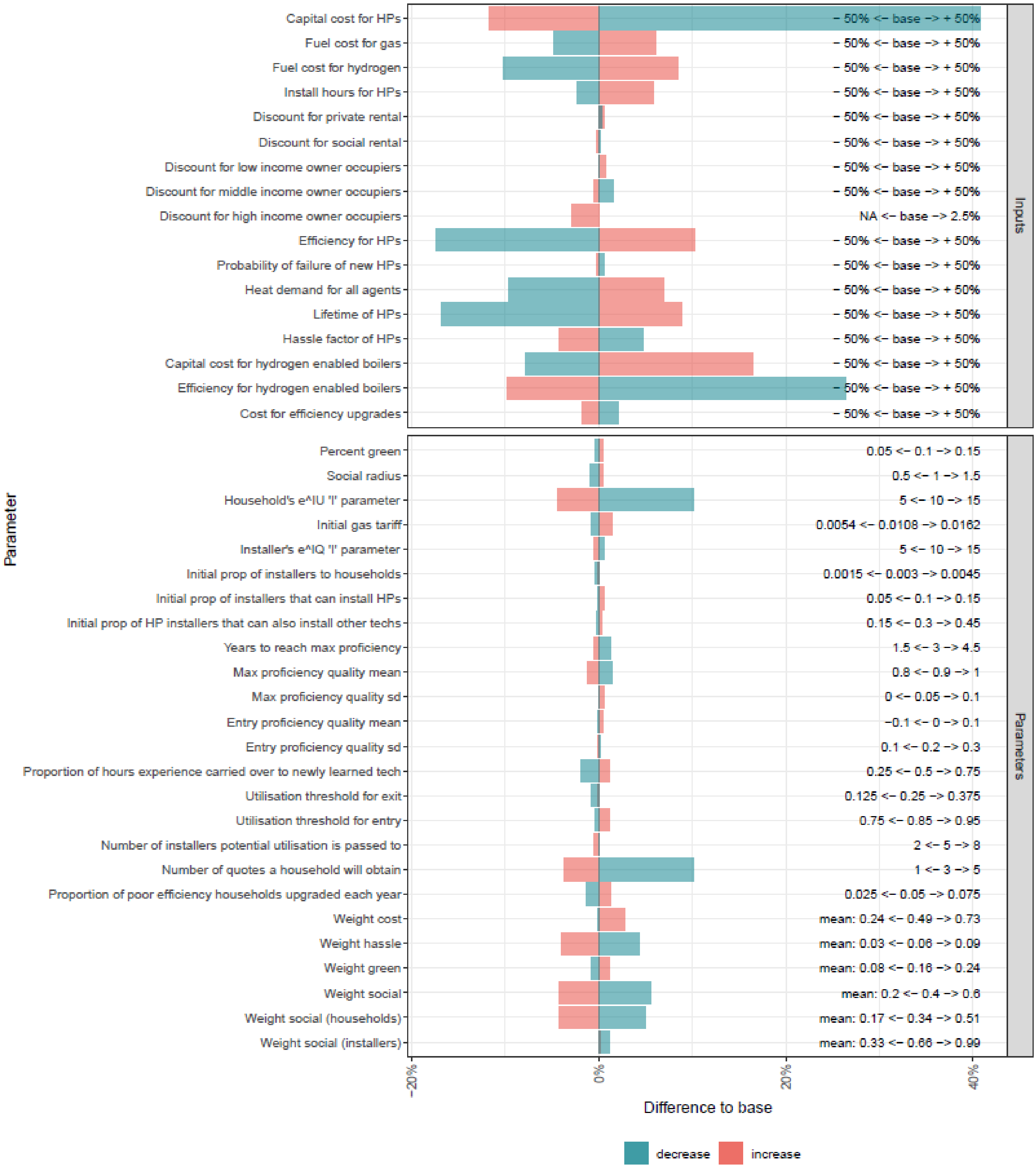
In many cases, the overall model results are relatively robust to changes in any one parameter: halving or increasing these parameters by a half results in a change in 2050 heat pump uptake of less than 5 percentage points. Some of the smallest impacts (particularly those where change in the output goes in the same direction for both sensitivities) are difficult to distinguish from the underlying spread of results from the simulation which will, due to its random nature, produce slightly different results when ran multiple times.

However a number of inputs do have a material impact on results:

- Inputs relating to heating technology cost have the greatest impact;
- two inputs which relate to the hetrogeneity of information available to owners (the “I” parameter and the number of quotes that are sought) have a sizable impact; and
- the weights on owners’ decision-making have a moderate impact.

Below, we explain each of these in turn.

Figure 57 Summary of sensitivity tests



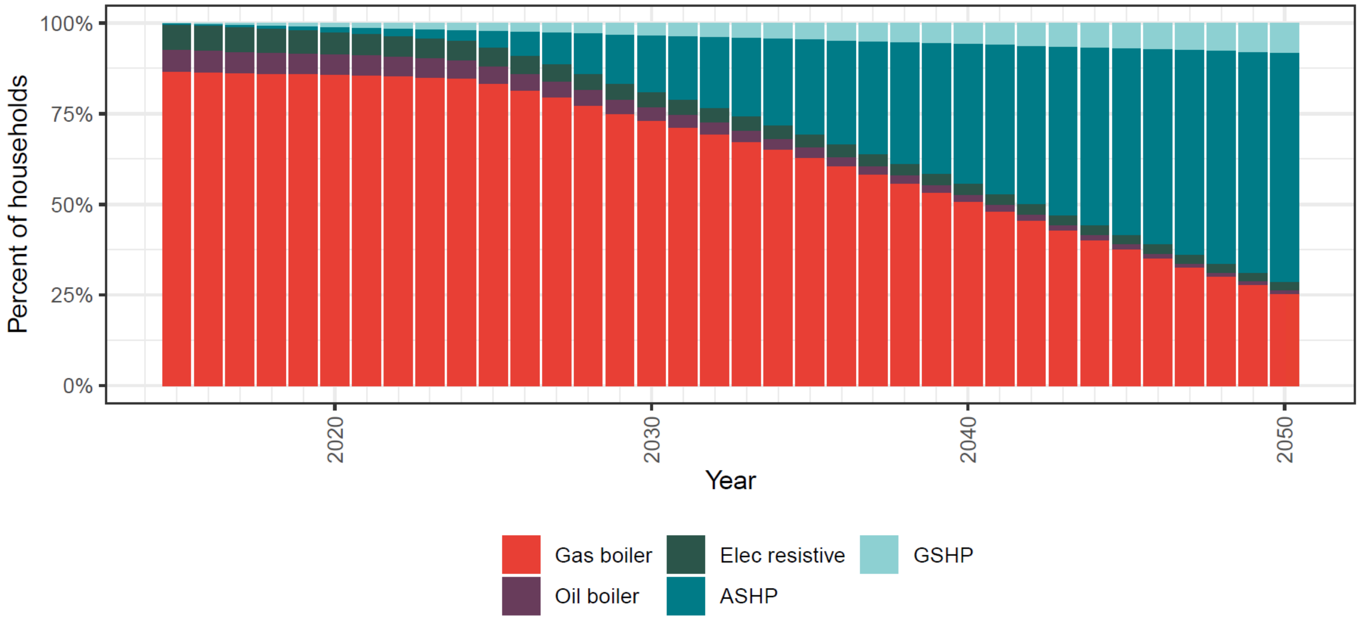
Source: Frontier Economics

4.4.1 Heating system costs

The model is most sensitive to a variety of inputs that directly affect the cost of heating systems: the capital cost, lifetime, fuel costs and efficiency of heating technologies. In many cases,[64] these inputs are likely to be known with greater certainty than the parameters regarding how property owners and installers will behave in the future.

The capital cost of heat pumps has the greatest impact, which is unsurprising given the importance of upfront costs discussed in section 3.2.2. A decrease in capital cost of 50% brings the upfront cost of an air-source heat pump much closer into line with a gas boiler. This increases modelled 2050 uptake by over 40 percentage points, demonstrating the substantial barrier posed by capital costs. Figure 58 shows the aggregate take-up of technologies under this scenario.

Figure 58 Aggregate take-up of heating technologies with 50% lower heat pump costs



Source: Frontier Economics

The take-up of heat pumps under this scenario is such that, by 2050, a number of feedback loops are working to increase heat pump uptake further:

- network costs increase;
- the prevalence of heat pump installations (which, by this point, will tend to be of high quality) leads to feedback through the "social" channel; and
- the reduced demand for gas boilers leads some installers to exit the market, which constrains the options for some owners who would otherwise purchase one (this effect is greatest in the mid-2040s, when over 2% of households wishing to purchase a boiler are unable to find a local installer with capacity).

Increasing or decreasing the **price of gas** by 50% leads to an increase or decrease in 2050 heat pump uptake of around 10 percentage points respectively. However, the other remaining barriers (especially capital costs) limit the impact of this sensitivity.

[64] Both gas boilers and heat pumps are mass produced technologies, although the costs associated with hydrogen boilers will be less certain.

4.4.2 Heterogeneity of information available to customers

Two parameters relating to the heterogeneity of owners' information and choices have a material impact on results.

The first is the **heterogeneity parameter** ("*l*", discussed in section 2.2.4). A higher value of this parameter means that the simulated property owners will be more likely to pick a technology that isn't modelled as having the highest utility – this could reflect unobserved heterogeneity, or owners being uncertain of the quality of the information available to them.

Increasing this parameter leads to a higher take-up of heat pumps. In the scenario we are using as our baseline, for most owners in most years heat pumps will not be the technology with the greatest utility. Introducing more uncertainty into their decision making will tend to increase overall take-up: If the uncertainty reduces the attractiveness of a heat pump then this will have no effect if they were never going to take one up, but in some instances it may increase the attractiveness to the extent that they take one up.

Increasing **the number of quotes that a household obtains from installers** also reduces heat pump take-up by a modest amount. This is a related effect: the more installers property owners consult, the more that the advice they receive is likely to be representative of the market as a whole (which will on average be in favour of gas or hydrogen boilers rather than heat pumps). If property owners consult fewer installers, there is a greater chance that they will happen to talk to an installer which has a particular expertise in heat pumps. This again adds more randomness into owners' decisions.

These sensitivities show how heterogeneity in how customers decide between heating systems can have an important impact on the overall outcome of the market. While our model has considered some forms of heterogeneity explicitly (see section 2.2.4), further research and model development could extend this – for example by incorporating the extent to which different types of property owner may have different perceived hassle costs.

4.4.3 Weights on decision-making

Changes to the weights on consumer decision-making have a moderate impact on results, but not as large as the other sensitivities discussed above. For example, halving the weight placed on the social influence of other households increases heat pump uptake by around seven percentage points (this increase is since, with heat pumps in the minority of heating systems, the social factor will overall act as a brake on uptake).

This shows that the broad results from current model are not too sensitive to the exact value of the weights used. However the functional form that we have used to model property owners' and installers' decisions is one of many possibilities. For example, we have assumed that even if a heating technology has a very high level of perceived hassle, there will always be some cost saving which could outweigh this. These structural assumptions in the model have not been tested.

5 CONCLUSIONS

In this chapter we describe the main conclusions that can be drawn from this pilot model.

- First, we discuss the implications that the model results shown above have regarding the barriers to low-carbon heat take-up.
- The following section explains how the interactions we have simulated are important in the design of policies.
- Finally, we describe some of the further research that is required to deploy this type of model, and how the framework of an ABM can itself help to structure this.

5.1 Barriers to low-carbon heat take-up

The modelling we have carried out has shown the importance of considering the non-monetary drivers of consumer decision-making. Compared to a model where consumer choices are driven only by cost-minimisation, the results are very different – and highlight the high barriers to the decarbonisation of the heating sector.

Given the assumptions in the model (which are ultimately driven by the underlying consumer choice experiments that have been used to populate it), the up-front cost of heat pumps is a particularly high barrier. This affects two groups in particular:

- Low-income owners (who we assume cannot afford these initial upfront costs) fail to benefit from their eventual lower lifetime technology running costs – a regressive outcome.
- The misaligned incentives that private landlords are assumed to have lead to a particularly low uptake of low-carbon technologies in this sector. At the extreme, such incentives could even lead to landlords replacing technologies such as heat pumps (after they have failed) with electric resistive heating, with lower capital but higher running costs.

Other factors which cause heat pump uptake in the model to be lower than in a cost-minimising model include the “hassle” associated with installing and running low-carbon technologies, and the lack of recommendations from installers and neighbours (due to the continued prevalence of gas boilers).

Note that this latter effect is likely to be sensitive to how social influence has been modelled: We assume that social influence will only provide a “push” for a heating technology that is more prevalent than others. This might not be the case if low-carbon heating technologies had significant benefits over traditional systems, in which case a property owner might only need to observe a small number of systems to be convinced of their merits. However, this model assumes that property owners’ experience of low-carbon heating systems is similar to (and often slightly inferior to) traditional systems.

These results suggest that:

- Policies which lead to a significant increase in the cost of gas, without addressing the issue of up-front costs, may be insufficient to lead to a complete transition to low-carbon forms of heating. This can be seen from the sensitivity where a high cost of carbon was added to the price of gas. While this could help overcome the non-monetary barriers for some groups, the very high discount rates assumed for private renters and low-income owner-occupiers mean that the lower capital-cost gas boilers are still the technology of choice for many.
- However, policies or business models which spread the up-front costs of renewable heating technologies (for example loans or lump-sum subsidies) could have a significant impact. This can be seen from the scenario where discount rates were reduced, as well as the “energy service company” scenario, which reduced discount rates alongside other changes.
- This may be the case even if it is not possible to reduce some of the “hassle” factors, which may be intrinsic to the technologies themselves and less amenable to policy intervention.

Alternatively, a move to hydrogen boilers may be able to overcome these barriers. This requires, as has been assumed in this model, that the cost and behaviour of these technologies is similar to gas boilers – we have not modelled the cost of building the infrastructure required to support a hydrogen transition. However:

- A significant degree of central co-ordination will be required. Our model has shown how the availability and mandation of hydrogen ready-boilers may be needed to ensure a smooth transition.
- If – as assumed in our model[65] – the costs of hydrogen powered heating are still above electrification, the presence of non-monetary barriers to electrically powered heating may mean that there are still adverse distributional consequences, with poorer owner-occupiers unable to benefit from lower costs due to electrification.

However, while these types of result are useful and demonstrate that the model is functioning in a way that appears reasonable, they do not require a full ABM. Demonstrating the relative impact of different barriers to low-carbon heating could be carried out in a simulation where property owners were modelled as having different discount rates, aversions to hassle etc, without any interactions between them: The results are ultimately driven by the findings of the choice experiments used to calibrate the model. The real value of an ABM comes from being able to simulate the results when the actions of one agent can affect another. This can lead to an emergent outcome which could not be forecast when only considering agents individually.

5.2 Implications of interactions between agents

The model shows that these interactions can have a significant impact on the overall take-up of heating technologies. As shown in section 3.4, policies encouraging take-up by one group can lead to increased take-up by others who

[65] Since the model does not currently consider reinforcement costs of the electricity network, this is a strong assumption which may well not hold in practice.

were not directly targeted. While some of this effect is due to the presence of fixed gas network costs, the social links in the model (recommendations from other owners or installers) also mean that installations carried out by one group can increase uptake by others.

There is therefore a material “multiplier effect”, where policies can have a wider impact other than the group they are directly aimed at. Future work could use this type of model to predict how these interactions could be best utilised to design cost-effective policies. For example, the model has shown how policies targeting specific groups can have a greater indirect impact if complementary policies are in place that reduce the barriers like upfront costs that other owners face. Demonstrator programmes or other very targeted policies may also have a greater impact if they are somewhat spread across the region, rather than being entirely concentrated in one area.

These specific results will depend on the exact way in which property owners and installers interact: The model currently assumes that they influence one another within a set geographic radius, while in practice some channels of influence (for example media or social networks) might not be so defined geographically. However they demonstrate how, in principle, policies can be designed to better exploit these types of linkage.

As noted in the following section, there are many uncertainties regarding the way in which property owners and installers will behave as new heating technologies reach mass market. Without considerable amounts of further research to calibrate the model, the ABM could not be used to produce a single central forecast with a high degree of certainty. However in the meantime, the model would still be useful for policymakers as a powerful way of answering “what-if” questions. For example, say that a particular policy was proposed which was intended to increase the take-up of low carbon heating by a certain amount. The model could be used to verify if there are at least certain plausible conditions under which this could occur. If the policy requires particular conditions, targeted research could be carried out to test if these hold.

5.3 Further developing and validating the ABM

ABMs can include a vast number of parameters defining how agents interact, and it is therefore important to ground them in evidence on how consumers react in the real world. This model has been calibrated from two main sources: Past research on customer behaviour (generally from choice experiments), and observed behaviour under the RHI.

There is nonetheless considerable uncertainty in these parameters. Consumers making decisions in real life may act differently to those in choice experiments, and those who have taken up the RHI to date are not representative of the wider population that will need to take up heat pumps in the future.

Our sensitivity tests show that the results are not especially sensitive to large changes in any single parameter regarding consumer choice. While the results are more sensitive to assumptions regarding the cost of technologies, these are likely to be better understood than the factors driving consumer behaviour.

However there is also uncertainty in the *structure* of the model – the functional forms that define how agents make their decisions. The model, by necessity, abstracts away from the complex way in which these choices are made in reality. For example:

- The model assumes that social influence occurs within a set geographic radius, when far more complex networks of social influence may exist;
- the linear nature of owners' utility functions means that even if a technology choice is seen as extremely poor in one dimension (e.g. hassle), a sufficiently good performance in other dimensions (e.g. cost) can overcome this; and
- installers are not assumed to have foresight of where there will be peaks in demand for their services in the future.

There is therefore currently insufficient evidence to show whether the predictions of the model will be borne out in reality, particular in circumstances (such as if the cost of gas becomes much higher) which have not been seen to date.

However these uncertainties are not a reason to use cost-minimisation models as a substitute for ABMs when attempting to forecast uptake.[66] Such models make even more simplistic assumptions regarding agent behaviour which have been shown to be unrealistic. Even with incomplete information, an ABM such as the one we have built can provide useful insights.

The very structure of an ABM, where the behaviours of each agent is made explicit, provides a clear and objective framework around which to build the evidence base for consumer decision-making. The process of constructing an ABM requires codifying a wide variety of assumptions – for example, the factors that property owners and installers take into account when making decisions, and their relative importance. While there may be substantial uncertainties around these assumptions, documenting them formally can help subject-matter experts engage more deeply. And, as low-carbon heating systems become more mainstream, it will be possible to carry out further choice experiments and econometric exercises which can provide additional validation to the inputs. Future demonstrators and trials should be designed in a way which enables evidence to be gathered and used to build on a model like this one.

[66] These types of models are still extremely valuable in understanding what the *optimal* pathway to decarbonisation is.

ANNEX A MATHEMATICAL SPECIFICATION OF CONSUMER CHOICE MODEL

In this annex we set out the specification of the model used to determine agent choice within the ABM.[67] We then describe some of the implications and limitations of this functional form.

A.1 Specification

Each modelled year, every consumer currently using a heating technology *t* of age *a* years will be required to choose a new heating technology with probability $Pfail_{t,a}$. This probability is an exogenous input to the model, specified in such a way that $Pfail_{t,a} = 1$ for a high value of *a*. This implies that the probability of a heating system failing increases with the age of the system, and is inevitable past a certain age.

Consumers base their decision of which heating technology to take up based on the relative attractiveness of a given choice. The probability of an individual of type *i* being attracted to a technology *t*, among all other technologies in their choice set, is given by:

$$P(i,t) = \frac{A_{i,t}}{\sum_t A_{i,t}}$$

Where $A_{i,t}$ is the attractivity of technology *t* for an agent *i*. This implies that if all technologies are equally attractive, the agent will pick them with equal probabilities.

The attractiveness of a technology, $A_{i,t}$, is given by:

$$A_{i,t} = e^{IU_{i,t}}$$

This functional form is based on that adopted in an ABM by Allen and McGlade (1986).[68] $U_{i,t}$ is the utility function of agent *i* choosing to install technology *t*. *I* is a parameter which is greater than or equal to zero, and can be seen as representing both the quality of information that individuals are presented with when making a choice and the extent of the heterogeneity in consumers' decision making.

For large values of *I*, individuals will choose (with a probability of close to 100%) the technology that has the highest associated utility, even if the differences in the utility of their choices are slight. This can be seen as simulating a world where:

- there are no other factors affecting agent decisions other than those present in the utility function (i.e. the model provides a complete summary of all information that is relevant to choice); and
- agents have a high confidence in the information available to them, and are therefore certain to switch to a technology even if the apparent benefits are only very marginal.

If $I = 0$, each individual's choice of heating technology will be made at random i.e. with equal probability (the utility function has no impact on choice, as the

[67] The same functional form is also used to model the decisions of installers regarding which technology to recommend, as described in section 2.3.2 of the main report.

[68] Allen, P.M. and McGlade, J.M. (1986), *Dynamics of discovery and exploitation: the case of the Scotian Shelf Groundshelf Fisheries* in Canadian Journal of Fisheries and Aquatic Sciences.

attractiveness of each technology is 1). Values of *l* which are only just above 0 will mean that the relative utility of choices has little impact, and can be seen as simulating a world where:

- there are a very large number of factors affecting agent decisions which are not modelled (and so decisions cannot be predicted from the factors in the utility function); or
- agents have very low confidence in the information available to them, and so require a very high benefit from a technology to be sure of switching to it.

The utility function, U_{it}, is a simple linear utility function given by:

$$U_{it} = f_{cost}(i,t) \cdot w_{cost} + f_{social}(i,t) \cdot w_{social} + f_{hassle}(i,t) \cdot w_{hassle} + f_{green}(i,t) \cdot w_{green}$$

Where w_{cost}, w_{social}, w_{hassle}, w_{green} are weights and $f_{cost}(i,t)$, $f_{social}(i,t)$, $f_{hassle}(i,t)$, $f_{green}(i,t)$, reflect respectively:

- **cost factors**: the relative cost-saving of a given technology;
- **social factors**: relating to the number of nearby high-quality installations of the technology, as well as recommendations from installers;
- **hassle factors**: the hassle of a given technology (which can also be used to model other non-monetary costs and benefits weighted equally by all agents); and
- **green factors**: the non-monetary benefit associated with picking a "green" technology.

These factors are described in more detail in section 2.2.3 of the main report.

A.2 Limitations of the model

This model has been chosen since it reflects the main observed determinants of heating system choice, while requiring only a very small number of parameters. This allows the model to be easily calibrated to the relatively small amount of data currently available, as well as making it clearer what is driving the results.

However this specification does impose some important constraints on agent behaviour, which we discuss below.

A.2.1 Independence of irrelevant alternatives

The functional form described above is very similar to that resulting from the conditional logit model.[69] Like the multinomial logit model, this specification assumes the independence of irrelevant alternatives (IIA). IIA implies that the odds ratios between two choices is independent of other alternatives.

This is a strong assumption, which will not generally hold in the context of heating technology choices. For example, consider a consumer choosing between two

[69] McFadden, D (1974) "*Conditional Logit Analysis of Qualitative Choice Behaviour*," in Frontiers in Econometrics, Paul Zarembka, ed. Newark: Academic Press, pp. 105–142.

technologies, a gas boiler and an ordinary air-source heat pump, in the case where the consumer is indifferent between the two (i.e. the utilities are the same – this means the attractiveness is also the same, and therefore the probability of taking up either technology is equal, at 50%).

Now consider the addition of a third option – a slightly different air-source heat pump. If the agent has a positive probability of taking this up, then the probability of taking up the gas boiler and the first air source heat pump must decrease. IIA implies that they must both decrease by the same amount, (the probability of taking up a gas boiler will still equal the probability of taking up the first air-source heat pump). Adding an almost identical alternative to the heat pump has resulted in a reduction of the probability of taking up the gas boiler, and increased the probability of taking up any type of heat pump.

At the extreme, more and more almost identical heat pumps could be added, and the model would predict the agent would have very little chance of picking a gas boiler. This is clearly incorrect – the air source heat pumps are much better substitutes for one another than the gas boiler. However IIA means that the model does not have a concept of whether one choice is a closer or more distant substitute for another.

In practice, this means that the number of choices available to agents in the model should be kept as low as possible, avoiding technologies which are similar to one another.

This effect could be mitigated by adopting a nested model, where the agent chooses the best of the similar technologies (e.g. out of all the heat pumps), and then compares to the gas boiler.

A.2.2 Unobserved heterogeneity in agent decision-making is not persistent

As discussed above, the parameter *l* can be thought of as reflecting unobserved heterogeneity in agents' decision making. For example, some agents may attach a greater importance than others to picking a technology that does not take up much space in their home. This will mean that, even after controlling for all the factors present in our utility function, we are not able to perfectly predict a consumer's choice. By having an *l* parameter that is low enough, some agents will pick a technology that is not "optimal" from the point of view of our utility function, but can be seen as reflecting such unobserved preferences.

In reality, were an agent to pick a "non-optimal" technology for such reasons, we would often expect to see this decision repeated in future choices.[70] However, the functional form described above does not simulate this: The probability of making a "non-optimal" choice in one period is independent of whether the same choice was made previously, and so it is most likely that the agent will reverse their decision and pick the "optimal" choice next time.

In practice, this effect is unlikely to make a material impact on this model since:

[70] By contrast, if agents pick a "non-optimal" technology due to a lack of information, it is reasonable that doing so gives them more information on the technology's costs and benefits, and could lead to them changing their choice at the next available opportunity.

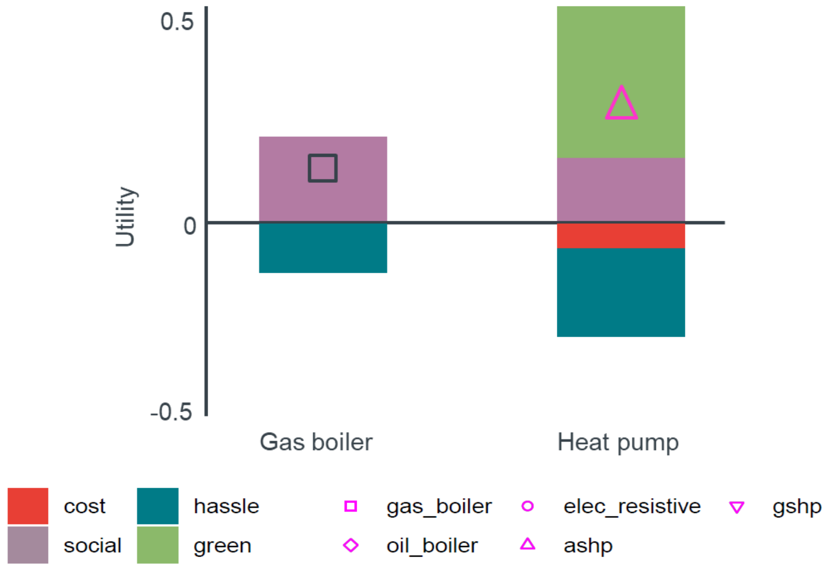
- Agents choose a new heating technology infrequently. It will therefore be relatively rare for this issue to occur.
- There are many sources of heterogeneity explicitly built in to the model (described in section 2.2.4). These will persist across multiple choices.
- If an agent takes up a heat pump, they will be more likely to take it up again in the future as we assume that the hassle of replacing like-for-like is lower.

ANNEX B UNDERSTANDING DRIVERS OF AGENT CHOICE WITHIN THE MODEL

This annex explains how the model can be used to understand the factors driving the choice of a particular agent,.

Figure 59 gives an illustrative example of how the model simulates a single choice made by an agent, in this case between a gas boiler and a heat pump.

Figure 59 Illustrative example of a green agent's decision making process



The four elements of the agent's utility function (cost, social, hassle, and green factors) are shown as two stacked bar chart – one for the gas boiler (on the left), and one for the heat pump (on the right).

- In this illustrative example, the consumer is already using a gas boiler. The relative cost of moving to a gas boiler is therefore zero. In this case, the cost of a heat pump is higher than a gas boiler, so this shows as a negative "cost" component for the heat pump. **On cost alone, the consumer will prefer the gas boiler**.
- More neighbours of this agent are using a gas boiler than a heat pump. The "social" component of the utility function is therefore higher for gas boilers. **On social factors alone, the consumer will prefer the gas boiler**.
- The heat pump is assumed to have a greater hassle associated with it than the gas boiler (this is shown as a greater negative element in the utility function). **On hassle factors alone, the consumer will prefer the gas boiler**.
- Finally, this is a "green" consumer, and so they are assumed to place an extra value on taking up the heat pump. **On "green" factors alone, the consumer will prefer the heat pump**.

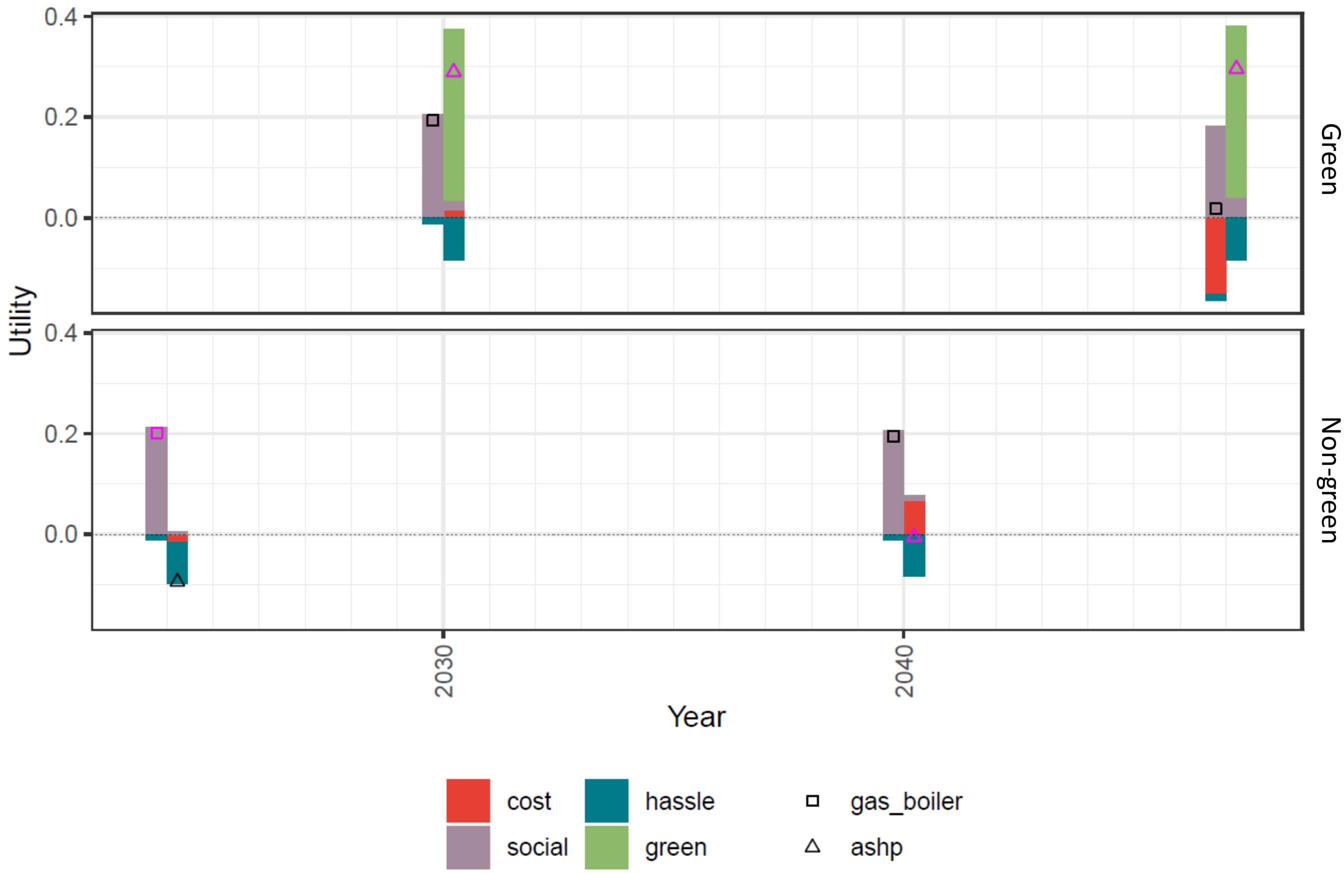
The square and triangle show the overall utility value (the sum of all these factors) for the gas boiler and heat pump respectively. Overall, the size of the "green" factor outweighs the other factors, meaning that this consumer has a higher utility associated with the heat pump.

The heat pump will therefore be more attractive to this agent, and will be chosen with a higher probability. However, as described in section 2.2.4, the model includes an element of randomness to simulate customer heterogeneity. In this case, the customer has chosen the heat pump (the model highlights the chosen technology by colouring its symbol purple – therefore the purple triangle illustrates that the heat pump was chosen, not the (square) gas boiler..

Using this visualisation, we can examine what is driving the decisions of individual agents in the model.

Figure 60 illustrates the decisions made by two agents, one "green" and one not "green". Unlike the illustrative example above, the agents make multiple decisions (each time their incumbent heating system fails). Each decision is represented by a set of bars like the illustration above.

Figure 60 Model results of random agents' individual decisions



Note: Each set of bars represents technology failure for the agent, which prompts them to make a decision on which technology to take up. Magenta shapes are the chosen technology.

Similar to the illustrative example above, this agent faces a choice between a gas boiler and an air source heat pump. Like that example, the "social" and "hassle" factors disincentives the take-up of a heat pump. The "green" agent has an additional factor encouraging take-up of the heat pump. Unlike the example above, by 2040 the heat pump is assumed to have *lower* costs than the gas boiler, and so the cost factor now incentivises heat pump take-up.

For a non-green agent, the hassle and social factors outweigh the cost factor, and so they are not incentivised to take up a heat pump. By contrast, the extra utility the “green” agent obtains from the heat pump encourages them to take this up.

The result (that the “green customer” is taking up a technology that is less expensive over the long-run) is therefore driven by the presence of non-monetary factors (social and hassle) which tend to reduce take-up of technology which is both “green” and more cost-effective (for non-green agents).

ANNEX C PREVIOUS AGENT-BASED MODELS OF THE HEAT MARKET

The modelling described in this report is not the first attempt to apply an ABM to decisions made in the heating sector. In this section, we briefly describe some of the other models that have been constructed (both in the heat market and in related areas) and the conclusions drawn from them. This is not intended to act as a complete literature review, but provides a starting point for the wider research in this area.

In general, these models have a narrower focus, but delve deeper into the psychology of the agents' decision making process than the model described in this report. For example, the ABMs relating to the heat market do not consider the impact of network costs, the interplay of owners' behaviour with installers' behaviour, nor the transition to hydrogen.

A.1 Modelling heat pump take-up under the RHI

Snape, Boit and Ryulatt (2015) used an ABM to simulate the take-up of heat pumps under the Renewable Heat Incentive (RHI) by households in an off gas grid semi-rural area. Agents in this model represent individual householders, who are making the decision whether to replace their existing failed heating system (oil or LPG) with a heat pump. The overall heating demand of agents differs (based on a physical model of heat loss).

Agents' decisions are assumed to be driven by three factors:

- an "economic" factor, reflecting the payback period of the heat pump;
- a "social" factor representing the opinions of neighbours who have a heat pump (these opinions are random and can be either positive or negative); and
- a "hassle" factor reflecting the greater hassle and disruption involved in replacing an existing system with a heat pump.

Agents are assumed to take up a heat pump if a weighted sum of these factors exceeds a threshold. The model was ran for a large number of different weights, to understand the sensitivity of results.

The results of this modelling show cumulative heat pump uptake increasing for a period until it reaches a plateau. As the model is run with a higher weight on the hassle factor, the level of take-up at the plateau abruptly falls. This demonstrates the importance of non-financial factors in the take-up of renewable heating.

A.2 Modelling renewable heating take-up in Norway

Sopha, Klöckner, and Hertwick (2011)[71] used an ABM to simulate the take-up of different forms of renewable heating in Norway. The model (which draws on data from a Norway-wide survey of consumers) models households choosing between three technologies: electric resistive heating, wood pellet stoves, of heat pumps.

[71] Sopha, Klöckner, and Hertwick (2011*), Exploring policy options for a transition to sustainable heating system diffusion using an agent-based simulation* in Energy Policy Vol 39, p2722-2729

Households are assumed to make this choice based on one of four randomly allocated "decision strategies" (which were based on the survey):

- **Repetition** – the household selects the same heating technology that it previously had.
- **Deliberation** – the household compares heating technologies, and chooses the one with the highest "intention" (described below).
- **Imitation** – the household selects the heating system that has the highest share of uptake among its peers.[72]
- **Social comparison** – the household selects either its previous heating system, or the heating system with greatest social uptake, according to the calculated intention.

The "intention" of a household to choose a heating system ultimately determines which heating system is adopted. It is based on a number of factors, including:

- Fuel price stability;
- indoor air quality;
- functional reliability;
- total cost;
- upkeep work;
- the extent to which the agent has a perceived social obligation to use an environmentally friendly heating system;
- take-up by neighbours.

The results of the model indicate that for significant diffusion of wood-pellet heating to occur, a simultaneous set of interventions are needed. These include:

- **Financial support** through creating a stable wood-pellet price;
- **Technical development** such as improved functional reliability of wood-pellet heating.

This demonstrates that for lesser-known heating systems, there is a strong aversion to adoption of a system that is perceived to be a hassle through and that interventions such as creating price stability or providing information on environmental performance and reliability can have a positive impact on the take-up of renewable heating technologies.

A.3 Modelling the emergence of district heating networks

Busch, Roelich, Bale and Knoeri (2017)[73] simulates the development of local heating schemes. In this model, the agents are not end-consumers, but different types of scheme developer – municipal, commercial and community. Each of these scheme developers have a distinct set of decision rules and capabilities and follow a multi-stage development process.

[72] The peers considered by the model include all agents within a certain geographic distance, and (with a random probability) the rest of the population.

[73] Busch, Roelich, Bale and Knoeri (2017), *Scaling up local energy infrastructure; An agent-based model of the emergence of district heating networks* in Energy Policy Vol 100, p170-180.

There are four key features of business models that the ABM is designed to reflect:

- **Decision chains** – implementing a business model requires a sequence of decisions as opposed to a single instantaneous decision. This allows for representation of the fact different capabilities are required at different parts of the decision making process.
- **Agent heterogeneity** – agents that develop heat network projects vary in their institutional forms and capabilities. Their decisions are based on different decision rules. This explains the variance in scale of projects and success rates between different agent types.
- **Agent learning** – agents can learn through previously successful projects. Their capacity to develop projects and capabilities required to pass subsequent decision processes increase.
- **Interaction** – agents work in the context of a social and political environment, interacting with other agents in their industry and with potential customers.

The results of the model indicate that local authorities play an important role in coordinating and promoting local energy infrastructure. This demonstrates the importance of modelling government policy, whether it be exogenously or endogenously, to assess how different policies can impact the aggregate outcome of the model.

A.4 Modelling residential solar photovoltaic adoption

Rai and Robinson (2015)[74] design a model of technology adoption, with an application to residential solar photovoltaic (PV). The primary agents in the model are single-family residential households, each who make a decision of whether to adopt solar or not.

Driven by the theory of planned behaviour, two key elements determine the agents' decision to adopt or not adopt solar – an attitudinal component and a control component:

- **Attitudinal component** – embedded in this component is a social network model, which feeds into the attitudinal and control attributes of all agents as the model cycles forward in time and agents react with each other and their environment.
- **Control component** – represents the agent's perception of whether they could afford solar or not, when comparing to a simple time-resolved payback calculation.

The decision criteria is that both an agent's attitude and control attributes must be above certain respective thresholds before they adopt solar. If the agent has a sufficiently strong attitude and control, then they will adopt solar.

[74] Rai, V., Robinson, S.A. (2015). *Agent-based modelling of energy technology adoption: Empirical integration of social, behavioural, economic, and environmental factors* in Environmental Modelling & Software Vol 70, p163-177.

This model shows how ABMs can be used to generate relevant policy insights, predictions, and emergent behaviour beyond conventional models. However, they must be grounded in real-world data and through rigorous validation.

A.5 Modelling electricity generation and investment

BRAIN-Energy (Bounded Rationality Agents Investments model) is an agent-based model of electricity generation and investment. It has been developed by Barazza and Li (2020)[75] to analyse the electricity sector's low-carbon transition arising from the microeconomic strategic investment decisions in power generation assets of heterogenous agents. The most recent version of the model has been calibrated to the UK with 2012 as the base year and models the long-run evolution of the electricity sector to 2050.

There are two main agents in the model: investor agents and policy agents.

- **Investor agents** represent the most important private investors in renewable energy technologies. They include incumbent utilities, new-entrants, local suppliers, and households. They differ by their initial technology portfolio, initial money endowment, risk, return, and time horizon of investments.
- **Policy agents** include the national government, local government, and regulators. These agents can set carbon price trajectories based on projected carbon budgets, subsidise investments in renewable generation assets, regulate supply through a capacity market, and provide support to demand-side response for households.

In this model, agents are heterogenous and boundedly rational. They have limited foresight of the future, and their investment decisions are based on their own, unique expectations of electricity demand, technology and fuel costs.

In each year, the investor agents choose whether to decommission unprofitable power stations, make decisions on electricity production from their existing assets, and reassess the profitability of previous investments and choose whether to build new power plants.

Although investment decisions are taken by each investor agent independently, they are able to see the outcomes of the investment decisions of other agents. Investor agents exhibit self-learning and imitation. They are able to learn from their own past investments as well as imitate the successful strategies of other investors. Further, the investment decisions are also affected by the policy environment and governance structure set by the policy agents.

The development of this model not only shows the importance of the myopic and path dependent choices of agents, it also indicates the significance of having a network of heterogenous agents and agent types that can interact with each other – this is one of the key benefits of using agent-based models.

[75] E. Barazza, BRAIN-Energy: online documentation – March 2020. https://www.ucl.ac.uk/energy-models/models/brain-energy, 2021.

A.6 Modelling supply and demand in an electricity network

Spataru and Barrett (2015)[76] developed the DEAM (Dynamic Energy Agents Model), which models individual electricity consumers (domestic, non-domestic, and transport sectors) and supplier agents for present and assumed future scenarios. The model was developed to explore techniques for handling increased and new patterns of electricity demand and local generation.

The load curves for consumers is dependent on several factors such as their annual energy consumption for different end uses, activity profiles across the day, week and year, and on the response of people and technologies to the weather. To allow for the effects of social activity patterns, weather, and changes such as insulation, installation of heat pumps or more efficient lighting, the load is calculated for each end use.

In this model, energy demand and supply is modelled for individual agents (households, businesses, generators, etc.) at a local distribution network operator level. Results are produced at this geographic granularity but can be aggregated to a regional or national level. Agents are connected to a node in a network (i.e. an electricity substation) so that loads can be calculated through the energy flows of domestic or non-domestic consumers, or for public energy suppliers. This allows for identification of possible future loads imposed on the electricity network.

The energy use of domestic agents depends on social factors and physical factors.

- **Social factors** include: household size; occupancy; internal temperature, and appliance use etc.
- **Physical factors** include: dwelling type (detached, semi-detached, flat), size, efficiency, and number of occupants etc.

Non-domestic energy use predominantly occurs in buildings driven by similar social and physics factors. Therefore the same model can be used for both domestic and non-domestic agent types.

The development of this model shows that, with an accurate description of the simulated market, agent-based models can be used as a decision support tool for governments and private companies alike.

A.7 Modelling energy service companies in the UK

Robinson, Varga and Allen[77] develop a model to assess the potential of energy service companies to contribute to the large scale upgrading of household energy efficiency.

The market dynamics of the interactions between two agent types are considered: residential households and energy provider companies. Residential dwellings are homogenous in all aspects (e.g. size and occupancy) and only differ in their unique,

[76] Spataru, C. and Barrett, M. (2015). *DEAM: A scalable Dynamic Energy model for demand and supply.* IEEE UKSIM-AMSS 17th International Conference on Modelling and Simulation, 25-27 March 2015.

[77] Robinson, M., Varga, L., Allen, P. (2015). *An agent-based model for energy service companies* in Energy Conversion and Management, Vol 94, p233-244.

randomly assigned energy efficiency rating. Two distinct types of energy providers are considered:

- A traditional provider supplies energy through a single utility (e.g. gas *or* electricity) and offers no additional energy services. Households pay for the energy they used and are not locked into a long-term contract. Therefore, they have full responsibility for upgrades in energy efficiency through the purchasing and installation of new appliances and insulation.
- The other type of energy provider considered, energy service company (ESCO), supplies multiple utilities (e.g. gas *and* electricity) as well as manages and maintains a customer’s household energy systems. This type of energy service provider undertakes any upgrades in household efficiency, with costs repaid by the customer over the duration of the contract period.

The decision of a household to switch towards energy service companies is determined from an ‘attractiveness array’, through which potential customers can assess the future benefits of energy costs saved over the duration of the contract period against the cost of an efficiency upgrade.

The model indicates that self-financing of energy upgrades that are necessitated by customers of traditional utility providers is a limiting factor to widespread efficiency improvements. Further, greater reductions in household energy costs could be realised through committing to longer-term contracts as this allows upgrade costs to be distributed over longer durations of time. Overall, the model highlights that a feasible approach to improving energy efficiency in the future is through the provision of energy services, as opposed to consumable products.

ANNEX D GLOSSARY OF TERMS

This glossary defines key technical terms used in this report relating to heating systems and agent-based modelling.

Figure 61 Glossary

Term	Definition
ABM (agent-based model)	A modelling approach which simulates the interactions between autonomous agents - entities which have properties (things they are) and rules/goals (things they do).
ASHP (air-source heat pump)	A form of heating that uses electricity to extract heat energy from the air outside the property and transfer it indoors. The heat pumps modelled in this report are high temperature units that can be connected to a standard wet radiator system.
Calibration	The process of adjusting a model's parameters to obtain outputs that are comparable to the real system on which it is based on.
CCS (carbon capture and storage)	A process of capturing waste carbon dioxide, transporting it to a storage site, and depositing it where it will not enter the atmosphere.
Discount rate	Specifies the degree to which the future is discounted by placing a present value on future costs and benefits. A discount rate of zero implies that the same weight is placed on costs and benefits in the future as today. Higher discount rates imply a lower weight on the future.
DNO (distribution network operator)	Firms which operate the network which transports electricity from the national transmission system to individual properties.
ECO (Energy Company Obligation)	A government energy efficiency scheme in Great Britain to help reduce carbon emissions and tackle fuel poverty. Obligated energy suppliers are required to carry out actions to improve the energy efficiency of homes.
Efficiency (of a heating technology)	The rate at which a technology (e.g. a gas boiler) can transform input fuel (e.g. gas) into useful heat.
Electric resistive heating	A form of heating in which a heating element directly converts electrical energy into heat. The electric resistive system modelled in this report consists of a hot water cylinder connected to a standard wet radiator system.
EPC (energy performance certificate) rating	A measure of a building's thermal efficiency, carried out by an assessor, and required before a home can be sold. The EPC rating runs on a scale from A (best) to G (worst).
ESCOs (energy service companies)	A variety of possible business models that bundle heat technologies with the provision of energy, and may help drive the uptake of new technologies.
GDN (Gas distribution network operator)	Firms which operate the network which transports gas from the national transmission system to individual properties.

Green Book	The standard guidance provided by the Treasury on how to appraise policies, projects and programmes. The Green Book includes a range of forecasts of carbon and fuel prices, which have been used within this model.
GSHP (ground-source heat pump)	A form of heating that uses electricity to extract heat energy from the ground outside the property and transfer it indoors. The heat pumps modelled in this report are high temperature units that can be connected to a standard wet radiator system.
Heat network	A system of insulated pipes which transports heat from a source (or multiple sources) to more than one end user.
"I" (unobserved heterogeity parameter)	A parameter within our model which determines how likely property owners are to select a heating technology that has a slightly lower utility. At the lowest value (zero) households will ignore the relative utility altogether.
Off-grid	Properties that are not connected to the natural gas network. In this model, such properties are either in rural locations, or high-rise flats that do not have a gas supply.
RAB (regulatory asset base)	The accumulated capital value of investments in a network, used as the basis for determining its allowed return (and therefore revenues).
RHI (Renewable Heat Incentive)	The Domestic Renewable Heat Incentive (Domestic RHI) is a government financial incentive to promote the use of renewable heat. Participants receive payments for the amount of renewable heat it is estimated their system has produced.
SMR (steam methane reformation)	A method used to produce hydrogen from a natural gas feedstock. Hydrogen produced by SMR is known as 'grey hydrogen' when the waste carbon dioxide is released to the atmosphere and 'blue hydrogen' when the carbon dioxide is captured and stored.
Steady state	A point which a system or process may trend towards and, once reached, does not change with time.
Thermal efficiency (of a building)	The amount of heat that needs to be generated to keep a building at a comfortable temperature - the worse the thermal efficiency, the more heat will be required.
Utility	Refers to the satisfaction received from using a good or service.

Source: Frontier Economics

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www.frontier-economics.com