The Economic Impact to 2030 of Decarbonising Heating in Scotland

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Cambridge Econometrics

Contents

Executive Summary

This report shows the potential economic impacts that might arise from a shift towards low carbon heating technologies in Scotland over the period to 2030. These are estimated based upon illustrative policy pathways which show the role that policy can play in shifting the future trajectory of Scottish heating demand away from fossil fuel-based technologies and onto a trajectory consistent with meeting the Scottish Government's decarbonisation goals.

- The modelling shows that there could be net positive economic impacts from the transition in the period to 2030.
- In 2030, there are an estimated 16,400 additional jobs created in our policy-compliant Extended scenario compared to a 'business as usual' reference case. Within this, there are a number of different dynamics taking place. Jobs are expected to be lost in fossil fuel-related industries, most notably in the manufacture of gas- and oil-fired boilers, and in the extraction, refinery and supply of these fuels (unless gas extracted offshore is exported to replace lower domestic demand), while jobs are likely to be created in the manufacture and installation of low-carbon heating technologies such as heat pumps and other forms of electric heaters where this happens within Scotland, and the generation and supply of electricity and other low carbon fuels. Compared to the reference case, around 11,600 jobs will be lost from reduced demand for fossil fuel technologies and fuels, and an estimated 28,000 jobs created via higher demand for low-carbon technologies and fuels. The majority of jobs (both from the individual flows and in terms of net effects) are created in the manufacturing and services sectors, reflecting the supply chains underpinning the technology and electricity supply industries.
- The analysis is subject to uncertainty, due to the assumptions that are required to be made to underpin the analysis. For example, we assume no change in the structure of the Scottish economy over the period 2021-30, and the analysis is carried out at a broad sectoral level, both reflecting data limitations. There is particular uncertainty around the spatial distribution of these impacts. Job losses in the oil & gas sector, if domestic demand cannot be replaced by demand for exports of gas, are likely to be focused in and around Aberdeen, reflecting the heavy specialisation of the sector in this region (including associated offshore activities). The changes in manufacturing demand from the shift in heating technologies presents both a risk and an opportunity to current regions specialising in this industry, including Fife and North and South Lanarkshire. The increase in electricity demand will provide major opportunities to regions currently specialised in the production or supply chains supporting renewable electricity generation, such as the onshore wind generation industry in North and South Lanarkshire.

- The impacts across different households is likely to be dominated by the changing nature of the costs associated with heating. Our analysis shows that subsidies can play a major role in equalising the costs of low- and high-carbon technologies, and ensuring that the typically higher up-front costs of heat pumps do not limit take up amongst financially constrained low-income households. In terms of the nature of the jobs created, the industries in which jobs are expected to be lost and created have a higher concentration of medium-low and low skilled workers than the Scottish average, but the specific nature of the jobs created will largely determine whether the new jobs can provide replacements or additional employment opportunity for those jobs lost in the shift away from fossil fuel-based technologies.
- The analysis is subject to several caveats, primarily related to the availability of data. The input-output framework that we use assumes spare capacity in the economy can be utilised to meet increased demand for new technologies and does not consider whether people with the relevant skills will be available in the workforce, either at the national or local level. The framework also assumes that supply chain linkages within the Scottish economy do not change over the period 2017 (the most recent year for which such data exists) and 2030 (the end year of our analysis). Finally, the input-output framework operates only at the broad sectoral level; it is not able to reflect the specificities (in terms of supply chains or imported content) of the very specific sub-sectors relevant to heating technologies (both high- and low-carbon).

1 Introduction

1.1 The purpose of this report

In this study we explore potential economic impacts over the period to 2030 from example pathways for decarbonising building heating in Scotland. The economic impacts (positive and negative) of scenarios for the delivery of low- and zero-carbon heat in the period to 2030 that are consistent with the Scottish Government's longer term policy goals are quantified, based on existing data and economic modelling.

The potential technology mixes used as inputs to the economic analysis are outlined only briefly in Chapter 2 of this report. The economic impacts are reported in greater detail in Chapter 3.

The rationale for economic impacts

The core focus of this analysis is the assessment of the potential economic impacts of decarbonisation pathways. Decarbonisation is often communicated purely in terms of costs. In energy system optimisation models, this is explicitly due to model design (where minimising system costs is an explicit goal of the model), and such analysis dominates mainstream understanding of the transition. Until recently, the CCC also talked almost exclusively about the 'costs' of decarbonisation, referring to a measure of resource costs for the transition. Such analysis misses the economic contribution that such activity can make; investment in an economy with spare capacity can create jobs and economic output, while such an approach also omits the difference between expenditure and investment, where investment can alter the productive capacity of the economy.

Our economic analysis is supported by technology modelling, which captures how, under different policy scenarios, future demand for Scottish heat out to 2030 might be met. This provides insight into the changing costs associated with heating (in terms of purchasing heating technologies and spending on fuels/electricity), which form the key inputs to the economic impact work.

The ultimate purpose of this research is therefore to assess the economic impacts associated with potential future pathways for achieving the Scottish Government's 2030 aims with regards to the heating of buildings, in order to highlight the opportunities that such a transition can provide to the Scottish economy for policymakers and the wider public.

The scope of the analysis

This report assesses the economic impacts of moving towards decarbonised heat in Scotland over the period to 2030. The modelling work includes explicit energy efficiency measures; it is assumed that by 2035, all residential properties in Scotland achieve an Energy Performance Certificate (EPC) rating of C, and that final demand for heating is reduced accordingly. This was based upon the draft Heat and Buildings strategy that was being consulted on when the analysis was carried out; however, the Scottish Government has since announced that such a transition to EPC band C should now be completed across the Scottish housing stock by 2033. In order to calculate impacts of these measures by 2030, a linear interpolation is applied, to calculate the reduction achieved in 2030, and therefore the trajectory for total heat demand. However, the economic impact of these energy efficiency measures is not assessed. Such analysis has previously been carried out in (Turner, et al. 2018), and the economic impacts as described there would be expected to occur as a result of this planned energy efficiency rollout. Furthermore, in this analysis the deployment of energy efficiency is assumed to take place in the baseline as well as the scenarios, so such measures would not lead to any further differentiation between the economic impacts in the scenarios.

1.2 Current policy aims

The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 sets targets for Scotland to achieve net zero by 2045 at the latest. In order to deliver this, interim emissions reduction targets as compared to emissions in 1990 have been set; emissions should be 56% below 1990 levels by 2020, 75% below by 2030, and 90% below 1990 levels by 2040.

The energy efficiency of the Scottish housing stock is improving (as noted in the Scottish house condition survey 2018). However, according to the Scottish Energy Statistics Hub, heating was responsible for 78% of Scottish household energy consumption in 2019. At the same time, 81% of Scotland's housing stock relies on mains gas as the primary heating fuel, and 6% on oil. This suggests that around 2.3m existing dwellings will have to shift to zero-carbon heating technologies before 2045, plus any new dwellings built since 2018 which do not use heating technologies which have the potential to be zero carbon. This highlights the scale of the challenge of achieving net zero in the domestic housing stock.

To specifically address this challenge, the Scottish Government has published the Heat in Buildings Strategy, which includes an update to the Energy Efficient Scotland route map.

There are multiple potential pathways to deliver a zero-carbon building stock. Most fundamentally, there is a balance between energy efficiency measures and switching to zero-carbon fuels; the deployment of efficiency measures can reduce the heat energy demand of households, reducing the additional electricity required to facilitate a switch away from fossil fuels. There are also complementarities between technologies and measures; for example, heat pumps become much more viable as a heating technology in an energy efficient home, where the lower peak output (and improved coefficient of performance at lower heating temperatures) are less impactful on the performance of the heating system.

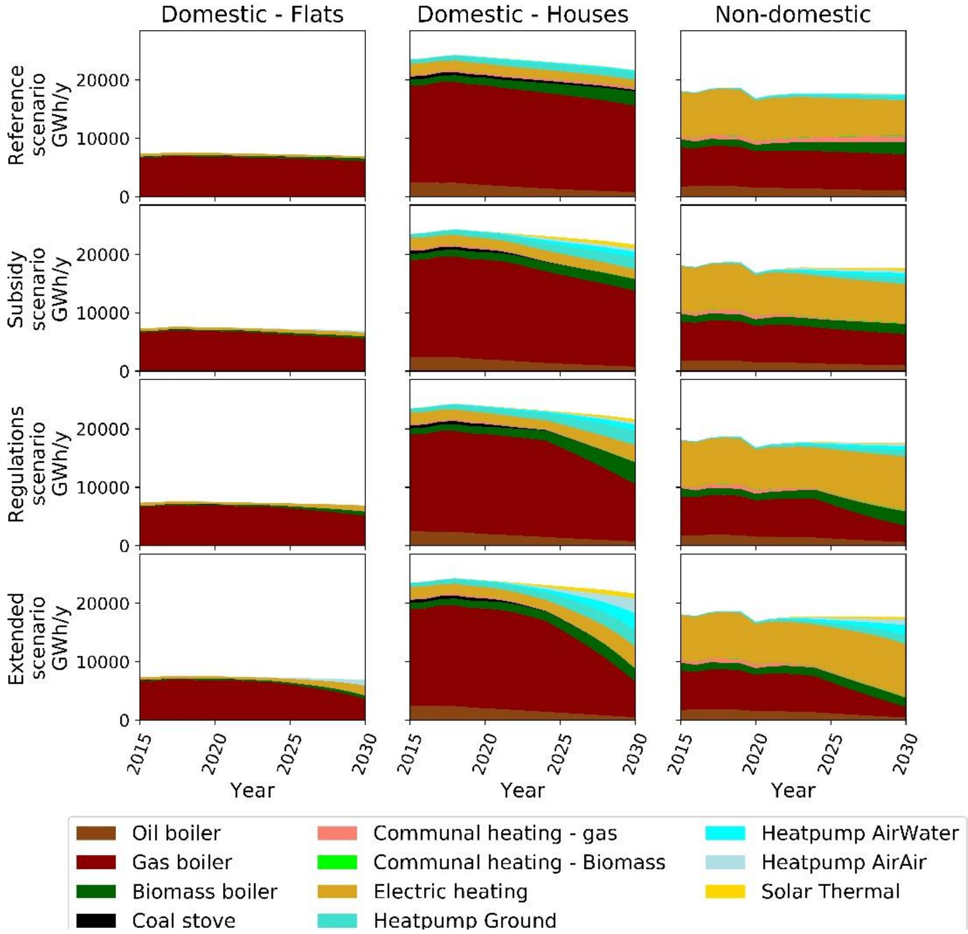
2 The heating technology scenarios

In this chapter we outline how heating demand is met by different technologies in the scenarios, and how that alters modelled consumer investment in heating technologies. The four simulated scenarios cover a reference scenario (reflecting the current policy trajectory), a subsidy scenario (providing financial support to the purchase of low-carbon technologies), a regulation scenario (enforcing the phase out of high-carbon technologies), and an extended scenario which combines (more stringent) subsidy and regulation measures. The full detail of the data/assumption inputs used to construct the scenarios are set out in Appendix C. The modelling approach is set out in Appendix D[1].

2.1 Heating demand by technology

Figure 2.1 illustrates what portion of the useful heat demand is met by the available technologies. Under the influence of the varying policy packages and limitations of specific building types, the way the heating demand is met changes over time. The simulated technology uptake affects final energy use, emissions and expenditure.

Figure 2.1: Heating technology take up under different scenarios (rows) and for different building types (columns)



[1] The full set of detailed modelling outputs are available upon request

Reference scenario

If no additional policies are introduced, our modelling suggests it is very likely that gas-based heating remains dominant in both flats and houses, while non-domestic buildings are heated primarily through electric heating (including electric boilers and electric storage heaters) and gas-based heating. Heat demand projections are a function of new building projections plus assumed efficiency gains. The increase in households, with an assumed constant split between houses and flats over time, leads to an increase in heating demand which is negated by energy efficiency gains in the existing stock. These gains are built on improving the EPC status of all buildings to at least band C by 2035. For non-domestic heating demand, we assume changes in gross value added (GVA) is correlated with changes in the number of non-domestic buildings, whilst a historical decrease in heating demand intensity was continued out to 2030.

Subsidy scenario

Applying subsidies to renewable forms of heating from 2022 onwards incentivises households and firms to move away from fossil-fuelled boilers. Our modelled scenario shows that the heat supply in houses and firms slowly moves away from gas boilers to other technologies, primarily heat pumps. The options for alternative technologies in the heat supply for flats is limited and only minor changes in the take up of technologies in these buildings are simulated by our model. To increase renewable heating in flats, communal forms of heating and heat networks could be deployed. However, these options have not been modelled, since they are regarded to require centralised decision-making while our model captures decisions by individual property owners.

Regulations scenario

In our phase-out regulation scenario, the installation of new fossil-fuelled boilers is banned from 2025 onwards. Consumers are forced to purchase a renewable technology when their boiler reaches the end of its lifetime. The simulated effect of a phase-out regulation differs in each building category. There is a greater uptake of renewable forms of heating in houses and non-domestic buildings. In flats, the effects of a phase-out are limited, primarily due to a lack of suitable alternative technologies.

Extended scenario

Neither subsidies nor regulations alone invoke a large enough change in the heating supply composition to meet the decarbonisation targets (see 0). For that reason, we combined the subsidies and regulations and complemented them with additional policies, such as a procurement scheme, and an increase in biomethane blending. The combined effect of these policies leads to an accelerated uptake of renewable forms of heating. In addition, the biomethane blending reduces the environmental impact of gas boilers.

Emission reductions

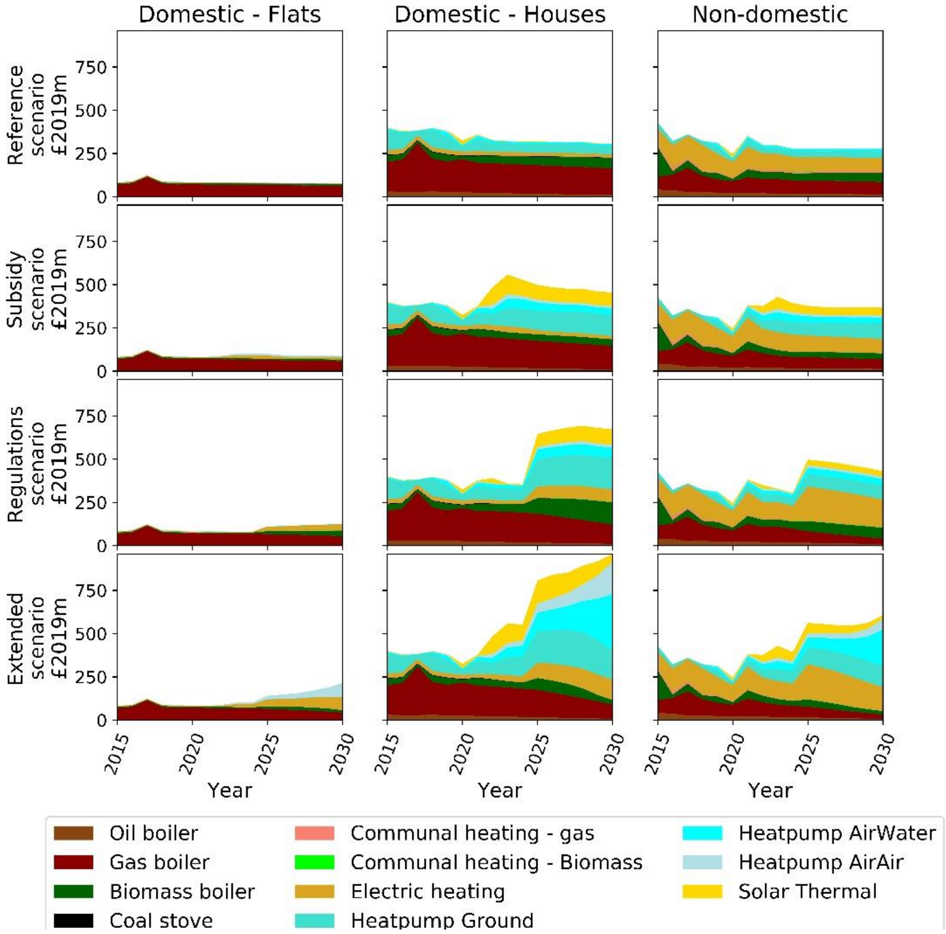
Across all domestic and non-domestic buildings, emissions reductions in 2030 of 32.9% (compared to the base year of 1990) are achieved in the Reference scenario, mainly due to improvements in energy efficiency. In the Subsidy and Regulation scenarios, emissions decrease by 44.3% and 58.7% respectively in 2030, compared to 1990 levels. Finally, the Extended scenario achieves a 74.3% decrease in emissions, which is close to the target for 2030. More detail on emission results are provided in Appendix B.

2.2 Investment in new heating technologies

The expenditure profiles for the different building types and scenarios we modelled are set out in Appendix B. Investments occur when households and business need to replace their existing heating unit at the end of its lifetime, or when they replace it prematurely (due to large cost differentials between the operation of existing and new technologies). Modelled scenarios in which more heat pumps are taken up show an increase in upfront costs, because heat pumps are relatively more expensive per unit of heating capacity and more capacity is needed due to climatic conditions to meet peak heat demand. Note that some of these upfront costs are subsidised in the Subsidy and Extended scenarios. Centralised investment in heat networks and/or communal heating could prove to be more cost-effective options in these scenarios but are omitted from the modelling due to the centrally-planned nature of their deployment.

Figure 2.2 shows the investment in heating technology profiles for each of the building types and scenarios. Rapid changes in investment occur

Figure 2.2: Stacked investment profile due to different heating technology diffusion pathways

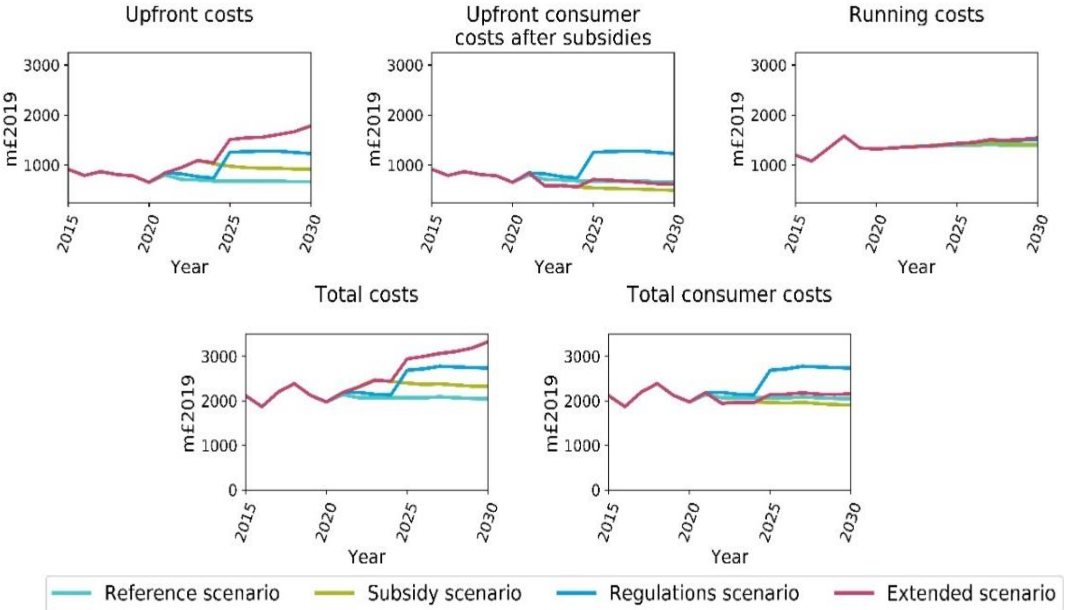


in the policy scenarios, because of a shift towards these more expensive (in terms of up-front cost) technologies. In the Regulation scenario expenditure on gas-boilers is displaced to a degree by expenditure in other heating technologies. For flats, no change in expenditure is expected. In the Extended scenario, expenditure is expected to increase 2.5 to 3-fold compared to the Reference scenario due to the high rate of substitution towards heat pumps in houses and non-domestic buildings. Higher expenditure is also seen in flats, due to higher rates of uptake of electric heating.

The changing ways in which heating demand is met changes not only upfront costs, but also running costs. Furthermore, maintenance costs differ between boiler types affecting the running costs. Figure 2.3 shows the effects of different scenarios on costs.

When subsidies, regulations, or a combination thereof (plus additional policies) are introduced in the Extended scenario, a much higher take-up of low-carbon technologies is seen, which is associated with higher upfront costs (first panel, top row). However, in the scenarios where subsidies have been implemented (Subsidy and Extended scenarios), some of these costs are not paid by consumers but rather by government (the impacts of which are shown in the second panel, top row). As different heating technologies that use different fuels are adopted, the total running costs across the system change (third panel, top row). Electrification is largely responsible for increasing running costs, due to the higher prices of electricity relative to gas; this effect outweighs the improved efficiency of heat pumps compared to conventional gas boilers. Combining the upfront costs and the running costs (first panel, bottom row), leads to a £1200m (in 2019 prices) increase in costs.

Figure 2.3: Scenario specific developments of upfront costs, upfront consumer cost, and running costs in the top row. Then, in the bottom row the total costs overall and the total costs faced by consumers are depicted.



Lastly, from the second panel in the bottom row, it becomes clear that the subsidies play a key role in ensuring that a low carbon heating does not substantially increase the heating costs faced by consumers. Phase-out regulations force consumers to choose more expensive, but low-carbon options.

3 The economic impacts of decarbonising heat

Building on the heating technology pathways set out in the previous chapter, we used the Scottish Supply, Use and Input-Output tables to evaluate the economic impacts associated with the different scenarios. More detail on the methodology is presented in Appendix A.

We carried this analysis out in two stages. Initially, we used the Scotland Input-Output tables to evaluate macroeconomic impacts of the different aspects of the decarbonisation of heating at the national level. Subsequently, we explored the distribution of these impacts, both spatially and in terms of socio-economic classification of households, using a combination of quantitative modelling, analysis of historical trends and qualitative narrative.

3.1 The economic footprint of transforming heating demand

All results presented and discussed below are based upon the assumption that the structure of the Scottish economy will not substantially change over the period from 2017-2030 – a necessary assumption for the application of static input-output modelling as carried out for this analysis. The input-output tables provide information on the domestic and imported content of each sector – so we are able to measure how much changes in demand are met through changes in domestic production versus imports, although this data is only available at the 2-digit SIC code level, not at the more detailed component level (this issue is discussed in more detail later in the chapter).

The analysis considers direct and indirect impacts, which is to say direct changes in expenditure (e.g. lower demand for gas boilers, and higher demand for heat pumps) and follow-on impacts through supply chains (for example lower demand for pilot lights and higher demand for electrical heat exchangers, as components of gas boilers and heat pumps respectively). It does not include the induced effects linked to overall changes in economic activity and employment (e.g. if employment in electrical equipment is higher, this creates additional wages in the economy, which increases demand for food & drink and other consumer goods/services). The analysis also does not seek to balance out changes in expenditure; so we do not consider whether household expenditure on other goods and services would decrease in order to facilitate higher expenditure on heating technologies, for example, or the follow-on economic impacts of these shifts.

The analysis splits the transition in heating technologies into four distinct effects[2];

[2] Installation and maintenance impacts are not assessed here because the requirements for different heating technologies are broadly similar. While there would therefore likely be some training required, it is not unreasonable to assume that the

- Reduced demand for high carbon technologies
  The shift away from gas- and other fossil fuel-based technologies will result in reduced output from the manufacture of gas and oil burners
- Increased demand for low carbon technologies
  The greater demand for heat pumps, electrical heating, biomass boilers and solar thermal technologies will increase output from manufacturers of such items
- Lower demand for high carbon fuels
  The shift away from fossil fuel-based technologies will reduce demand for, and therefore output from, gas and oil to fuel these types of boilers
- Higher demand for low carbon fuels (including electricity)
  Increased usage of heat pumps and other low-carbon technologies will increase demand for low carbon fuels (chiefly biomass and electricity), leading to higher output from these industries.

In the analysis that follows, each of these impacts is considered in turn. The reason for this approach is that economic analyses often focus on *net* impacts, in terms of both employment and output. Even when providing some sectoral breakdown of impacts, the focus is on net changes within a given sector, which ignores that different jobs are being created and lost, both in terms of the sub-sector in which the activity takes place, and the geographical location of the activity. For example, manufacturing jobs are lost in gas boiler manufacture, and created in heat pump manufacture – and while both are manufacturing jobs, they require different skills, and are very likely to be based in different places. Through evaluating the job impacts in separate stages, our analysis provides more detailed insight into the creation and loss of jobs and economic activity.

The economic impacts scale with the level of decarbonisation achieved in the scenarios; so the smallest changes in employment and output are seen in the Subsidy scenario, followed by the Regulation scenario, with the largest impacts (both positive and negative) in the Extended scenario. There are similar narratives across all three scenarios, as the underlying dynamics are similar.

The shift away from high carbon technologies results in a small number of jobs losses linked to the supply of the heating technologies themselves, most notably in the manufacture of the equipment. However, our modelling suggests that the potential job gains from a shift to low-carbon technologies will create more jobs than are lost; in manufacturing (linked to the production of the technologies) and services (through supply chain effects). In the Extended scenario, just over 3,100 jobs are lost in 2030 due to the transition away from high-carbon technologies, with 1,400 of those in manufacturing. The switch to cleaner technologies is expected to create 22,800 jobs, however,

same portion of the workforce could ultimately provide maintenance for heat pumps that currently provides this service for conventional gas boilers.

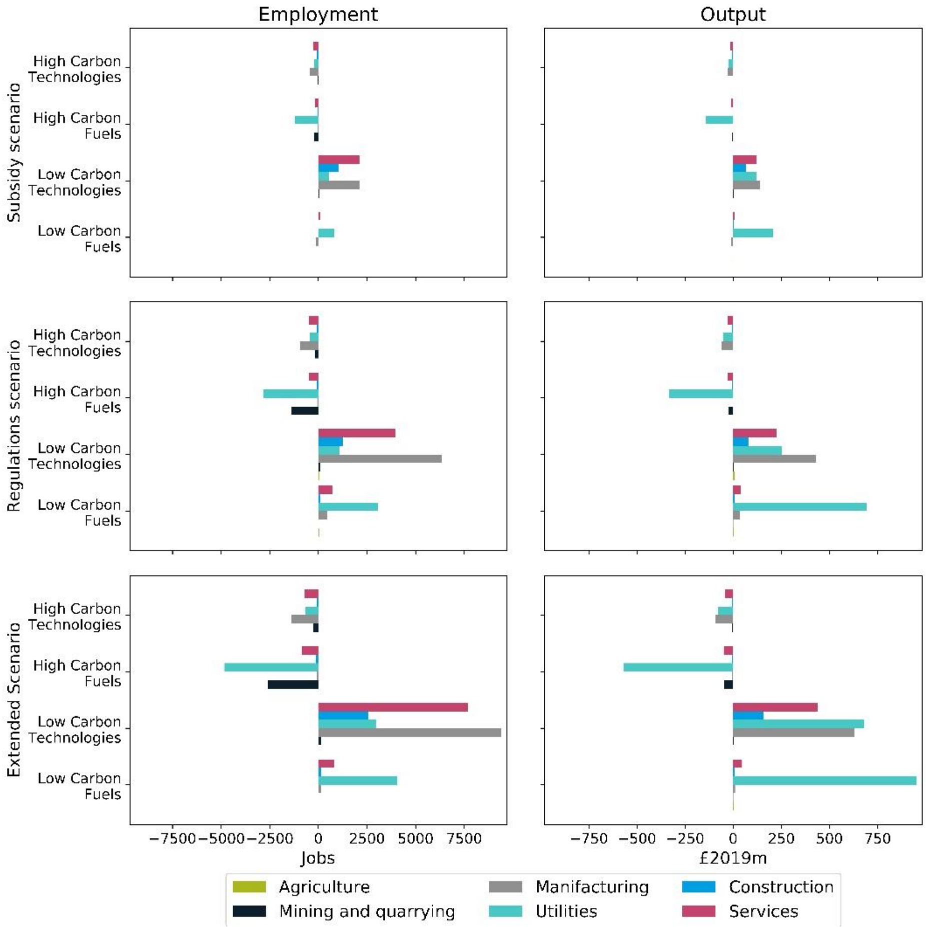
with over 9,400 in manufacturing and a further 7,700 in services (see Table 3.1).

Table 3.1 Employment changes in the Extended scenario in 2030

Employment difference from baseline, jobs	Switch away from high-carbon technologies	Change in demand for high-carbon fuels	Switch towards low-carbon technologies	Change in demand for low-carbon fuels	TOTAL
Agriculture	-4	-8	+22	+16	**+26**
Mining & quarrying	-264	-2,613	+150	+12	**-2,715**
Manufacturing	-1,386	-102	+9,413	+145	**+8,070**
Utilities	-671	-4,825	+2,957	+4,071	**+1,532**
Construction	-95	-118	+2,575	+140	**+2,502**
Services	-710	-837	+7,679	+819	**+6,951**
TOTAL	**-3,130**	**-8,503**	**+22,796**	**+5,203**	**+16,366**

Conversely, more jobs are lost from reduced demand for high-carbon fuels (primarily gas and oil, with a substantial domestic supply chain) than are gained from increased demand for low-carbon fuels (chiefly electricity). The driver of these outcomes are slightly different; in the case of technologies, the higher up-front costs of low-carbon technologies vis-à-vis their high carbon equivalents means more is spent on them, leading to more jobs being created in the production of low-carbon equipment. In terms of fuels, while the difference in overall expenditure is small (as can be seen in Figure 2.3), the higher labour productivity of the electricity supply sector as compared to gas extraction supply leads to smaller job creation in the electricity sector than the number of jobs lost in the gas industry. These dynamics are demonstrated across the scenarios (see Figure 3.1). However, it should be noted that there is substantial uncertainty around the impacts on the oil & gas sector in particular. This analysis assumes that reduced domestic demand for natural gas for heating would lead to a reduction in supply from offshore rigs; however, it is more likely that this gas would instead be sold into different markets, and it is unlikely that domestic demand would have a major impact on global prices for gas, *so in fact there may be minimal (or no) jobs lost in the Scottish extraction industry as a result of this transition*.

Figure 3.1: The economic impacts of the scenarios in Scotland in 2030



The impacts on economic output vary from the impacts seen on employment, in terms of relative sectoral weight (i.e. the size of impact in one sector relative to another). This primarily reflects the labour intensity of the different sectors; the utilities sector, for example, has relatively high productivity (based upon data in the input-output tables), and therefore a large impact on output translates into a smaller impact in terms of employment, relative to the impacts in other sectors (notably manufacturing, which typically has a productivity below the economy-wide average). The net impact on gross output in 2030 is an increase of just over £2bn; this is equivalent to a 0.6% increase in the size of the 2017 Scottish Economy, and therefore a slightly smaller percentage increase in the (anticipated) larger Scottish economy of 2030.

In aggregate, the employment impacts are net positive in all scenarios; in the Extended scenario almost 16,400 jobs are created in 2030, once jobs created and jobs lost are balanced against each other. This suggests that overall, the transition can be expected to have a positive impact on the Scottish economy, although continued investment in new low-carbon heating technologies from households and businesses will be required to sustain this effect.

Table 3.2 Gross output changes in the Extended scenario in 2030

Gross output difference from baseline, £m (2017 prices)	Switch away from high-carbon technologies	Change in demand for high-carbon fuels	Switch towards low-carbon technologies	Change in demand for low-carbon fuels	**TOTAL**
Agriculture	-0.3	-0.5	0.0	+1.7	**+0.9**
Mining & quarrying	-5.2	-47.3	+4.0	+0.4	**-48.1**
Manufacturing	-91.3	-6.3	+629.8	+9.6	**+541.8**
Utilities	-80.4	-568.0	+680.6	+950.7	**+982.9**
Construction	-5.8	-7.2	+158.3	+8.6	**+153.9**
Services	-41.8	-49.2	+438.9	+45.6	**+393.5**
TOTAL	**-224.8**	**-678.5**	**+1,911.6**	**+1,016.6**	**+2,024.9**

It should be noted that this analysis reflects existing Scottish supply chains and assumes that reduced demand from final consumers and industry cannot be replaced by demand from elsewhere (including overseas). This assumption is questionable in respect specifically to the oil & gas extraction industry; as outlined previously, while domestic demand for natural gas will go down as a result of the transition to low-carbon technologies, it is reasonable to think that domestic extraction/production will not go down, but instead that gas that was previously consumed domestically will instead be sold into the international gas markets.

The analysis above is based upon (in the baseline and all scenarios) an assumption that all Scottish homes are upgraded to a minimum of EPC band C by 2035, which was the suggested target at the time this analysis was carried out. The Scottish Government has since committed to deliver this change to the housing stock no later than 2033. This more accelerated rollout of energy efficiency would not change the key messages contained in this economic analysis, although the precise impacts (in terms of specific changes in output and employment) would be expected to change slightly. This is because energy efficiency has the effect of reducing effective heat demand. Under a more rapid deployment of energy efficiency, final heat demand in the period to 2030 would be expected to reduce slightly more rapidly than was modelled. This does not affect the demand for heating technologies, but would reduce overall demand for heating fuels (including electricity), across the baseline and scenarios. This is likely to reduce job losses in the utilities sector, as the change in demand for gas and electricity would be smaller (reflecting the slightly more efficient housing stock needing less in terms of energy inputs), but such impacts would be minor.

3.2 The spatial distribution of activity

Predicting precisely where these jobs will be created within Scotland is a challenging task; it requires knowledge of the existing spatial distribution of existing specific industries and value chains (for example, where are current gas boiler manufacturers and heat pump manufacturers located across Scotland, and where do they source their components from?), but most importantly also requires a prediction of where future activities will take place, and what location decisions will be taken by new/existing firms as demand for these products scales up (for example, will heat pumps continue to be manufactured primarily in existing locations, but at greater scale, or will firms seek to take advantage of the availability of skilled labour in regions where declining demand for gas boilers has led to job losses?). In the analysis that follows, we seek to explore what existing economic data can tell us about the potential geographical impacts of the transition, but further in-depth analysis through survey and case studies should be considered to evaluate these issues in more depth.

In order to consider the differential impacts upon the sub-national economies within Scotland, we evaluated existing industrial structures and assessed which regions currently demonstrate some specialisation in the relevant sectors (in particular, in oil & gas extraction, electrical equipment manufacture, machinery & equipment manufacture, electricity supply and gas supply), in order to understand both where existing jobs (in fossil fuel-related activities) are likely to be lost, and also where there is the greatest likelihood (due to the existence of a suitably skilled workforce, and an existing base of firms) of new jobs being created.

Using data from the Business Register Employment Survey (BRES) for 2017, the local authorities with the greatest shares of Scottish employment in the relevant key sectors have been identified in Table 3.3.

This provides some insight into where the sectoral impacts can be expected to be concentrated. It is unsurprising that over 80% of jobs in Scottish oil & gas extraction are in Aberdeen and the surrounding area (including on offshore rigs), and it is therefore likely that the job losses in this sector (expected to total 2,700 by 2030 in the Extended scenario) will be focused in this region. However, as noted above, the true impact on the gas extraction industry may well be much lower than set out in this analysis, if the gas is sold into export markets when domestic demand falls.

Table 3.3 Local authority shares of Scotland sectoral employment, 2017

Oil & gas extraction 1.2% of total Scotland employment in 2017		Electrical equipment 0.6% of total Scotland employment in 2017		Machinery & equipment 0.6% of total Scotland employment in 2017		Electricity supply 0.5% of total Scotland employment in 2017		Gas supply 0.2% of total Scotland employment in 2017	
Aberdeen City	67%	Fife	26%	Fife	17%	Glasgow City	17%	City of Edinburgh	29%
Aberdeen-shire	14%	West Dumbarton -shire	11%	West Lothian	10%	Perth and Kinross	16%	South Lanarkshire	29%
Highland	4%	North Lanark-shire	9%	Aberdeen -shire	10%	North Lanark-shire	12%	Glasgow City	14%
Fife	2%	Aberdeen City	8%	North Lanark-shire	9%	South Lanark-shire	10%	Aberdeen City	6%
North Lanark-shire	2%	South Lanark-shire	8%	Aberdeen City	8%	Highland	7%	North Lanarkshire	6%
City of Edinburgh	2%	Glasgow City	5%	Renfrew-shire	8%	City of Edinburgh	5%	Renfrew-shire	4%

Source: BRES

While employment in the other sectors is more spread across Scotland, it's clear that Fife, with a specialisation in electrical equipment *and* machinery & equipment, faces a major restructuring challenge, with jobs likely to be lost in the manufacture of existing high carbon technologies, but a major opportunity to leverage specialisations to become a focal point for the production of the low carbon alternatives. North and South Lanarkshire will face the same challenge, albeit on a smaller scale. However, it should be noted in all cases that the data only tells us that these regions focus in the broad electrical equipment and machinery & equipment sectors; from this data it is not possible to accurately identify whether there are specific activities relating to boiler or heat pump manufacturing in these locations. Such analysis would require a much more focused data collection exercise, such as a survey, to establish precisely where specific components and products are manufactured. If this were to be carried out, it should focus on mapping out existing producers and supply chains in both the old and new technology value chains; this might best be achieved through a nationwide survey carried out through manufacturing members' organisations.

When looking at fossil fuel supply, Edinburgh, South Lanarkshire and Glasgow are the areas where gas jobs are focused (representing over 70% of total Scottish employment in this industry) and would expect to bear the brunt of job losses. Conversely, increased demand for electricity could be expected to boost employment in some of the existing key regions for electricity supply, including the offshore wind supply chain clusters in Glasgow and Edinburgh, as well as renewables activities in the Highlands and onshore wind in particular in North and South Lanarkshire. While some regions (notably Glasgow and Edinburgh) are boosted in terms of the size of these industries due to headquartering effects (e.g. SSEN and Scottish Power have major offices in Glasgow), it is reasonable to think that jobs would increase in these locations, alongside generation sites, if total demand for electricity increased.

While such analysis of, and interpolation from, historical data can provide understanding of where existing jobs might be lost, there is greater uncertainty around where new jobs might be created. Most obviously, given the ongoing decarbonisation of electricity generation, it is not clear that future employment in the electricity sector will be in the same technologies, and therefore in the same locations as existing jobs – although given the advanced state of Scotland's efforts to decarbonise this sector the analysis does at least suggest employment opportunities in regions which already have some degree of specialisation in generation via renewables.

Impacts across the income distribution

The quantitative analysis outlined above does not seek to evaluate the distributional impacts of the transition. However, the technology switching, and information on the cost of technologies and fuels, which is used to calculate the economic impacts outlined above, provides detail into how the nature of consumer expenditure can change in the transition. In the Extended scenario (the focus of our analysis), total expenditure on heating technologies (i.e. the replacement of existing, primarily gas, boilers with new heat pumps and other low-carbon technologies) increases substantially, although subsidies offered by government bring these costs down broadly into line with the reference case. This shift in expenditure (and in particular the higher unsubsidised upfront 'investment' costs associated with low-carbon heating technologies) is likely to be easier to manage for higher income households, who have the financial liquidity to be able to afford to pay a higher purchase price for the technology (or access to finance to allow it). This demonstrates how important the use of relevant government policy levers (such as subsidies), well targeted at those households that are least able to pay higher up-front costs, are in ensuring the successful deployment of low-carbon technologies.

Conversely, lower income households face two challenges; first, that they are more finance-constrained; meaning that without subsidies they are less likely to be able to afford the greater up-front cost of these technologies, and find it more difficult to borrow money commercially to do so; second, that low-income households are less likely to be owner-occupiers, and more likely to be in rental or state-provided accommodation. The ‘split incentives’ challenge associated with these types of tenancy agreements is well explored in the academic literature (Aydin, Eichholtz and Holtermans 2019) (Economidou 2014) (Gillingham, Harding and Rapson 2012), and relates to the fact that in non-owner occupied properties, one party (the landlord) pays for the installation and maintenance of heating technologies, and another (the tenant) pays the ongoing energy costs. There is therefore little cost incentive for the owner to pay for the installation of (more costly) low-carbon technologies since they will not reap the benefits of lower running costs. The end result of this is that such households are less likely to switch to the low-carbon technologies.

Ultimately, what this suggests is that, in terms of income distribution, the impacts of the transition could be very unequal without specific government intervention to address this (e.g. through direct procurement). Without policy support to encourage and facilitate take-up amongst low-income households, the majority of the adopters of these new technologies could be expected to be middle- and high-income households. As Chapter 2 shows, total system costs faced by consumers are similar in the Reference and Extended scenario, but the higher unsubsidised up-front costs for low-carbon heating technologies could present a major potential barrier to take-up from low-income households unless financial support is suitably deployed to support take-up (as assumed in the Extended scenario).

The question of how the jobs impacts of the transition play out across the income distribution is less clear. The Annual Population Survey gives occupational breakdowns for employment in Scotland by broad industry group in 2017; the key information for relevant sectors is summarised in Table 3.4 below.

Table 3.4 Occupational skill levels in broad sectors, Scotland, 2017

	B Mining and quarrying	C Manufacturing	D Electricity, gas, air conditioning supply	Scotland economy-wide average
Skill level 1[3]	4%	9%	0%	11%
Skill level 2	21%	28%	27%	36%
Skill level 3	34%	39%	39%	26%
Skill level 4	40%	24%	33%	27%

Source: Office for National Statistics, Annual Population Survey

[3] Skill levels are as defined in the SOC2010 methodology, mapping 2-digit SOC codes to the four levels. See: https://www.ons.gov.uk/methodology/classificationsandstandards/standardoccupationalclassificationsoc/soc2010/soc2010volume1structureanddescriptionsofunitgroups

This suggests that the sectors in which the most prominent changes (both positive and negative) are expected have a relatively large proportion of relatively low-skilled (and therefore likely to be low-income) workers in them. For example, around 74% of workers in the mining & quarrying industry were medium-low (level 3) or low (level 4) skilled in 2017, compared to an economy-wide average of 53%. However, because the proportions are broadly similar across the affected industries (73% in manufacturing, and 72% in electricity and gas supply) it is not clear that shifting employment between these industries will have a substantive impact upon the distribution of household income across Scotland. From the evidence presented here, it appears likely that the direct impacts of changing heating technologies will have a more substantive distributional effect. However, it is important to note that the data above is for broad industries only; the value chains associated with the production of both fossil fuel and low-carbon heating technologies have specific labour requirements which do not necessarily directly match up to these industry 'averages'. A more detailed assessment of the specific occupations and skills needed in the respective value chains could provide further insight into the changing demands that this technology shift is likely to place on the Scottish labour force.

4 Conclusions

This report has set out the potential economic impacts from a modelled transition away from fossil fuel heating and towards low-carbon alternatives in Scotland.

The analysis demonstrates that there are net positive economic impacts from the transition. Our modelling suggests the shift to (more expensive) low-carbon heating technologies will lead to the net creation of around 16,400 jobs in 2030 in our Extended scenario. The modelling estimates that around 11,600 jobs will be lost as a result of reduced demand for fossil fuel heating technologies and fuels, while an estimated 28,000 jobs will be created in the manufacture of low-carbon heating technologies and the supply of low-carbon fuels (chiefly electricity). This highlights one of the key challenges in managing the transition; ensuring that, as far as possible, the new jobs created can be matched to those workers that are losing their jobs in fossil fuel-related activities. If this can be achieved, by policies such as job- and skill-matching, and the implementation of relevant re-training schemes, then the worst of the spatial and distributional impacts of concentrated job losses could be mitigated. Such measures can also ensure that the Scottish labour force is suitably equipped to meet the future demands of the domestic heat industry, avoiding major supply-side constraints.

Furthermore, the analysis of heating technology deployments highlights some challenges in achieving the deep decarbonisation envisaged in the high-level targets of the Scottish Government. For example, due to their nature, heat pumps have a limited opportunity to penetrate the heating of flats, and it is important that policy frameworks take this into account and give the potential for the deployment of relevant technological solutions (including the use of heat networks and more substantive energy efficiency deployments), to ensure that heating costs do not increase substantially. This also points towards some potential concerns around the distributional impacts of the transition, where specific measures are likely to be required to ensure that the split incentives for property owners and tenants are overcome to ensure that rental properties (and the residents of them) are helped to take up low carbon heating technologies.

4.1 Challenges to achieving these outcomes

The modelling set out in this report is based upon a number of assumptions which must be addressed when considering how likely the modelled outcomes are to be achieved ‘in the real world’;

- The input-output framework used for the analysis is purely demand-driven. This means that it is assumed that an increase in demand for (e.g.) heat pumps can be met by spare capacity in the economy, with no supply-side constraints. In practice, at a minimum, workers will require training to acquire the relevant specialist skills, and there could be more general shortages in the labour market in particular roles (most notably those requiring highly specific skillsets), which policy must seek to address to facilitate the transition of the Scottish economy.

- The supply chain analysis assumes that the nature of intra-sectoral linkages (i.e. the level of inputs from different sectors required to produce £1m of a good or service) do not change over the period. However, clearly the economy is not static, and does evolve over time. While this can be expected to result in changes to the precise economic activity and employment created through supply chains, over the ten-year period to 2030 it would not be expected to fundamentally change the messages from the analysis.
- The input-output analysis operates at a 2-digit sector level. This means that, for the purposes of this analysis, it is assumed that demand for (for example) electrical equipment is met through the same mixture of intermediate inputs, whether that electrical equipment is part of a gas boiler or a heat pump. In practice, different capital, and most probably different labour skills, are required for the manufacture of these two components. The analysis seeks to address this through separately analysing the jobs created and the jobs lost in the transition, but nonetheless it is important to highlight that the jobs lost and the jobs gained within a single industry will not necessarily require the same skills or be in the same place. Furthermore, although the input-output tables, and therefore our analysis, include demand for imports (and therefore leakage out of the Scottish economy), the analysis does not include detailed data (or assumptions) on the export content of the different heating technologies – so there is the potential for domestic demand for heat pumps to be captured by imports to the Scottish economy to a greater extent than in the impacts presented here.

These issues demonstrate that the quantitative work, both the input-output modelling and the data analysis that follows, can only tell part of the story. Such data-driven approaches necessarily make assumptions and should be part of a wider narrative around the impacts of the transition which is sector- and place-based.

The decarbonisation of heating is part of the wider decarbonisation journey that the Scottish economy, and indeed an increasing number of global economies, are committed to. In the transition to a zero-carbon Scotland in 2045, the nature of the economy will shift substantially, as consumers move away from consumption of fossil fuels and products based upon fossil fuels, such as plastics. This transition requires careful management, and clear signposts and certainty to industry, to ensure that the economy can adjust in response to changing consumer demands and regulation. However, such transitions have (and continue to be) managed in the past. It is also worth noting that decarbonisation is just one of a number of transitions that will affect the development of the Scottish economy over the coming years, including long-term trends such as automation and the increasing use of AI, the changing demographics (aging) of the Scottish population, the pace of globalisation, and changing use of resources. In such a context, the decarbonisation challenge, while it presents transformative challenges to some sectors, could be nonetheless a relatively small part of the overall transformation of the economy, and of Scotland more widely, in the coming years.

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Appendices

Appendix A Input-output modelling of the Scottish economy

Through the estimation of heat demand and the simulation of competition between boiler types, we can estimate how the boiler composition can change over time under the influence of policy portfolios aimed at heat decarbonization in Scotland. From the boiler composition, estimates for consumer investment in boilers and final energy demand, and therefore consumer expenditure, can be calculated. Based upon these model results, the wider economic impacts of heat decarbonization in Scotland can be estimated via Input-Output analysis and will yield impacts on employment and GVA (Scottish Government 2015).

The key input into this analysis was the Scottish Supply, Use and Input-Output table for 2017, which shows interlinkages between sectors, and how these combine to meet final demand for industrial output. Type I multipliers were taken from the published tables; as such, the economic impacts calculated include *direct* and *indirect* impacts only – the jobs and economic activity that is created/lost in the changed production of the goods/services for final demand, and those created/lost through supply chains (i.e. the production of intermediate goods/services which contribute in one way or another to production of the final output). *Induced* effects are excluded in our analysis – these are the multiplicative impacts which result from changes in employment via direct and indirect effects. For example, if net employment and aggregate wages in an economy are higher via direct and indirect impacts, those wages would ultimately be re-spent back into the economy, generating further demand for output and therefore employment. However, these *induced* effects are subject to some uncertainty (and substantial debate amongst economists), and for the sake of clarity are excluded from this analysis.

An input-output led approach like this is well-suited to short- and medium-term analysis such as that carried out in this report, which seeks to assess outcomes to 2030. The approach relies upon static input-output tables; the economic structure of the economy (i.e. the inter-sectoral supply chain linkages) do not change in this type of analysis, and this is a more important restriction the further into the future the analysis goes.

Other key characteristics of the analysis are described in more detail below.

A.1 Quantifying impacts

Model logic

Direct impacts can broadly be defined as the effects of the changes in final demand for heating technology and fuels, excluding knock-on impacts in the wider economy. These further effects, *indirect impacts*, are felt through supply chains to the industries directly affected.

Model inputs

The method draws upon outputs from the heat technology modelling:

- Demand for different heating technologies;
- Costs of each heating technology, with content broken down by economic sector;
- Projections for fuel/electricity prices, sourced from BEIS.

Inputs are supplied for all three scenarios

The model inputs are populated for three scenarios (Subsidy, Regulation and Extended). The structure and nature of the inputs are the same across scenarios.

Characterisation of the supply chain

Initial mapping of each heating technology to economic sectors is based upon expert judgement, and reflects inputs used in previous similar modelling exercises. The further characterisation of the supply chain draws on the linkages implied in the Scottish Input-Output table for 2017.

Model calculations

Once the scenario inputs are characterised, the analysis of direct impacts then seeks to:

- apply evidence from Scottish Input-Output tables to identify impacts on value added;
- apply data on labour intensity to estimate the impact on Scottish employment.

The analysis was divided into four impacts; changes from reduced demand for high-carbon heating technologies, increased demand for low-carbon heating technologies, reduced demand for fossil fuels and increased demand for low-carbon fuels. Value added and employment effects are calculated for each, across each of the scenarios.

Impacts

The direct impacts relate to the direct impacts of the shifts in consumer expenditure modelled over 2020-30. Indirect impacts are those that occur through supply chains to meet the changes in final demand over the same period.

Gross output effects are calculated by applying sector-by-sector Type I multipliers from the IO tables to the change in final demand in each economic sector, to understand how intermediate demand for other goods and services beyond final demand is affected. Employment impacts are calculated based upon the gross output effects and estimates of labour productivity in 2017 based upon gross output from the IO tables and employee data from NOMIS[4], the UK Office for National Statistics portal for labour market statistics.

Input-output coefficients

Input-output coefficients tell us the proportion of intermediate inputs used in production. These vary across sectors because different sectors will have different input requirements for production. IO coefficients are calculated by dividing expenditure on intermediate purchases by the value of total output.

[4] The NOMIS series used measures employees by industry, so excludes the self-employed.

The matrix of IO coefficients used in the analysis contains more sectoral detail. The Type I Leontief inverse table is 98 x 98 where rows correspond to the input sectors and the columns correspond to the output sectors.

The Leontief inverse

As defined by the OECD, the Leontief inverse shows "the input requirements, both direct and indirect, on all other producers, generated by one unit of output"[5]. It is therefore central to the analysis as it defines the sensitivity of the model economy to scenario changes. It is derived by matrix inversion using IO coefficients. Specifically, it is derived using the expression $L = (I - A)^{-1}$. Where L is a 98 x 98 matrix of coefficients, I is an identity matrix and A is a matrix of input-output coefficients.

A.2 Modelling assumptions

All modelling approaches require certain assumptions. The assumptions which are made shape the strength of the modelling approach to different tasks and the robustness to uncertainties about the future.

The approach is suited to impact estimation but not forecasting

The modelling carried out in this report adopts a constant 2017 version of the Scottish economy out to 2030. This is because the objective of the report is to identify accurate and robust impacts (i.e. difference from the baseline) rather than forecasts (e.g. the level of GDP in 2030).

The approach needs to make assumptions about accounting relationships in the economy

The modelling approach also needs to make a series of assumptions about accounting relationships within the economy. For instance, if the electrical equipment sector experiences a boost to output (and revenue), we need to build a picture of how that additional revenue is spent. The approach needs to know how much revenue gets taken as surplus by firms and how much gets spent on employees, inputs to production and taxes. Building this picture across all sectors of the economy, the approach characterises how sectors of the economy trade with one another.

The modelling does not capture changes to accounting relationships over time

These details are created in the modelling approach by using the existing Scottish Input-Output relationships. Crucially, the information is only available in historic data (the latest year at the time of analysis was 2017). This means that the modelling does not capture changes to accounting relationships over time.

For instance, suppose that because of technological change, the electrical equipment sector relies less on mining sectors and more on service sectors in future years. This would mean that, if the electronics sector is shocked in 2025, the approach would over-estimate the knock-on impacts on the mining sector and under-estimate the knock-on impacts on services sectors.

[5] https://stats.oecd.org/glossary/detail.asp?ID=1519

This being said, changes to accounting relationships in the wider economy over time are typically very gradual and the forecast period (2020-2030) does not extend extremely far into the future.

Ex-ante impact assessments require assumptions about the future

More generally, the results presented in this report are an ex-ante assessment (i.e. predicting future impacts) and should be interpreted as such. Ex-post impact assessments (i.e. evaluating past impacts) have the advantage of adopting observational data on economic context over time, which affects the sensitivity of the economy to certain shocks. Given that these observations are not available for ex-ante assessments, they are less robust to radical changes in the nature of the wider economy in the future.

The future labour intensity of the opportunities is uncertain

As described earlier in this appendix, direct employment impacts draw on estimates of the labour intensity of the opportunities. This data is based on historical data. However, there are a number of challenges associated with this estimation. Firstly, it is not certain that the labour intensities will scale proportionately. For instance, economies of scale may mean that at higher projected levels of output, labour intensities will differ.

Secondly, the analysis assumes that labour intensity (and hence labour productivity) are constant over time. This is a simplifying assumption. In practice, labour productivity is likely to increase over time and therefore the employment impacts could be lower (all other things being equal) in the future.

Appendix B Deployment of heating technologies in Scotland to 2030

B.1 Framing the analysis

We applied a technology diffusion model, FTT:Heat, to assess how different heating technologies could be deployed in the period to 2030 to meet Scotland's heat demand under different policy scenarios. More detail is provided on the modelling framework in Appendix A.

We constructed a baseline projection, setting out how, absent any further policy intervention, heating demand in the period to 2030 is expected to be met. This reflects the existing deployment of heating technologies (since the majority of technologies currently in use would be expected to continue to be in use in 2030).

Three policy scenarios were then modelled. In the first, 'Subsidy', additional policies focused on market-based instruments, and in particular providing subsidies to reduce the up-front cost by 75% of low carbon heating technologies from 2022 onwards. Electric heating, heat pump ground, heat pump air/water, heat pump air/air, and solar thermal are considered low carbon heating technologies. Biobased heating technologies have been excluded from this subsidy package.

In the second, 'Regulation', policies are focused on regulation, for example specifically phasing out gas boilers. From 2025 onwards new capacity of these technologies cannot be installed and they phase out at a rate that is approximately inverse to their lifetimes. Such a policy will likely have to be imposed by the UK government.

Finally, the 'Extended' scenario introduces both market-based and regulatory policies to meet the stringent targets set for Scottish heat decarbonisation by 2030. In addition to the subsidies and regulations, it includes a government procurement program, through which the Scottish Government can encourage the take-up of low-carbon heating technologies via bulk procurement for installation into buildings. Lastly, in this scenario biomethane blending rates increase to 7.5% on a volume basis, a conservative projection compared to what is proposed in scenarios for the Energy Networks Association (Navigant 2019).

It should be noted that the first two scenarios *do not* meet current Scottish Government targets – they are instead exploratory scenarios to evaluate the potential impact of policy measures. The key focus of the analysis, therefore, is on the Combined scenario and its potential impacts.

Table B.1 summarises the policies introduced in the different scenarios.

Table B.1: Policies introduced into the different scenarios

Scenario \ Policy	Regulations	Subsidies	Procurement program	Biomethane blending[6]
Reference scenario	Limited additional communal heating and gas grid extension	No subsidies	No procurement program	At a constant 1.5% of the gas supply
Subsidy scenario	As reference	75% subsidies on the upfront costs of renewable heating	No procurement program	At a constant 1.5% of the gas supply
Regulation scenarios	As reference + Complete phase-out of fossil fuelled boiler sales	No subsidies	No procurement program	At a constant 1.5% of the gas supply
Extended scenario	As reference + Complete phase-out of fossil fuelled boiler sales	75% subsidies on the upfront costs of renewable heating	Flats: procurement program to increase electric heating[7] and air-to-air heat pumps. Houses & non-domestic buildings: procurement program to increase heat pumps.	Grows to 7.5% of the gas supply in 2030

B.2 Modelled technology pathways

To model the technology pathways under different conditions, we evaluated historical uptake of heating technologies, as this is the point of departure for the scenarios. In our analysis, we constructed historical data on useful heat generation (final energy use for heat purposes minus efficiency losses) for the period between 2005 and 2018 for domestic flats, domestic houses, and non-domestic buildings. Over this period, Scottish homes were predominantly heated by burning natural gas, while about half of the non-domestic buildings utilise electric heating (see Figure 2.1).

[6] Hydrogen blending was not taken into account in this study due to lack of data.

[7] In practice, flats will have a greater choice of low carbon heating options, in particular district and communal heating. However due to the nature of the modelling approach, they are not represented here.

Heat projections for domestic buildings

We developed projections of useful heat demand. A sizeable proportion of flats and houses are rated EPC band C or lower (57.3% of all dwellings, Scottish Housing Condition Survey (2019)). The Scottish Government is aiming to bring all homes up to EPC band C by 2033. However, at the time this analysis was carried out, the expected target was for all homes to be EPC band C by 2035, and it is this slower rollout of energy efficiency that is included in this analysis. Therefore, three factors determine the demand for domestic heat:

- Increasing building efficiencies
- Changes in the number of households per local authority
- A split between flats and houses between local authority

Heat demand for non-domestic buildings

To project future heat demand, gross value added (GVA) projections by local authority were used as an estimate for the number of non-domestic buildings (GVA projections were modelled by Cambridge Econometrics and includes estimated COVID-19 impacts[8]). About 86% of the non-domestic buildings were rated EPC band D or worse (The Scottish Government 2018), leaving plenty of room for improvement. From the historical non-domestic energy demand and estimates on heating technology efficiencies, estimates for historical useful heat demand were obtained. By connecting the historical useful heat demand with the historical GVA, useful heat demand intensities (as a function of GVA) were obtained. Therefore, non-domestic heat demand projections depend on:

- GVA projections
- Energy efficiency improvements (i.e. energy intensity reductions), based on the 2010 to 2018 compound annual growth rate in non-domestic energy intensity (GWh/m£2016 GVA)

Simulation of future heat technology uptake

By applying the Future Technology Transformations for heat (FTT:Heat) methodology (see Appendix D), it is possible to look at the effects of different policy packages on the supply-side of heating. Technology substitution is cost-based, context-driven, region-dependent, and realistically constrained in this framework (Knobloch, Mercure and Pollitt, et al. 2017).

If no additional policies are introduced (Reference scenario), it is very likely that gas-based heating remains dominant for both domestic building types, while gas-based heating grows a bit at the expense of low-quality electric heating. This is mainly due to non-domestic GVA being projected to grow faster in gas-dominant regions, which therefore leads to more rapid heating demand growth in these areas and the continued domination of gas heating.

Emissions by heating technology

The technological composition of heating demand affects the emission profile of each building type (see Figure B.1). In the Reference case, a stagnant profile is found for flats. The increase in the number of flats is offset by an increase in building efficiency, but gas boilers remain

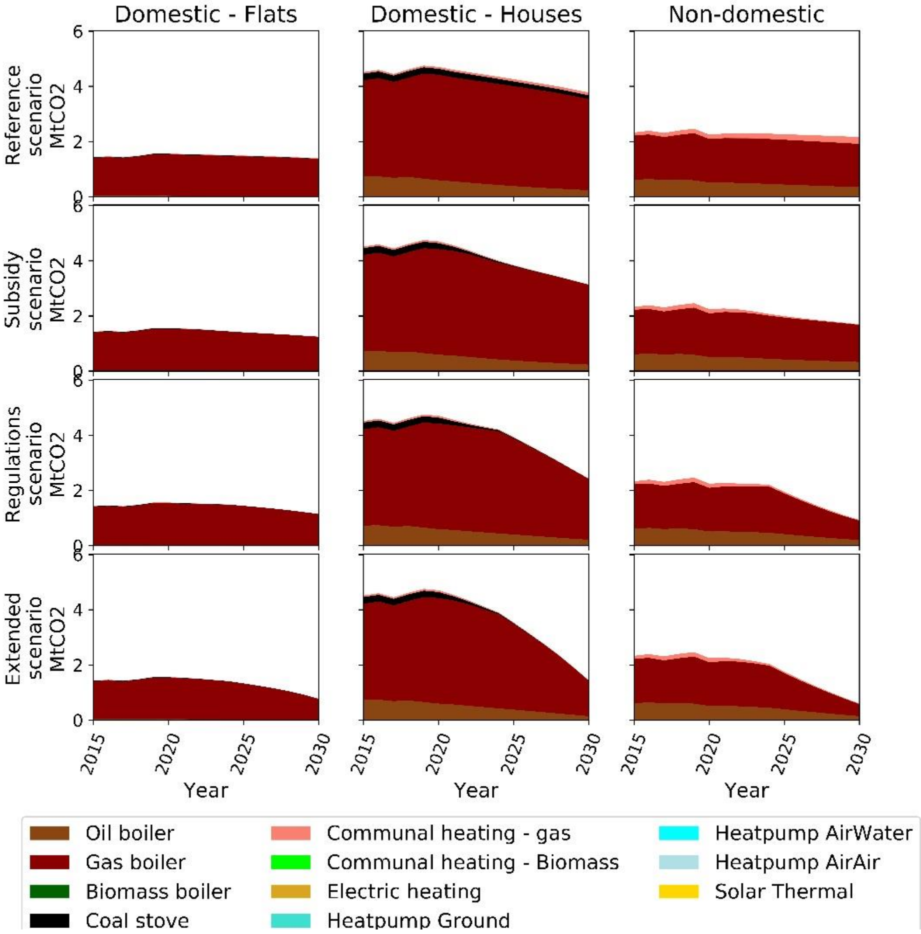
[8] See (Pollitt, et al. 2020).

dominant as little technology substitution takes place. In houses, a steady decrease in emissions is seen. This is due to increased efficiency and marginal substitution from gas boilers to renewable heating technologies. For non-domestic buildings a slight increase in emissions occurs, which is mainly driven by increasing GVA in some local authorities where fossil-fuelled heating is a slightly greater proportion of the technology mix, leading to a deployment of new fossil fuel-based heating at a greater rate than realised energy efficiency measures can fully counterbalance.

Decision-making in terms of investment in specific technologies responds to the policies enacted, and this is reflected in the emissions profiles. Houses and non-domestic buildings show some emission decreases in the subsidy and regulations scenario. Flats show a stagnant profile in both scenarios. We found major emission decreases under the Extended scenario for houses and non-domestic buildings due to replacement of gas boilers by heat pumps. Emissions from flats also decrease in this scenario, albeit at slower pace.

The emissions outcome is summarised in Table B.2 for each of the scenarios and building types.

Figure B.1: Emission profile by heating technology under the different scenarios



Note(s): Direct emissions only.

Table B.2: Numerical emission data by scenario and building type, and percent changes to the base year (=1990).

	1990	2018	2030	2030	2030	2030
Unit: $MtCO_2$	Base year	Last historical datapoint	Reference scenario	Subsidy scenario	Regulation scenario	Extended scenario
Flats	n.a.	4.42	3.77	3.14	2.43	1.43
Houses	n.a.	1.68	1.39	1.25	1.15	0.78
Domestic	8.0	6.1	5.16	4.5	4.74	2.21
Non-domestic	2.9	2.4	2.16	1.70	0.93	0.60
Total	10.9	8.5	7.32	6.2	5.67	2.81
Change compared to 1990 base year	**0%**	**-22.2%**	**-32.9%**	**-44.3%**	**-58.7%**	**-74.3%**

Expenditure on heating technologies

Beyond affecting the emission profile, the technological composition also affects expenditure on heating technologies. End of life replacement and premature scrapping can affect the expenditure profile (see Appendix D). Expenditure on heating technologies is based on installed heating capacity. For certain technologies more capacity is needed to provide Scottish buildings with enough space and water heat throughout the day and through the year. Due to the specific technologies within heat pumps, although they are more efficient than other heating technologies, the cost of the technology itself is higher than the cost of a gas boiler to meet an equivalent typical Scottish heat demand. As a result, the rate of heat pump uptake has a large effect on expenditure outcomes in the scenarios.

Appendix C FTT:Heat - Data input and treatment

C.1 Scope of FTT:Heat

The version of FTT:Heat used to analyse decarbonisation of the supply side of heating in Scottish buildings is largely based on FTT:Heat as developed by Dr. Knobloch and operated by Cambridge Econometrics (Knobloch, Mercure and Pollitt, et al. 2017). Whereas the standard model looks solely at domestic buildings, here a distinction was made between non-domestic buildings (combination of public and commercial buildings) and domestic buildings which were separated into flats and houses explicitly.

The spatiotemporal coverage is 32 local authorities that cover all of Scotland and it runs from 2018 (end of historical data, start of simulation) until 2030. FTT:Heat includes 11 heating technologies.

C.2 Data inputs and treatment

Techno-economic data

The supply-side of heat decarbonisation means substituting heating technologies for technologies that do not generate (direct) emissions. Substitution only occurs when consumers consider the alternative renewable technologies as a viable option. Among others, this depends on techno-economic data as represented in Table C.1. Decision-making to substitute technologies depends on upfront investment costs and operational costs, such as repair & maintenance (termed O&M in the table), fuel costs, and any policy cost or benefit if applicable. To capture gaps in the input data and get a measure for intangible costs, gamma values are estimated. These also cover unlisted limitations of technologies. The table below lists the technologies included in this analysis.

Historical energy use for heating

The “Scottish Energy Statistics Hub” (SESH) reports non-electrical heat demand for domestic and non-domestic buildings by fuel and local authority for the period 2005 to 2018 (Scottish Energy Statistics Hub 2020a). SESH draws the data from the “Sub-national total final energy consumption data” (Department for Business, Energy & Industrial Strategy 2018) and “Energy Consumption in the UK: end use” (Department for Business, Energy & Industrial Strategy 2020). The former reports electricity consumption by sector and by local authority for the period of 2005 to 2018. The latter reports end-use energy use by fuel and by sector for the years 2016 to 2019, but as a UK aggregate. These numbers are used to estimate the electrical demand for heating purposes. See Table C.2 for final energy demand in domestic buildings and Table C.3 for final energy demand in non-domestic buildings.

Through the ongoing Renewable Heat Incentive (RHI), installation of renewable heating technologies is supported. This data is tracked and reported on by SESH (Scottish Energy Statistics Hub 2020c). It also reports the number of accreditations per local authority which guides the regional allocation of renewable technologies (Scottish Energy Statistics Hub 2020b, Scottish Energy Statistics Hub 2020f).

Mapping energy to local technology composition

Finally, the non-electrical final energy demand, the electrical final energy demand, and the renewable heat generation need to be harmonised and mapped to specific heating technologies and local authorities. Some of the technologies included in the RHI use the same fuel as listed in the final energy demand figures (both electrical and non-electrical).

First, the regional final energy use was mapped to technologies. Second, the share of flats and houses connected to the grid, the number of accreditations, and the flats/houses composition of a region were used to allocate renewable technologies to local authorities (National Records of Scotland 2017). If the renewable technologies used the same energy carrier as technologies already filled based on the final energy use figures, then this amount was subtracted from those technologies.

Communal heating for non-domestic buildings was allocated based on the share of regional non-domestic GVA to the country total. A similar approach was followed for communal heating for the domestic buildings.

Table C.1: Cost components for each of the technologies included in this analysis.

Heating technologies	Investment	O&M	Fuel cost	Lifetime	Efficiency	Gamma value	Capacity factor	Emission factor	Payback threshold	Capacity factor
	€2015/kW	€/kW	€/kWh	years	%	-	MWh/ kW	gCO2/ kWh	years	MWh / kW
Oil boiler	595.61	23.82	0.08	20	0.8	0.01	2.17	266.76	4	2.17
Gas boiler	504.87	10.10	0.08	20	0.87	0.03	2.17	201.96	4	2.17
Biomass boiler	608.41	2.43	0.05	20	0.85	-0.02	2.17	0	4	2.17
Coal stove	287.34	5.75	0.06	20	0.7	0.08	2.17	353.88	4	2.17
Communal heating - gas	308.28	18.50	0.05	20	0.87	0	2.17	201.96	4	2.17
Communal heating - Biomass	308.28	18.50	0.05	20	0.85	0	2.17	0	4	2.17
Electric heating	605.27	0.63	0.21	20	1	-0.08	2.17	0	4	2.17
Heatpump Ground	1536.19	16.29	0.21	20	3.5	-0.02	2.17	0	4	2.17
Heatpump AirWater	837.50	17.45	0.21	20	2.5	-0.03	1.71	0	4	1.71
Heatpump AirAir	579.06	59.33	0.21	20	2.5	0.01	1.97	0	4	1.97
Solar Thermal	832.81	8.99	0.00	20	1	-0.01	0.65	0	4	0.65

Table C.2: Final energy use for heat in domestic buildings.

Domestic heat demand (GWh)			2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Scottish Energy Statistics Hub	Non-electric heat demand	Coal	607	547	626	663	664	693	684	654	626	535	539	536	522	505
		Manufactured fuels	370	354	322	385	293	331	299	297	337	300	287	285	305	308
		Petroleum products	4218	4499	3872	4116	4003	4534	3493	3478	3581	3171	3176	3170	3112	3122
		Gas	35329	34343	34469	33342	30730	30330	28959	28802	28073	27700	27315	27459	28352	28361
		Bioenergy & wastes	549	574	582	690	752	969	842	1071	1261	1198	1353	1454	1445	1579
		SESH Total heat	***41073***	***40316***	***39872***	***39196***	***36442***	***36857***	***34277***	***34301***	***33878***	***32903***	***32671***	***32903***	***33736***	***33876***
Estimates for combination of space and water heating		Bioenergy	549	574	582	690	752	969	842	1071	1261	1198	1353	1454	1445	1579
		Coal	976	901	949	1048	957	1023	983	950	963	835	826	820	827	813
		Electricity	2817	2754	2728	2632	2599	2585	2535	2491	2422	2447	2414	2307	2101	2094
		Gas	34460	33498	33622	32521	29974	29584	28246	28093	27383	27018	26644	26784	27694	27686
		Oil	4218	4499	3872	4116	4003	4534	3493	3478	3581	3171	3176	3170	3112	3122
		Total non-electrical	***40204***	***39471***	***39024***	***38376***	***35687***	***36111***	***33565***	***33593***	***33188***	***32222***	***31999***	***32228***	***33077***	***33200***
		Total	***43021***	***42226***	***41752***	***41008***	***38286***	***38696***	***36100***	***36084***	***35609***	***34669***	***34413***	***34535***	***35178***	***35295***

Table C.3: Final energy use for heat in non-domestic buildings.

Non-domestic heat demand (GWh)			2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Scottish Energy Statistics Hub	Non-electric heat demand	Coal	109	100	103	104	137	107	113	99	110	113	24	23	26	27
		Manufactured fuels	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Petroleum products	3418	3168	2993	2889	2836	2873	2948	2957	2909	2958	3111	3239	3265	3311
		Gas	12197	11651	11962	11468	9703	10885	9843	10565	10041	9316	8335	8100	8560	8555
		Bioenergy & wastes	226	194	207	225	507	665	579	630	975	1006	1683	1356	1444	1299
		SESH Total heat	***15949***	***15113***	***15264***	***14685***	***13183***	***14531***	***13484***	***14252***	***14035***	***13392***	***13153***	***12718***	***13295***	***13192***
Estimates for combination of space and water heating		Bioenergy	226	194	207	225	507	665	579	630	975	1006	1683	1356	1444	1299
		Coal	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Electricity	6314	6343	6257	6217	5908	6052	5883	5871	5924	5597	5402	5374	5457	5650
		Gas	11234	10732	11018	10563	8938	10026	9066	9731	9249	8580	7677	7461	7884	7880
		Oil	2387	2213	2090	2018	1981	2007	2059	2066	2032	2066	2173	2262	2281	2313
		Total non-electrical	***13848***	***13138***	***13315***	***12805***	***11425***	***12698***	***11705***	***12427***	***12256***	***11652***	***11533***	***11079***	***11609***	***11491***
		Total	***20162***	***19481***	***19572***	***19022***	***17333***	***18750***	***17588***	***18298***	***18180***	***17249***	***16936***	***16454***	***17066***	***17141***

C.3 Projections for useful energy demand

The demand-side perspective is important in the context of heat decarbonisation. Heat demand can be split in terms of heat required and the energy demand needed to generate that heat. The former is called useful energy demand (UD) while the latter is called final energy demand (FD) (Madureira 2014). The UD can then be further divided in heat required for hot water (UD_W) and heat required to elevate indoor space temperatures (UD_S).

Historical UD figures were obtained by scaling the FD (by technology) figures with estimates for efficiency as obtained via the process described in C.3 for each of the building types. Projections of UD for each building sector are discussed below.

Non-domestic demand

The historical UD values for non-domestic buildings were divided by the historical GVA timeseries for each local authority. This gives UD intensity (in units of GWh/£2019m). The UD intensity is then connected to GVA projections that include estimated effects due to the COVID-19 pandemic (Cambridge Econometrics produces these projections per local authority on an annual basis). Non-domestic buildings are assumed to decrease their UD intensity by a rate equal to the annual compound rate between 2010 and 2018 and this rate was continued into the projected time period to mimic efficiency gains (i.e. insulation improvements) of non-domestic buildings. Improved insulation is a heating demand-side solution which will contract the need to supply heat. Therefore, this is reflected in the UD projections.

Domestic demand

The regional historical FD (by technology) is scaled to UD through technological conversion efficiencies. The National Records of Scotland reports shares of flats and houses of the total number of dwellings for each local authority. This was combined with building archetypes developed by Element Energy for the Scottish Government from which the average UD for flats could be extracted. Combining the shares of dwelling types (flats and houses) with the dwelling specific UD, the total UD could be split into a UD specific for flats and a UD specific for houses.

Element Energy also reported on average UD by dwelling type in 2035 by assuming that all dwellings are upgraded to EPC band C. In combination with household projections per local authority and by assuming that the split between houses and flats remains constant, projections of UD for houses and flats per local authority up to 2030 were obtained.

This settles the heat demand side, which serves as a fixed input for each of the scenarios, to which FTT:Heat matches the supply side.

Appendix D FTT:Heat - Simulating the effect of policies

FTT:Heat approaches technological diffusion from a non-equilibrium, bottom-up simulation perspective. In the FTT philosophy, agents ground their technology decisions – in this case boiler types – on perceived costs but they do so with bounded rationality (i.e. imperfect knowledge, imperfect foresight, constrained access to information) while not discarding inertia, habits, and loyalty (McCollum, et al. 2017). This approach is significantly different from the economic philosophies used in most IAMs. Other models assume fully rational utility or profit maximising agents with perfect foresight and unbounded access to information.

While the economic philosophy behind the models employed by Cambridge Econometrics is different from the mainstream, there is use for them and the output is valued by policymakers. For example, FTT:Heat has roots in providing insights to European policymakers (Knobloch, Mercure and Pollitt, et al. 2017), and has subsequently been applied to decarbonisation scenarios on an East Asian (Knobloch, Chewpreecha, et al. 2019) and global scale (Knobloch, Pollitt, et al. 2018) as well. With adaption, FTT:Heat has provided scenario-based analysis for the decarbonisation of the Scottish heat supply.

An economic agent in FTT:Heat can choose to replace their heating technology when the existing one reaches their end of lifetime (EoL) or prematurely if an alternative heating technology meets a certain payback threshold.

D.1 End-of-Lifetime replacements

We will first turn to EoL replacements. The FTT methodology of estimating agent's decision-making was developed by Mercure (2012). The mathematical framework for FTT:Heat will be repeated here. First, the net present value (NPV) of the utility (providing heat) for each boiler type is estimated. See Eq.1.

Levelised cost of heat

$$NPV_{utility} = \sum_{0}^{\tau} \frac{P(t) \cdot V(t)}{(1+r)^t} \qquad \text{Eq.1}$$

Where: P is the unit price of useful heat (alternatively, the perceived value of utility); V is the requirement for heat (equal to 1 unit of useful heat provided); r is the discount rate; and τ is the lifetime of the technology.

$$NPV_{expenses} = \sum_{0}^{\tau} \frac{IC(t) + OM(t) + FC(t)}{(1+r)^t} \qquad \text{Eq.2}$$

Where: IC is the investment cost component; OM is the repair and maintenance cost component; and FC is the energy cost component.

Using the NPV estimates for expenses and utility, a break-even cost can be calculated. This is done by first dividing the NPV of the expenses by the NPV of the utility as depicted in Eq.3. If this ratio is set to equal 1, then the break-even point between discounted expenses and discounted utility can be estimated.

$$\frac{NPV_{expenses}}{NPV_{utility}} = \frac{\sum_{0}^{\tau} \frac{IC(t)+OM(t)+FC(t)}{(1+r)^t}}{\sum_{0}^{\tau} \frac{P(t)*V(t)}{(1+r)^t}} \qquad \text{Eq.3}$$

$$1 = \frac{\sum_{0}^{\tau} \frac{IC(t)+OM(t)+FC(t)}{(1+r)^t}}{\sum_{0}^{\tau} \frac{P(t)*V(t)}{(1+r)^t}} \qquad \text{Eq.4}$$

If we assume sales prices, P(t), remain constant over the lifetime of the technology, then this can be extracted from the summation.[9] While prices fluctuate over time, it is reasonable for consumers to assume constant prices due to imperfect market foresight. See Eq.5 (note that V(t) equals 1, as we are considering 1 unit). This price is also referred to as the levelised cost (LC), see Eq.6. The breakeven price is referred to as such throughout this document.

$$P = \frac{\sum_{0}^{\tau} \frac{IC(t)+OM(t)+FC(t)}{(1+r)^t}}{\sum_{0}^{\tau} \frac{1}{(1+r)^t}} \qquad \text{Eq.5}$$

$$LCOH^{base} = P \qquad \text{Eq.6}$$

Where: $LCOH^{base}$ is the levelised cost without calibration.

The $LCOH^{base}$ only covers real costs (e.g. investment costs, fuel costs, etc.) and no intangible 'costs'. Intangible costs can be anything from the perception that renewable heating technologies are unreliable to already having a connection to the gas grid which makes a gas-based option more attractive. They include habits and loyalty. In addition, gamma values also cover data gaps.

[9] $f(x) = \sum_{0}^{\tau} x$ is homogenous of degree 1.

$$LCOH^C = LCOH^{base} + \gamma = \frac{\sum_0^\tau \frac{IC(t)+OM(t)+FC(t)}{(1+r)^t}}{\sum_0^\tau \frac{1}{(1+r)^t}} + \gamma \qquad \text{Eq.7}$$

Where: $LCOH^c$ is the calibrated levelised cost; and γ is the gamma value to calibrate the levelised costs to match historical trends.

However, the levelised costs are not perfectly defined due to local variations (Mercure 2012). Moreover, investors and consumers may have different perceptions and valuation of future costs, i.e., consumers are heterogeneous in their behaviour and decision-making. For these reasons, the cost categories are assumed to be distributions, and therefore the LCOH will be distributed as well. Its standard deviation is then given by Eq.8

$$sdLCOH = \frac{\sum_0^\tau \frac{\sqrt{sdIC^2+sdOM^2+sdFC^2}}{(1+r)^t}}{\sum_0^\tau \frac{1}{(1+r)^t}} \qquad \text{Eq.8}$$

Where: sdLCOH is the standard deviation of LCOH, and sdxx is the standard deviation of the respective cost components. Note that this assumes that the covariance between the cost categories is zero.

The mean and standard deviation of the LCOH are calculated for every technology option and serve as inputs for the EoL decision making core. Technologies are compared on a pair-wise basis and the decision making is based on the construction of binary logits (see Eq.9 and Eq.10).

$$\boldsymbol{F_{i\to j} = \frac{1}{2} + \frac{1}{2} erf\left(\frac{LCOH_j - LCOH_i}{sdF_{ij}}\right)} \qquad \text{Eq.9}$$

$$F_{j\to i} = 1 - F_{i\to j} \qquad \text{Eq.10}$$

Where: F represents EoL replacement preferences; erf() indicates the error response function; LCOH indicates the mean of the levelised cost; and sdF_{ij} indicates the standard deviation of preference, which is a function of the standard deviation of the LCOHs of both technologies (see Eq.11 below).

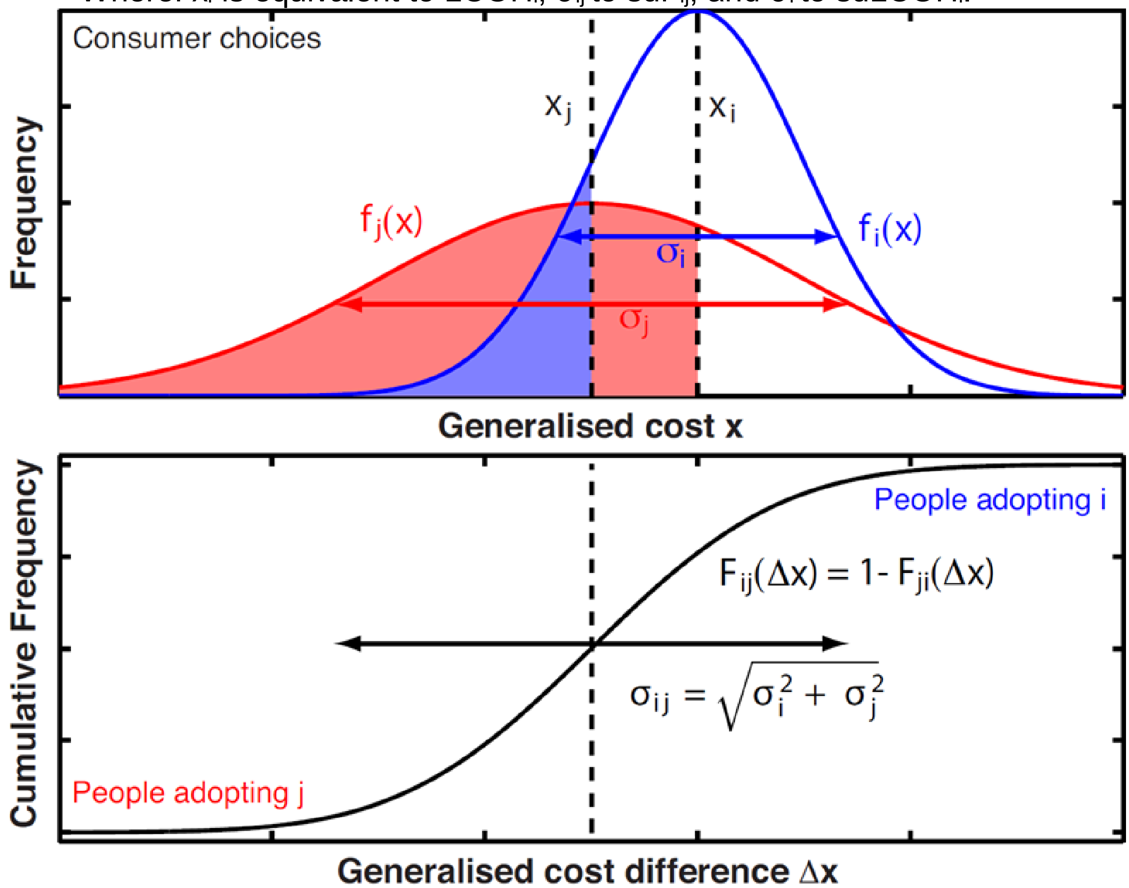
$$sdF_{ij} = \sqrt{sdLCOH_i^{\,2} + sdLCOH_j^{\,2}} \qquad \text{Eq.11}$$

Eq.12 and Eq.13 below are equivalent to Eq.9 and Eq.10; they are rewritten to align with variable notation used in Figure A.1.

$$F_{i \to j} = \frac{1}{2} + \frac{1}{2} erf\left(\frac{x_j - x_i}{\sigma_{ij}}\right) \qquad \text{Eq.12}$$

$$\sigma_{ij} = \sqrt{\sigma_i{}^2 + \sigma_j{}^2} \qquad \text{Eq.13}$$

Where: x_i is equivalent to $LCOH_i$; σ_{ij} to sdF_{ij}; and σ_i to $sdLCOH_i$.



Notes: Illustration of consumer preferences when presented with two choices. Top panel shows the LCOH distributions of two technology options (i and j, with their respective mean, x, and standard distribution, σ). Bottom panel illustrates the binary logit as a function of the cost differences. The width of the binary logit is determined by the standard deviation of the preferences (σ_{ij}). Courtesy to Jean-Francois Mercure and Florian Knobloch.

Figure D.1: Illustration of consumer preferences when presented with two choices.

An illustration of different cost distributions of technologies and how this leads to the construction of a binary logit is illustrated in Figure D.1. The top panel shows the mean and standard deviation of two technology types. The bulk of the consumers will perceive that technology j is cheaper than technology i. Yet, for some the perceptions or local conditions may be such that technology j is (or is perceived as) more expensive than i.

D.2 Premature replacements

Now, we turn our attention to consumer preferences to prematurely replace the existing heating technology. This is estimated by comparing the marginal cost (MC) of the existing technology to the “total pay-back cost” (TPB) of an alternative technology. The MC of each heating technology is calculated as depicted in Eq.14 and the standard deviation in Eq.15.

Marginal costs of heat

$$\boldsymbol{MC(t) = OM(t) + FC(t) + FiT(t) + \gamma} \qquad \text{Eq.14}$$

$$sdMC(t) = \sqrt{sdOM(t)^2 \cdot FC(t)^2} \qquad \text{Eq.15}$$

When the difference of the marginal costs between the existing and an alternative technology over the whole pay-back threshold is greater than the investment of the alternative technology, then the consumer may choose to prematurely replace its existing technology. This is depicted in Eq.16.

$$\boldsymbol{\sum_{t=0}^{pb} \left(MC_j - MC_i\right) > IC_i(t)} \qquad \text{Eq.16}$$

Where: pb is the pay-back threshold.

The consumer will likely assume that the marginal costs for both technologies will remain constant over the pay-back threshold. In that case we can rewrite Eq.15 to Eq.16 which provides an estimate for the total pay-back costs (TPB).

$$MC_j > MC_i + \frac{IC_i(t)}{pb} = TPB_i \qquad \text{Eq.17}$$

The standard deviation associated with TPB is given in Eq.18.

$$sdTPB(t) = \sqrt{sdOM(t)^2 \cdot sdFC(t)^2 + \frac{sdIC^2}{pb^2} + \left(\frac{IC^2}{pb^4}\right) \cdot sdpb^4} \qquad \text{Eq.18}$$

Premature replacement preferences are calculated in a similar way to the EoL replacement preferences. See Eq.19 and Eq.20. A binary logit is constructed based on pair-wise comparisons of marginal costs and total pay-back costs. Unlike the EoL replacement preferences, the premature replacement preferences of consumers adopting technology i and the premature replacement preferences of consumers adopting j do not have to add up to 1. The calculation allows for no premature replacements to occur at all as it is possible that the marginal costs of the existing technology is lower than the total pay-back costs of all the alternatives.

$$FE_{i\to j} = erf\left(\frac{MC_j - TPB_i}{sdFE_{ij}}\right) \qquad \text{Eq.19}$$

$$FE_{j\to i} = erf\left(\frac{MC_i - TPB_j}{sdFE_{ji}}\right) \qquad \text{Eq.20}$$

The standard deviations used in the equations above are depicted in Eq.21 and Eq.22.

$$sdFE_{ij} = \sqrt{sdTPB_i{}^2 + sdMC_j{}^2} \qquad \text{Eq.21}$$

$$sdFE_{ji} = \sqrt{sdMC_i{}^2 + sdTPB_j{}^2} \qquad \text{Eq.22}$$

D.3 Market share dynamics

Based on these consumer preferences (both EoL and premature), market share changes can be estimated. While market share changes are informed by preferences, they are not the only deciding factor. The uptake of new technologies is constrained by the production capacity of such technologies. Furthermore, new technologies may only come in when existing technologies need to be replaced, either at the end-of-lifetime or prematurely. The market share dynamics should also portray the fact that (especially) consumer choices are influenced by behavioural patterns, besides the economic considerations (Grubb, Hourcade and Neuhoff 2014, Knobloch and Mercure 2016). One part of this comes through in the standard deviations associated with preferences, and another part comes through by taking into account the existing stock of each technology.

To estimate market share changes an adapted version of the Lotka-Volterra equation will be used. The Lotka-Volterra equation is more commonly known as the “predator-prey” equation in the field of ecology, where it originally stems from (Volterra 1926, Lotka 1920).

For market shares to move from technology j to technology i, it is deemed to be proportional to: pre-existing market shares of both technologies; how fast technology i can be built; by what rate technology j is decommissioned; and the preference for i over j. This is shown in Eq.23. The opposite is also true, see Eq.24.

$$\Delta S_{j \to i} \propto \frac{S_i}{BT_i} \cdot \frac{S_j}{LT_j} \cdot F_{ij} \qquad \text{Eq.23}$$

$$\Delta S_{i \to j} \propto \frac{S_j}{BT_j} \cdot \frac{S_i}{LT_i} \cdot F_{ji} \qquad \text{Eq.24}$$

Where: S is the market share of a technology; BT is the build-time; LT is the lifetime; and F is the preference.

By combing both equations above, the net market share change from technology j to i (which may be negative) can be estimated. This is expressed in Eq.25 and Eq.26.

$$\sum_j \Delta S_{j \to i} = \Delta S_i = \sum_j S_i S_j \cdot \left(F_{ij} A_{ij} - F_{ji} A_{ji}\right) \cdot \Delta t \qquad \text{Eq.25}$$

$$\Delta S_{i \to j} = -\Delta S_{j \to i} \qquad \text{Eq.26}$$

Where: A_{ij} is the substitution rate by which technology i can substitute technology j, given by Eq.27.

$$A_{ij} = \frac{\kappa}{BT_i \cdot LT_j} \qquad \text{Eq.27}$$

Where: κ is a time constant.

Similarly, for estimating premature market share changes depend on the MC and TPB driven consumer preferences (FE), the pre-existing market shares and the scrappage rate (SR). This is depicted in Eq.28 and Eq.29.

$$\sum_j \Delta SE_{j \to i} = \Delta SE_i = \sum_j S_i S_j \cdot \left(FE_{ij} SR_{ij} - FE_{ji} SR_{ji}\right) \qquad \text{Eq.28}$$

$$\Delta SE_{i\to j} = -\Delta SE_{j\to i} \qquad \text{Eq.29}$$

Where: SR_{ij} is the scrappage rate by which technology i can prematurely substitute technology j and is given by Eq.30. It is the inverse of the pay-back period minus the EoL replacement rate to make sure to exclude EoL replacements from the premature replacements dynamics.

$$SR_{ij} = \frac{1}{pb} - A_{ij} \qquad \text{Eq.30}$$

Where: pb is the pay-back period.

D.4 Simulating the effect of policies

Policies may change the rate of technology uptake through a variety of ways. In this analysis, subsidies are used to amplify the attractiveness of renewable heating technologies. They do so by lowering the investment cost component which lowers the LCOH and MC and therefore amplify the preferences to substitute towards the subsidised technologies.

Phase-out regulations on high carbon heating technologies will change the investor preferences. If a full phase-out is simulated, then the preferences for substituting towards these technologies is set to zero.

Biomethane blending will lower the emission intensity of gas boilers as a proportion of the gas burned displaces fossil fuel gas. It is assumed that the production of biomethane takes up as much carbon dioxide as is released during combustion.

Government procurement or kick-start programs are modelled as exogenous market share changes which may affect market shares at any given time in combination with EoL and premature market share changes.

Technological limitations & assumptions

Not all heating technologies are suitable for every building. For example, residents of flats face a space constraint and therefore it is unlikely that technologies such as solar thermal or individual heat pumps can be installed to supply those dwellings with renewable heat. To prevent the model from simulating an erroneous uptake of particular technologies for particular building types, constraints have been put in place. These constraints apply to all scenarios.

In this analysis it was further assumed that communal heating does not increase in market shares as it is not a consumer decision but rather a centralised decision. Gas grids were also assumed not to be expanded anymore. This was reflected in the model by setting maximum market shares for gas boilers in each local authority and in each building domain (non-domestic, domestic flats, and domestic houses).

To mimic learning-by-doing by global uptake of heating technologies, an exogenous decrease of investment costs was implemented. This decrease was informed by a baseline scenario of the global E3ME-FTT model, operated by Cambridge Econometrics.

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