



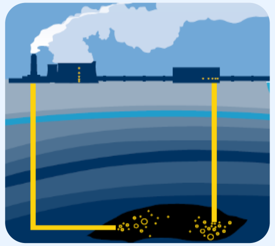



Low Carbon Heat Study – Phase 1

The Kensa Group

25th May 2023

elementenergy
an ERM Group company

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The following acronyms are used throughout this report

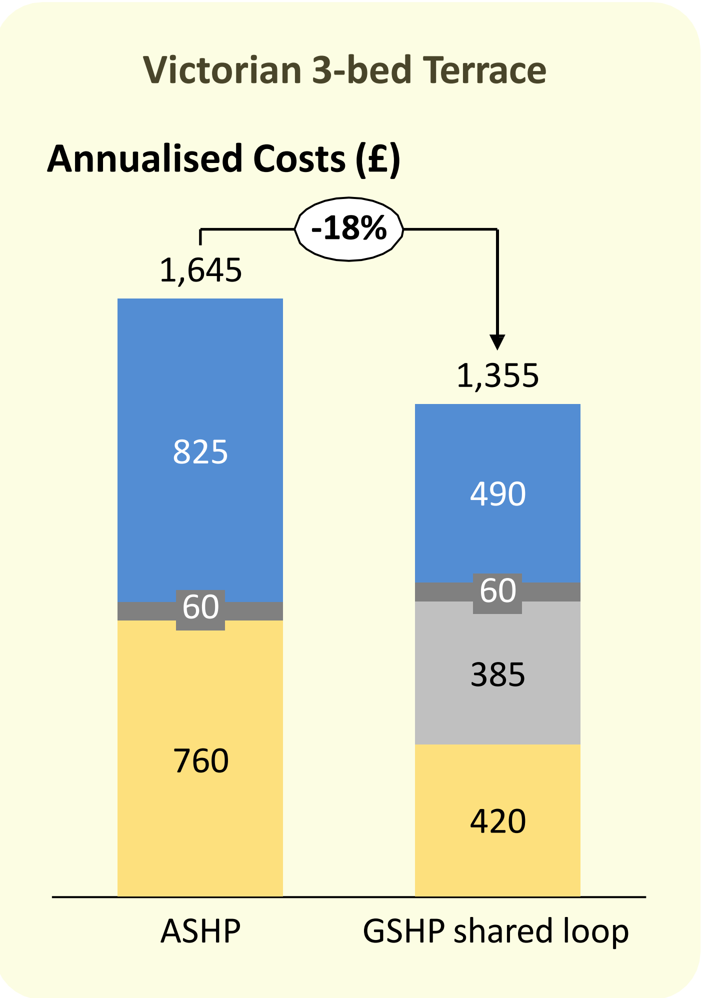
Acronyms

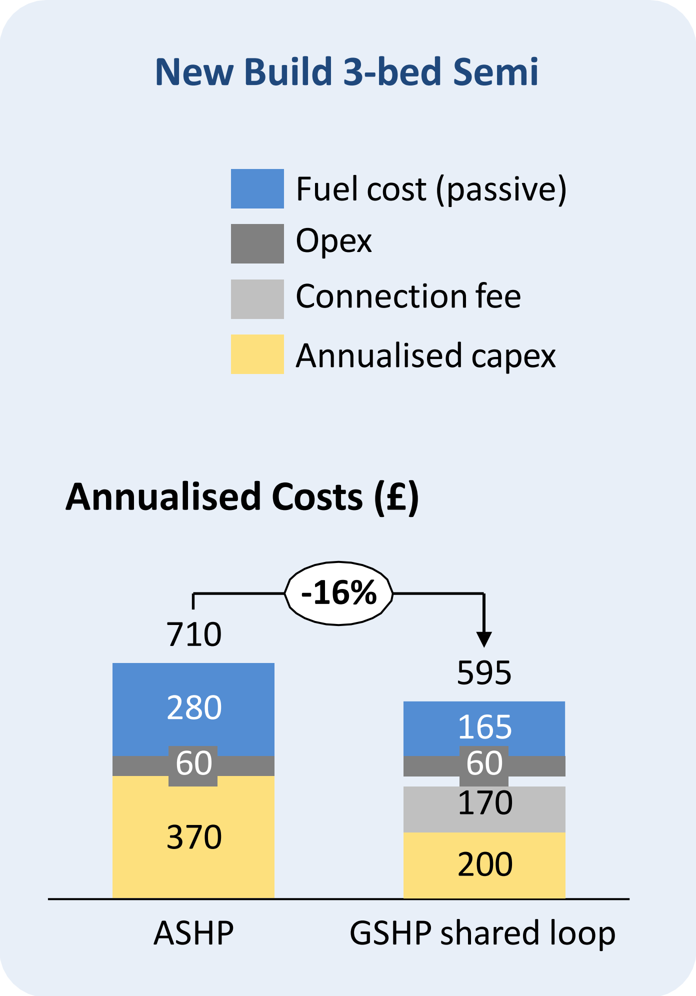
AHSP	Air source heat pump
BEIS	Department for Business, Energy and Industrial Strategy
COP	Coefficient of performance
GSHP	Ground source heat pump
IRR	Internal rate of return
RES	Renewable energy sources
SAP	Standard Assessment Procedure

GSHP shared loop systems have annualised costs in the region of 15%-20% lower than ASHP systems

Single Page Summary

- The **annualised costs for GSHP shared loop systems are up to £290 per year (18%) lower than for ASHP** systems for the retrofitted property. The new build offers annualised savings of £115 per year (16%).
- Annual fuel costs are around are around 40% lower for the GSHP shared loop system than an ASHP system in a typical year, increasing to 45% in a 1-in-20 cold year.
- The **combined annual fuel costs and connection fee** (based on 2020 capex) **for GSHP shared loop systems are generally around £50 more than ASHP** systems
- When instead **using the 2030 capex costs to calculate the connection fee**, **most scenarios** have **lower combined annual fuel costs and connection fee for the GSHP shared loop systems than ASHP systems.**
- **Thermal mass flexibility** offers similar percentage reductions in fuel costs across the technologies studied, which translates to **greater fuel cost savings for the ASHP systems due to the higher initial costs**.
  - Cost reductions for the retrofit of £100-£150 are achievable in the GSHP shared loop system with thermal mass flexibility alone, reduced to £20-£50 for the new build.
- A **heat battery offers an alternative to thermal mass flexibility** to access low-cost hours of electricity.





This study aims to quantify the difference between ASHP and GSHP performance, running costs and total lifetime costs, considering the effects of British weather conditions and building types

Kensa have commissioned a study by Element Energy to undertake modelling to compare the upfront and running costs of air-source and ground-source heat pumps (with a shared ground loop). The modelling includes the impact of British weather conditions on heat pump performance and the opportunities afforded by time-of-use tariffs by shifting operation of the heat pump to different times of the day. The results will be used by Kensa to inform future decisions and provide an evidence base when interacting with other organisations.

- **Specific aims** of the project are to:
  1. *Quantify the impact of local weather conditions/ground conditions on hourly COPs for ASHPs/GSHPs including the impact of defrost cycles*
  2. *Quantify the impact of hourly COP variation on annual COP and fuel bills*
  3. *Quantify the value of flexibility afforded by heat pump technologies, including the effect of varying COPs, when consumers are willing to allow small deviations from preferred temperature and/or through the use of a heat battery*
  4. *Quantify the benefits of a shared ground loop system*
  5. *Explore the range of 'connection fees' – in the form of an annual charge to consumers for connection to shared ground loop infrastructure owned by an external party – which allow GSHPs with a shared ground loop to be cost effective when compared to individual ASHPs*

- The modelling of the ASHP system performance was based on published data from manufacturers and literature to model the impact of defrost cycles and local weather conditions on ASHP COP. Hourly weather data from the Met Office was then used to generate hourly COPs.
- The modelling of the GSHP systems was based on a shared ground loop model, which seeks to address the high installation costs associated with GSHP systems compared to ASHP systems by **removing the cost of the groundworks from the upfront cost to the consumer**.
  - The **groundworks are installed and managed by a separate entity from the householder** and the **householder pays a connection fee** to use the infrastructure, akin to the standing change included in gas and electricity bills.
  - The shared ground loop model can be made more commercially attractive through economies of scale: designing and installing large-scale ground infrastructure to serve many properties simultaneously.

The modelling in this study incorporated various sensitivities to take into account weather patterns, house types, householder behaviour, fuel cost variations and technology options

Project Scope

Technology	• Two technologies are compared: a single ASHP system and a GSHP with a shared ground loop.
Location	• Leeds was identified as representative of the UK average for temperature and humidity (also used in SAP). The nearest location that had suitable weather data (complete hourly data) was the nearby town Bingley.
Weather Years	• Based on average winter temperatures over the last 40 years, 2015 was identified as an average year. 2010 was identified as a 1-in-20 cold year and was used to model the impact of a cold winter.
Building Types	• A 3-bed Victorian terrace property was chosen to represent the average UK building, used to determine expected heat demand and heat loss rates. A new-build semi was also studied.
Heat Demand Profiles	• Demand profiles were modelled based on literature., which used smart meter data to model daily heat demand profiles whose shape and peak height depend on daily external temperatures.
Householder Types	• Two householder types were studied, with variations in tolerance to temperature fluctuations allowing preheating using the thermal mass of the home: 'comfort' tolerating ±0.5°C and 'economy' tolerating +2°C, -1°C.
Heat Battery	• A heat battery was also incorporated in some scenarios to study the impact of increased flexibility on household fuel bills.
Electricity Cost Projections	• Three electricity cost projection scenarios were studied, varying costs and the level to which they incentivise moving demand away from peak times.

Two heat pump systems were studied: an ASHP and a shared loop GSHP system

Modelling Heat Pump Performance

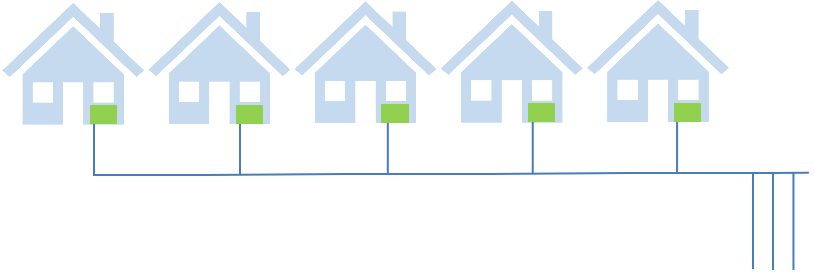
- Two heat pump systems were studied, as detailed below, with hourly COPs calculated based on hourly input data for temperature and, in the case of ASHPs, hourly humidity values.
- Hourly input data was taken from historic local weather data for the ASHP and ground temperatures from modelled GSHP system.

ASHP

- Modelled as a single-property ASHP system
- Weather dependant performance modelled based on real-world data for hourly temperature and humidity
- ASHP COPs based on published data by ASHP manufacturers, providing COPs at a range of temperatures
- A defrost penalty of 0.46 plus a humidity correction factor was applied to the COP relevant hours in the frost zone
  - This defrost penalty was calculated based on relevant literature and data published by ASHP manufacturers
- Details of the modelling are provided from slide 40.

GSHP Shared Loop

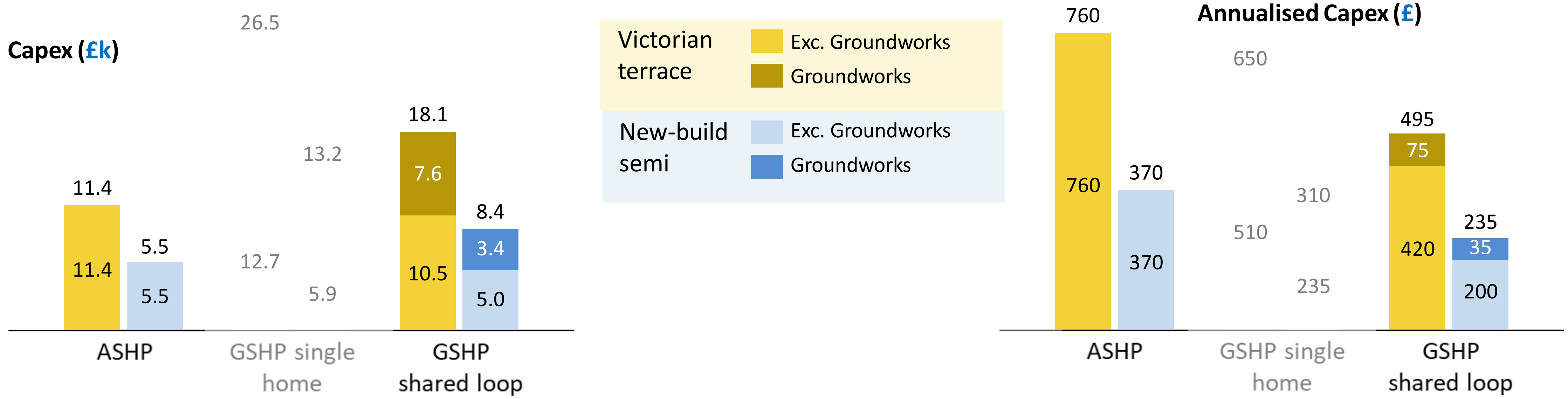
- GSHP were modelled as individual heat pumps in each property with a ground loop shared between multiple properties
- To study a connection fee model, the costs of the groundworks are separated from the cost of the and an annual connection fee used to pay for groundworks with a return on investment
- The performance was modelled by Genius Energy Labs using GLD software
- Details of the modelling are provided from slide 47.



In separating the cost of groundworks, the GSHP shared ground loop system means that upfront costs to consumers of a GSHP system are below that of an ASHP system

Comparison of Installation Costs

- The analysis in this study sought to compare the total costs to the consumer of each of the options studied, covering the upfront costs, fuel costs, and O&M/servicing costs over the technology lifetime.
- The costs for GSHP systems were provided by Kensa based on previous deployments.
- For the ASHP costs, the same costs as for the GSHPs were used for equivalent components (i.e. for the heat distribution system, hot water cylinder) with all other costs based on the "Cost of installing heating measures in domestic properties" by Delta-EE for BEIS.
- The total capex for a GSHP system in a single home is 130% higher than for ASHP
  - The difference between ASHP systems and GSHP system is reduced to 60% higher for the GSHP shared loop system
  - **Excluding the cost of ground works, the capex of the GSHP shared loop system becomes 10% lower than that of the ASHP system.**
- However, the longer lifetime of the GSHP system (25 years compared to 15, plus 100-year lifetime of groundworks) means that the **annualised cost of the GSHP shared loop** system is **around half that of the ASHP** system.



The connection fee required for the owner of the shared ground loop infrastructure to achieve a 4% IRR is in the region of £385 for the Victorian terrace and £170 for the new build semi in 2020

Connection Fee Calculations: Top Down

- To understand the expected connection fee, we have considered a range of IRR (internal rate of return) and economic lifetimes for the shared ground loop infrastructure investment.
- The connection fee depends heavily on the **initial capex invested** (shown in the difference between the retrofit and new build connection fees) and the **lifetime of the investment** (shown in the figures).
- For a **4% IRR** with a **40 year** investment lifetime using 2020 capex costs, the connection fee required is:
  - **Victorian terrace: £385**
  - **New build semi: £170**

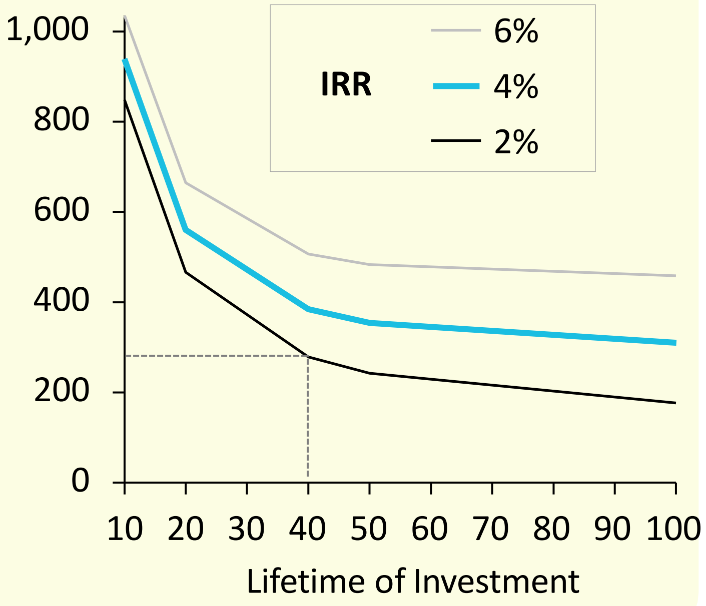
The above values are used as the connection fee later in the analysis.

- Using 2030 values for the capex, accounting for the expected cost reductions for the shared ground loop, the connection fees become:
  - Victorian terrace : £283
  - New build semi: £125

Victorian 3-bed Terrace

Based on shared ground loop capex of £7,620 per property in 2020

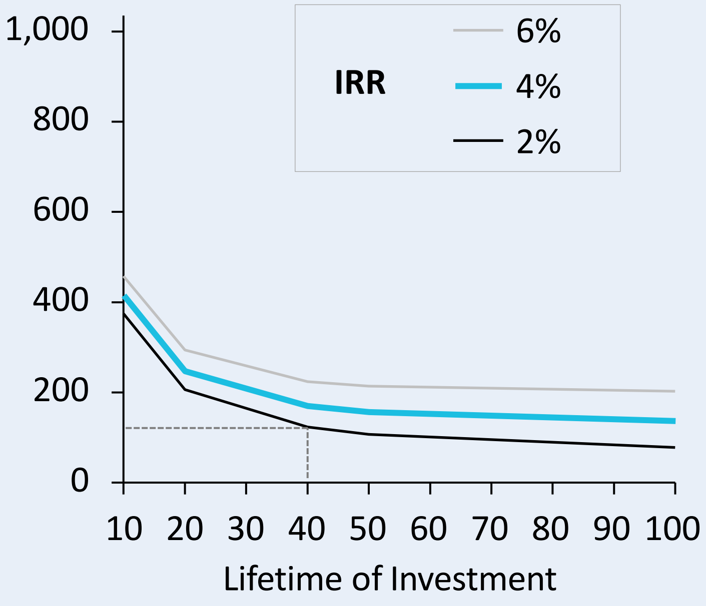
Annual Connection Fee



New Build 3-bed Semi

Based on shared ground loop capex of £3,370 per property in 2020

Annual Connection Fee

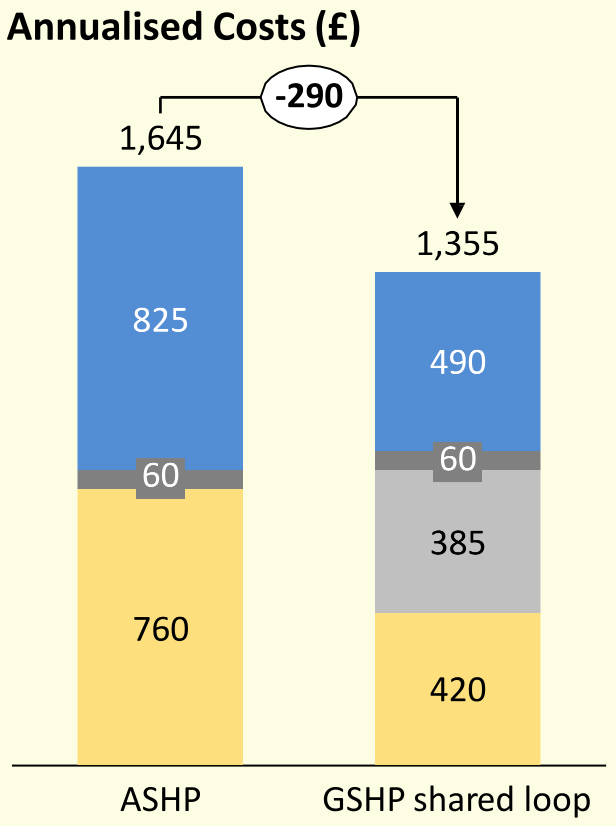


Compared to ASHP systems, the annualised cost for the GSHP shared loop system is around £290 lower for the retrofit and £115 lower for the new build home

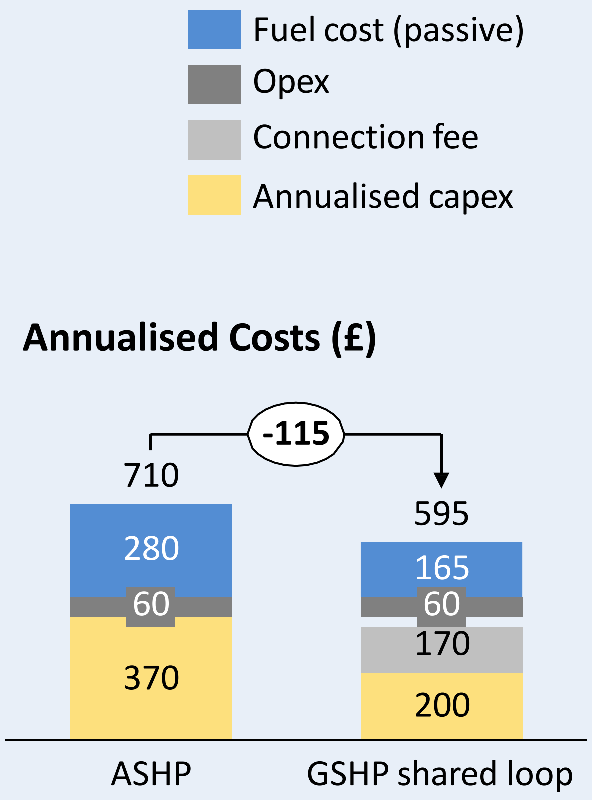
Total Annualised System Costs

- The figures right show the **annualised costs for capex, opex, fuel costs and connection fee**. All costs shown are for 2020 (i.e. 2020 capex values, and 2020 baseline electricity costs).[1]
- These figures show the base level costs before any space heating flexibility is applied:
  - Space heating is 'passive' in this scenario
  - Hot water is intrinsically flexible through using a hot water tank.
- For passive heating, the annual cost (combined fuel cost and connection fee) is around £50 more per year for the GSHP shared loop system than for the ASHP in the retrofit, £55 more the new build.
- Annualised capex costs for the householder (i.e. excluding groundworks) are £340 lower than ASHP costs for the retrofit and £170 lower for the new build.
- Combining fuel costs, connection fee and annualised capex, the **annualised costs for GSHP shared loop systems are up to £290 per year (18%) lower than for ASHP** systems for the retrofitted property. The new build offers annualised savings of £115 per year (16%).

Victorian 3-bed Terrace



New Build 3-bed Semi



1. Data from 2020 was used as the last year of complete data before this study began in 2021. Using 2020 data means the energy price volatility in 2021 and 2022 do not affect the results shown here.

Percentage fuel cost savings from thermal mass flexibility are similar for each technology such that ASHP systems show greater absolute cost reductions due to the larger passive fuel cost

Thermal Mass Flexibility

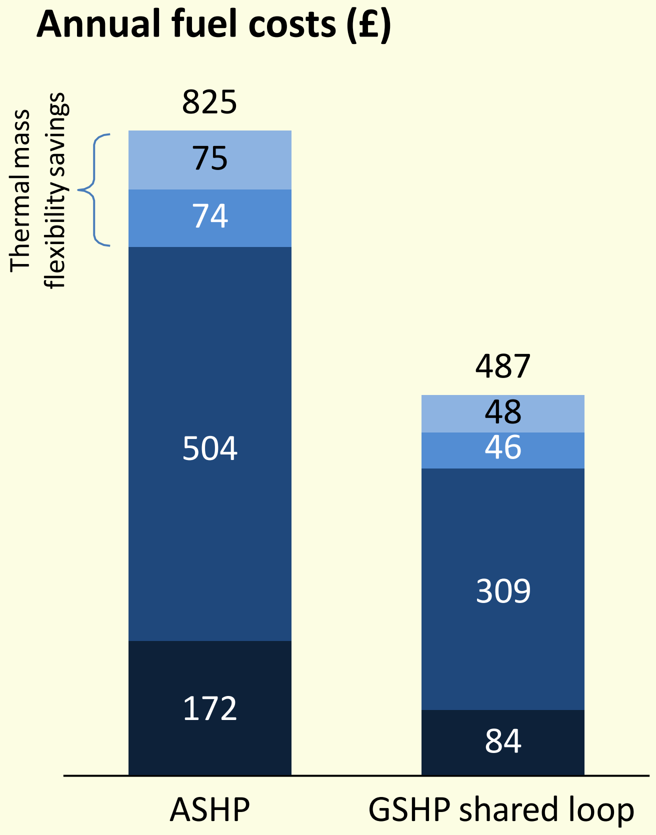
Fuel costs

- The figures shown here illustrate the difference in annual fuel costs between ASHP and GSHP systems plus the **potential savings from flexibility using the buildings' thermal mass.**
- The figures are for **2020 baseline electricity costs**. Baseline costs were taken from 2020 as this was the last year unaffected by fluctuating energy prices.

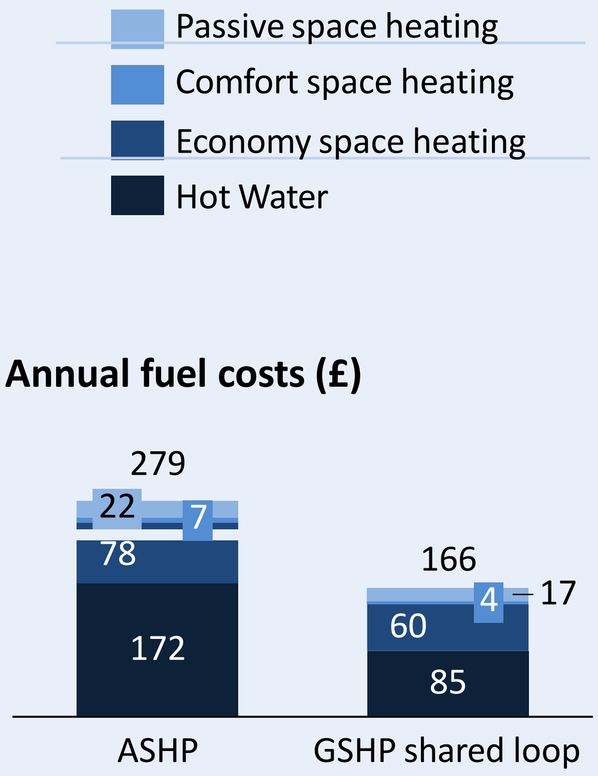
Thermal Mass Flexibility

- The percentage savings are relatively similar across the technologies
  - Therefore **ASHP systems see greater absolute savings** from flexibility.
- Flexibility from **Comfort householder type** offers fuel cost savings of
  - **£75** compared to passive operation for the ASHP **retrofit**, £48 for the GSHP systems (~10% for both technologies)
  - **£22** for the ASHP **new build, £17 for the GSHP**
- Compared to passive operation, **Economy householder type** offers fuel cost savings of
  - **£149** for the **ASHP retrofit**, **£94** for the **GSHP retrofits** (around 20% for both technologies)
  - **£29** for the **ASHP new** build, **£21** for the **GSHP new build** (10%-13% reductions)

Victorian 3-bed Terrace



New Build 3-bed Semi



For the retrofit property, all scenarios have fuel savings from GSHP shared loop systems relative to ASHP systems equal to or higher than the 2030 connection fee

Comparison: Fuel Cost Savings vs Connection Fee for GSHP shared loop

- The figure shows the **difference in fuel costs between ASHP and GSHP shared loop system**
  - If a GSHP shared loop system was to incur the same annual charges for the user, i.e. the connection fee was balanced by the fuel cost savings, the figure on the left would represent the maximum chargeable connection fee.
  - The values are shown for each of the three electricity cost projections.

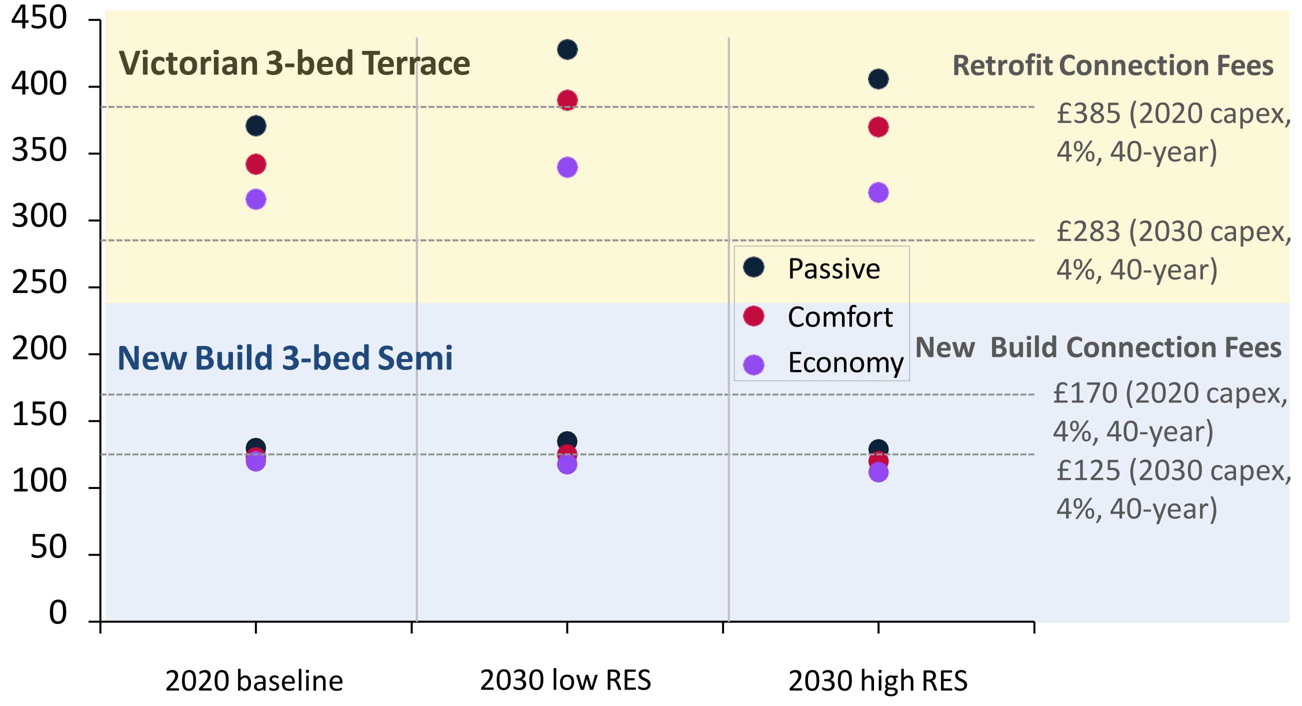
- ***Note that these comparisons are between the annual fuel cost savings and the connection fee only; the comparisons do not account for the lower annualised capex of the GSHP systems***.

- The difference in fuel costs between the systems are:
  - Retrofit: £320 - £440
  - New build: £110 - £135

- Flexibility measures bring the difference down to the lower end of those ranges, due the larger absolute reduction in ASHP fuel costs than GSHP fuel costs from flexibility.

- By 2030, for the retrofit property, all scenarios have lower combined annual fuel costs and connection fee for the GSHP shared loop system than for the ASHP system, with the new build properties being within £15.

Fuel cost savings between ASHP and GSHP systems (£/year)



In the cold year, fuel costs for the ASHP in the retrofit increase by £240-£270, compared to increases of £100-£110 for the GSHP

Comparing Weather Years

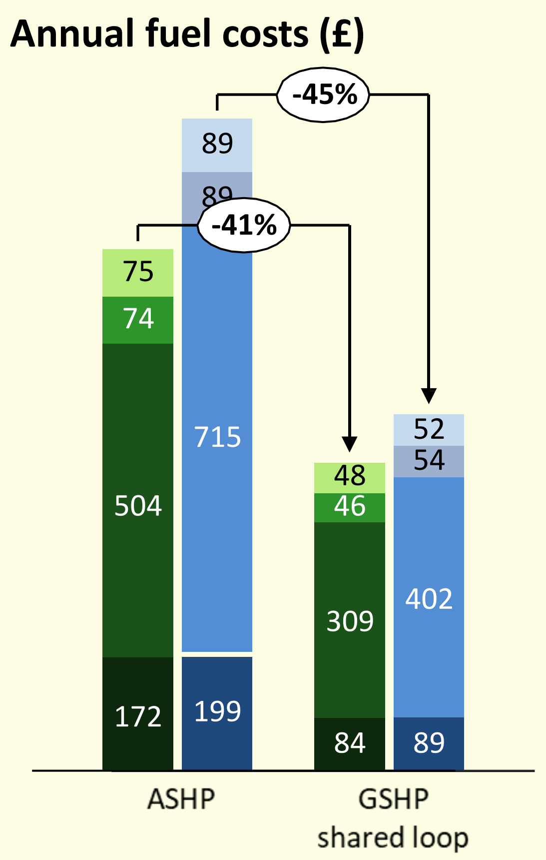
Weather years

- Two weather years were compared to understand the difference between ASHP and GSHP performance in a typical year (2015 in green) and a 1-in-20 cold year (2010 in blue).
- Demand for space heating increased by around 20% in the cold year compared to the average year, while demand for hot water increased by around 5%.

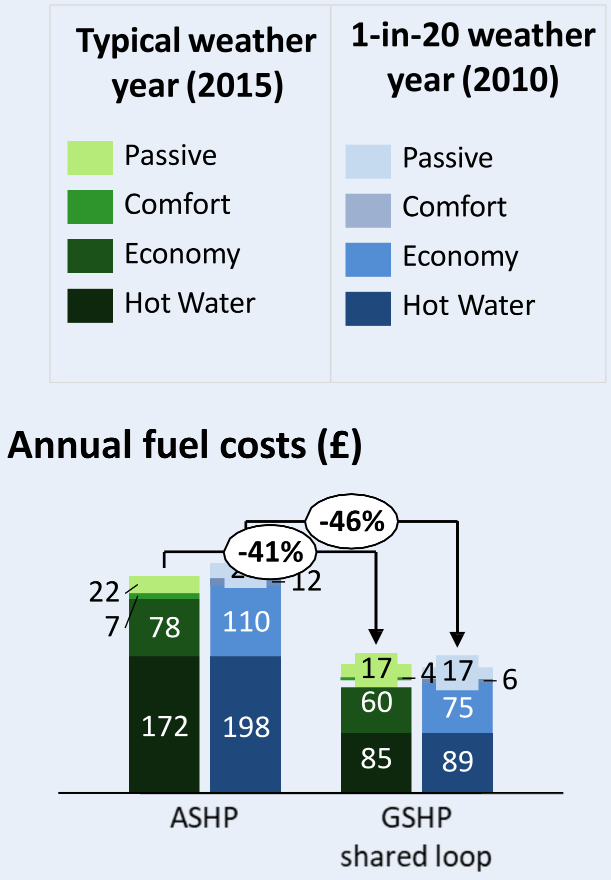
Comparing Fuel Costs

- The figures shown here **compare the fuel costs in the average year and the cold year, not including the connection fee.**
- Fuel cost savings for the GSHP relative to the ASHP increase from 41% in the average year to 45%/46% in the cold year.
- In the passive case, ASHP fuel costs increase by around £270 in the cold year, compared a £110 increase for the GSHP system for the retrofit (increases of £64 and £21 for ASHP and GSHP respectively in the new build).
- The impact of flexibility in 2010 is lower than in 2015 (in terms of %).
- The **fuel cost savings in the cold year** are £495 for the retrofit and £156 for the new build, **comparable to the £170 connection fee for the new build** and **far above the £385 connection fee for the retrofit**.

Victorian 3-bed Terrace



New Build 3-bed Semi



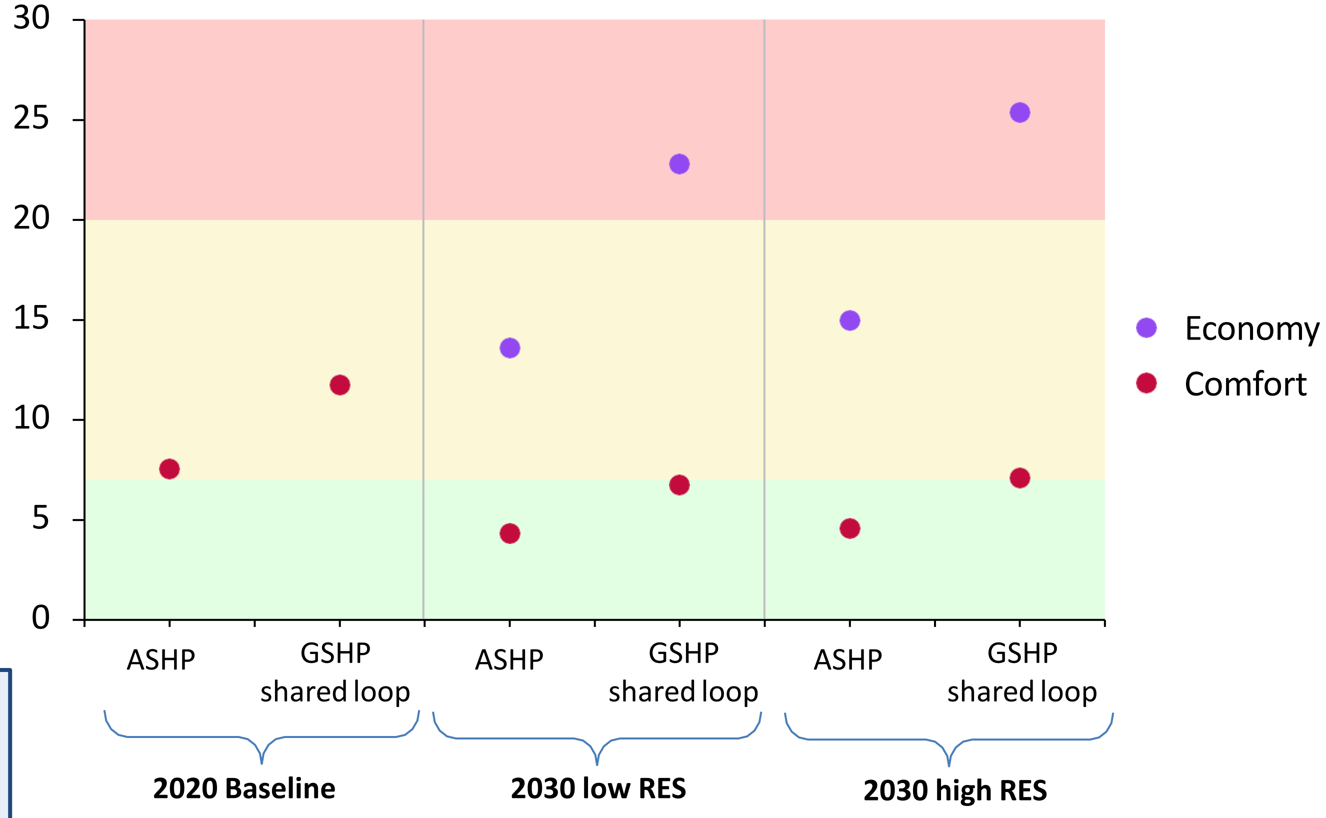
A heat battery makes greatest financial sense with the comfort household and only in the retrofit case, with payback times as low as 5 years

Incorporating a Heat Battery

- A heat battery allows increased access to low-cost electricity through time of use tariffs.
- The figure on the right shows the payback times for a heat battery. These calculations are based on the reduction in fuel costs from using a heat battery compared to thermal mass flexibility alone
  - Results are only shown for the retrofit using 2015 energy costs, as **no new-build scenarios have payback times below the 20-year** heat battery lifetime.
  - The economy results for the 2020 baseline electricity costs are also not shown as they are greater than 30 years
- The figure right has been coloured according to the following thresholds
  - The **green band** on the figure to the right highlights which scenarios have **payback times of 7 years or less**, most attractive to homeowners.
  - The **yellow band** on the figure highlights scenarios where the **payback is between 7 years and the lifetime of 20 years**.
  - The **red band** indicates payback times longer that the expected system lifetime.

- The figure right highlights how a **heat battery becomes a more attractive investment with the RES 2030 cost projections** and in the **comfort households**.
- Here, the **comfort household also represents other types of homes with lower hours of flexibility**, such as those with **higher heat loss** or **lower thermal mass.**

Payback times (years) for the Victorian Terrace 2015 scenarios



This study aims to quantify the difference between ASHP and GSHP performance, running costs and total lifetime costs, considering the effects of British weather conditions and building types

Kensa have commissioned a study by Element Energy to undertake modelling to compare the upfront and running costs of air-source and ground-source heat pumps (with a shared ground loop). The modelling includes the impact of British weather conditions on heat pump performance and the opportunities afforded by time-of-use tariffs by shifting operation of the heat pump to different times of the day. The results will be used by Kensa to inform future decisions and provide an evidence base when interacting with other organisations.

- **Specific aims** of the project are to:
  1. *Quantify the impact of local weather conditions/ground conditions on hourly COPs for ASHPs/GSHPs including the impact of defrost cycles*
  2. *Quantify the impact of hourly COP variation on annual COP and fuel bills*
  3. *Quantify the value of flexibility afforded by heat pump technologies, including the effect of varying COPs, when consumers are willing to allow small deviations from preferred temperature and/or through the use of a heat battery*
  4. *Quantify the benefits of a shared ground loop system*
  5. *Explore the range of 'connection fees' which allow GSHPs with a shared ground loop to be cost effective when compared to individual ASHPs*

- This report is the **Main report**, which summarises the methodology and outputs.
- Appendix sections are included at the end of this report with more detail on various aspects of the methodology.
- The outputs of the modelling will also be provided to Kensa in the form of an excel spreadsheet.

This report covers Phase 1, Household level analysis

Focus of this report

Phase 1: Household level analysis

Definition of house and householder types and associated heat demand → Definition of heating technology cost and performance → Development of dynamic electricity cost projections → Household level analysis

- Development of house and householder archetypes with associated heat demand and level of flexibility
- Detailed understanding of technology cost and performance under different weather conditions
- Development of hourly electricity cost profiles for three future energy scenarios
- Comparison of upfront and operational costs by technology type and archetype

Phase 2: National level analysis

Extension to national level analysis → Assessment of grid impacts → Funding options and support

- Phase two will extend the analysis to a national level
- Wider impacts including the impact on the electricity grid will be assessed
- An assessment of funding options and suitable government support will be included

Two heat pump systems were studied: an ASHP and a shared loop GSHP system

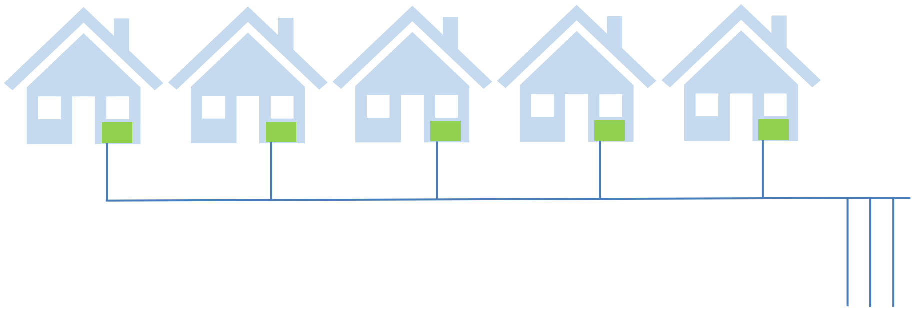
Technology Elements

ASHP

- Single-property ASHP system
- Performance modelled by Element Energy
- Real-world data used for hourly temperature and humidity
- ASHP COPs based on published data by ASHP manufacturers, providing COPs at a range of temperatures
- A defrost penalty was applied during relevant hours calculated based on relevant literature and data published by ASHP manufacturers
- Details of the modelling are provided from slide 40.

GSHP Shared Loop

- GSHP in individual properties with a ground loop shared between multiple properties
- The costs of the groundworks are separated from the cost of the household installation to study a connection fee model to pay for groundworks with a return on investment
- The performance was modelled by Genius Energy Labs using GLD software
- Details of the modelling are provided from slide 47.



The shared ground loop model separates the cost of groundworks from GSHP installation costs to reduce upfront costs to customers and take advantage of economies of scale

Shared Loop Model

- The shared ground loop model seeks to address the high installation costs associated with GSHP systems compared to ASHP systems by **removing the cost of the groundworks from the upfront cost to the consumer**.
- The **groundworks are installed and managed by a separate entity from the householder** and the **householder pays a connection fee** to use the infrastructure, akin to the standing change included in gas and electricity bills. This model removes the issue of higher initial investment for householders for GSHP systems.
- This model can be made commercially viable through economies of scale: designing and installing large-scale ground infrastructure to serve many properties simultaneously.
- **This study separates the costs to consumers from the cost of the groundworks** to study how the upfront and ongoing costs could be adapted to make high efficiency GSHP systems accessible to consumers. The considered costs to consumers are:
  - Upfront costs excluding groundworks
  - Fuel bills
  - Maintenance costs
  - Connection fee
- This consumer offering must be balanced with a **commercial offering that enables and encourages investment** in shared ground loop infrastructure. The commercial analysis considers:
  - Upfront cost of groundworks
  - IRR and investment lifetime.

The connection fee required for a 4% IRR is in the region of £400 for the Victorian terrace and £200 for the new build semi using 2020 values for the capex

Connection Fee: GSHP Shared Loop

- To understand the expected connection fee, we have considered a range of IRR (internal rate of return) and economic lifetimes for the shared ground loop infrastructure investment.

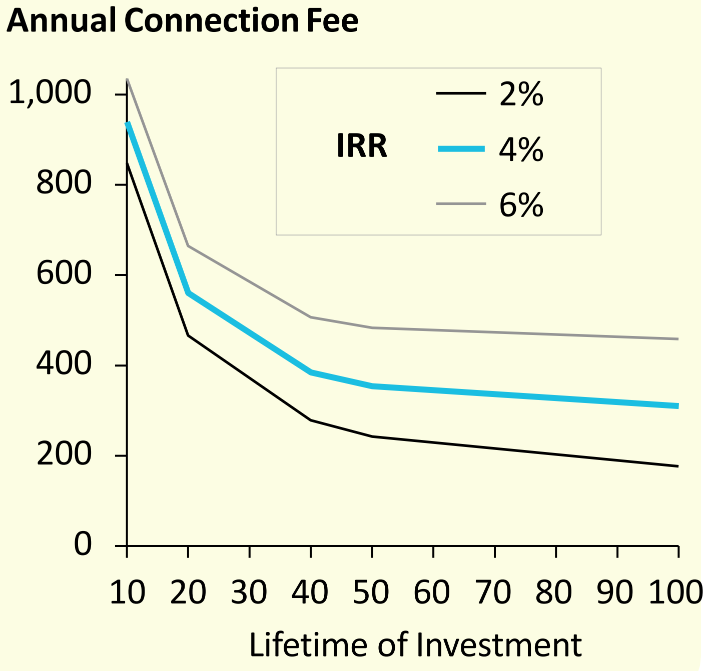
- For a **4% IRR** with a **40 year** investment lifetime using 2020 capex costs, the connection fee required is:
  - Victorian terrace: £385
  - New build semi: £170

The above values are used as the connection fee later in the analysis.

- Using 2030 values for the capex, accounting for the expected cost reductions for the shared ground loop, the connection fees become:
  - Victorian terrace : £283
  - New build semi: £125

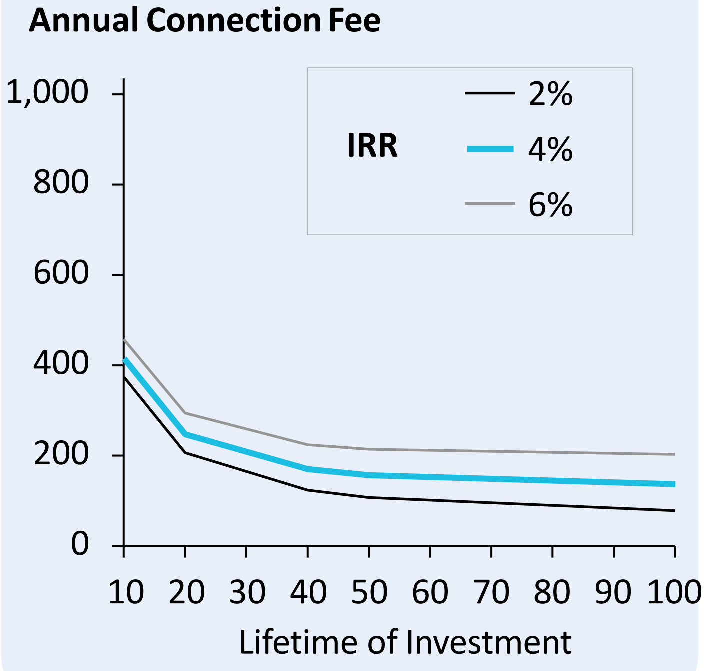
Victorian 3-bed Terrace

Based on groundwork capex of £7,620 per property in 2020



New Build 3-bed Semi

Based on groundworks capex of £3,370 per property in 2020



To model real-world system performance, hourly weather data was utilised: Leeds was chosen as an average UK location, 2015 was chosen as an average weather year and 2010 as a 1-in-20 cold year

For this study, weather data was used to model the performance of each of the heat pump systems in real-life weather conditions.

The modelling placed a number of requirements on the data that could be used:

- Weather data at hourly resolution was required
  - The Met Office provides data at various resolutions but few datasets are complete, this restricted the years and locations that could be chosen.
- The required metrics were air temperature and humidity, as these were needed to calculate the COP of the ASHP each hour.

Location

The decision on which location to use was based on two primary factors:

- Location representative of an average UK climate
- Location has complete weather data available for the chosen years.

Leeds was found to be close to the UK averages for temperature and humidity. Leeds is also used in the SAP framework to represent a UK average.

Weather data is not available for Leeds itself, the closest location with full hourly data is Bingley, a village to the north west of Leeds:

- **Weather data from the nearby town of Bingley** has been used to predict hourly heat demand and heat pump performance.

Year

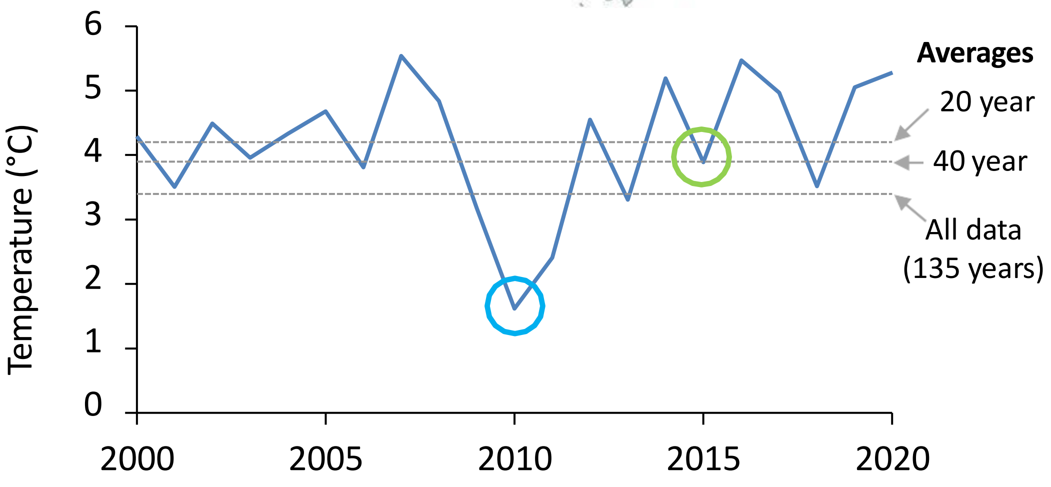
It was decided to study **two weather years, an average weather year and a year 1-in-20 extreme cold winter**.

The availability of complete hourly datasets meant that years would have to be chosen from no earlier than 2010.

Average winter temperatures were plotted for each year

- While 2013 and 2018 had average winter temperatures close to the UK average over the last 100 years, **2015 had an average closer to that of the last 40 years** and is therefore more likely to be representative of the coming 40 years
- **2010 represents a 1-in-20 year extreme cold** winter for the UK

Average UK Winter Temperature



Two property types were chosen for the analysis: a Victorian terrace representing an average UK retrofit, and a new-build semi-detached to study new developments

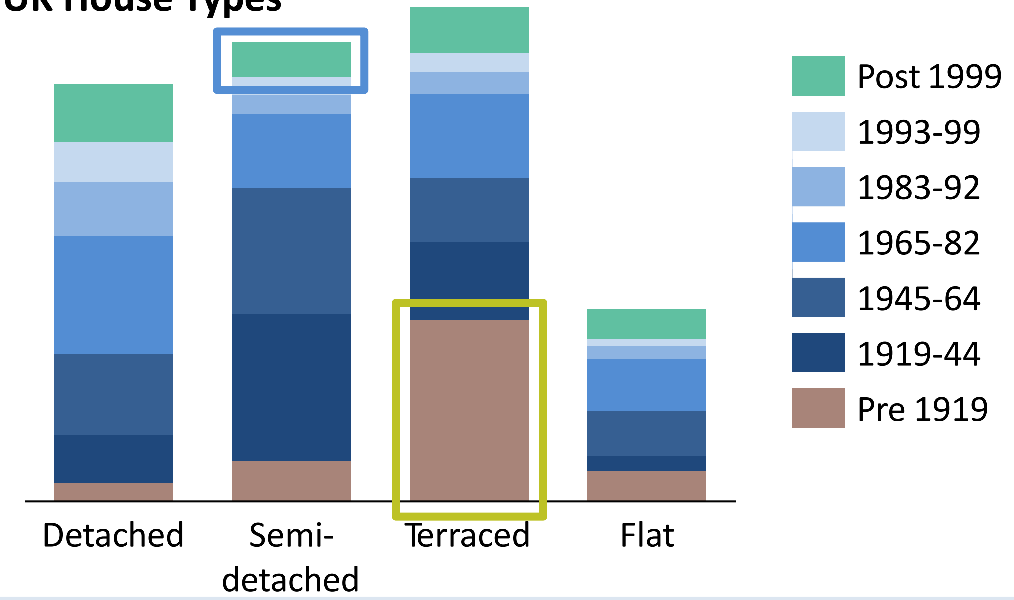
Overview

- Two property types were chosen to model as part of this study:
  - A **retrofit** property
  - A **new-build** property to understand the suitability of shared GSHP technologies for new developments
- To model both the impact of hourly COPs on overall heat pump performance and the opportunities for shifting demand, the hourly heat demands for each property were established.
- Across heat pump studies, modelling the shape of the demand profile has been a recurring issue with a chronic lack of data on how optimal heat pump operation differs from current user profiles with a gas boiler.
  - For this study, analysis carried out in Watson 2019 using gas demand profiles from smart meter data was used to estimate heat demand at half-hourly intervals for both space heating and hot water.

Building Types

- The two building types chosen for study were:
  - A **3-bed Victorian terrace representing an average UK home**
  - A **3-bed new build semi-detached home** representing a common new-build house type.
- Victorian Terrace
  - Terraced and semi detached houses are the two most **common housing types** in the UK
  - Pre-1919 terraced housing accounts for 12% of the UK housing stock
  - Older housing is considered **harder to decarbonise** due to difficulties in reducing the heat demand to very low levels.
- The choice of house type impacted the **heat demand** and the **heat loss rates**, which in turn impact the flexibility available. These are discussed further on the coming slides.

UK House Types[1]



1. NEED Energy Consumption Tables 2019 https://www.gov.uk/government/statistics/national-energy-efficiency-data-framework-need-consumption-data-tables-2021

Hourly gas demand profiles for space heating, hot water and cooking were generated based on the daily external air temperature using a methodology published in 2019 by Watson et. al.

Heat Demand Profiles

- The daily heat demand profiles were generated using profiles modelled by Watson et. al., published in 2019.[1] These profiles were based on smart meter data from gas heated homes.
- The Watson et. al. paper provides functions for calculating the gas demand for space heating and for hot water (separated) based on the external air temperature.
- A series of daily demand profiles were provided, the shape of which is also dependent on the external temperature, with colder days having higher, flatter demand profiles
  - This effect can be seen in the figure on the right which has higher daytime demand for the coldest winter day (blue) compared to an average winter day (green)
  - The demand profile methodology is illustrated on the next slide.
- Daily demand profiles for each property were generated by spreading the daily demand across the appropriate daily profile.

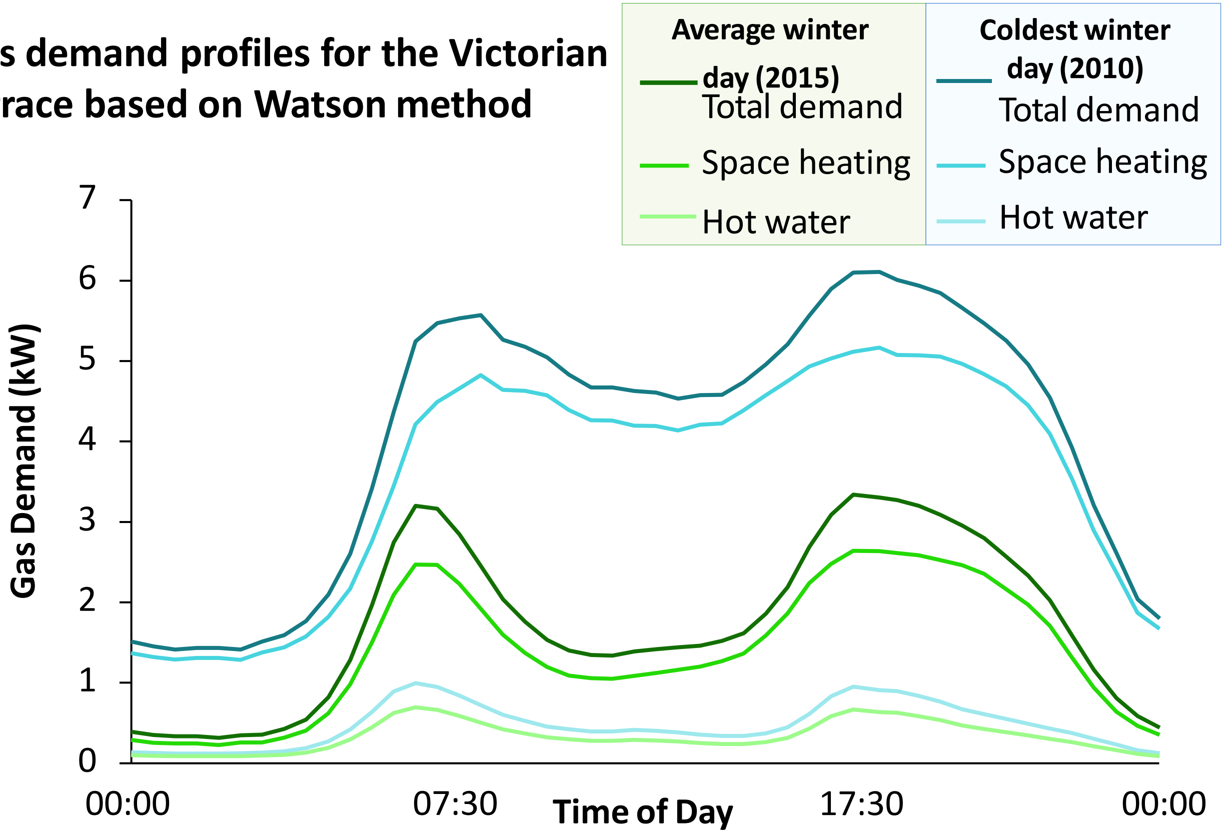
Victorian Terrace

- The Watson method was used to calculate the daily gas demands for space heating and hot water for the Victorian Terrace property in each of the weather years studies.
  - In 2015, the overall gas demand was 15.7 MWh per year, higher than the NEED mean values but within the range for the building type.
  - In 2010, the overall demand increased to 18.3 MWh/year, due to a large increase in demand for space heating and a small increase in hot water demand

New-Build Semi-Detached

- The space heating values calculated using the Watson method were calibrated down for the new build (hot water was assumed to remain the same) to 6.5 MWh per year, in line with the NEED UK lower quartile values for Post-2002, 3-bed, semi-detached homes.

Gas demand profiles for the Victorian terrace based on Watson method



Gas Demand (MWh/year)	Victorian Terrace		New-Build Semi-Detached	
	2015	2010	2015	2010
Space Heating	11.7	14.1	2.5	3.0
Hot water	3.7	3.8	3.7	3.8
Cooking	0.3			

1. Watson et. al. "Decarbonising domestic heating: What is the peak GB demand?" https://www.sciencedirect.com/science/article/pii/S0301421518307249 2019

The NEED database was used to understand the likely gas demand values for each of the property types

Heat Demand Values from NEED

The National Energy Efficiency Database (NEED) has measured gas demand values for UK homes, split by region, property type, property age and number of bedrooms. This database was used to estimate the gas demand for each of the property types.

- The figure right shows the **median heat demand** for various property types. Each bubble represents a region, with the size of bubble representing the number of properties.

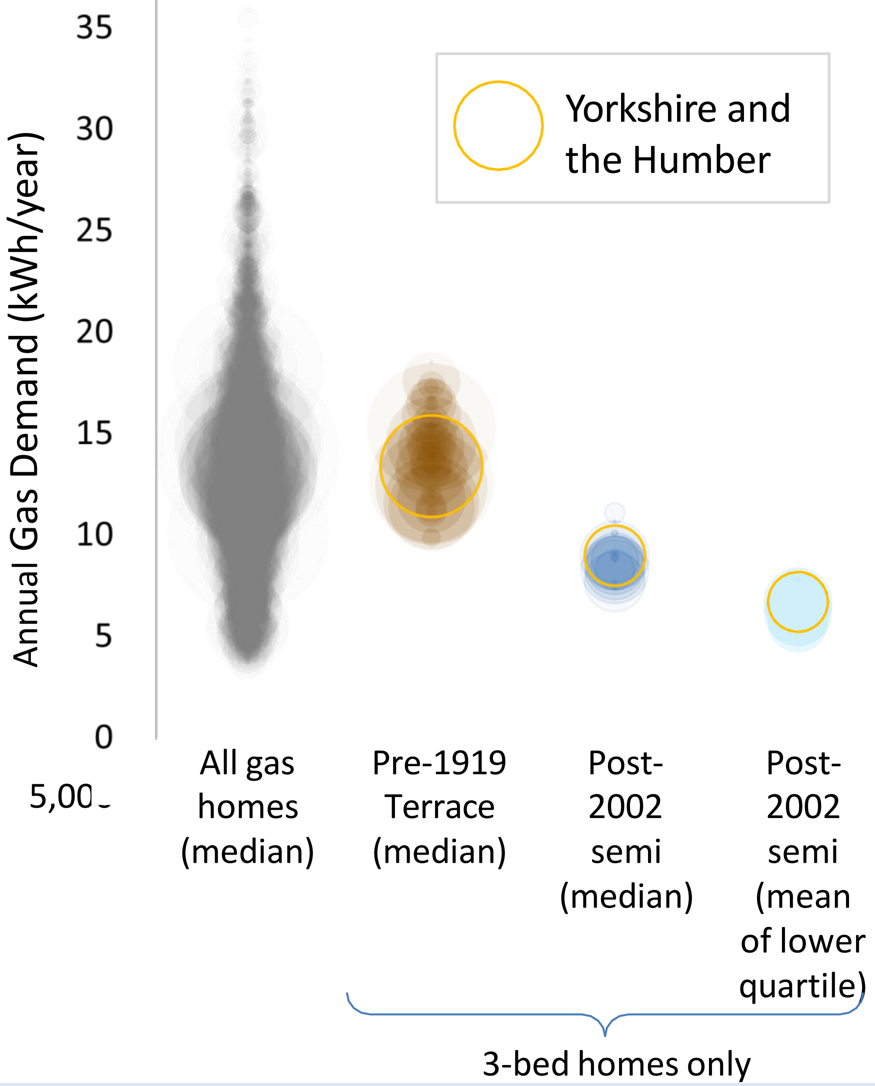
New-Build Semi-Detached

- **Post-2002, 3-bed, semi-detached** properties have gas demands in the range of 8-13 MWh per year. As this set groups together all properties built since 2002, the average is not reflective of properties being built now, so the lower quartile value was used as a proxy for more recently build homes
  - UK: mean 6.5 MWh/year
  - Yorkshire and the Humber: mean 6.8 MWh/year.
- The heat demands calculated for an average property via the heat demand profile generation process were calibrated down to give a total gas demand of 6.5 MWh/year for the new-build property.

Victorian Terrace

- **3-bed pre-1919 terraced** houses have **gas demand** values in the across a range of 10-20 MWh per year
  - UK: mean 14.5 MWh/year
  - Yorkshire and the Humber region: mean 15.0 MWh/year, median 14.1 MWh/year
- These values are lower than those generated using the method from Watson 2019, the values from the Watson calculations were used in the further analysis as the Watson calculated were based on smart meter data and to maintain consistency within the heat demand profile calculations in terms of the heat demand split between space heating and hot water.

Median gas demand values[1]



1. NEED Energy Consumption Tables 2019 https://www.gov.uk/government/statistics/national-energy-efficiency-data-framework-need-consumption-data-tables-2021

Our process for calculating half-hourly demand profiles uses warm weather profiles to establish the hot water and cooking demand then assigns remaining demand to space heating

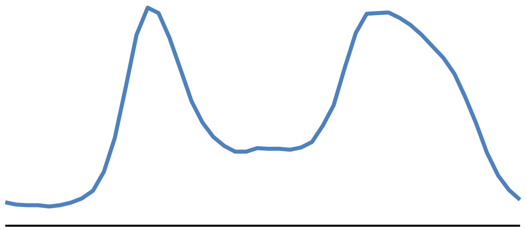
Calculating Half Hourly Heat Demand Profiles

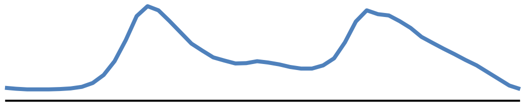
Daily Gas Demand

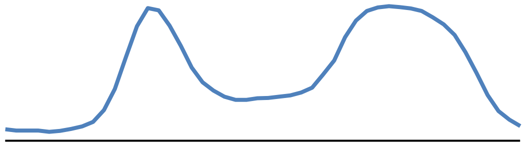
Calculate average temperature for each day of the year → Calculate daily gas demand for space heating and hot water → Calibrate total gas demand to archetype gas demand

Half-hourly Gas Demand

Spread **total gas demand** across temperature-dependent half-hourly gas demand profile → Spread **cooking and hot water gas demand** across warm weather half-hourly gas demand profile (i.e. profile with no space heating) → Subtract cooking and hot water demand profile from total demand profile to find **space heating gas demand** profile







Half-hourly Heat Demand

Convert gas demand to heat demand using boiler efficiency values for space heating, hot water and cooking

1. Boiler efficiencies used are provided in the appendix on slide 99.

Two household types were studied, with varying tolerance to changes in internal temperature in order to model access to flexible time-of-use tariffs

Demand Side Response

- Demand side response, DSR, is a mechanism for managing peak demand on the electricity grid by reducing demand
- Shifting demand away from peak times enables greater use of renewable energy and reduces requirements for upgrades to grid infrastructure
- Time-of-use tariffs reward DSR by increasing the cost per unit of electricity at the peak and reducing the cost at times of low demand

Householder Types

- Two householder types have been studied to understand how the tolerance of households to variations in internal temperatures impact the value offered by flexible time-of-use tariffs: a **household that values comfort** (low flexibility, ±0.5°C) and a **household that values economy** (high flexibility, +2°C/-1°C)
  - The overall heat demand for the two households is kept the same, i.e. the economy household does not have a lower temperature set point than the comfort home
- Published works have similarly used a 1°C and 3°C flexibility range for DSR studies and found that the impact of 1°C variations are likely to be acceptable to inhabitants without additional incentives[1]
- The DSR events modelled in this study use **flexibility afforded by the building's thermal mass** to allow the buildings to be preheated prior to peak demand, switched off over peak times then to recover after the peak
- The length of the DSR window depends on the heat loss rate of the building and therefore changes between the retrofit and the new build properties studied

Temperature variations for householder types

Comfort	Economy
±0.5°C	+2°C/-1 °C

1. Romanchenko et. al., *Flexibility Potential of Space Heating Demand Response in Buildings for District Heating Systems*, **2019** https://ieeexplore.ieee.org/document/8273810

The hours of flexibility available strongly depend on the input values chosen for the thermal mass and heat loss rate of the buildings being studied

Hours of Flexibility Calculation

$$hours\ of\ flexibility\ (h) = \frac{builing\ thermal\ mass\ (kWhK^{-1}) \times allowed\ temperature\ change\ (K)}{building\ heat\ loss\ rate\ (kWK^{-1}) \times (T_{inside}(K) - T_{outside}(K))}$$

Input Variables

Building thermal mass

- A mock up of the properties based on heat capacity values listed in SAP and assumptions on build type led to thermal mass values within 50 to 100 $\mathrm{kJm^{-2}K^{-1}}$ of the medium 250 $\mathrm{kJm^{-2}K^{-1}}$ depending on the construction elements chosen. *Details in Appendix: Archetype Analysis.*
- The medium value is used as a default in SAP and without strong evidence to use an another value, the default value of 250 $\mathrm{kJm^{-2}K^{-1}}$ was used in this study.
- Both property types had average floor areas of 85-86 m^2
- The building thermal mass value was therefore 21,500 kJ/K, equivalent to **6.0 kWh/K**.

Allowed temperature change

- Determined by household type
  - **3°C** for economy
  - **1 °C** for comfort

Calculated Variables

Building heat loss rate

- Heat loss rates for each of the buildings were calculated by modelling the properties in software used to generate EPC certificates, Stroma FSAP 2012. U-values were based on the expected value for a property of that age. *Details in Appendix: Archetype Analysis.*
- The values for the Victorian terrace varied between 150 W/K and 230 W/K depending on the levels of insulation modelled. For the flexibility calculations, the worst case scenario for the Victorian terrace was used:
  - **230 $\mathrm{WK^{-1}}$** for the Victorian terrace house
  - **100 $\mathrm{WK^{-1}}$** for the new-build semi-detached.

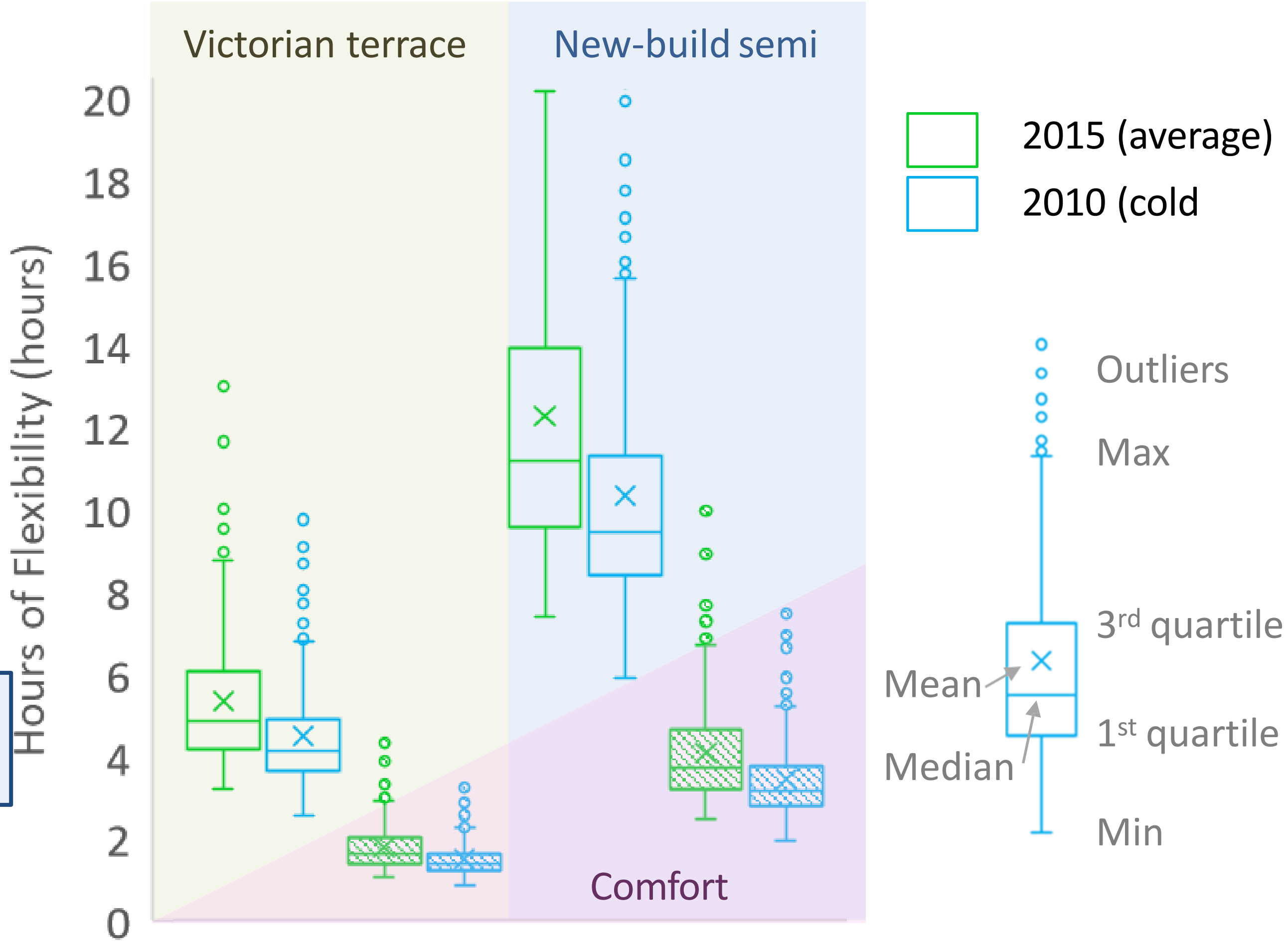
Temperature delta

- $T_{inside} = SAP\ uses$ **21°C**
- $T_{outside}$ varies, **modelling therefore used daily values for hours of flexibility based on average daily temperature**

The householder type (comfort or economy) sets the limit on internal temperature variation, which impacts the hours of flexibility available to make use of time-of-use tariffs through DSR

Overview of Thermal Mass Flexibility

- The figure right shows a box and whisker plot representing the **daily hours of flexibility afforded in each scenario**.
- The hours of flexibility shown right represent the **number of hours over which a DSR event can take place**:
  - For example, 4 hours of flexibility means the building can be preheated then the temperature allowed to drop over 4 hours, before catching up again at the end of that period.
  - The **amount the property can be preheated** and the **temperature range through which it is allowed to drop is set according to the limits of each household type**: comfort ±0.5°C, economy +2°C/-1°C
- The lower heat loss rates of the new build compared to the retrofitted property leads to much longer hours of flexibility,
  - In the region of 3-5 hours for the comfort household in the new build compared to 1-2 hours in the retrofit.
  - For the economy household, the hours of flexibility stretches to 4-6 hours for the retrofit and 10-14 hours for the new build.
- The comfort scenario, considered here as a householder who prefers little variation in internal temperature, can also be applied to households with other reasons for reduced hours of flexibility e.g. low building thermal mass or higher heat loss rates.



To study costs for the split ownership model, costs for the groundworks are split from other GSHP installation costs and reincorporated through a connection fee considered in the fuel cost analysis

System Cost and Lifetime

Costs Included

- The analysis in this study sought to compare the total costs to the consumer of each of the options studied, covering the upfront costs, fuel costs, and O&M/servicing costs over the technology lifetime.
- This section considers the upfront costs, servicing costs and the technology lifetimes while the fuel costs are considered in detail in the Household Level Analysis section..

Sources

- The costs for GSHP systems were provided by Kensa based on previous deployments.
- For the ASHP costs, the same costs as for the GSHPs were used for equivalent components (i.e. for the heat distribution system, hot water cylinder) with all other costs based on the "Cost of installing heating measures in domestic properties" by Delta-EE for BEIS.

Split Ownership Model

- With reference to the split ownership model for the ground array proposed by Kensa, the costs of the groundworks are separated from the rest of the installation costs.
- The cost of groundworks is then incorporated into consumer fuel costs through a connection fee, shown in slides 21, set at:
  - GSHP shared loop
    - Victorian terrace £385
    - New build semi: £170.

GSHP costs are based on previous Kensa deployments while ASHP costs are based on a mixture of Kensa and Delta-EE costs

Capex Costs

- Values for each cost element are shown for ASHP and GSHP
  - For GSHP, costs are shown both for an installation on an individual house basis (house-by-house) and the costs per house for the shared loop model (street-by-street). Following the high-level comparison in this section, only the costs for the shared loop model are taken forward in the analysis and the cost of the groundworks is covered by a connection fee.
- The total GSHP street-by-street costs (i.e. including groundworks costs) are around 35% higher than ASHP but 30% lower than GSHP costs when installing on a house-by-house basis
  - The benefits from economies of scale is most significant in the reducing the cost of ground works, with savings of around £5,700 per property vs individual installations for the retrofit on groundworks alone.
- Cost used for a heat battery was taken as £500 (shown right), provided by Kensa.

Additional Costs (per property)	
Heat battery	£500 uplift

Cost Element	ASHP			GSHP House-by-House			GSHP Street-by-Street		
	Cost (£)		Source	Cost (£)		Source	Cost (£)		Source
	Retrofit	New build		Retrofit	New build		Retrofit	New build	
Technology	£3,570	£3,040	*Delta-EE*	£4,800	£4,000	*Kensa*	£4,320	£3,600	*Kensa*
Hot water tank	£1,080	£1,080	*Delta-EE*						
Labour	£1,800	£1,400	*Delta-EE*	£2,340	£1,390	*Kensa*	£1,520	£1,140	*Kensa*
Heat distribution system	£4,975	-	*Kensa*	£4,975	-	*Kensa*	£4,365	-	*Kensa*
Groundworks	-	-		£12,870	£6,600	*Kensa*	£7,175	£3,000	*Kensa*
Design/PM Costs	*Included in tech. costs*		*Delta-EE*	£1,460	£1,170	*Kensa*	£735	£615	*Kensa*
Total	**£11,425**	**£5,520**		**£26,445**	**£13,160**		**£18,115**	**£8,355**	

1. Delta-EE study for BEIS "Cost of installing heating measures in domestic properties" https://www.gov.uk/government/publications/cost-of-installing-heating-measures-in-domestic-properties

GSHPs are generally expected to require less maintenance than ASHP as the mechanical elements are less exposed, however, with no evidence to quantify this a flat rate was used for both

Operation and Maintenance Costs

- In Element Energy's work for the CCC, OPEX costs were assumed to be the same for all technologies and for all sizes.
- In discussions, Kensa indicated the maintenance would be expected to be lower for GSHPs than ASHPs but we have found no sources to quantify this.
- Heat pump servicing was found to be around £100-£200
  - Servicing was advised to be carried out every 2-3 years
  - We have therefore included an OPEX cost for both ASHP and GSHP of **£60 per year**.

Lifetimes

- Kensa states a design lifetime of 20 years for GSHPs system, with the exception of the groundworks, which are assumed to have a 100-year lifetime.
- ASHP lifetimes are generally quoted at 10-15 years.[1]
- Lifetimes for ASHP and GSHPs are often given as 12 years for ASHP and 20 for GSHP, or 15 years for ASHP and 25 years for GSHP
  - Here, we have used the longer set of lifetimes from that range, particularly as we are including an opex cost, which should lead to a longer lifetime.
- Lifetime values for solar thermal systems are generally given in the range of 20 years.[2]
- As heat batteries in domestic settings are a relatively new commercial offering, limited data is available on lifetimes in real-world operation
  - 10-year warrantees are standard,[3] with suggestions of 20-year lifetimes[4]
  - A **lifetime of 20 years** was used in this study.

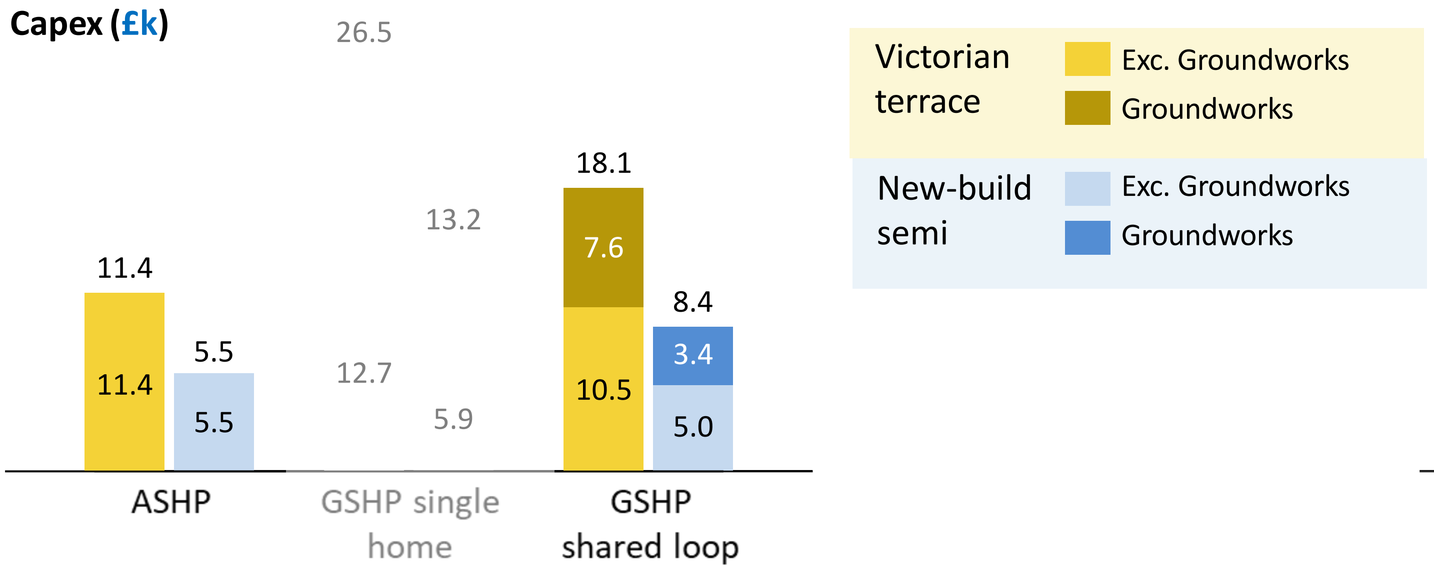
Technology	Lifetime (years)
ASHP	15
GSHP	25
GSHP groundworks	100
Heat battery	20

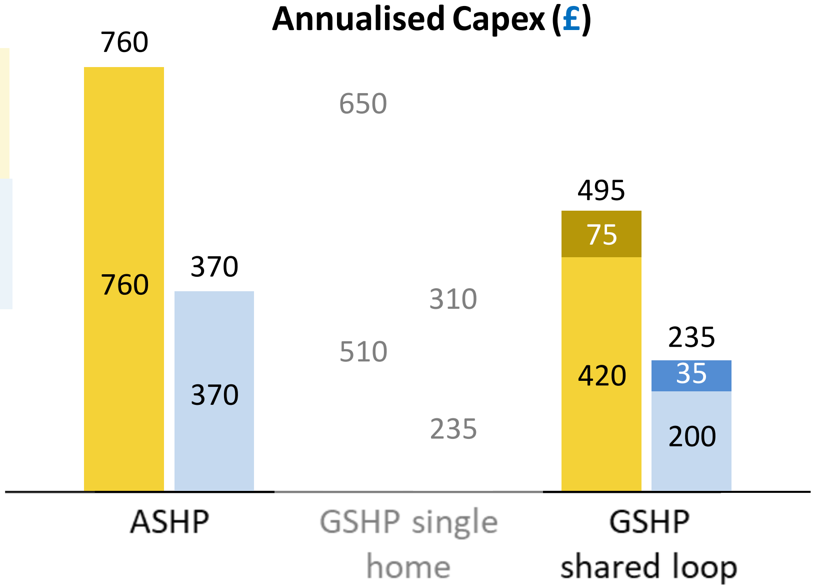
1. Evolved Thermal Energy: Ground Source vs Air Source Heat Pump https://evolvedthermal.com/ground-source-vs-air-source-heat-pump/
2. Renewable Energy Hub: Solar thermal system lifespan, maintenance and warrantees https://www.renewableenergyhub.co.uk/main/solar-thermal-information/solar-thermal-system-lifespan-maintenance-and-warranties/
3. Sunamp https://sunamp.com/
4. TNO: Heat battery for the home https://www.tno.nl/en/focus-areas/circular-economy-environment/roadmaps/sustainable-chemical-industry/heat-battery-for-the-home/

In separating the cost of groundworks, the GSHP shared ground loop system means that upfront costs to consumers of a GSHP system are below that of an ASHP system

Comparison of Installation Costs

- The analysis in this study sought to compare the total costs to the consumer of each of the options studied, covering the upfront costs, fuel costs, and O&M/servicing costs over the technology lifetime.
- The costs for GSHP systems were provided by Kensa based on previous deployments.
- For the ASHP costs, the same costs as for the GSHPs were used for equivalent components (i.e. for the heat distribution system, hot water cylinder) with all other costs based on the "Cost of installing heating measures in domestic properties" by Delta-EE for BEIS.
- The total capex for a GSHP system in a single home is 130% higher than for ASHP
  - The difference between ASHP systems and GSHP system is reduced to 60% higher for the GSHP shared loop system
  - **Excluding the cost of ground works, the capex of the GSHP shared loop system becomes 10% lower than that of the ASHP system.**
- However, the longer lifetime of the GSHP system (25 years compared to 15, plus 100-year lifetime of groundworks) means that the **annualised cost of the GSHP shared loop** system is **around half that of the ASHP** system.



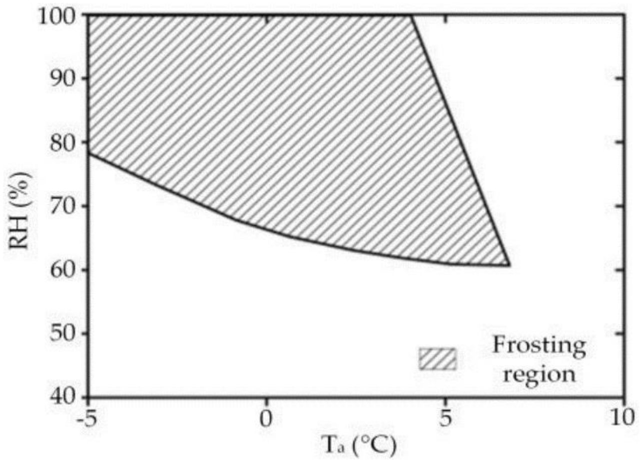


Reports from published literature indicate that the hourly decrease in COP for ASHPs when in the defrost zone is in excess of 0.4

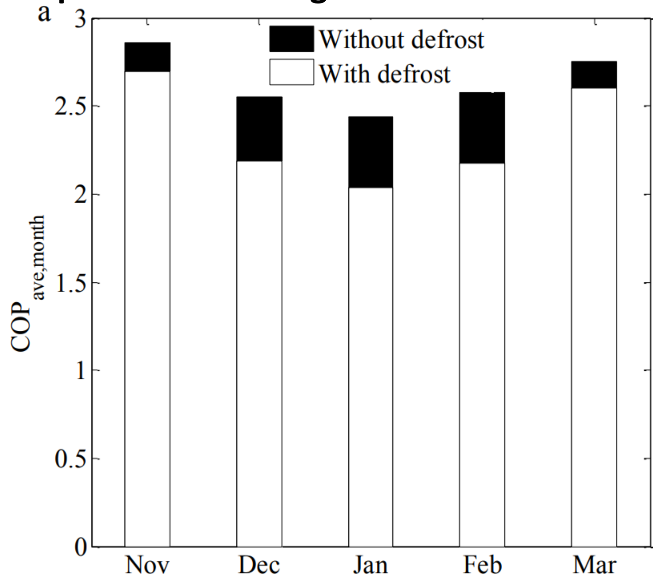
ASHP Performance Modelling

- In certain weather conditions, frost forms on the external elements of an ASHP and the unit must perform a defrost cycle. This cycle involves heating the external elements to remove the frost. Most ASHPs use a reverse cycle defrost mode, which runs the heat pump in reverse, pulling heat from the building and returning it to the external elements.
- **Defrosting is required in conditions of low temperature and high humidity**, as shown in the upper figure on the right[1]
  - Such **conditions are typical of a UK winter**
- The COP of the ASHP is reduced in three ways during the defrost cycle:
  - The heat pump is using electricity to power the cycle
  - The heat pump is not heating the building during the defrost cycle
  - Heat is being drawn from the building to heat external elements.
- The reduction in COP as a result of defrosting is not well quantified in literature.
  - Some manufacturers quote some of their reported COPs values as explicitly including the impact of defrost cycles but the difference between values that do and do not include defrosting are not shown and **it is not clear if SCOPs are quoted with any defrosting impact included**.
  - A Vocale 2014 study,[2] based on first principles calculations using weather data from a number of Italian cities found **monthly COP penalties of up 0.4** when including the impact of defrost cycles. Some results from the Vocale 2014 study are shown in the lower figure on the right.

Frost region [1]



Impact of defrosting from Vocale 2014[2]



1. Adachi et. al. "On the refrigeration cycle property of heat pump air conditioners operating with frost formation." *Refrigeration* **1975**
2. Vocale et. al. "Influence of Outdoor Air Conditions on the Air Source Heat Pumps Performance" *Energy Procedia* **2014**

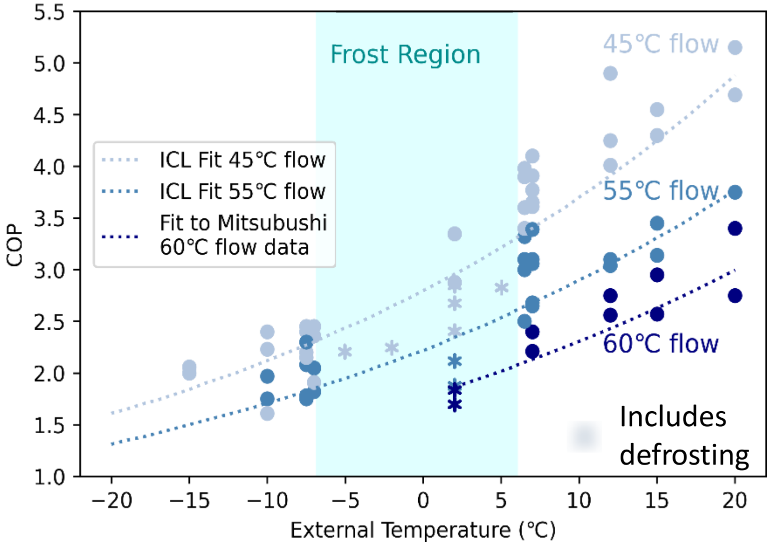
The average value for the defrost penalty, based on the Mitsubishi and NIBE datasets, is 0.46 – consistent with the values reported in literature

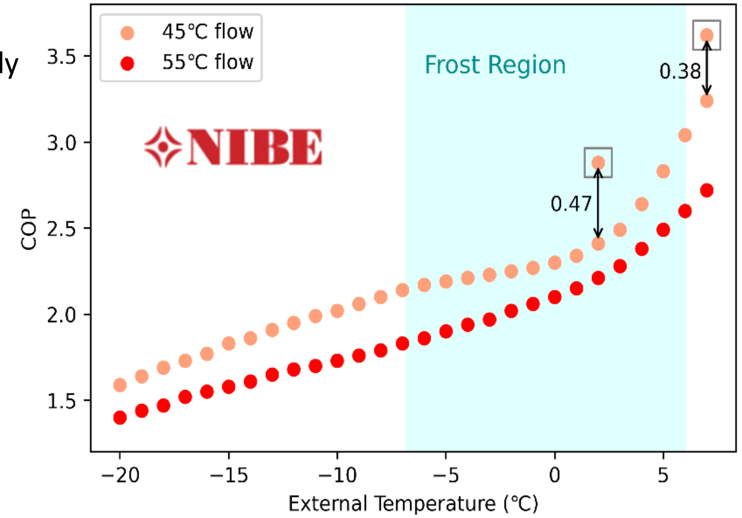
Quantifying the Impact of Defrost Cycles

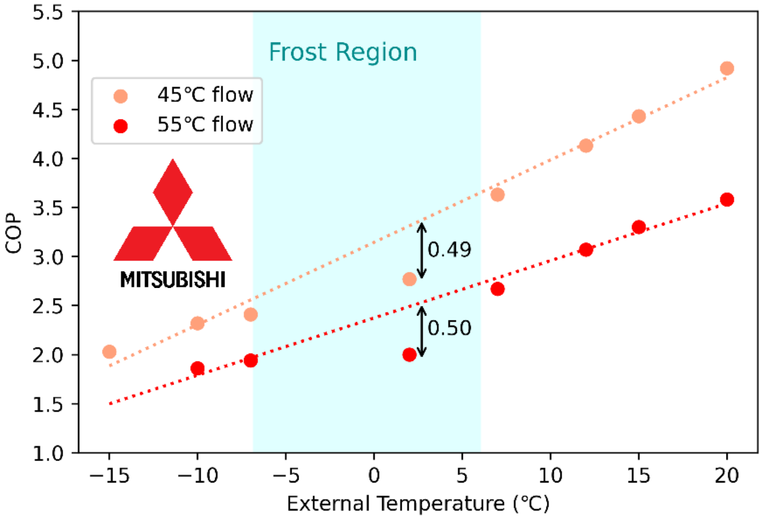
- The Vocale 2014 study found that the **highest monthly COP penalty** for defrosting was around **0.4**
  - If all hours in that month were in the frost region, this would suggest a defrost penalty of 0.4. We assume not all hours are within the frost region, therefore the hourly defrost penalty must be >0.4.
- The defrost penalty used in our modelling is based on an average of the defrost values calculated from the NIBE and Mitsubishi datasets, shown in the table below. More detail on this process is provided in Appendix: ASHP COP Methodology but a brief over view is given below
  - NIBE provided two COP values at 2°C and 7°C, one set as part of a series explicitly including the impact of defrost cycles; the difference between theses values was taken as the defrost penalty
  - Mitsubishi provided a set of COP values, one of which explicitly included the impact of defrost cycles; a linear function was drawn between the values that did not include defrosting and the deviation of the value that includes frosting taken as the defrost penalty

NIBE		Mitsubishi		Average
2°C	7°C	45°C flow	55°C flow	
0.47	0.38	0.49	0.50	**0.46**

- For the ASHP COP calculations, the 0.46 defrost penalty was used when the hourly weather datapoint was within the frost region.





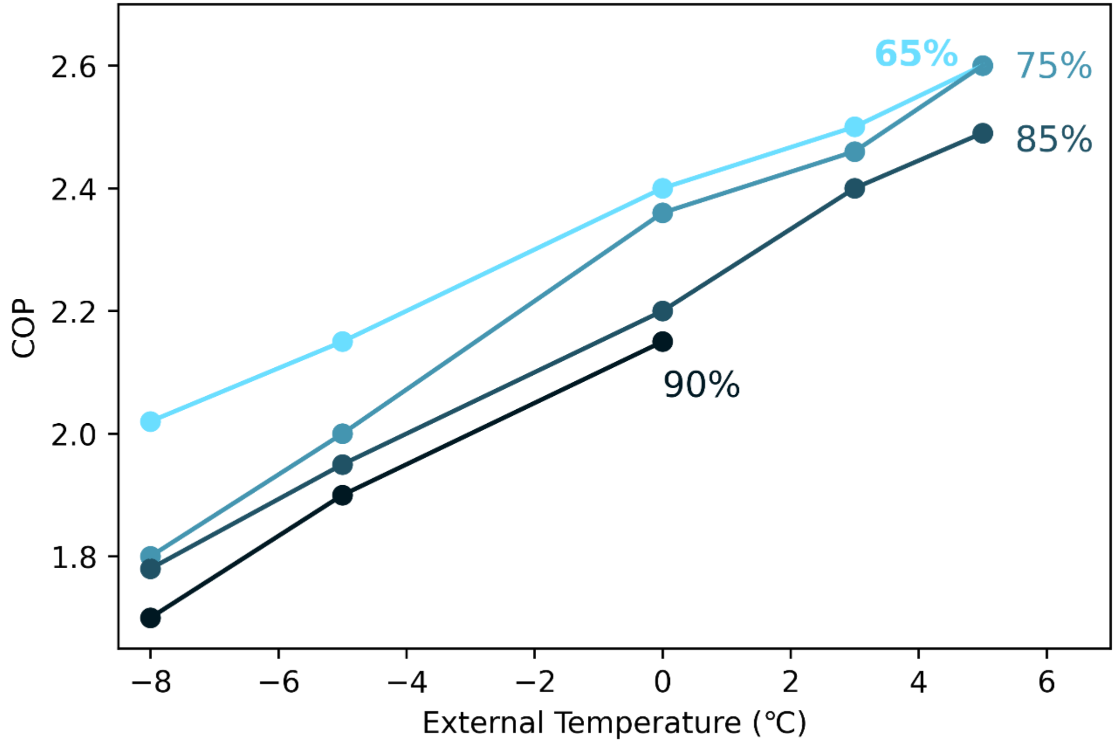


The data reported by manufacturers is measured under standard test conditions of 85% humidity, therefore an additional correction factor has been applied where humidity deviates from 85%

Additional Impact of Humidity

- ASHPs COPs are measured under standard test conditions with a humidity of 85%
- The data from the Zhang 2014 study (shown right) shows the **negative impact of humidity on COP in weather conditions that would require defrosting**
  - These values are not as high as the defrost penalty but can provide a small, humidity dependant adjustment to ensure the COP values account for the local climate as far as possible.
- Based on the Bingley 2015 data, nearly 70% of hours in the heating season have humidity higher than 85%, rising to over 80% of the hours in the coldest months.
- While this humidity correction may even out across the year, humidity drops during the day so can affect the optimisation of flexibility.
- As the data presented here is associated with the impact of humidity on defrosting, the **additional humidity correction was only applied in hours within the frost region.**

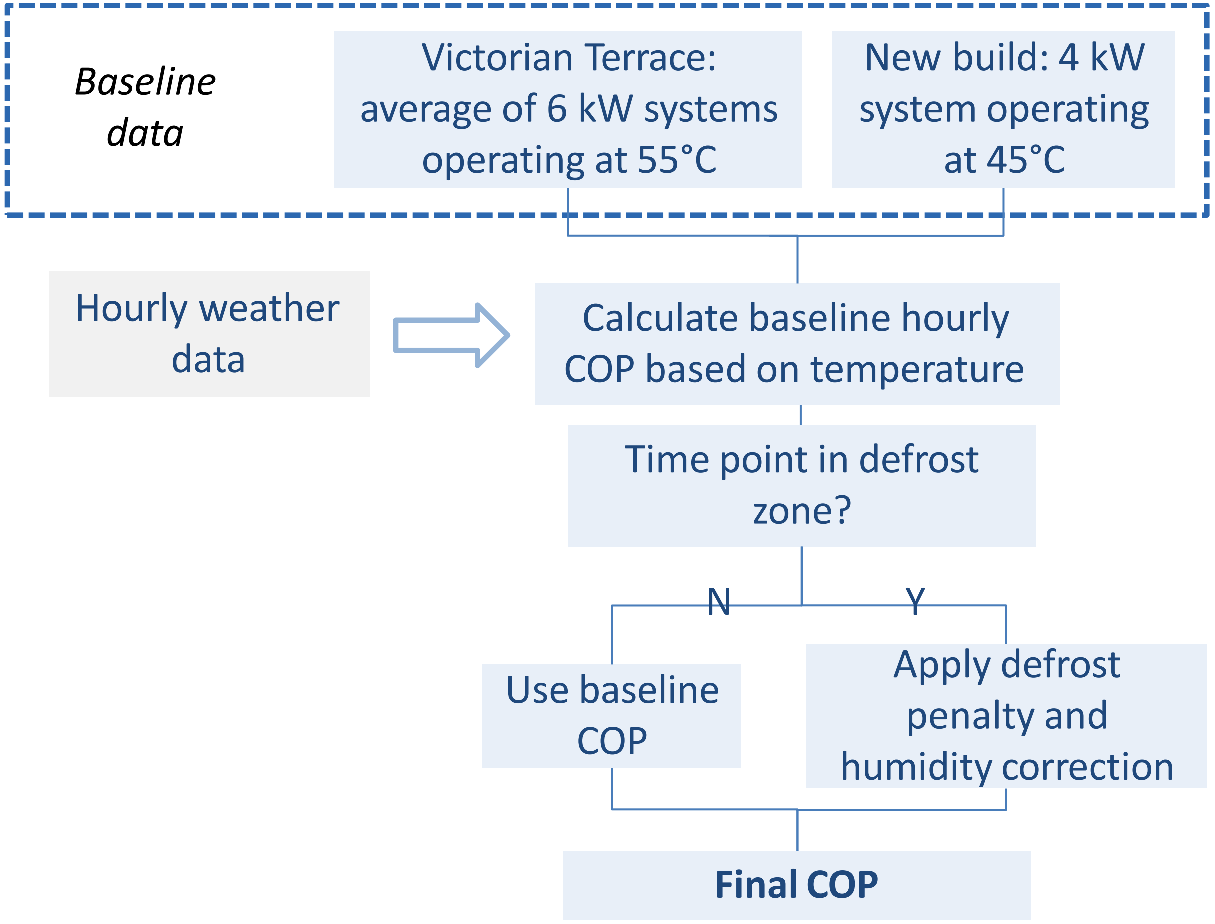
COP vs external temperature for various humidity values



Hourly COP values have been calculated using manufacturer data as a baseline, then applying a defrost penalty and humidity correction when a timepoint is in the frost region

Apply Hourly Temperature and Humidity Dependent COPs

- For each hourly weather point:
  - The baseline COP is calculated using Mitsubishi data[1]
    - Victorian Terrace: Average of data from two 6 kW models operating at 55°C flow
    - New build: 4 kW model operating at 45°C
  - If the timepoint is in the frost zone
    - A set **defrost penalty of 0.46** is applied
    - A **positive or negative humidity correction** factor is applied based on whether the humidity is lower or higher than 85% respectively
  - If the timepoint is not in the frost region, no penalties or corrections are applied.
- The **COP is then applied to the heat demand for each half-hourly time point**.



1. The Mitsubishi dataset was the most complete of the ASHP manufacturers investigated over the temperature ranges relevant to this study. Additionally, the data was well aligned with other sources indicating that these values were reasonable to use for a typical ASHP installation.

The two years chosen show distinctly different distributions of hours within the frost region over the heating season

Hours in the Frost Region

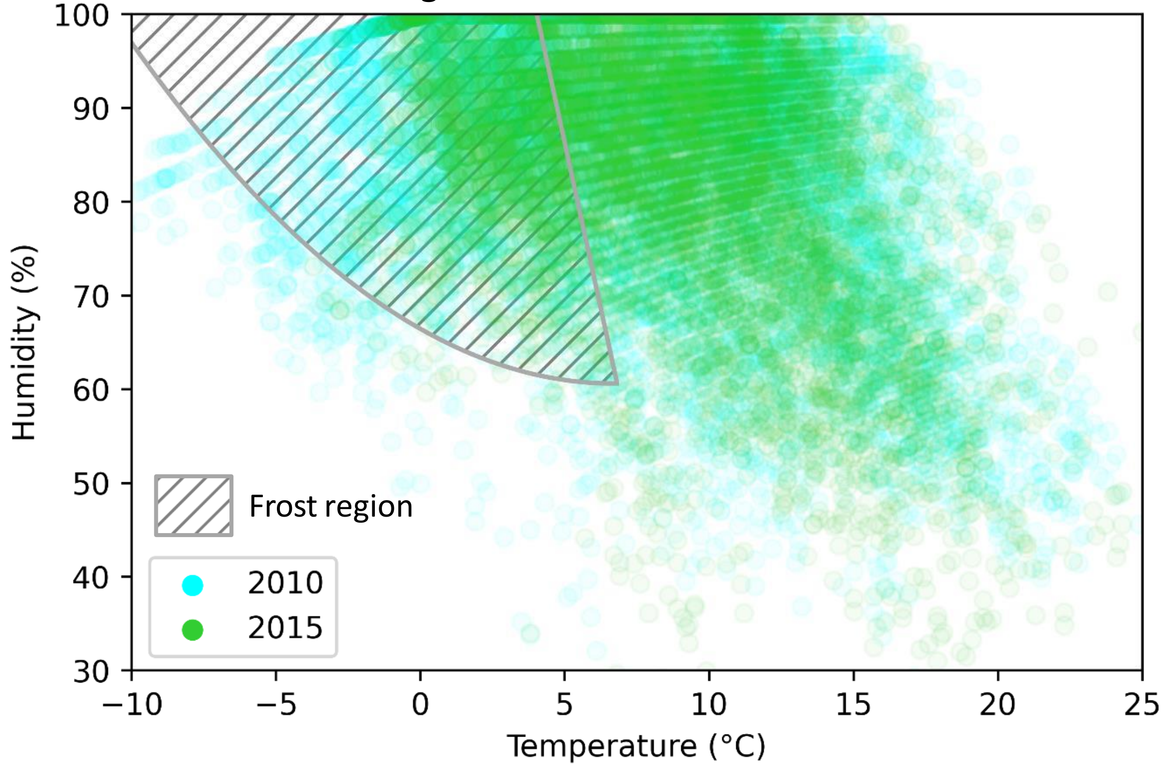
- The impact of defrost cycles was naturally expected to vary between weather years.
- Two weather years were compared to understand the difference between ASHP and GSHP performance in an average year (2015) and in a 1-in-20 cold year (2010).

Impact on Heat Pump Performance

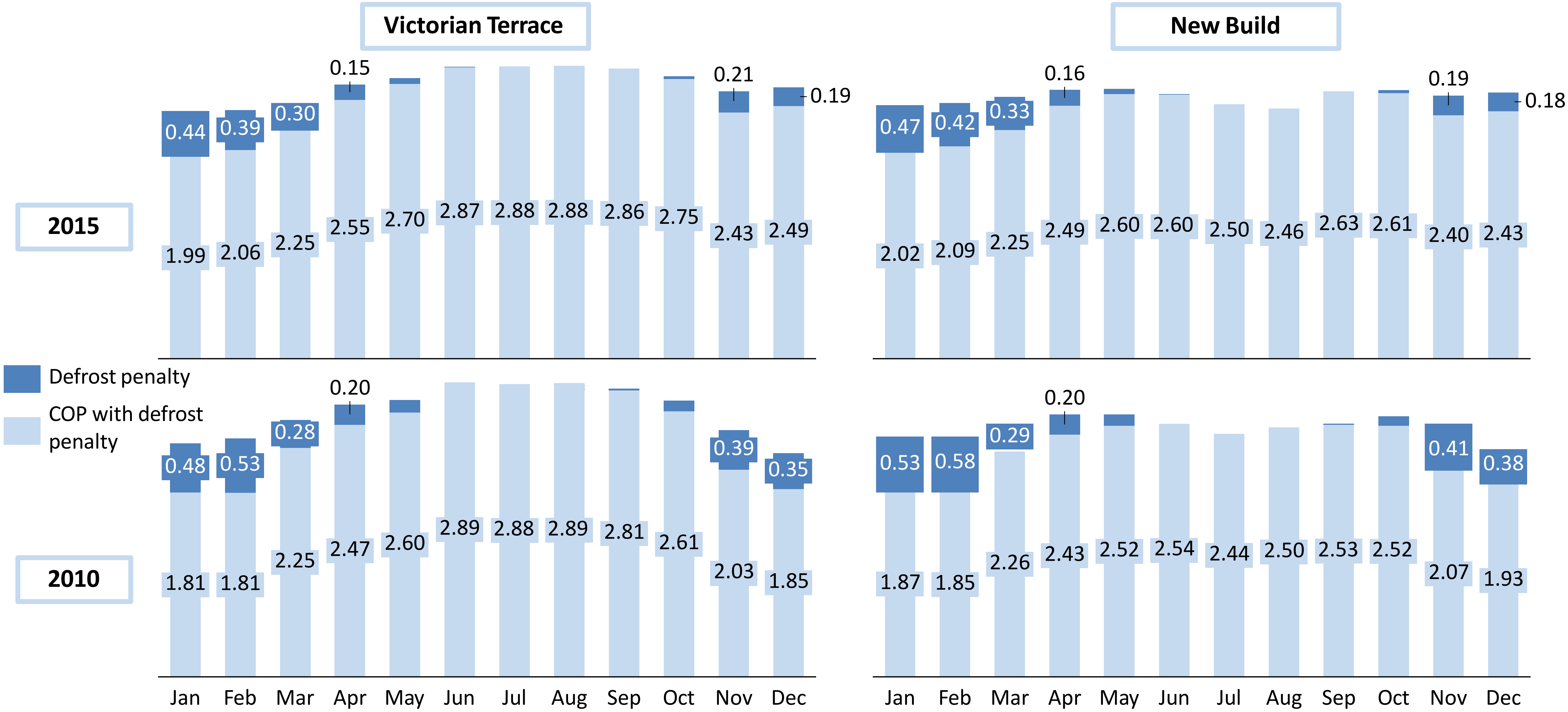
- As ASHP system performance is directly related to external temperature, it was expected that ASHP systems would fare worse in cold weather conditions than in an average year.
- The figure rights shows a plot of shows **air temperature against humidity for each hour of the year** in 2010 (blue) and 2015 (green).
  - In 2010, 35% of hours were in the frost region, compared to 25% in 2015, increasing the impact of defrost cycles on ASHP performance.

Year	2010	2015
Annual hours in frost region	35%	25%
Heating season hours in frost region	61%	42%

Hours in the frost region for 2015 and 2010



Defrost penalties reduce the monthly ASHP COPs by close to 0.5 in the coldest months of the average year (2015), going above 0.5 in some months in the 1-in-20 cold year (2010)



GSHP COPs were calculated using the temperature outputs from the GLD modelling and the temperature dependant COPs published by Kensa for their Evo 7 heat pump

GLD Modelling

Overview

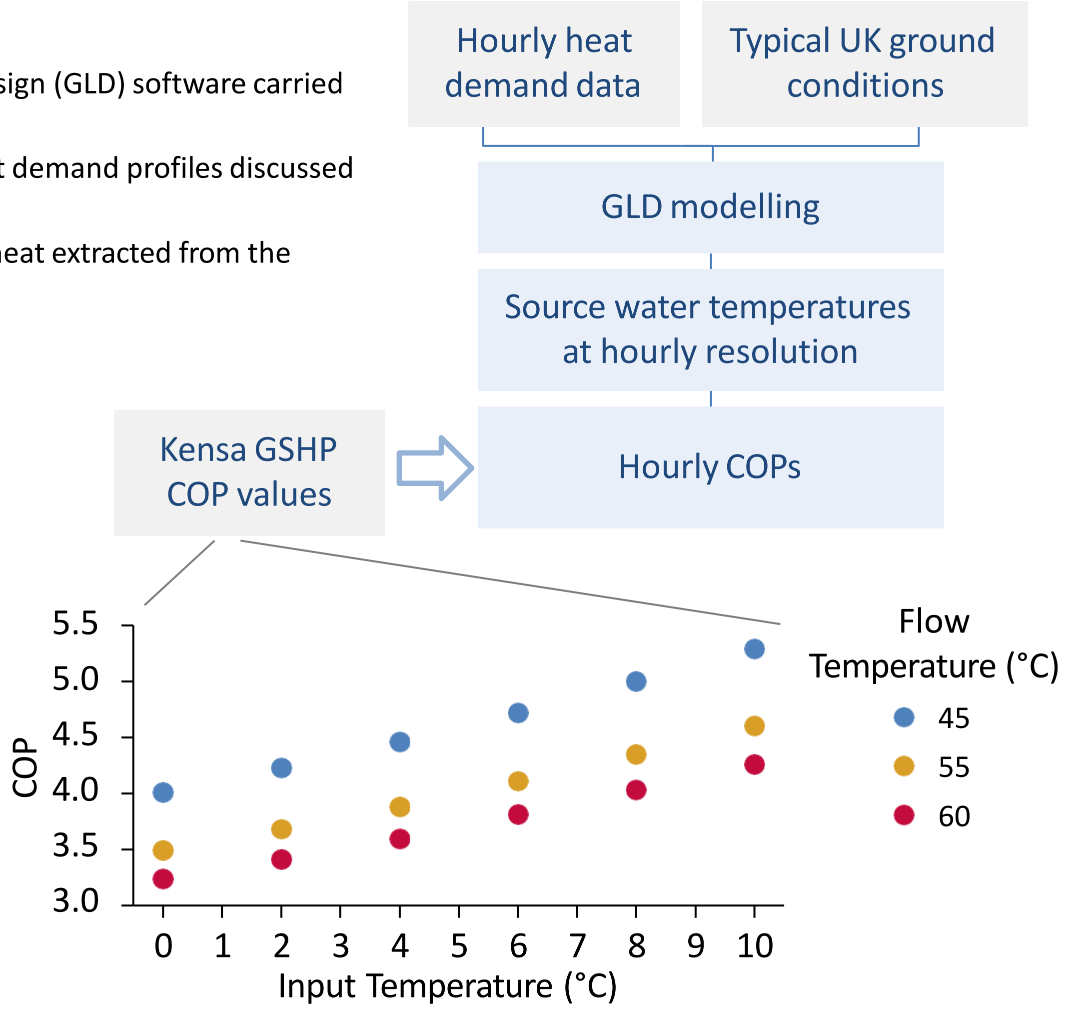
- GSHP performance modelling was based on operational performance as calculated in Ground Loop Design (GLD) software carried out by Genius Energy Labs.
- The GLD modelling was run at hourly resolution runs over the system lifetime based on the hourly heat demand profiles discussed on slide 26.
- The GLD software tracks the source temperature in detail over the heating season, accounting for the heat extracted from the source over time as well as the ground and weather conditions.

Ground Array Model

- The following details were assumed in the GLD GSHP shared loop model
  - 1 borehole per dwelling
  - Borehole depth
    - Retrofit: 216 m
    - New build: 74 m
  - For ground conditions, the most frequently encountered values for the UK were used:
    - conductivity 2.1W/mK, diffusivity 0.1m^2/day, undisturbed ground temperature 11.0°C

Heat Pump Systems

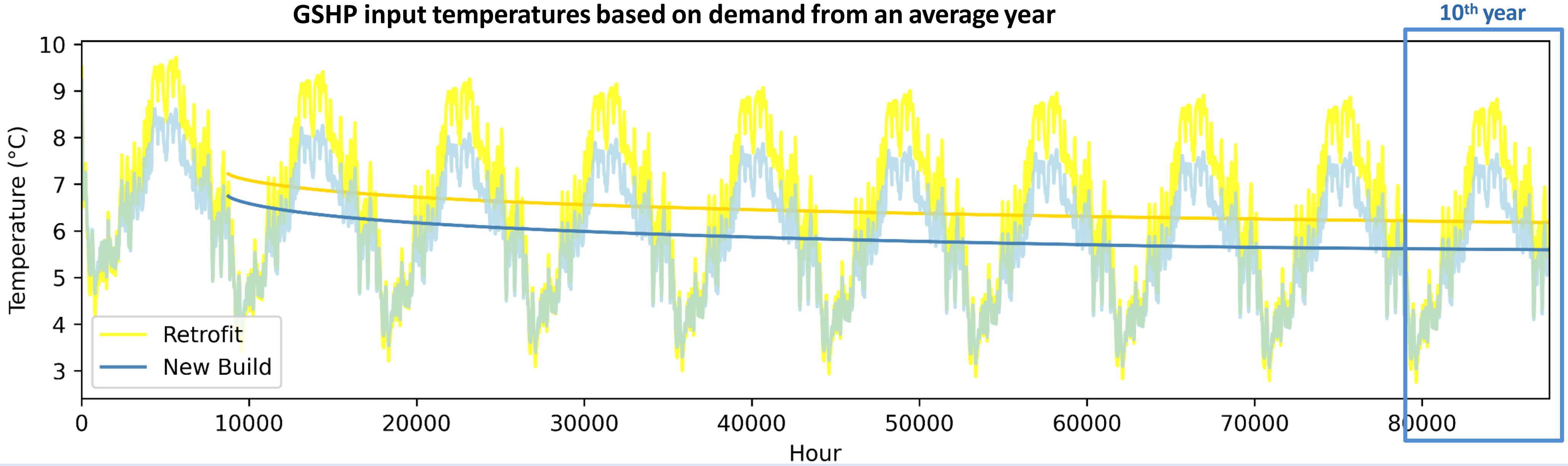
- COP values for the GSHP systems were based on published Kensa data for the **Evo 7 heat pump**, the model Kensa would expect to install in a retrofit property like the Victorian terrace house
- Kensa is currently developing a version of its Shoebox model, designed specifically with new-build properties in mind, that will use the same compressor system as the Evo 7 and is therefore expected to have similar COPs
  - Therefore, the **same COP relationships were used for both the retrofit and the new build**



By the 8th year of operation, the ground temperatures around the borehole have stabilised; temperature data from the 10th year of operation was therefore used to model GSHP COPs

GSHP Performance Modelling

- The figure below shows the **variation in the daily average temperature outputs** from the first 10 years of operation, plus the yearly average values (flatter lines).
- As can be seen from the yearly average values, the ground temperature slowly drops over the first few years of operation, stabilising by the 8th year
  - The **10th year of operation was therefore chosen to use as the input temperatures to generate the hourly GSHP COPs**.
- For the 1-in-20 cold year, the ground temperatures were started from the end of the 9th year for consistent comparison with the 2015 average year values.
  - The impact of the cold year is primarily the increase in heat demand from the properties reducing the ground temperature more over the winter, as opposed the impact of lower than average air temperatures.
- Within any given year, the ground temperature drops over the winter months as a significant amount of heat is extracted during the heating season and recovers over the summer months when less heat is extracted



Three electricity cost projections were developed: one based on historic electricity process (2020) and two based on future cost projections based on Element Energy's ISDM model

Electricity Cost Projections

- A sensitivity analysis was carried out on the electricity cost to understand the impact of changing electricity prices on the economic comparisons between ASHP and GSHP systems.
- To model the impact of changing electricity costs, three sets of half-hourly cost projections were used:
  - One set using historic 'real-world' hourly electricity costs from which Element Energy have constructed a generic time-of-use tariff
  - Two sets representing future hourly electricity costs in an energy system with a higher level of variable renewable generation and increased gas / carbon costs, and a correspondingly higher level of price volatility, based on runs of Element's Integrated System Dispatch Model (ISDM) for the future UK power system aligned to National Grid FES scenarios.

Generic Time-of-Use Tariff

- A generic time-of-use tariff was created by combining wholesale costs, distribution charges and other fixed charges
  - Electricity data from 2020 was used to create the historic time-of-use tariff, referred to as 2020 Baseline
  - The future runs varied the wholesale costs based on the share of renewable energy assumed on the system, these are referred to as the 2030 high RES and 2030 low RES scenarios.
- The time-of-use tariff used in this study did not incorporate any flexibility in the standing charge portion of consumer bills. Incorporating flexibility into the standing charge would be a mechanism for increasing the attractiveness of load shifting to customers, with wider system benefits.

ISDM Model

- The ISDM model was developed to determine the optimised configuration and operation of power systems to ensure the security of supply with very high penetration of renewable energy sources. ISDM was developed to represent multi-vector low or zero carbon energy systems with high penetration of variable renewable energy sources. By placing equal emphasis on demand side flexibility technologies as it does on the supply side and so overcomes many limitations of traditional power dispatch models. The starting point for the modelling used is the set of hourly energy demand profiles. The model is populated with a detailed breakdown of the demand by end use types. The demand is differentiated based on its hourly profile and potential for flexibility.

Wholesale cost and distribution use of system charges are used to profile the time-of-use tariff, with remaining costs added as fixed components

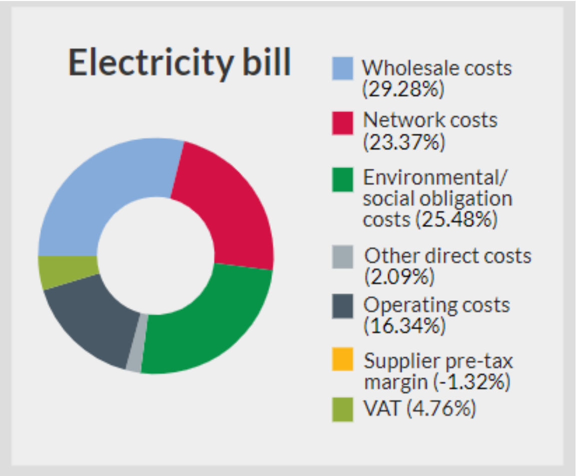
General Time-of-Use Tariff

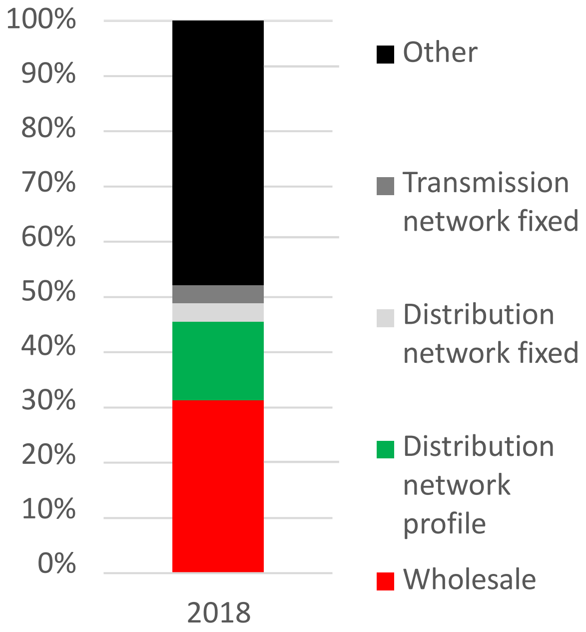
Generating a Time-of-Use Tariff

- A time varying retail tariff was used to model the operational savings potential based on an existing and two future tariffs.
- Currently, the only existing dynamic time-of-use tariff is the Octopus Energy Agile tariff. While this is only an experimental tariff, we expect more dynamic tariffs to emerge in the future to incentivise the use of flexible technologies.
- The conversion of the modelled wholesale costs to future tariff was carried out based on a general time-of-use tariff.

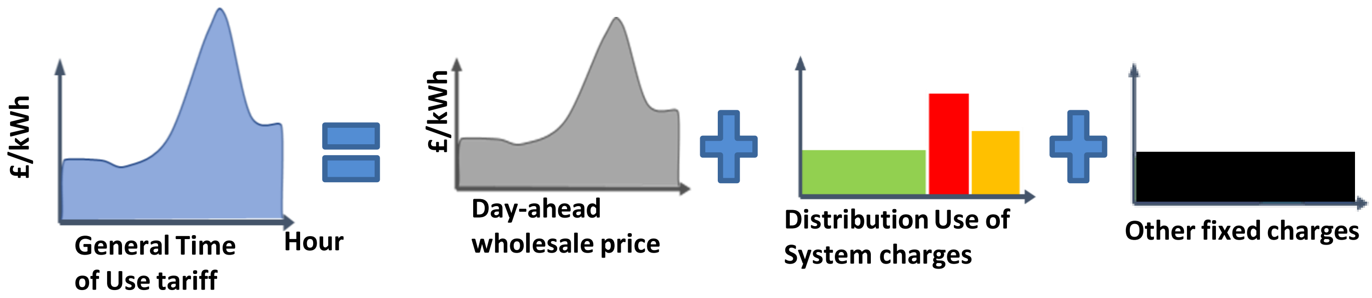
Details of Input Values

- Nearly half of electricity cost is based on fixed costs that are not time varying and therefore independent of demand profile.
- Wholesale costs and distribution use of system charges are the only two components that are dynamic.
- Therefore, wholesale costs were not scaled further and the future electricity cost projections use current distribution use of system charges as well as 'other fixed charges' to generate general time-of-use tariff.





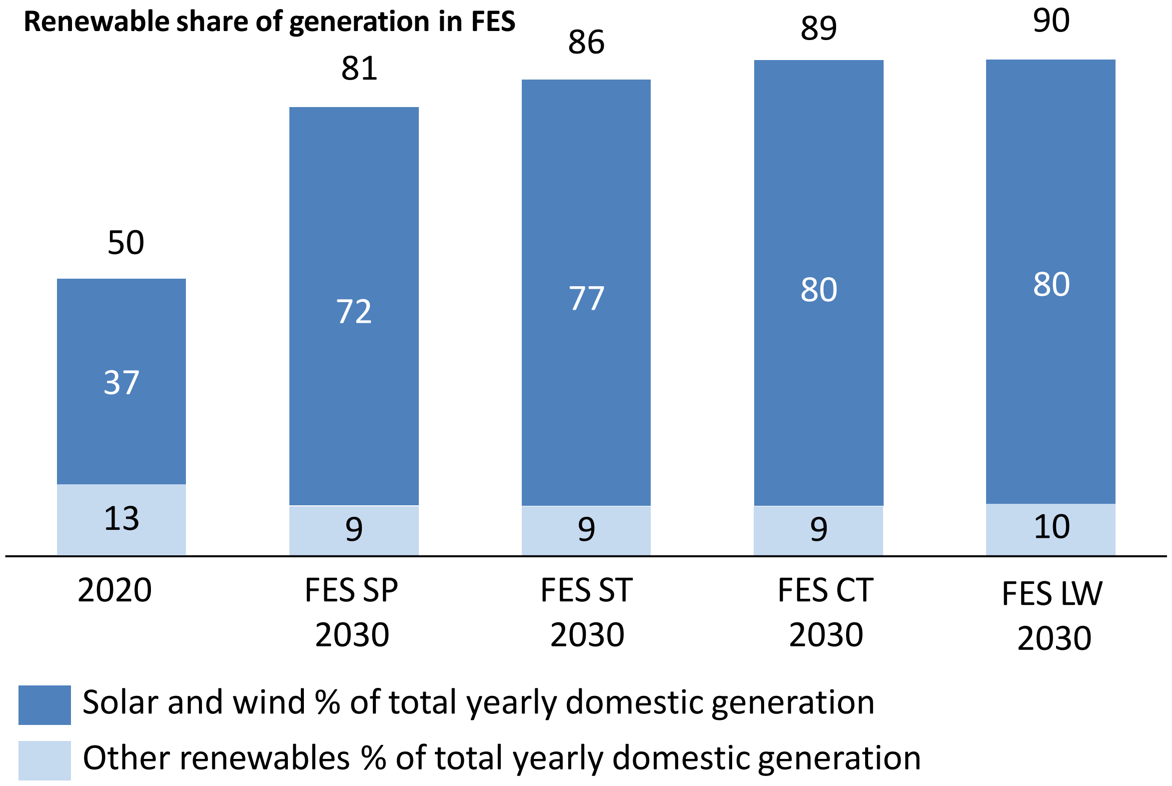
General Time of Use tariff



The two future electricity cost projections differ in the generation share of renewable energy within the national system

RES 2030 Scenarios

- One of the key variations for the two future tariff profiles is the share of RES which impacts the level of volatility in the diurnal tariff profiles
- To capture sufficient variation in the generation mix, the future electricity projections used relevant renewable energy share from the most and the least ambitious decarbonization scenarios from FES, namely: **Steady Progression** and **FES Leading The Way**
- We have also used **FES Leading The Way demand** and **generation mix** as the basis for 2030 runs, which gives a higher share of electric vehicle and heat pump demand
- For the two future tariff projection runs, cost and demand is kept constant while **wind + solar capacities** is varied for the high/low renewable generation share
- Based on NG FES scenarios, the RES share is varied from a low of **81%** to a high of **90%**



FES scenarios: Steady Progression (ST), System Transformation (ST), Consumer Transformation (CT), Leading the Way (LW)

To generate the electricity cost profiles, BEIS high cost projections for gas and carbon prices were used

Fossil and carbon price assumptions

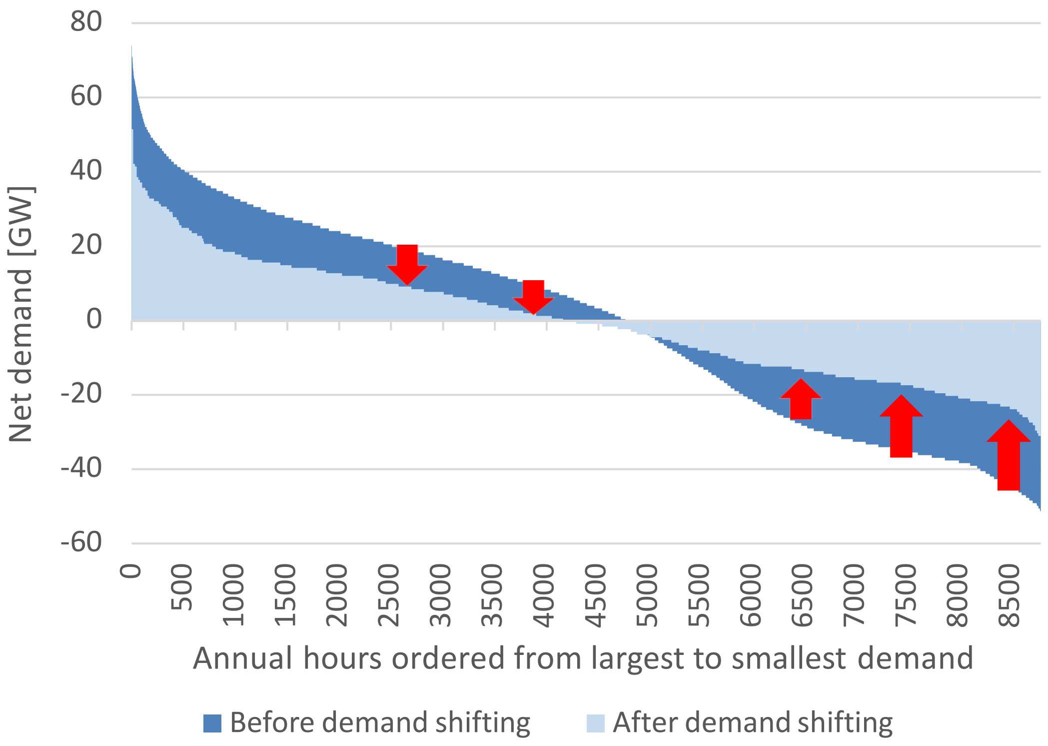
Fossil Fuel and Carbon Price Assumptions

- Wholesale costs in dispatch model are determined by short run marginal cost (SRMC) of the marginal plant in merit order.
- This results in low costs for hours of curtailment, while hours with residual unmet demand will have SRMC determined by gas CCGT / peaking plants for most of the hours.
- Therefore the gas and carbon price assumptions have a significant impact on resulting wholesale prices.
- There is a high degree of uncertainty in gas prices for 2030 and uncertainty over whether current spikes in market gas prices will return back to historical trends.
- This study has used BEIS high gas cost of **£28.3/MWh[1]** in 2030 combined with BEIS high ETS carbon cost of **£131/t[1].**

Flexibility

- Another factor that influences the level of price volatility is the amount of flexibility already assumed in the demand profiles.
- Increasing flexibility flattens the net demand profile and thus reduces the need for dispatchable generation and resulting wholesale cost.
- For current modelling runs we have used a **passive wholesale cost profile** as these profiles would form the baseline for any domestic demand side response measures that we include in our modelling.
- This will be extended by introducing combined EV and heating DSR measures in Phase 2 to identify system level impacts and competition between various sources of flexibility.

DSR measures flatten the net demand curve



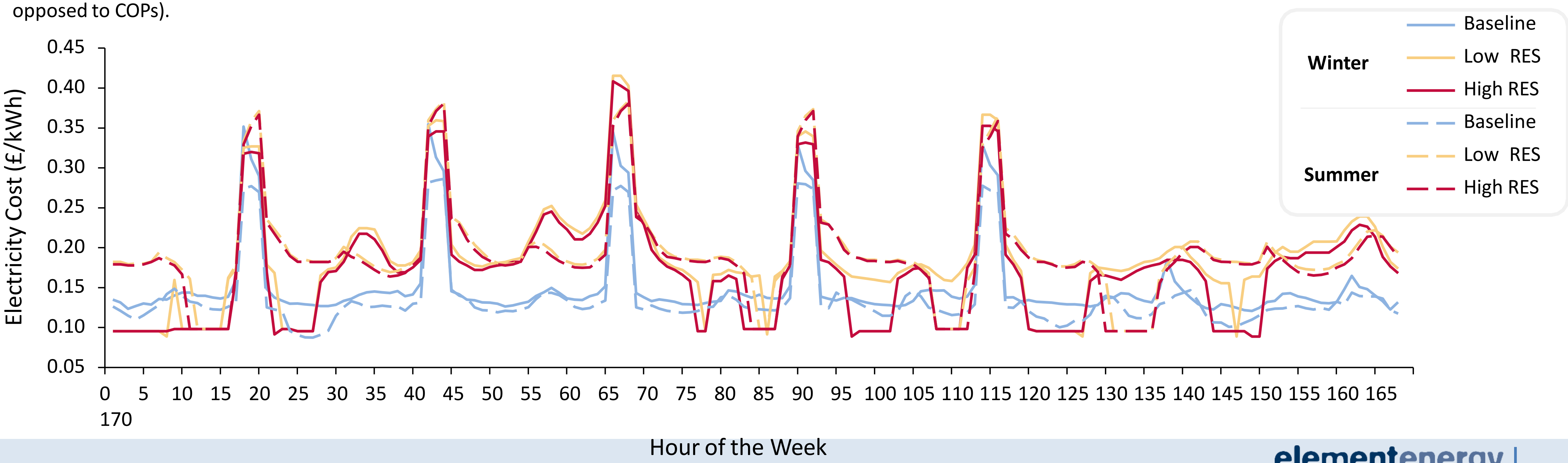
Note: the net demand represents the demand after subtracting the non-dispatchable "must-run" generation from the overall demand

1 BEIS 2021 Green book

The high and low RES 2030 projections have higher average costs than the 2020 baseline but with more variation incentivising flexible demand

Electricity Cost Projections

- The figure below shows **how hourly costs vary across a week** in the winter (solid lines) and in the summer (dashed lines) for each of the three electricity cost projections.
- **Unit costs peak in weekday evenings**, with higher peak costs in the RES 2030 scenarios than in the 2020 baseline.
- The **2030 high & low RES projections have generally higher costs** than the 2020 baseline but with **more variation in unit cost** across the day, increasing the financial incentive to move demand away from peak times
- Comparing the high and low RES projections, we see the high RES projection hitting the lower values for longer periods offering greater potential for lowering fuel costs with flexibility.
- The daily peaks are around 2-2.5 times higher than the average value for the day, such that **electricity prices become the dominant factor in optimising load shifting** (as opposed to COPs).



Element Energy's Flexible Asset Model (FAM) was used to optimise demand shifting to take into account variation in electricity prices and system COPs

Introduction to FAM

- Element Energy's Flexible Asset Model (FAM) has been developed to optimise the deployment of flexibility in various forms in response to external signals
  - In this study, these external signals are varying electricity prices and varying system COPs.

- In this study, the FAM has been configured to incorporate flexibility from:
  - **Preheating the thermal mass of the building**: allowing the operation of the heat pump to be shifted forward in time by an amount dependent on the thermal mass of the building, its heat loss rate and the allowable temperature reduction as defined by the householder type, as discussed on slides 32 & 33.
  - **Heat battery**: allows the HP operation to be shifted forward in time according to the thermal capacity of the heat battery and the heat loss rate of the building.

- The FAM was run for all combinations of the following elements:
  - **2 x technology options**: ASHP and GSHP shared loop
  - **2 x weather years**: average year (2015) and cold year (2010). The fuel costs shown on the following slides are for the average year unless stated otherwise.
  - **3 x electricity cost projections**: a baseline cost set using 2020 costs and flexibility, then two future projections based on RES 2030 scenarios with high or low renewable energy contributions. The fuel costs shown on the following slides use the 2020 baseline costs unless stated otherwise.
  - **2 x building types:** a retrofit property represented by the Victorian terrace home, and a new-build semi-detached property
  - **2 x householder types**: comfort and economy households with ±0.5 °C and +2/-1°C flexibility respectively
  - **2 x heat battery scenarios**: one scenario without a heat battery and one with a heat battery. The fuel costs shown on the following slides are without a heat battery unless stated otherwise.

- The following slides show how each of the elements above, in various combinations, affect the fuel costs for each of the building types.

The runs discussed today compare the technologies across the building types, householder types and the weather years using 2020 electricity costs

Flexible Asset Model Runs

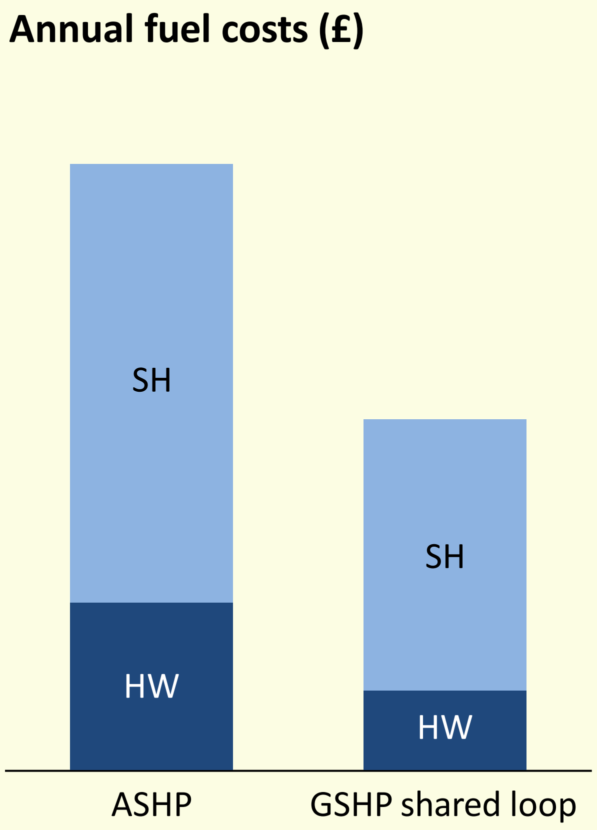
House Type	Victorian 3-bed Terrace				New Build 3-bed Semi			
Weather Year	**2015** 'average year'		**2010** 'cold year'		**2015** 'average year'		**2010** 'cold year'	
Flexibility Level	Comfort	Economy	Comfort	Economy	Comfort	Economy	Comfort	Economy
Heat Battery	*Yes / No*	*Yes / No*	*Yes / No*	*Yes / No*	*Yes / No*	*Yes / No*	*Yes / No*	*Yes / No*
Electricity Cost Projections	2020 Baseline 2030 High RES 2030 Low RES	2020 Baseline 2030 High RES 2030 Low RES	2020 Baseline 2030 High RES 2030 Low RES	2020 Baseline 2030 High RES 2030 Low RES	2020 Baseline 2030 High RES 2030 Low RES	2020 Baseline 2030 High RES 2030 Low RES	2020 Baseline 2030 High RES 2030 Low RES	2020 Baseline 2030 High RES 2030 Low RES

The following slides compare fuel costs across the two technologies for both property types, each section highlighting a different aspect of the modelling

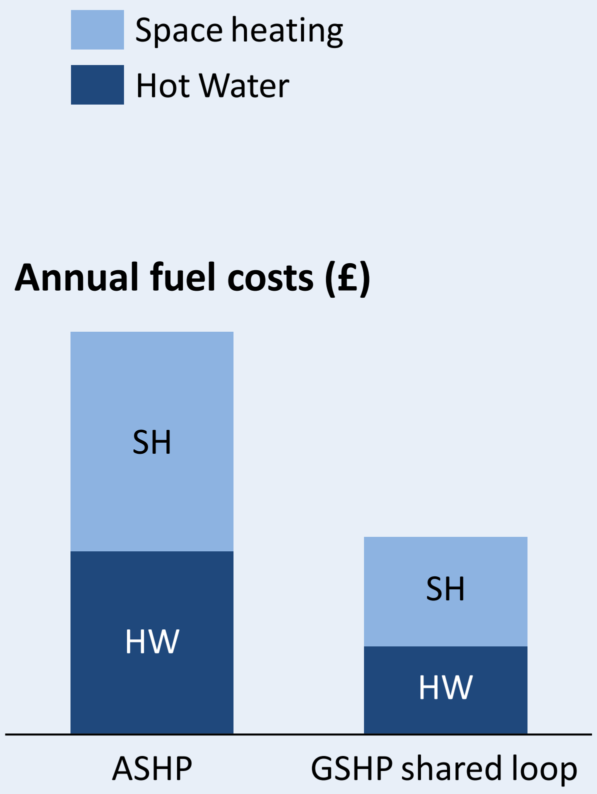
Modelling Annual Fuel Costs

- The following slides compare annual fuel costs between the two technologies: ASHP and the GSHP shared loop.
  - The figures right show an example of the figures on the following slides with results shown side by side for the retrofitted Victorian terrace and the new build semi-detached.
- The values shown **include fuel costs for space heating and hot water**:
  - Space heating is initially modelled as a passive demand, with various levels of flexibility introduced throughout the analysis
  - Hot water demand is always flexible as a hot water tank is included in all scenarios
- The **connection fee is not included in the figures on the following slides** as the connection fee should be considered alongside the annualised capex.
- Each of the following sections compares a different aspect of the modelling including:
  - Thermal mass flexibility
  - Weather years
  - Electricity cost projections
  - Flexibility from using a heat battery.

Victorian 3-bed Terrace



New Build 3-bed Semi



On fuel costs alone (not including connection fee), the GSHP shared loop system offers savings of around 40% compared to ASHP systems

Annual Fuel Costs with Passive Operation

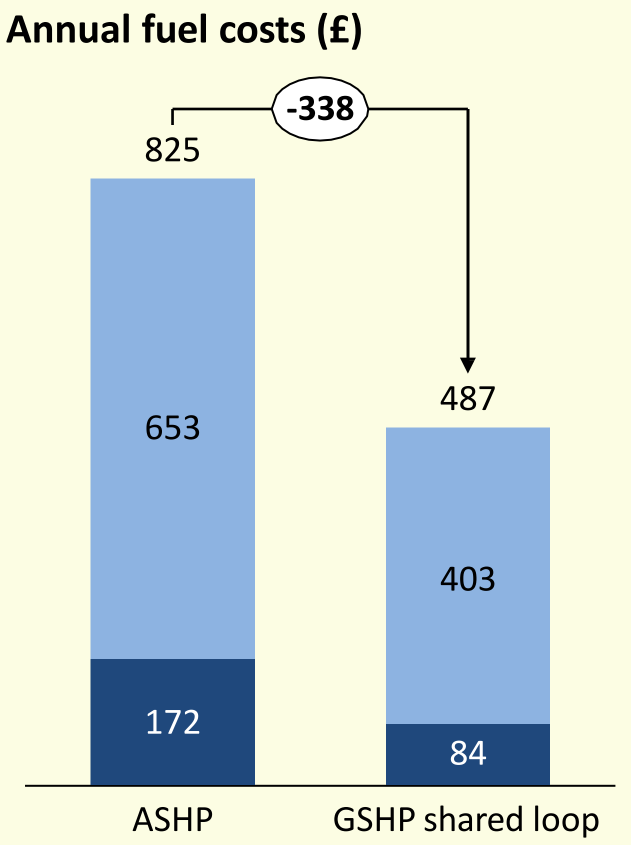
Details

- The figures shown here illustrate the difference in annual fuel costs between ASHP and GSHP systems.
- The figures shown right are for **2020 baseline electricity costs** with passive space heating and a hot water cylinder.
- The connection fee values shown are based on a 4% IRR, a 40 year investment lifetime and 2020 capex costs.

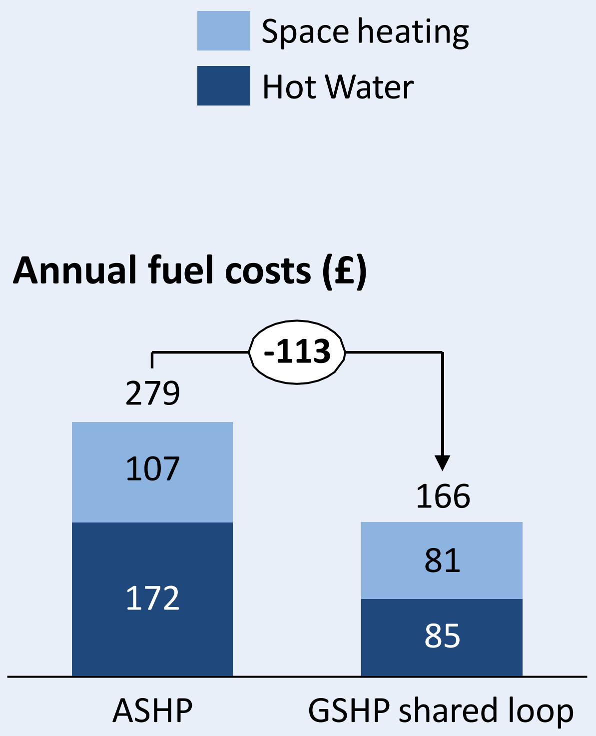
ASHP vs GSHP

- Without the connection fee, **GSHP systems offer annual fuel cost savings of around 40% compared to ASHP**.
- The savings for the retrofit are around £338 per year, compared to around £113 for the new build.

Victorian 3-bed Terrace



New Build 3-bed Semi



Flexibility using the building's thermal mass offers fuel cost savings of 8% to 19%, which translates to greater absolute savings for the ASHP systems than the GSHP systems

2020 Baseline Fuel Cost Comparison with Thermal Mass Flexibility

Details

- The figures shown here illustrate the difference in annual fuel costs between ASHP and GSHP systems plus the **potential savings from flexibility using the buildings' thermal mass**
- The figures shown right are for **2020 baseline electricity costs**.

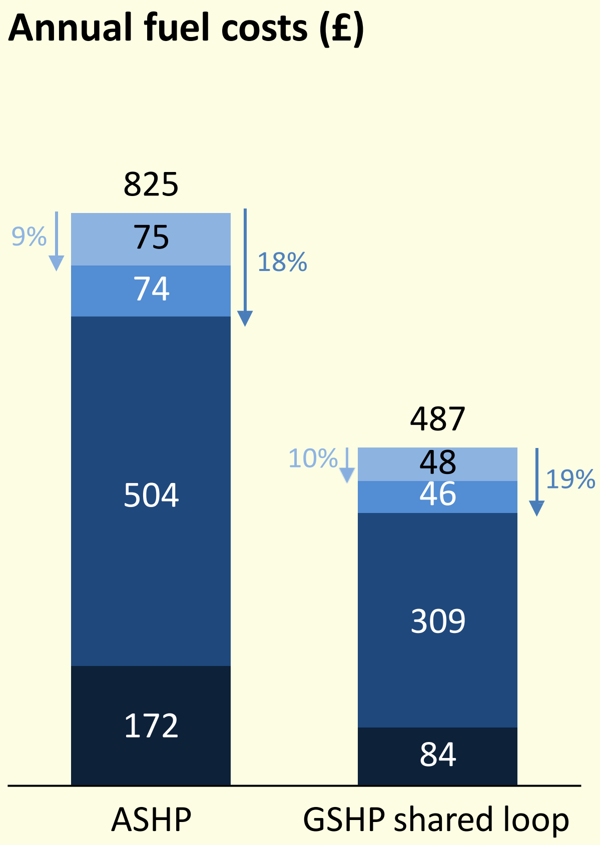
ASHP vs GSHP

- The percentage savings from thermal mass flexibility are similar across the technologies
  - Therefore **ASHP systems see greater absolute savings** from flexibility.

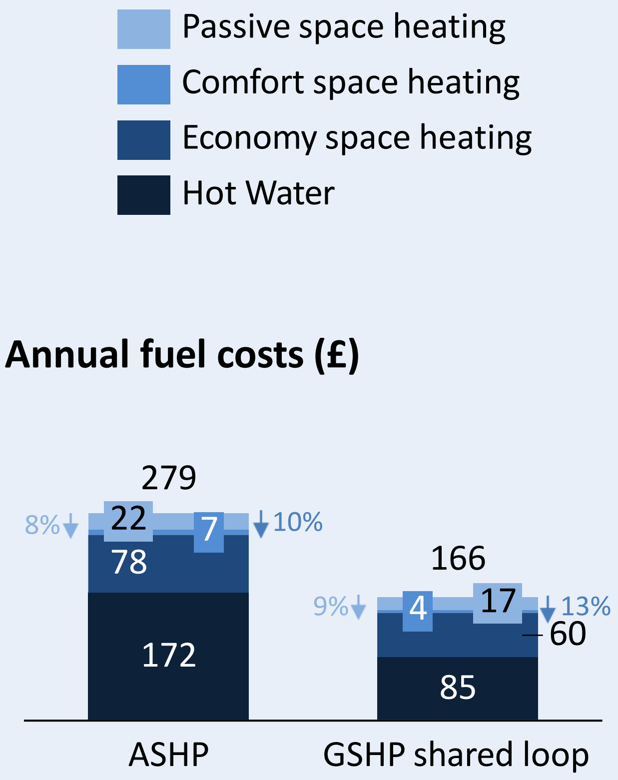
Thermal Mass Flexibility

- Flexibility from **Comfort householder type** offers fuel cost savings compared to passive operation of
  - **Retrofit: £75** for the **ASHP**, **£48** for the **GSHP** systems (~10% for both technologies)
  - **New build: £22** for the **ASHP, £17** for the **GSHP**
- Compared to passive operation, **Economy householder type** offers fuel cost savings of
  - **Retrofit: £149** for the **ASHP**, **£94** for the **GSHP retrofits** (just under 20% for both technologies)
  - **New build: £29** for the **ASHP**, **£21** for the **GSHP** (10%-13% reductions)

Victorian 3-bed Terrace



New Build 3-bed Semi



The 2030 low RES scenario has higher overall costs than the 2020 baseline but greater benefits from flexibility

2030 Low RES Fuel Cost Comparison with Thermal Mass Flexibility

The following two slides show annual fuel costs, similar figures to that shown on slide 64, but with the future electricity cost projections.

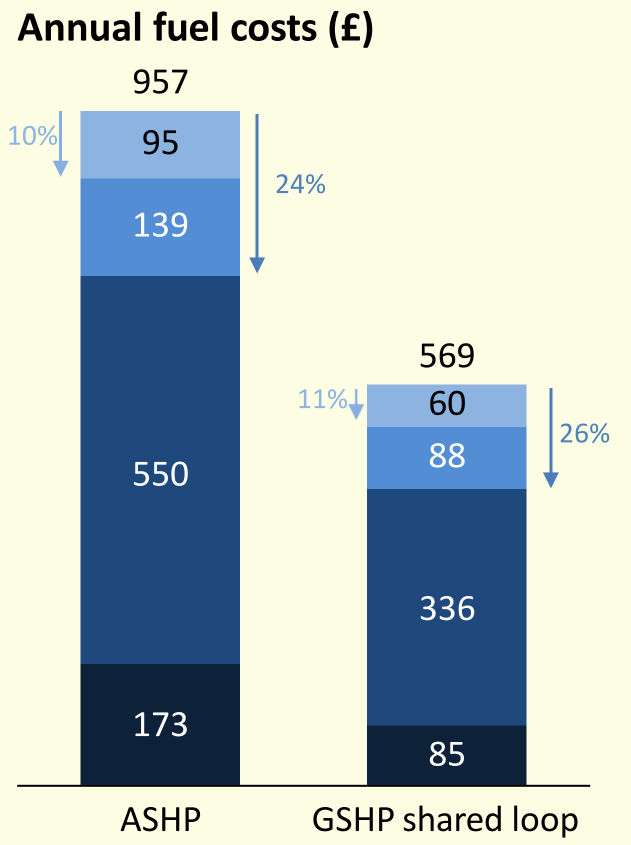
Electricity Cost Projection

- The figures shown right are for the **2030 low RES fuel costs**
- The **fuel costs in all scenarios are higher** than in the 2020 baseline
  - The increase in electricity costs translates to an **increase in fuel cost savings for GSHPs** compared to ASHPs.

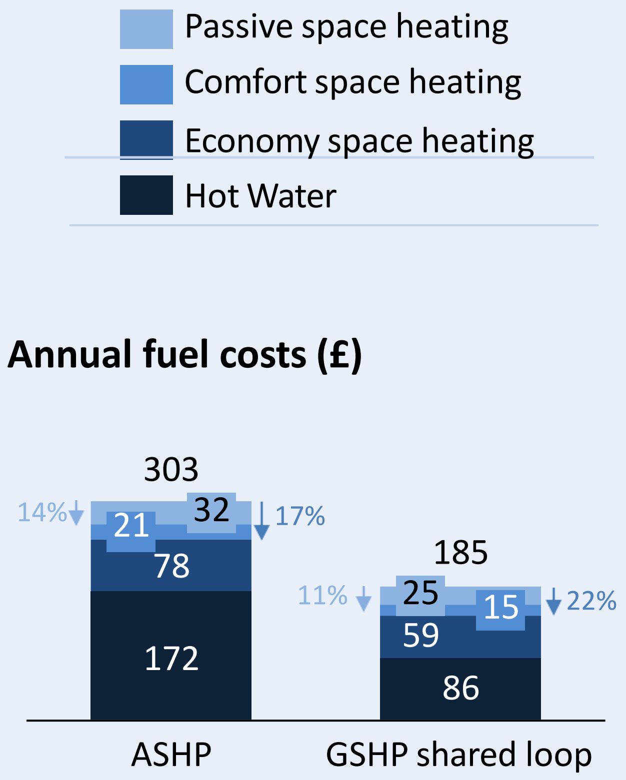
Thermal Mass Flexibility

- Percentage fuel cost savings in the comfort scenario are similar to those with the 2020 baseline electricity costs, however, in the economy scenario savings increase to close to 30% (compared to 20% with 2020 baseline)

Victorian 3-bed Terrace



New Build 3-bed Semi



Costs in the 2030 high RES scenario are above the 2020 baseline but below the 2030 low RES scenario for passive space heating with economy fuel costs almost equal to the 2020 baseline

2030 High RES Fuel Cost Comparison with Thermal Mass Flexibility

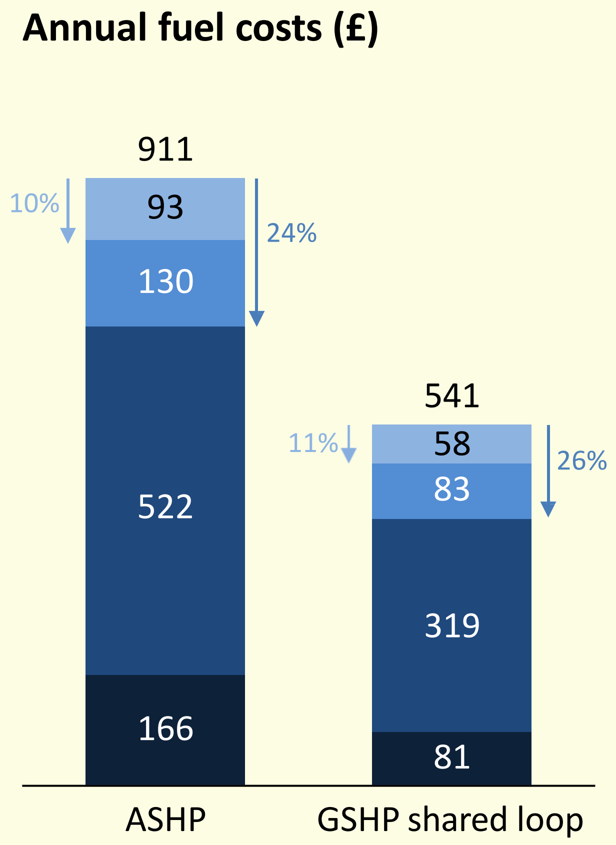
Electricity Cost Projection

- The figures shown right are for the **2030 high RES electricity costs**
- The costs in all scenarios are higher than in the 2020 baseline but lower than the low RES 2030 costs
  - The same pattern is observed in the absolute savings moving between technologies
- In the **passive** scenario, **annual fuel costs for the GSHP system are £370 lower than for the ASHP system**, almost fully compensating for the £385 connection fee
  - The greater ASHP savings from reduce the fuel costs savings for the GSHP to £288.

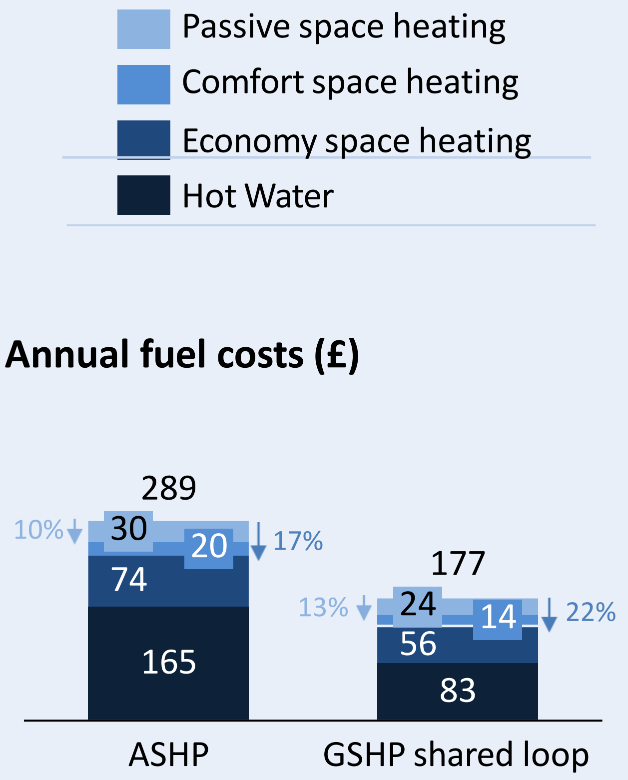
Thermal Mass Flexibility

- As with the 2030 low RES scenario, percentage fuel cost savings in the comfort scenario are similar to those with the 2020 baseline electricity costs, however, in the economy scenario savings increase.
- **Comfort** offers savings of:
  - **10%-11%** for the **retrofit**
  - **10%-13%** for the **new build**
- **Economy** offers savings of:
  - **24%-26%** for the retrofit
  - **17%-22%** for the new build.

Victorian 3-bed Terrace



New Build 3-bed Semi



For the retrofit property, all scenarios have fuel savings from GSHP shared loop systems relative to ASHP systems equal to or higher than the **2030** connection fee

Comparison: Fuel Cost Savings vs Connection Fee (GSHP shared loop)

- The figure shows the **difference in fuel costs between ASHP and GSHP shared loop system**
  - If a GSHP shared loop system was to incur the same annual charges for the user, i.e. the connection fee was balanced by the fuel cost savings, the figure on the left would represent the maximum chargeable connection fee.
  - The values are shown for each of the three electricity cost projections.

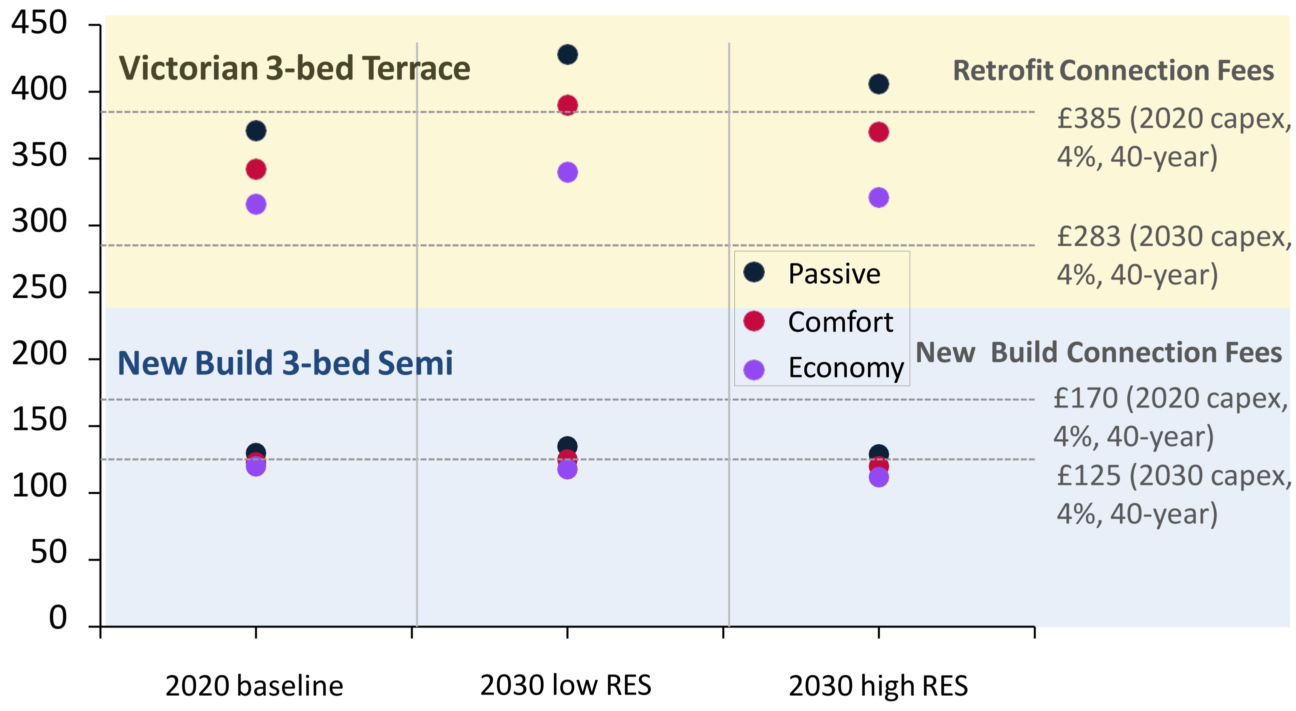
- ***Note that these comparisons are between the annual fuel cost savings and the connection fee only; the comparisons do not account for the lower annualised capex of the GSHP systems*.**

- The fuel cost difference between the systems is:
  - Retrofit: £270 - £440
  - New build: £100 - £150

- Flexibility measures bring the difference down to the lower end of those ranges, due the larger absolute reduction in ASHP fuel costs than GSHP fuel costs from flexibility.

- By 2030, for the retrofit property, all scenarios have lower combined annual fuel costs and connection fee for the GSHP shared loop system than for the ASHP system, with the new build properties being within £15.

Fuel cost savings between ASHP and GSHP systems (£/year)



In the cold year, fuel costs for the ASHP in the retrofit increase by £240-£270, compared to increases of £100-£110 for the GSHP

Comparing Weather Years

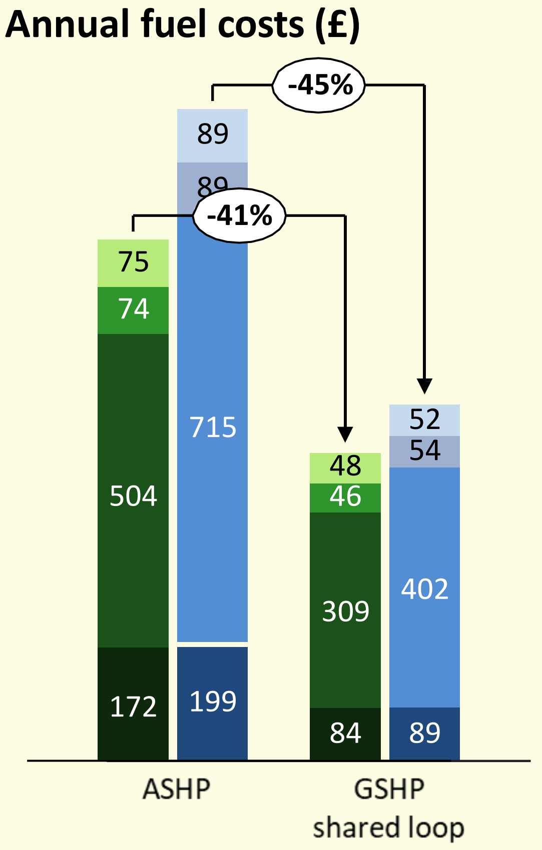
Weather years

- Two weather years were compared to understand the difference between ASHP and GSHP performance in a typical year (2015 in green) and a 1-in-20 cold year (2010 in blue).
- Demand for space heating increased by around 20% in the cold year compared to the average year, while demand for hot water increased by around 5%.

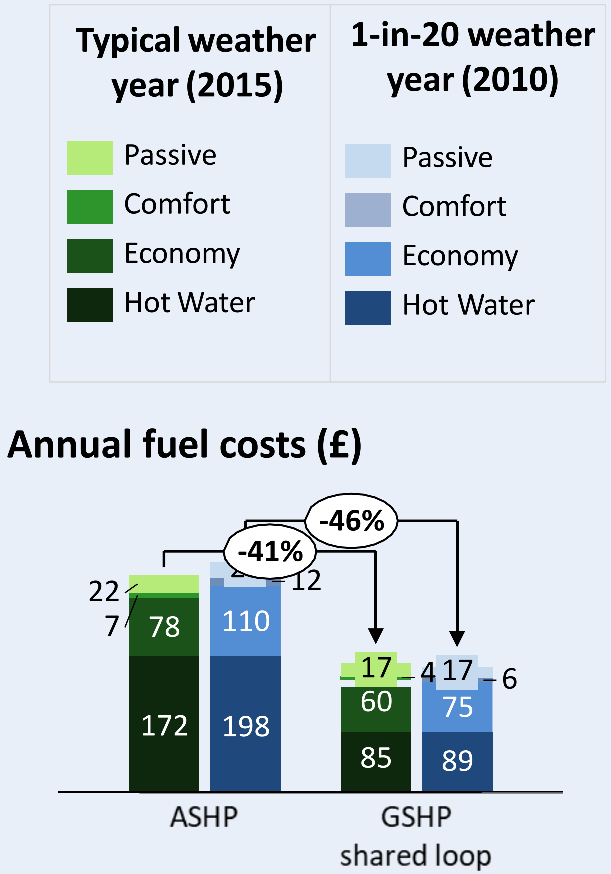
Comparing Fuel Costs

- The figures shown here **compare the fuel costs in the average year and the cold year, not including the connection fee.**
- Fuel cost savings for the GSHP relative to the ASHP increase from 41% in the average year to 45%/46% in the cold year.
- In the passive case, ASHP fuel costs increase by around £270 in the cold year, compared a £110 increase for the GSHP system for the retrofit (increases of £64 and £21 for ASHP and GSHP respectively in the new build).
- The impact of flexibility in 2010 is lower than in 2015 (in terms of %).
- The **fuel cost savings in the cold year** are £495 for the retrofit and £156 for the new build, **comparable to the £170 connection fee for the new build** and **far above the £385 connection fee for the retrofit**.

Victorian 3-bed Terrace



New Build 3-bed Semi

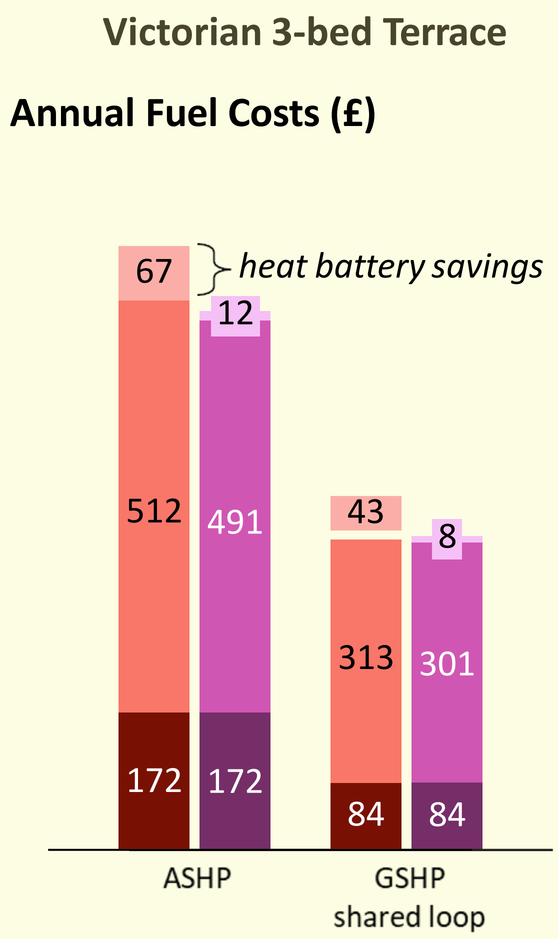


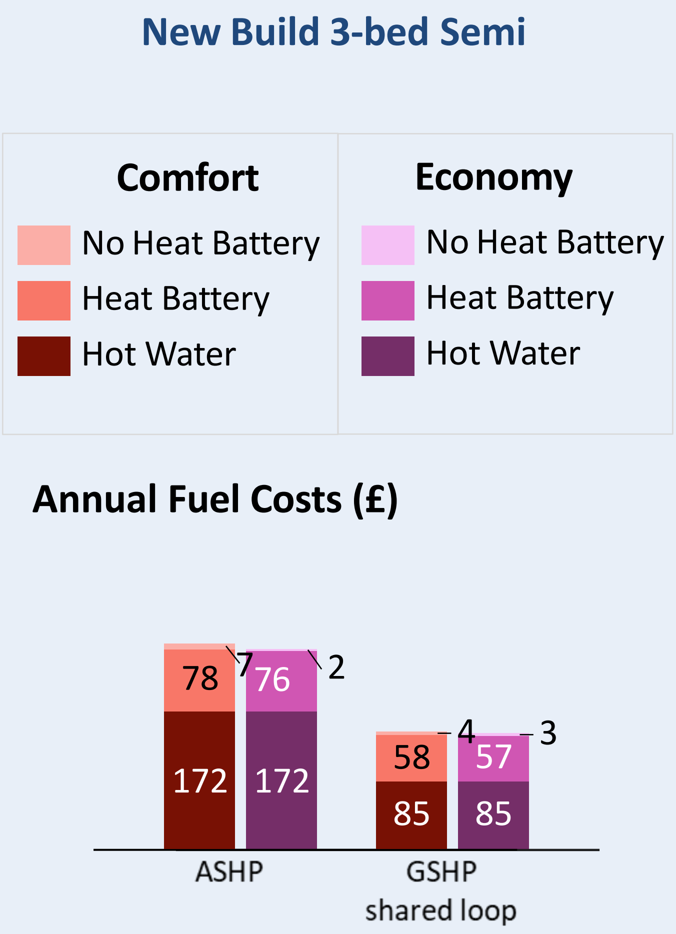
Only the comfort scenario in the retrofit has cost savings high enough to justify the additional capex of a heat battery with 2020 electricity costs

Heat Battery: 2020 Baseline

- The incorporation of a heat battery adds an additional level of flexibility into the heat demand profiles of the buildings.
- The figure right compares the impact of including the heat battery on fuel costs for the **2020 baseline electricity costs**.
- The heat battery increases the capex costs by £500, with an assumed lifetime of 20 years
  - The **comfort scenario** for the **retrofit ASHP** has a **payback period of 7.5 years**
  - The **retrofit GSHP comfort** scenarios have **payback times of 12 years** which is unlikely to be desirable to the majority of homeowners
  - None of the retrofit economy scenarios or any of the new-build scenarios have payback times shorter than the 20-year lifetime of the battery.

- In the **retrofit** scenario, the **inclusion of a heat battery brings the fuel costs in the comfort scenario down to being similar to those in the economy scenarios**
  - The heat battery therefore offers an alternative to using the building thermal mass for accessing the benefits of flexible tariffs.



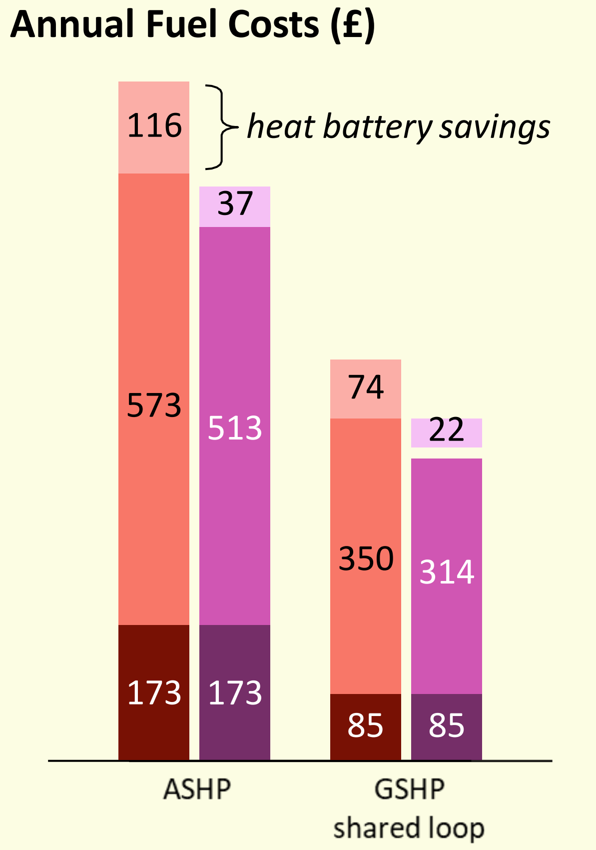


The 2030 RES scenarios are more favourable for incorporating a heat battery for the retrofit scenarios, with payback times of 4-7 years in the comfort scenarios

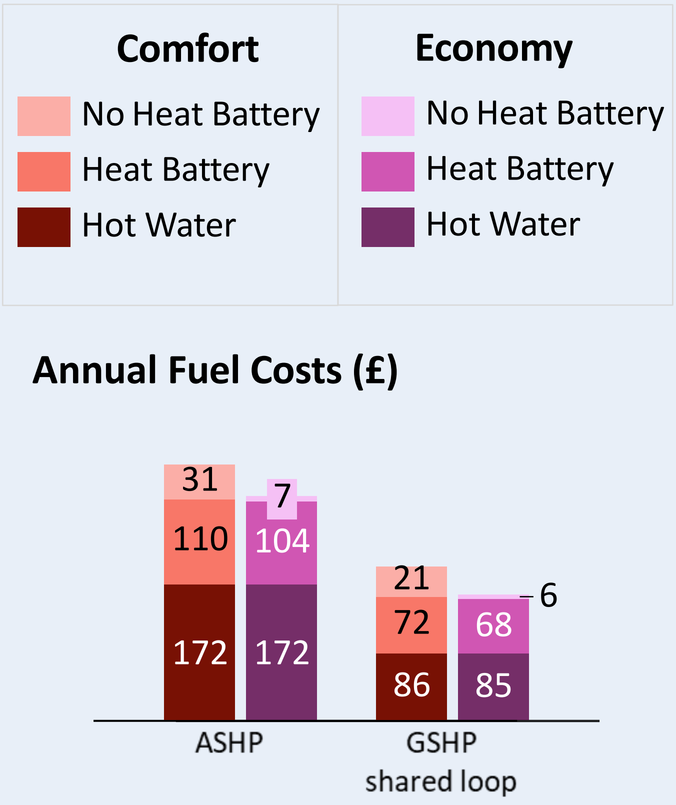
Heat Battery: 2030 Low RES

- The figure right compares the impact of including the heat battery on fuel costs for the **2030 low RES electricity costs**.
- Fuel costs in the 2030 RES scenarios vary more across a day than in the 2020 baseline, incentivising more flexible demand.
- This increased in financial benefit for flexibility means that:
  - **ASHP systems** in **retrofits** have payback times of around **4 years** in the **comfort scenario, 14 years** in the **economy scenario**
  - **GSHP systems** in retrofits have payback times of 7 years in the comfort scenario but the economy scenarios do not payback within the technology lifetime
  - In the new build, only the ASHP comfort scenario has a payback time shorter than the technology lifetime, at 16 years.

Victorian 3-bed Terrace



New Build 3-bed Semi

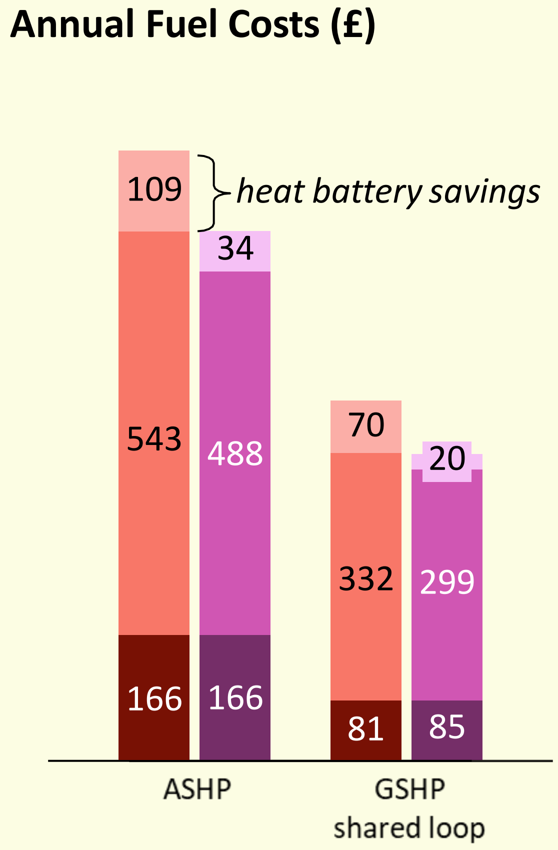


Across the electricity cost projections, the heat battery has the greatest impact in the comfort scenario, offering an alternative to using the building thermal mass to access low-cost electricity

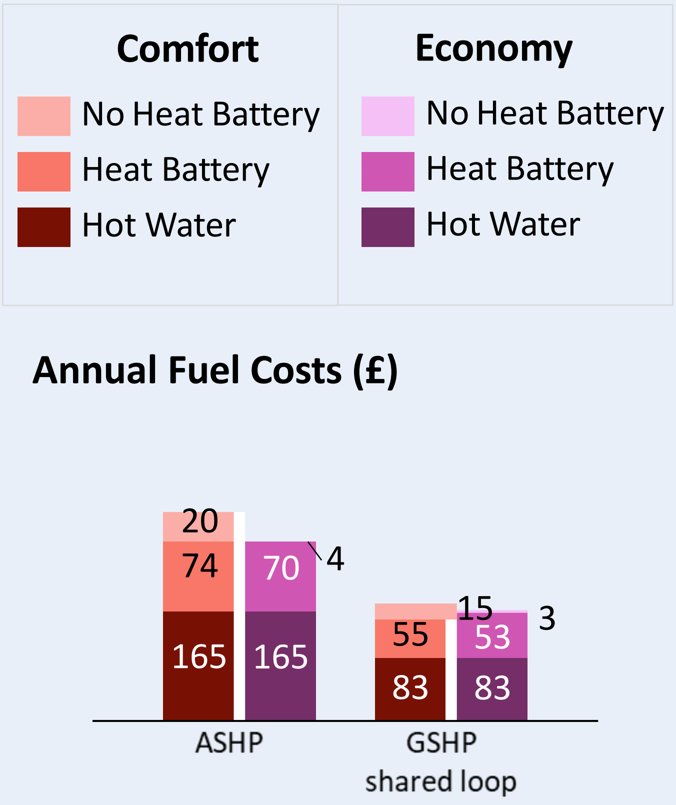
Heat Battery: 2030 High RES

- The figure right compares the impact of including the heat battery on fuel costs for the **2030 high RES electricity costs**.
- The **high RES 2030 scenario shows a broadly similar picture to the low RES 2030** in terms of percentage reductions from including a heat battery.
- However, the increased number of low tariff hours means that the heat battery is less critical for accessing those hours.
- The retrofit scenarios have payback times of:
  - 5 years for the ASHP comfort
  - 7 years for the GSHP systems with comfort
  - 15 years for the ASHP with economy.

Victorian 3-bed Terrace



New Build 3-bed Semi



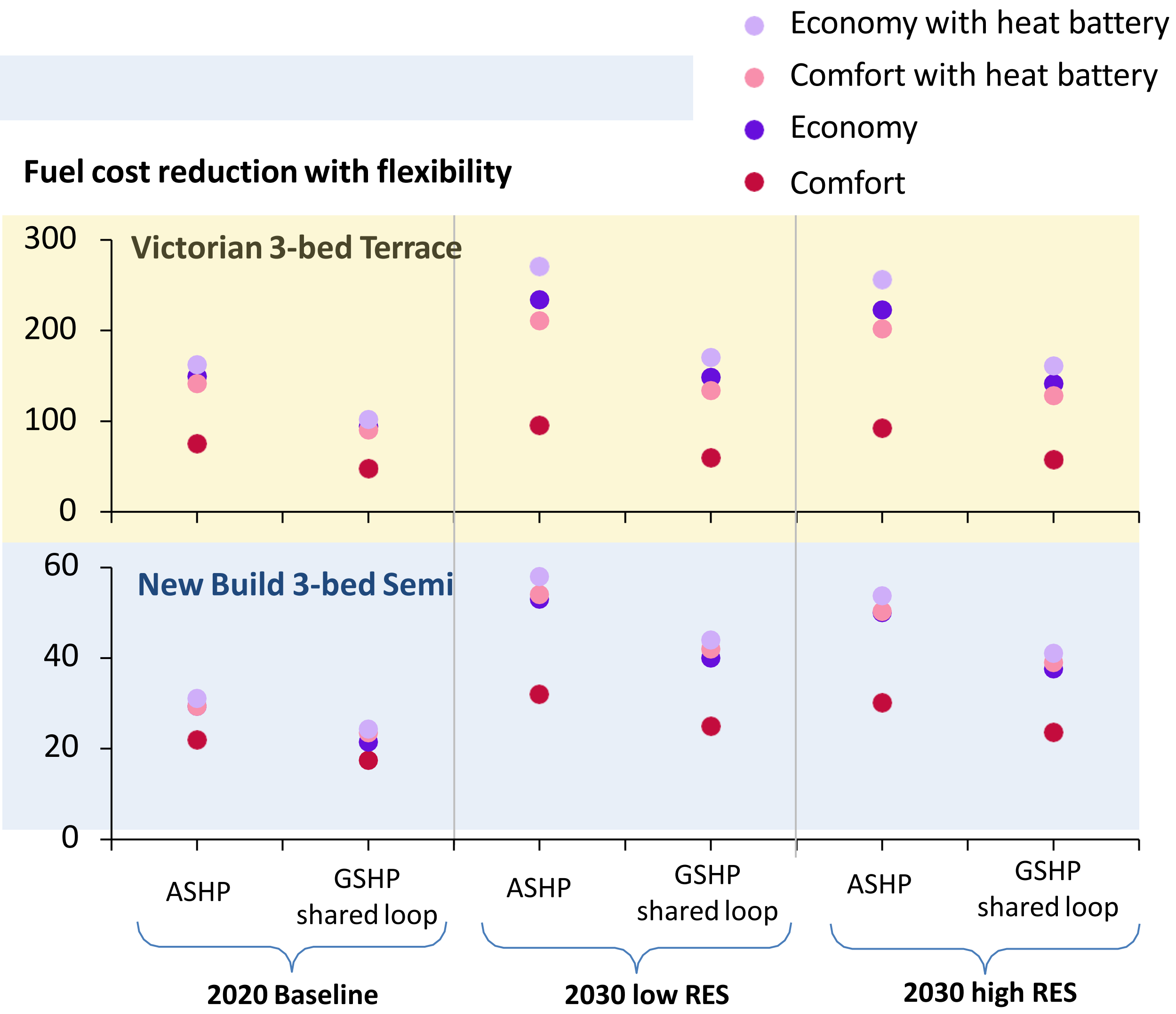
The heat battery is particularly beneficial for the comfort household as it offers an alternative to thermal mass flexibility to access low-cost electricity

Impact of Flexibility Measures on Fuel Costs

- The figure on the right shows the **reduction in fuel costs with both thermal mass flexibility and a heat battery**.
- As discussed previously, flexibility measures have a larger impact on ASHP fuel costs than GSHP due to the higher passive costs and similar percentage reductions.
- The figure on the right illustrates how, particularly for the new build, the use of a **heat battery brings flexibility savings in the comfort household in line with that of the economy household**.
  - The heat battery has much less of an effect on the fuel costs in the economy household, as the economy hours of flexibility generally already allow access to the low-cost electricity hours.

- A **heat battery therefore offers a mechanism for optimising time-of-use tariffs even with limited hours of flexibility offered through thermal mass**.
- The alternative to thermal mass flexibility offered by the heat battery enables a greater degree of flexibility in homes with reduced hours of flexibility either through householder behaviour (as modelled in this study) or due to low building thermal mass or higher building heat loss.

Fuel cost reduction with flexibility

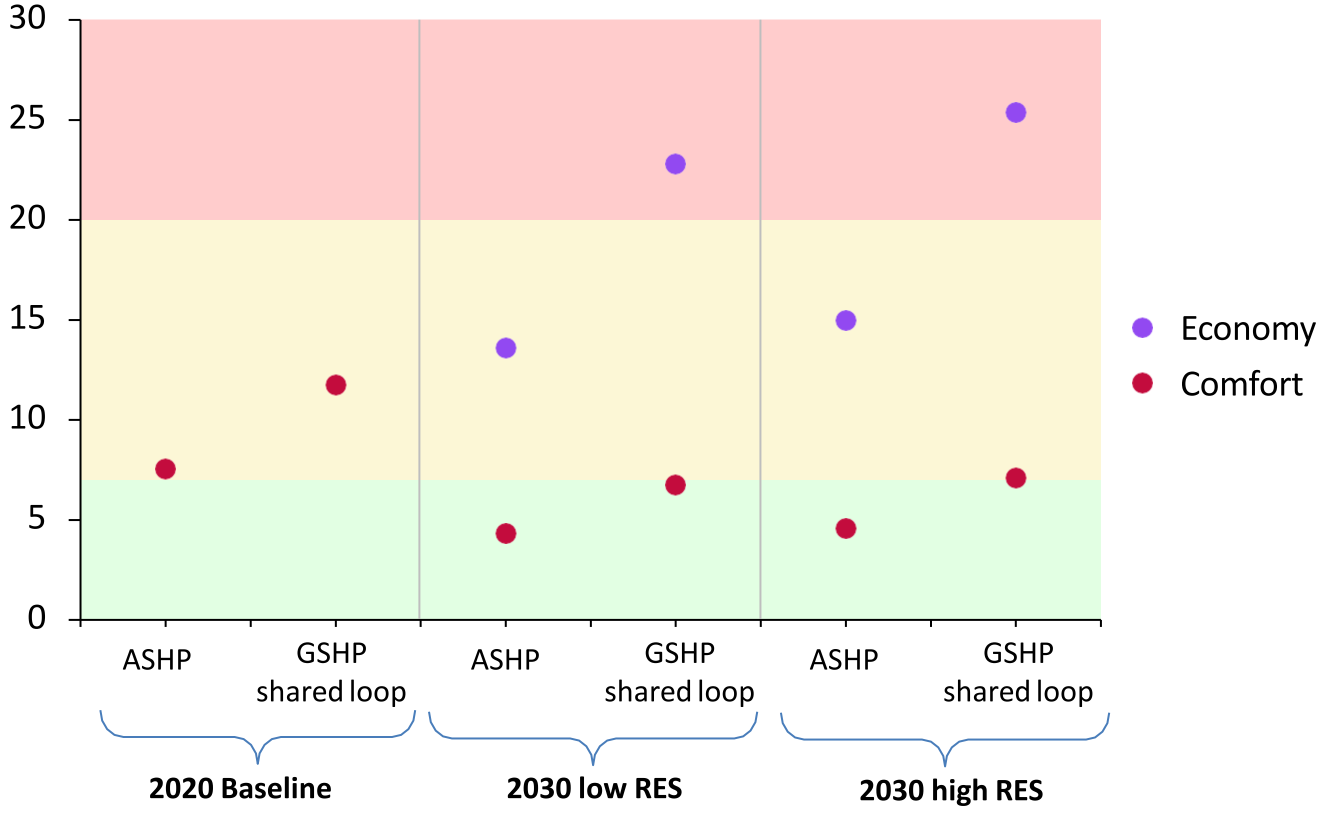


A heat battery makes greatest financial sense with the comfort household and only in the retrofit case, with payback times as low as 5 years

Incorporating a Heat Battery

- A heat battery allows increased access to low-cost electricity through time of use tariffs.
- The figure on the right shows the payback times for a heat battery. These calculations are based on the reduction in fuel costs from using a heat battery compared to thermal mass flexibility alone
  - Results are only shown for the retrofit, as **no new-build scenarios have payback times below the 20-year** heat battery lifetime.
  - The economy results for the 2020 baseline electricity costs are also not shown as they are greater than 30 years
- The figure right has been coloured according to the following thresholds
  - The **green band** on the figure to the right highlights which scenarios have **payback times of 7 years or less**, most attractive to homeowners.
  - The **yellow band** on the figure highlights scenarios where the **payback is between 7 years and the lifetime of 20 years**.
  - The **red band** indicates payback times longer that the expected system lifetime.
- The figure highlights how a **heat battery becomes a more attractive investment with the RES 2030 cost projections** and in the **comfort households**.
- The **comfort household also represents other types of homes with lower hours of flexibility**, such as those with **higher heat loss** or **lower thermal mass.**

Payback times (years) for the Victorian Terrace 2015 scenarios



The annualised costs incorporate the annual costs (fuel costs, connection fee and servicing costs) plus the capex costs annualised across the system lifetime

Annualised Cost Analysis

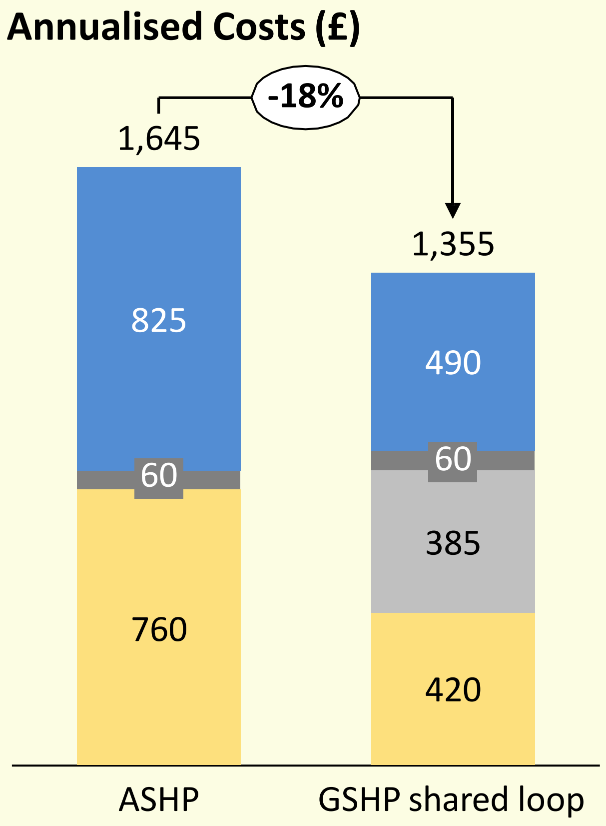
- The following slides bring together the all the costs set out in the previous sections to compare the annualised costs for each technology
  - Connection fees discussed in slides 21
  - Capex costs discussed on slide 36
  - Opex costs on slide 37
  - Fuel costs discussed in the Household level analysis section
    - The following slides show the 2020 baseline electricity costs with fuel costs shown for economy, comfort and passive operation.
- The system lifetimes, shown on slide 37, are used to calculate the annualised capex costs.

Compared to ASHP systems, the annualised cost for the GSHP shared loop system is around £340 lower for the retrofit and £115 lower for the new build home

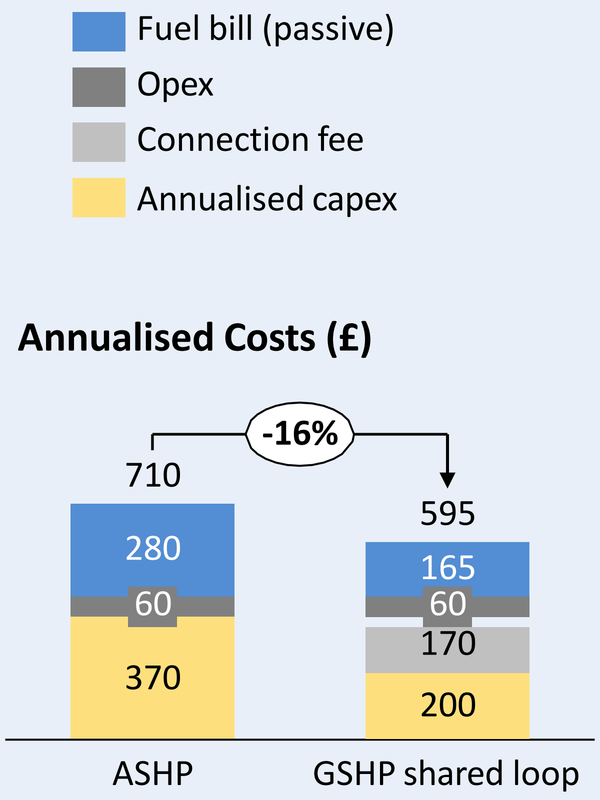
Total Annualised System Costs

- The figures right show the **annualised costs for capex, opex, fuel costs and connection fee**. All costs shown are for 2020 (i.e. 2020 capex values, and 2020 baseline electricity costs).
- These figures show the base level costs before any space heating flexibility is applied:
  - Space heating is 'passive' in this scenario
  - Hot water is intrinsically flexible through using a hot water tank.
- For passive heating, the annual cost (combined fuel cost and connection fee) is around £50 more per year for the GSHP shared loop system than for the ASHP in the retrofit, £55 more the new build.
- Annualised capex costs for the householder (i.e. excluding groundworks) are £340 lower than ASHP costs for the retrofit and £170 lower for the new build.
- Combining fuel costs, connection fee and annualised capex, the **annualised costs for GSHP shared loop systems are up to £290 per year (18%) lower than for ASHP** systems for the retrofitted property. The new build offers annualised savings of £115 per year (16%).

Victorian 3-bed Terrace



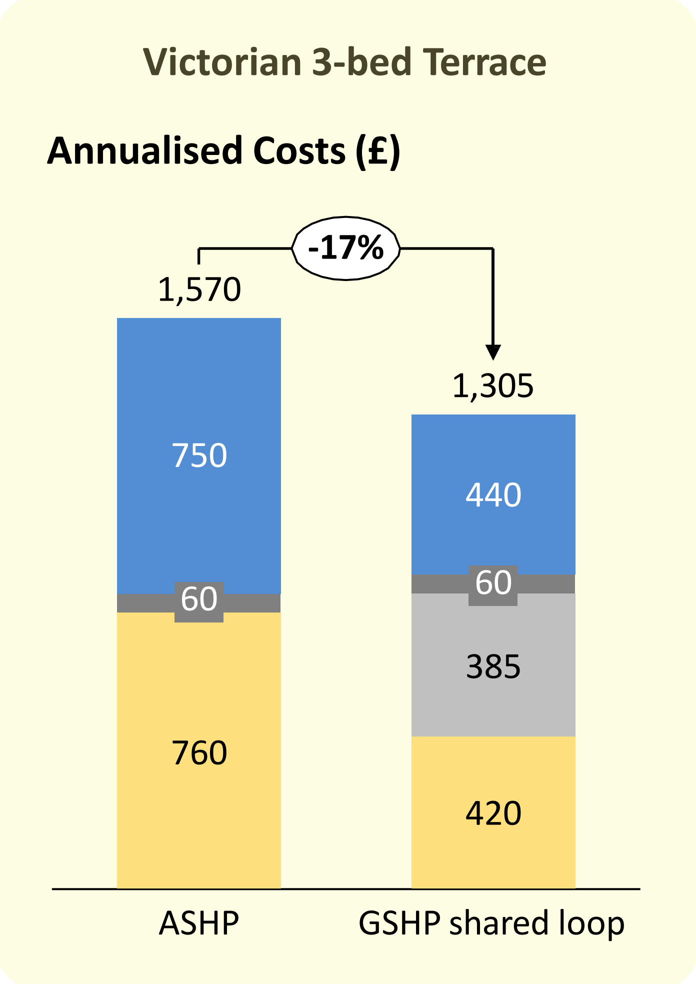
New Build 3-bed Semi

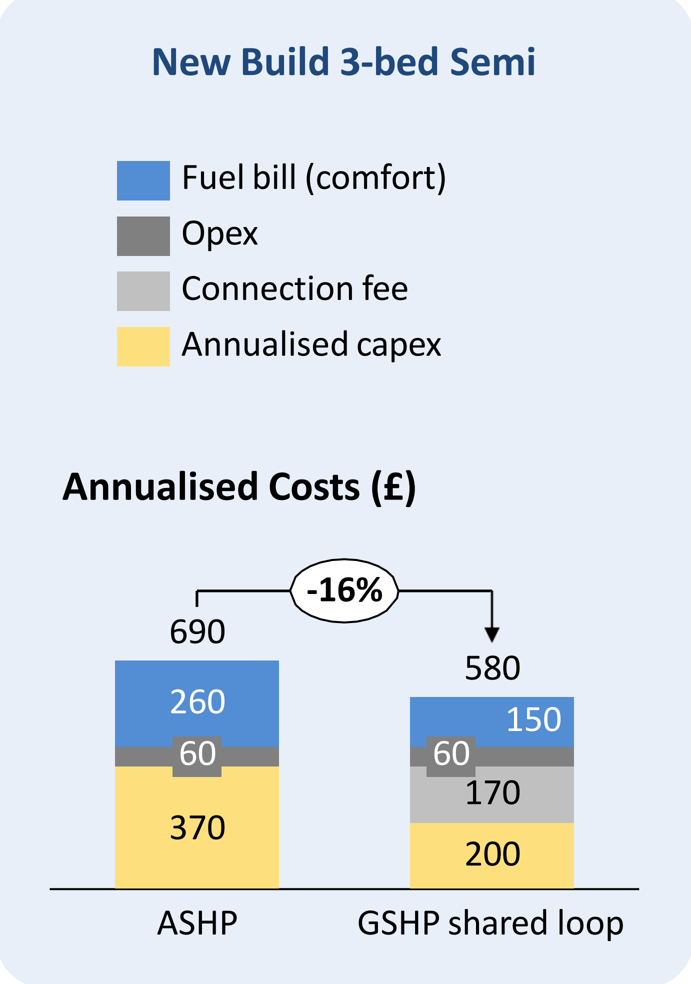


For the comfort scenario, the difference between the annualised costs reduces from £290 to £265, favouring ASHP systems due the larger impact flexibility has on ASHP fuel costs

Annualised Cost of Heat Pump Systems: Comfort Household

- The figures right show the **annualised costs for capex, opex and fuel costs**.
- The capex costs shown are for 2020 with the 2020 baseline electricity costs.
- These figures show the fuel costs for the **comfort** household.
- When comparing the annualised figures:
  - The flexibility offered by the comfort scenario reduces fuel costs by around 10% for both the ASHP and GSHP systems.
  - The **difference between the annualised costs for ASHP and GSHP shared loop system reduces by only around £35** in the retrofit, from £290 less for GSHP in passive to £265 less with comfort. The new build changes by only £5 per year, with annualised savings from the GSHP system reducing from £115 per year to £110.
  - This change has very little impact on the % difference between the ASHP and GSHP systems.





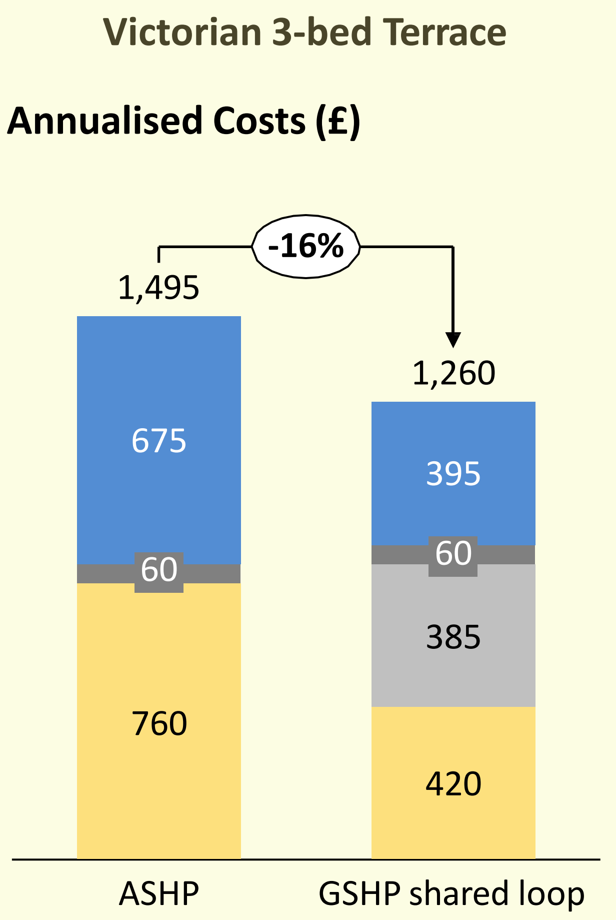
Flexibility offered by the economy scenario reduces the annualised cost savings for the GSHP shared loop system over the ASHP system by £55 per year, around 20% of the savings

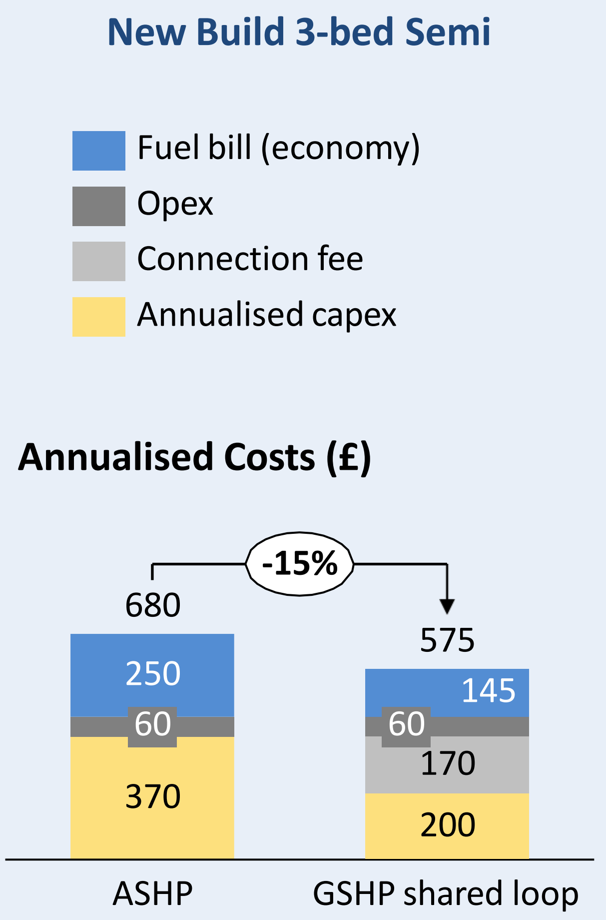
Annualised Cost of Heat Pump Systems: Economy Household

- The figures right show the **annualised costs for capex, opex and fuel costs**.
- The capex costs shown are for 2020 with the 2020 baseline electricity costs.
- These figures show the fuel costs for the **economy** household.
- When comparing the annualised figures:
  - The flexibility offered by the comfort scenario reduces fuel costs by around 15%-25% depending on the electricity profile used.
  - The percentage difference between the ASHP and GSHP shared loop systems reduces by 1%-2% when moving from passive to economy for the retrofit.
  - The **difference between the annualised costs for ASHP and GSHP shared loop system reduces by around £55** in the retrofit, from £290 less for GSHP in passive to £235 less with economy. The new build changes by only £10 per year, with annualised savings from the GSHP system reducing from £115 per year to £105.

Conclusion

- **Flexibility reduces the annualised cost savings for the GSHP shared loop system over the ASHP system by £55 per year when considering annualised costs**, from £290 to £235.





Annualised costs for the GSHP shared loop systems are around 25% lower than for the ASHP system for the retrofit and 20% lower for the new build

Key Messages

Annual Fuel Costs

- GSHP systems offer fuel cost savings of around 40% compared to ASHP systems in the average year.

Combined Annual Fuel Cost and Connection Fee

- The annual fuel cost savings for the GSHP system compared to the ASHP are lower than the calculated connection fees required based on 2020 capex. As such, the GSHP systems have higher annual costs by around £50-£100.
- Calculating the connection fee using 2030 capex, the annual fuel cost savings for GSHP versus ASHP are higher than the connection fee.

Total Annualised Costs

- The combined annual fuel costs and connection fee are a maximum of 15% more than ASHP; capex costs (excluding groundworks) are around 10% lower than ASHP costs. Combined with the much longer lifetimes for the GSHP system, total annualised costs for the GSHP systems are around 25% lower than for the ASHP system for the retrofit and 20% lower for the new build.

Average Year vs Cold Year

- In the 1-in-20 cold year, the fuel cost savings from GSHP systems increases from 40% to 45%, reflecting the reduced impact of cold weather on GSHP systems compared to ASHP systems due to the relative stability of the ground temperature compared to the air temperature

Electricity Cost Projections

- The 2030 RES scenarios have higher average electricity costs but greater flexibility in the tariffs
- Fuel costs in the passive scenario are higher in the 2030 RES scenarios than with the 2020 baseline costs but can be brought close to 2020 costs by shifting demand times through flexibility measures.

Flexibility through the use of thermal mass and a small temperature variation tolerance or a heat battery leads to fuel cost savings of up to 40% in the average year

Key Messages

Thermal Mass Flexibility

- The fuel costs for the ASHP and GSHP systems have similar percentage reductions when incorporating flexibility
  - This is because the optimisation process is dominated by the large daily fluctuations in electricity unit cost relative to the daily variation in COP
  - With similar percentage reduction, flexibility reduces the absolute fuel costs of ASHP more than GSHPs because ASHP have much higher passive fuel costs
- Comfort flexibility through thermal mass offers savings in the region of 10% for the retrofit and 20% for the new build relative to passive heating
  - the larger impact for the new build is a result of the greater hours of flexibility for the same temperature drop tolerance offered by the new build due to the lower heat loss rate.
- Economy flexibility offers savings in the region of 20%-35% for the retrofit and 25%-40% for the new build relative to passive heating (comfort new build already allow access to much of the low-cost electricity hours)

Heat Battery

- The additional of a heat battery to the Comfort householder type brings fuel costs in line with the Economy householder type without a heat battery
- The additional of a heat battery to the Economy householder type has little impact on the fuel costs as the Economy flexibility already allows access to much of the low-cost electricity hours
- A heat battery is therefore an alternative to thermal mass flexibility (where householder is less tolerant to temperature variation, and/or thermal mass is low, and/or heat loss is high)

Phase 1 of this study is now complete, phase 2 (if taken forward) will focus on national level analysis to compare the impact of ASHP and GSHP systems on the wider energy system

Future Work and Next Steps

Future Work

- This report has covered the analysis carried out in phase 1 of this study, which has focussed on household level analysis for two house types.
- In phase 2, the analysis would be extended to a national level, taking into account a larger range of building types and consider the impact of each technology system studied on the wider energy system.
- The national level analysis will consider a larger number of house and householder types, to enable modelling of the full UK building stock.
- The impact of the different scenarios for heat pump rollout (GSHP vs ASHP) on upstream electricity generation, transmission and distribution can then be quantified as part of the wider electricity system.
- Where the phase 1 analysis assumes a set of half-hourly electricity costs as an input, the Phase 2 national analysis determines the half-hourly electricity costs as an output.
- This “whole system” assessment will be carried out using Element’s ISDM model, was designed to optimise the electricity supply and demand at a national level, expressly accounting for the flexibility afforded by each demand segment and/or by grid-level storage assets. The outputs of the modelling will include:
  - Peak electricity system demand
  - Generation cost
  - Network cost
  - Total electricity system cost
- When combined with the capital and operating costs as used in Phase 1, this will also allow a comparison of the scenarios in terms of total annualised cost of heating across the national stock.

Next Steps

- Handover of model data to Kensa
- Discussion of phase 2 analysis.

Leeds represents a UK average for weather data

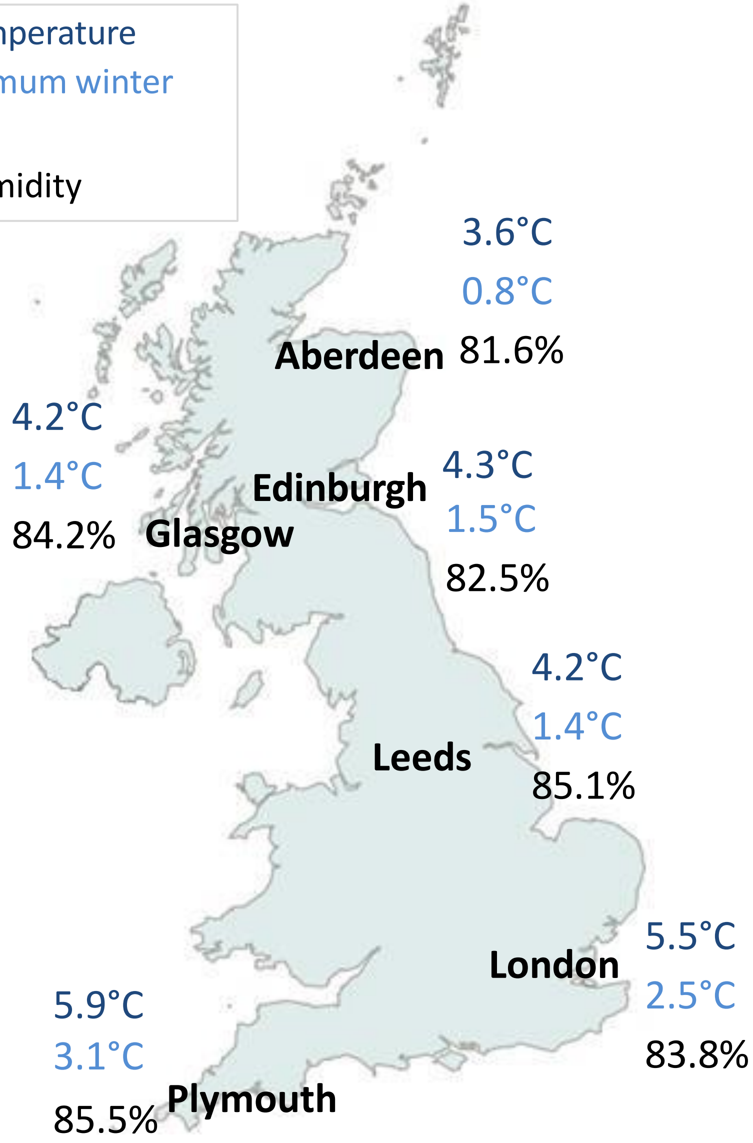
Recap

Comparing UK Cities

- Seasonal (winter) weather data was compared across six cities.
- These values represent the winter averages over the period 1980 to 2010.
- As discussed previously, Leeds is used in SAP to represent a UK average.
- Aberdeen represents the more extreme case with lower temperatures but also lower humidity.

Average winter temperature
Average daily minimum winter temperature
Average winter humidity

UK Average
4.2°C
1.2°C
86.1%

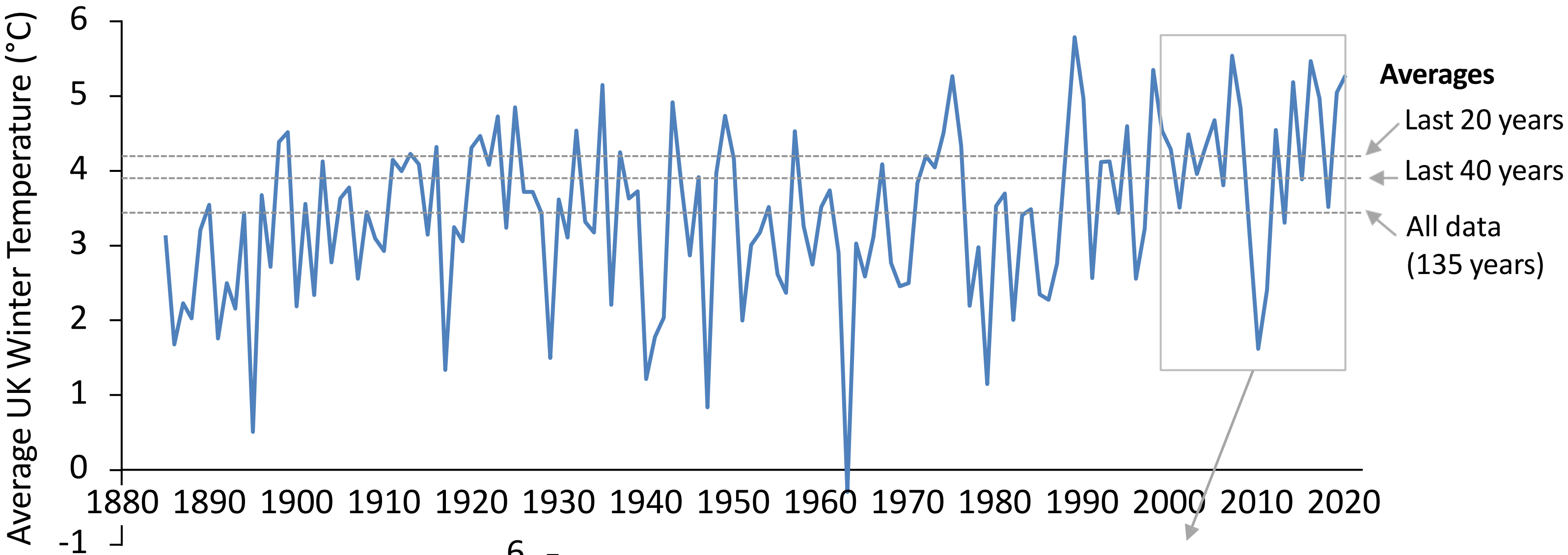


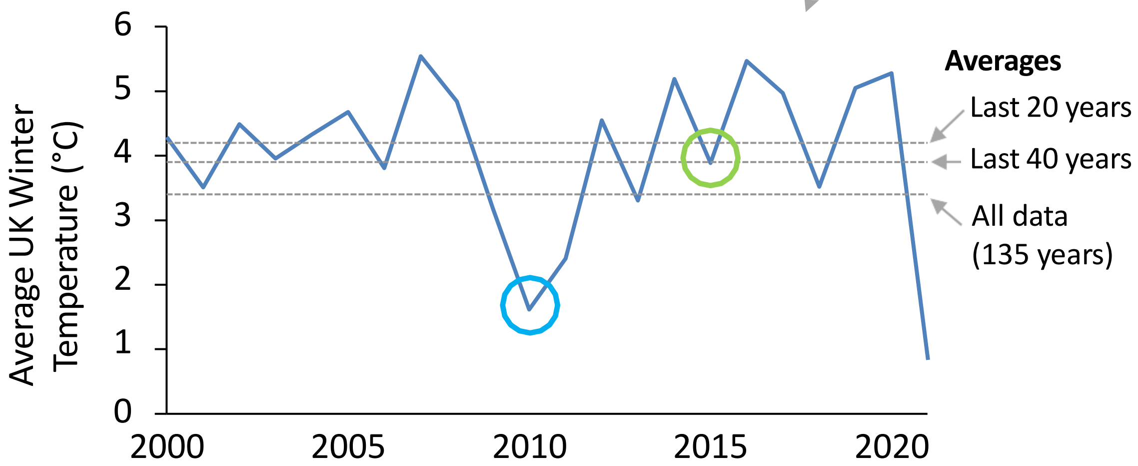
Source: HadUK Gridded Climate Data https://data.ceda.ac.uk/badc/ukmo-hadobs/data/insitu/MOHC/HadOBS/HadUK-Grid/v1.0.2.1

Historic data for average winter temperatures across the UK has been compared to establish an average year and a 1-in-20 year for extreme cold

Average Winter Temperature

- 2015 represents an average year in the last 40 years
  - 2015 has one of the most complete datasets for hourly air temperature and humidity
  - This year is above average for the data as a whole (135 years) but is likely to be more reflective of an average over the coming years
- 2010 represents a 1 in 20 year winter
  - Use 2010 to represent an extreme winter

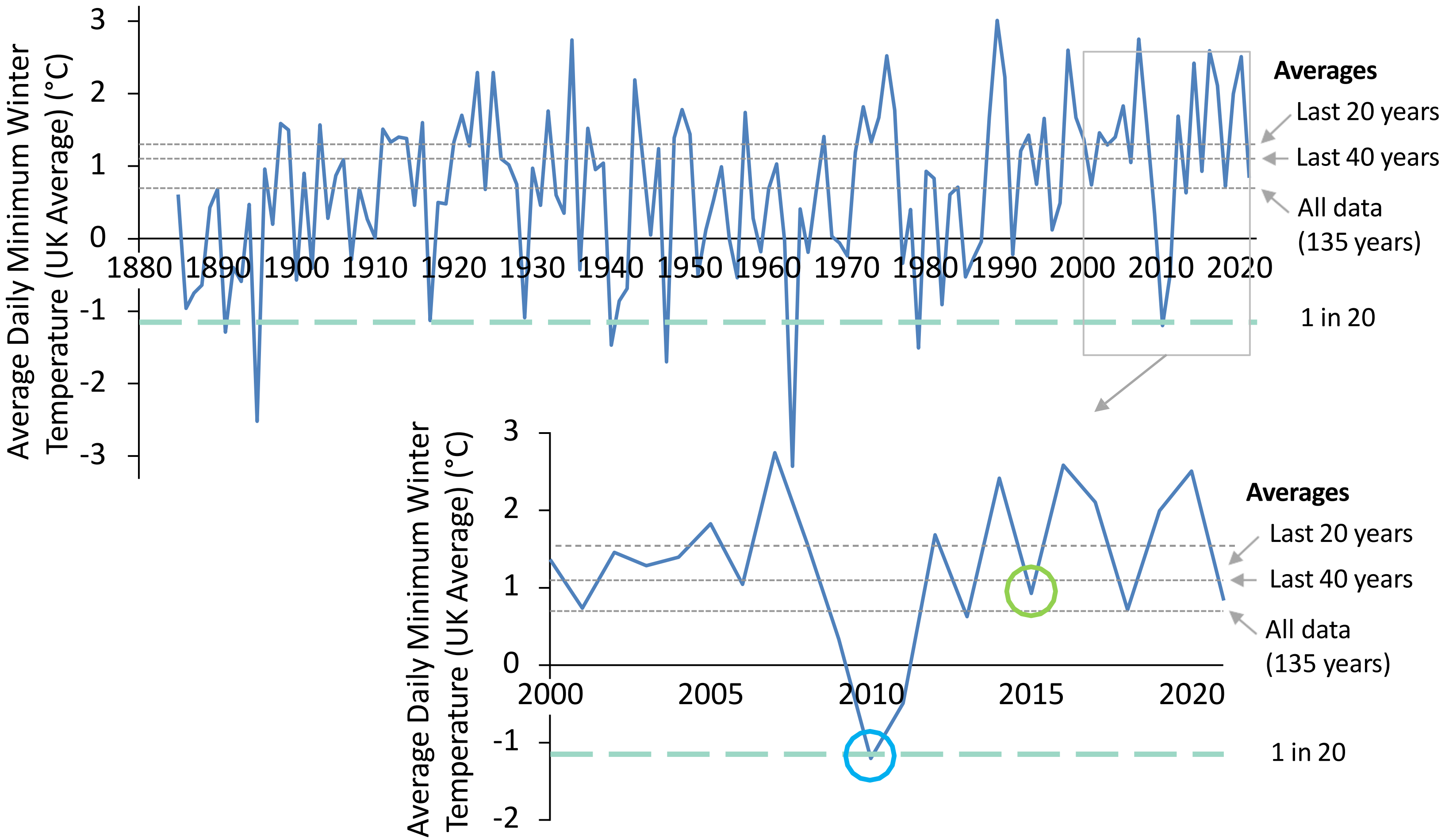




The average daily minimum winter temperatures have also been considered to ensure the cold year, 2010, is capturing periods of extreme cold, as opposed to simply being below average all winter

Average Minimum Winter Temperature

- The average daily minimum is the seasonal mean of daily minimum air temperature for the UK for winter.
- 2015 represents an average year in the last 40 years
  - The average minimum temperature in 2015 is slightly below the average across the last 40 years but is the closest in the last 10 years (those with the best datasets).
- 2010 represents a 1 in 20 year winter



Complete hourly weather data is not available for Leeds but is available for the nearby town of Bingley, where Kensa already have some installations

Bingley Data

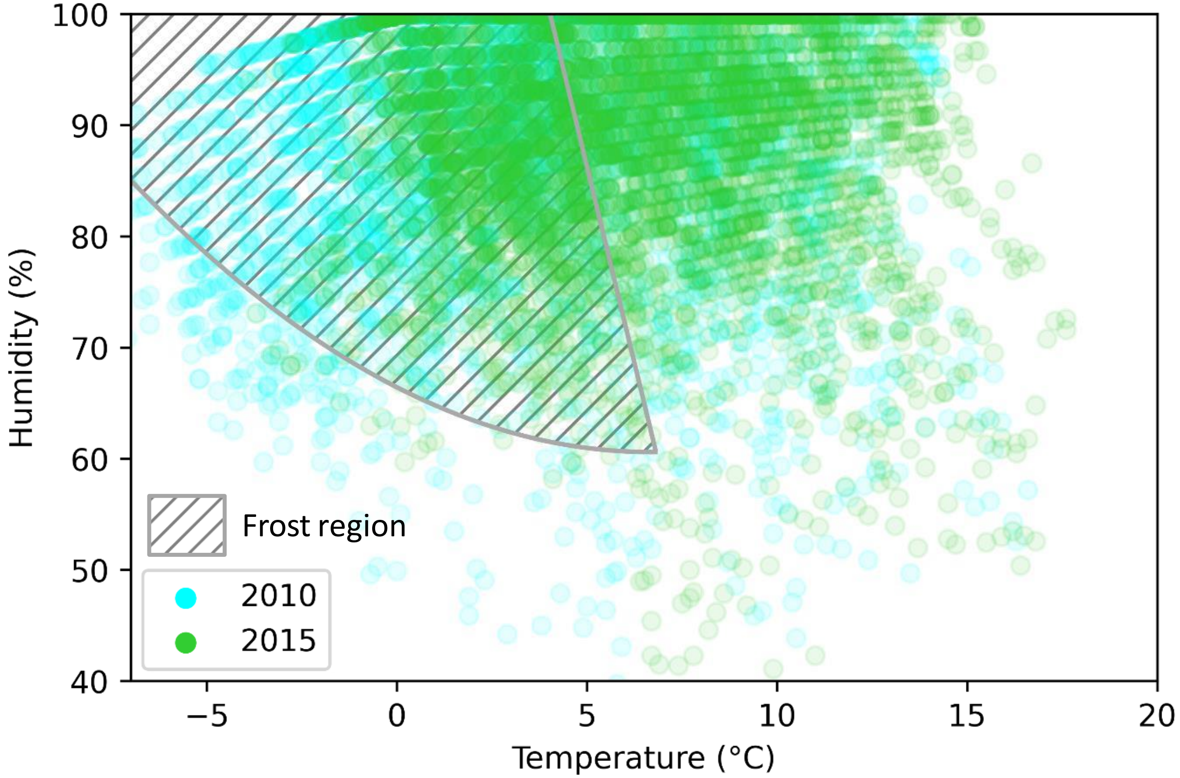
- Bingley chosen:
  - Town close to Leeds
  - Complete weather for multiple years weather data
- Data used
  - Met Office CEDA Archive https://data.ceda.ac.uk/badc/ukmo-midas-open/data/uk-hourly-weather-obs/dataset-version-202107/west-yorkshire/00513_bingley-no-2/qc-version-1
- Hourly data
  - Gives air temperature and humidity for each hour in the year
- Questions to be addressed using hourly data
  - Is 2015 an average year in terms of humidity?
  - Are there any anomalies in the data that make 2015 or 2010 less favourable years to study?
    - e.g. do the average values come out as yearly averages only because two extremes cancel each other out?
  - How many hours are in the frosting region?

The two years chosen show distinctly different distributions of hours within the frost region over the heating season

Hours in the Frost Region

- The hours in the frost region in Bingley have been considered for 2010 and 2015.
- The figure on the right shows **air temperature against humidity for each hour of the heating season** in 2010 (blue) and 2015 (green).
- The **hatched area shows the frost region**, within this area, ASHPs would be expected to require a defrost cycle.
- In 2010, the cold year, we see that the distribution of hours is pushed towards the colder temperatures with a small portion being pushed outside of the frost region at very low temperatures due to the wide range of humidity
- The individual plots for each year are provided on the next slide for comparison.

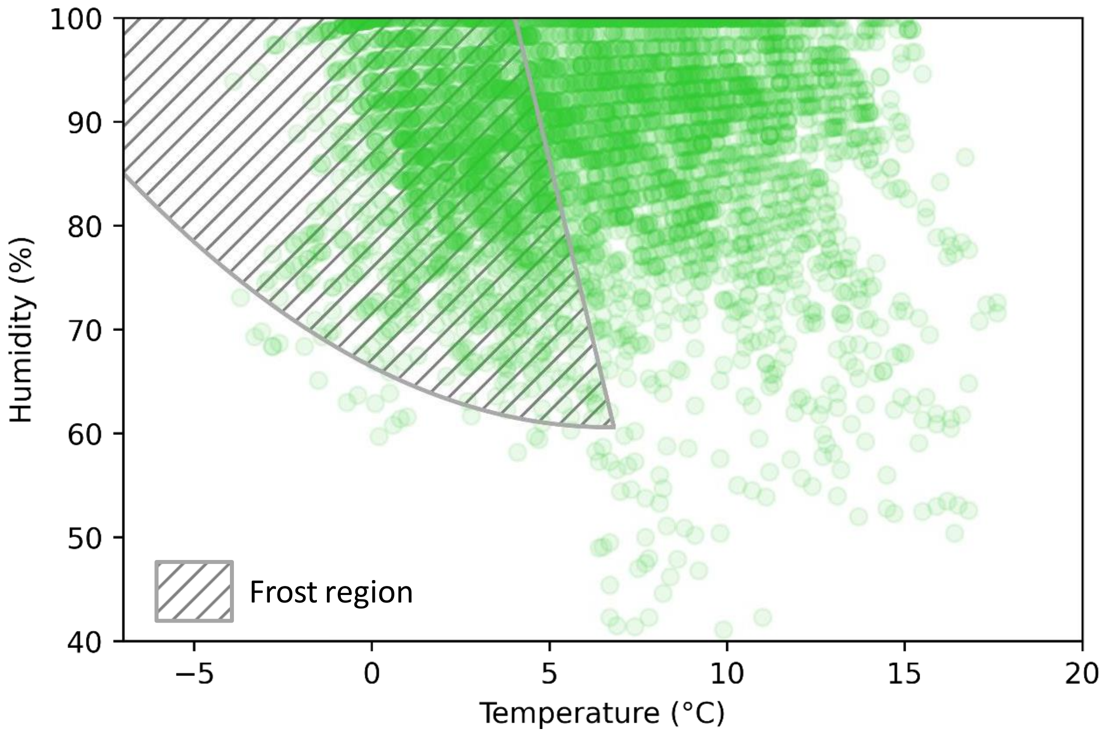
Year	2010	2015
Annual hours in frost region	35%	25%
Heating season hours in frost region	61%	42%



The 2010 cold year has 61% of hours in the heating season within the frost zone, compared to 42% in the 2015 average year, as well as a much broader distribution of points within the frost region

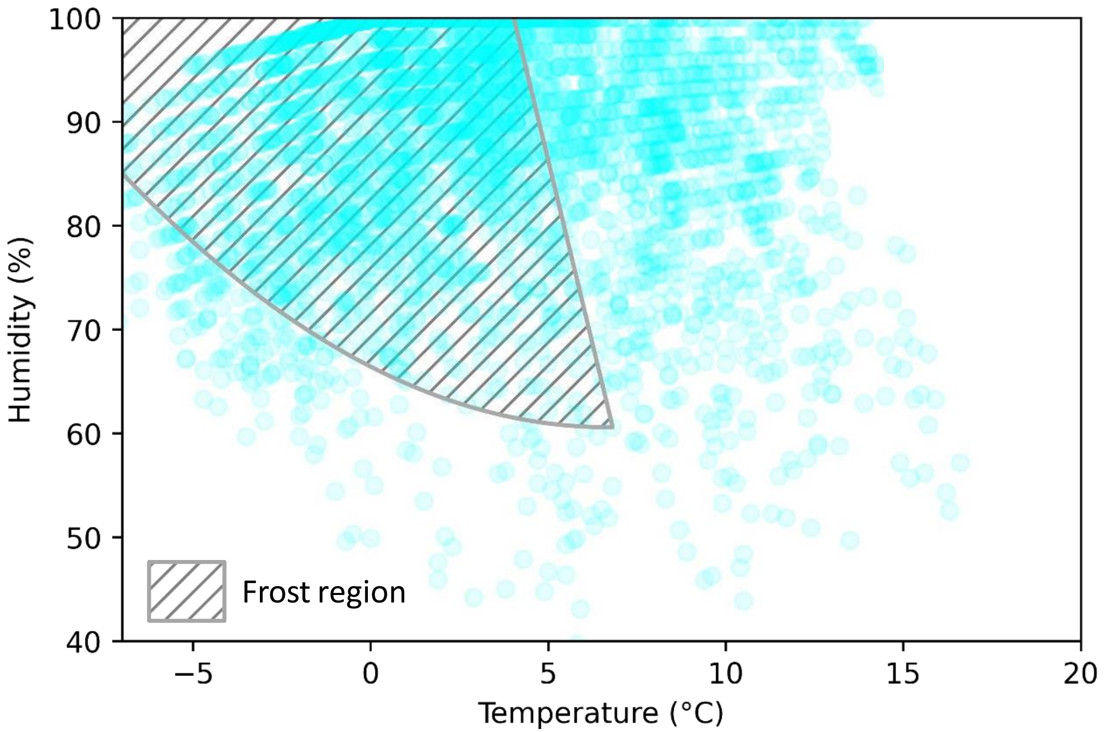
2015 Average Year

- **25%** of annual hours in the frost region
- **42%** of hours in the heating season in the frost region



2010 Cold Year

- **35%** of annual hours in the frost region
- **61%** of hours in the heating season in the frost region



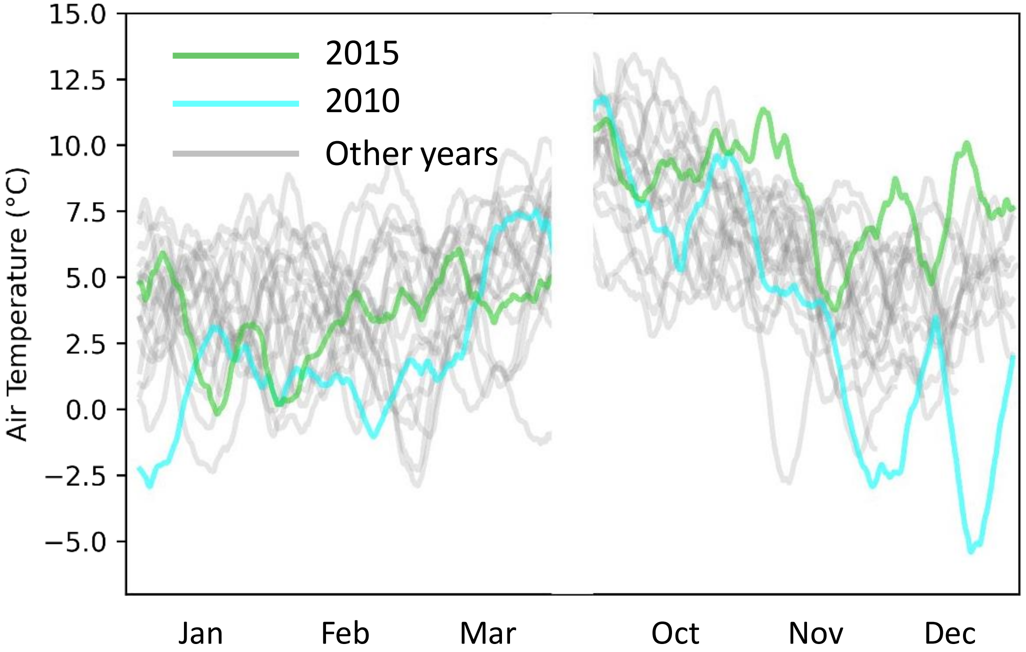
Source: Met Office CEDA Archive https://data.ceda.ac.uk/badc/ukmo-midas-open/data/uk-hourly-weather-obs/dataset-version-202107/west-yorkshire/00513_bingley-no-2/qc-version-1

Weekly data was used to understand temperature and humidity variation across the chosen years to ensure annual averages were not the result of one weather event e.g. a cold snap

- This data below shows a rolling average of the hourly data, averaged over a week, for Bingley.
- The grey lines show all years from 2000 to 2020 to illustrate a 20-year range.
- The break in the figures is where the months outside the heating season have not been plotted.

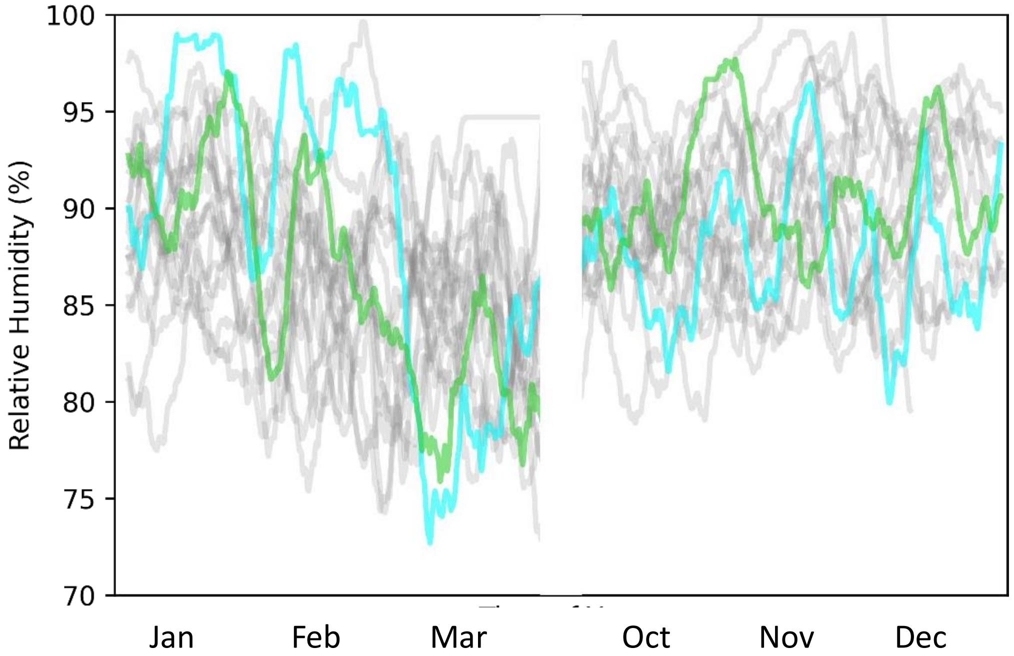
Air Temperature

- 2010 was the coldest of the last 10 years for January, November and December
- 2015 has a warm December but a cold February

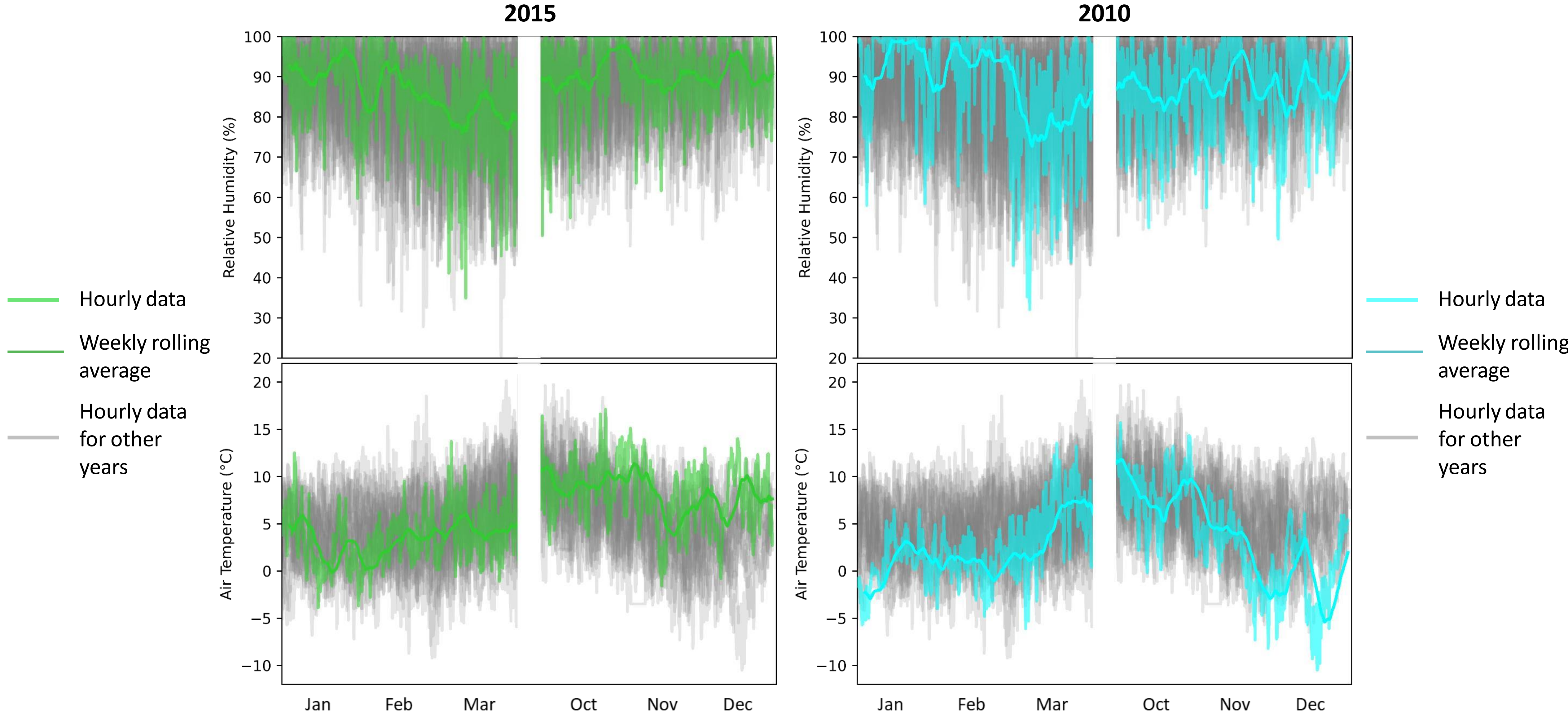


Humidity

- Humidity in the very cold months of 2010 (Nov, Dec) was lower than average, these times are largely responsible for the hours outside the frost region



Hourly data shows a wide range of humidity values throughout the heating season



A mock up of the Victorian property gives thermal values very similar to the 250 kJ/m²K SAP default value with the new build between the medium and high (450 kJ/m²K) values

Building Thermal Mass

- The thermal mass parameter (TMP) for each of the properties was estimated using the following equation and based on k-values given in SAP.

$$TMP = \frac{\sum \kappa \times A}{TFA}$$

- An average floor area of 86 m² was used, based on an average floor area for the type of buildings being studied.
- However, these values are highly dependent of unknown features of the building such as the density of the plaster and blocks used.
- The main elements that effect the values shown here are the construction of both the internal and external walls, and the floor.

	Victorian Terrace			New build		
	Type	k-value (kJ/m²K)	Area (m²)	Type	k-value (kJ/m²K)	Area (m²)
Ground floor	Suspended timber (given value includes insulation)	20	43	Slab on ground, screed over insulation	75	43
Party floor	Timber I-joists, carpeted	30	43	Precast concrete plank floor (screed laid on insulation) ,carpeted (E-FC-3)	30	43
Ceiling	Carpeted chipboard floor, plasterboard ceiling	18	43	Carpeted chipboard floor, plasterboard ceiling	18	43
Roof	Any – all have same value	9	50	Any – all have same value	9	50
External walls	Solid walls (no dense plaster assumed)	110	88	Cavity wall; dense plaster, lightweight aggregate block, filled cavity, any outside structure (medium cavity wall value)	140	113
Party walls	Single plasterboard	70	51	Single plasterboard	70	26
Internal walls	Dense block, plasterboard on dabs	75	71	Dense block, plasterboard on dabs	75	87
Thermal mass values for building		***254***			***348***	

The medium SAP value is used for both the retrofit and new build properties as it is a more defensible number than that calculated on the previous slide

Additional Notes on Building Thermal Mass

- The building thermal mass calculated on the previous slide was around 350 kJ/m^2K, higher than the medium SAP value of 250 kJ/m^2K used in the flexibility hours calculation.
- The medium SAP value was chosen as a more defensible value than a value calculated based on unknown construction elements.
- In the case of the new build, this has relatively little effect on the overall results as the heat loss rates are so low that the hours of flexibility are long enough to take advantage of flexible tariffs even with lower thermal mass.

Heat loss values for the Victorian terrace property were calculated using the SAP methodology

Heat Loss Rates Calculated from SAP

- The U-values listed below were used in SAP calculations to generate a heat loss value for the Victorian terraced property, based on SAP 2012.

Building element	U-value (W/m^2K)
Floor (uninsulated)	1.2
Walls	1.3 (uninsulated), 0.53 (uninsulated)
Roof (insulated)	0.4
Windows (double glazed)	2.8

- The heat loss values for the Victorian terrace varied between 150 W/K and 230 W/K depending on whether walls were assumed to be insulated or uninsulated
  - The heat loss values for uninsulated walls were taken forward into the hours of flexibility calculations.

Boiler Efficiencies

- Boiler efficiencies were used based on the United Kingdom Housing Energy Fact File[1]

- Boiler efficiencies for space heating were
  - Victorian terrace (based on values for existing properties): 81.9%
  - New build: 85.5%

- Boiler efficiencies for hot water were assumed to be 10% lower, consistent with Watson 2019.

1. United Kingdom Housing Energy Fact https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/345141/uk_housing_fact_file_2013.pdf *published 2013*

The process for quantifying the impact of defrosting on ASHP performance has been based on literature studies and published data from heat pump manufacturers

Quantifying the Impact of Defrost Cycles on COPs

Understanding the impact of defrosting on ASHP COP

- Literature review to understand the expected impact of frosting on COPs
  - Vocale et. al. considered impact of defrost cycles **based on calculations from first principles, they found monthly COP penalties of up to 0.4, indicating that the hourly COP penalty >0.4**
  - Zhang et. al. showed the **negative impact of increased humidity on the COP** within the frost region.

Establishing temperature vs COP relationships without the impact of defrosting

- Temperature dependent COPs were collated from data published by various manufacturers
  - Only some manufacturers explicitly include the impact of defrost cycles
  - A **baseline, temperature-dependent COP was established based on manufacturer data that did not include the impact of defrosting**.

Quantifying the defrost penalty

- The **defrost penalty was quantified using two sets of manufacturers data**
  - NIBE and Mitsubishi each included some data points that included the impact of defrosting and some that did not
  - A mixture of methods (detailed on the following slides) were used to quantify the defrost penalty
  - The defrost penalties were generally found to be in the region of **0.35-0.55**.

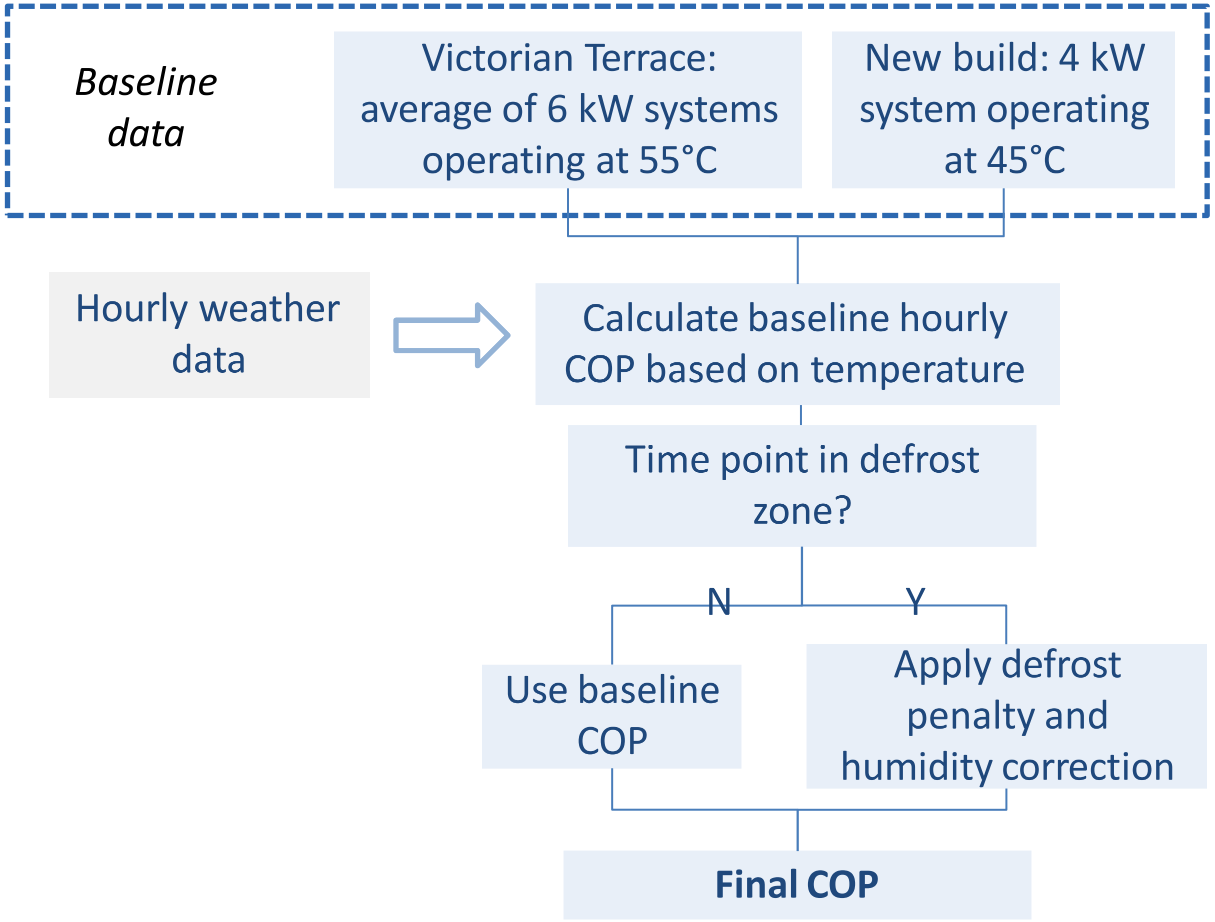
Quantifying the additional impact of varying humidity

- Industry standards for measuring COPs included a fixed humidity of 85%
  - An **additional humidity correction was applied to the defrost penalty to account for humidity variation** (detailed on slide 106)

Summary: Hourly COP values have been calculated using manufacturer data as a baseline, then applying a defrost penalty and humidity correction when a timepoint is in the frost region

Apply Hourly Temperature and Humidity Dependent COPs

- For each hourly weather point:
  - The baseline COP is calculated using Mitsubishi data
    - Victorian Terrace: Average of data from two 6 kW models operating at 55°C flow
    - New build: 4 kW model operating at 45°C
  - If the timepoint is in the frost zone
    - A set **defrost penalty** is applied
    - A **positive or negative humidity correction** factor is applied based on whether the humidity is lower or higher than 85% respectively
  - If the timepoint is not in the frost region, no penalties or corrections are applied.
- The **COP is then applied to the heat demand for each half-hourly time point.**

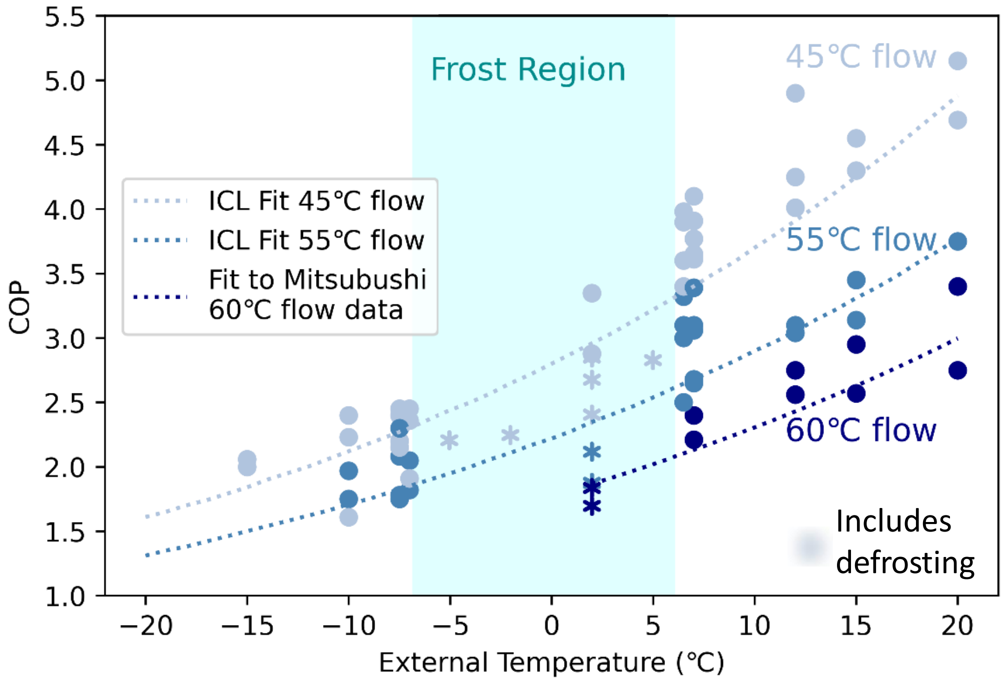


Before applying a defrost penalty, baseline COPs without a defrost penalty were established using reported values from manufacturers

Bringing Together Manufacturer Data

- Data was brought together from the following manufacturers
  - NIBE
  - Mitsubishi
  - Grant
  - Vaillant
  - Samsung
  - Daiken
  - LG
  - Hitachi
- Some manufacturers (NIBE and Mitsubishi) provide data at a range of values and indicate that the impact of defrost cycles is included in those values. Other manufacturers include COP values only at one or two points (e.g. 2°C and 7°C).
- Imperial College London has compiled manufacturers values, from which a line of best fit is shown in the figure on the right.

COP vs external temperature collected from various data sources

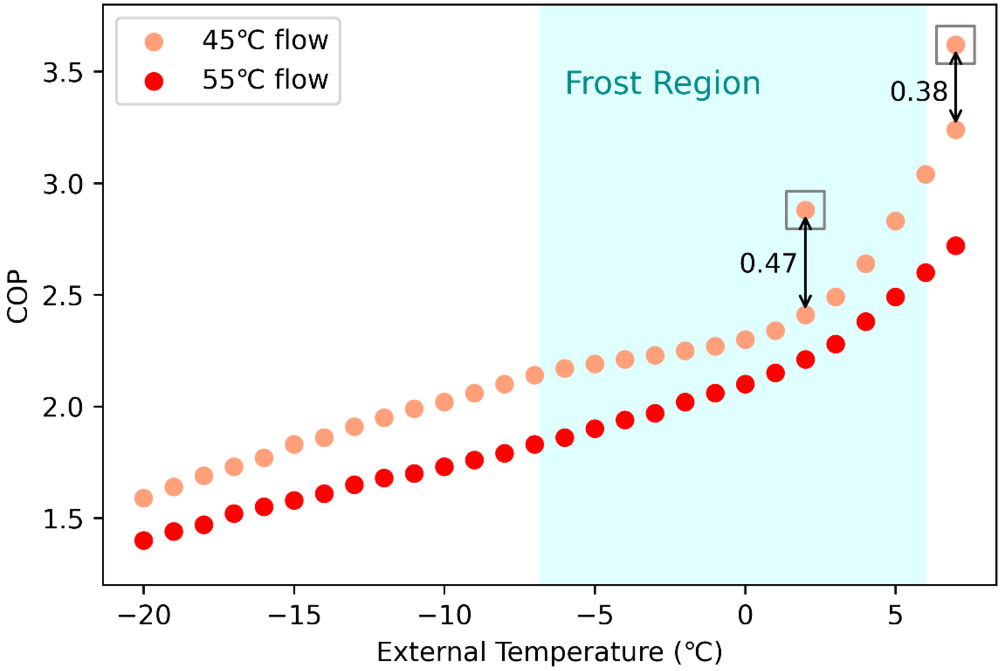


The two most comprehensive manufacturers datasets, NIBE and Mitsubishi, indicate that defrosting reduces the COP by around 0.4-0.5, consistent with other literature values

Impact of Defrost Cycles

- NIBE provides COPs at 1°C intervals between -20°C and 7°C
- The values given in their **figures include the impact of defrosting**
- However, different, higher, COP values are quoted in the **tables** at 2°C and 7°C
- **We assume these higher COP values quoted in the table do not include the impact of defrost cycles**
- The difference between these COP values at 2°C and 7°C are 0.38 and 0.47 respectively, expected to be the impact of defrost cycles
- Additionally, the NIBE data shows a downward bowing of the COP values in the temperature range -7°C to 7°C, where frosting primarily occurs

NIBE



The two most comprehensive manufacturers datasets, NIBE and Mitsubishi, indicate that defrosting reduces the COP by around 0.4-0.5, consistent with other literature values

Impact of Defrost Cycles

- Mitsubishi provide data points at uneven intervals between -15°C and 20°C
- The accompanying information indicates that only the 2°C data point includes defrosting
- This 2°C point, well inside the frost region, deviates significantly from the linear distribution of the other points.
- The difference between the expected COP values at 2°C values based on the linear functions and the quoted COPs are again around 0.49-0.50, consistent with the NIBE data
  - If the functions plotted are exponentials instead of linear, the penalties are reduced to 0.27 and 0.35
  - These values are below the expected value of 0.4 based on the Vocale paper.

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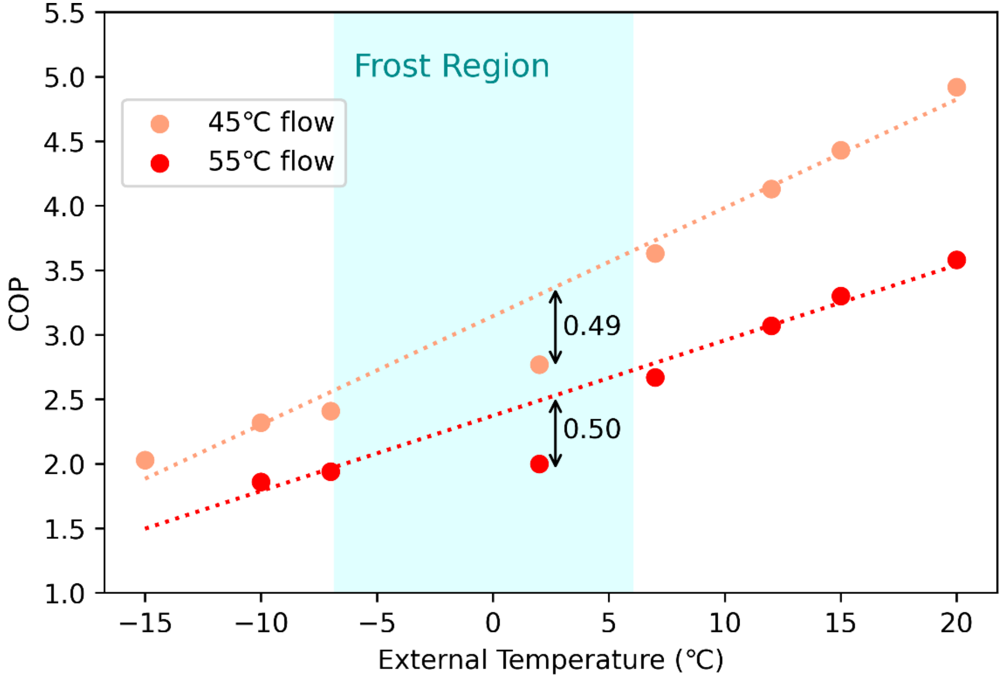


Source: NIBE https://www.nibe.eu/assets/documents/25739/231846-8.pdf, Mitsubishi https://library.mitsubishielectric.co.uk/pdf/book/ATW_Databook_R32_2020#page-68-69, Vocale et. al. https://www.sciencedirect.com/science/article/pii/S187661021400071X

The average value for the defrost penalty, based on the Mitsubishi and NIBE datasets, is 0.46 – consistent with the values reported in literature

Summary: Impact of Defrost Cycles

- Vocale et. al. found that the **highest monthly COP penalty** for defrosting was around **0.4**
  - If all hours in that month were in the frost region, this would suggest a defrost penalty of 0.4. We assume not all hours are within the frost region, therefore the hourly defrost penalty must be >0.4.
- The defrost penalty used in our modelling is based on an average of the defrost values calculated from the NIBE and Mitsubishi datasets, shown in the table below.

NIBE		Mitsubishi		Average
2°C	7°C	45°C flow	55°C flow	
0.47	0.38	0.49	0.50	**0.46**

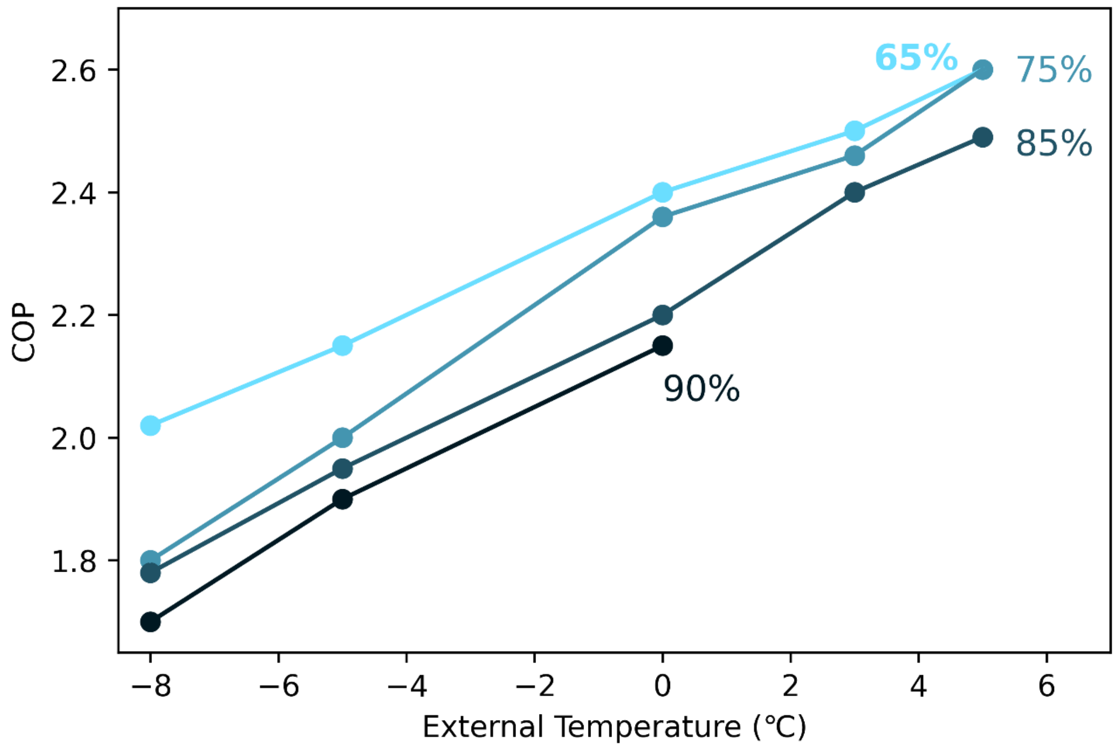
- For the ASHP COP calculations, the 0.46 defrost penalty was used when the hourly weather datapoint was within the frost region.

The data reported by manufacturers is measured under standard test conditions of 85% humidity, therefore an additional correction factor has been applied where humidity deviates from 85%

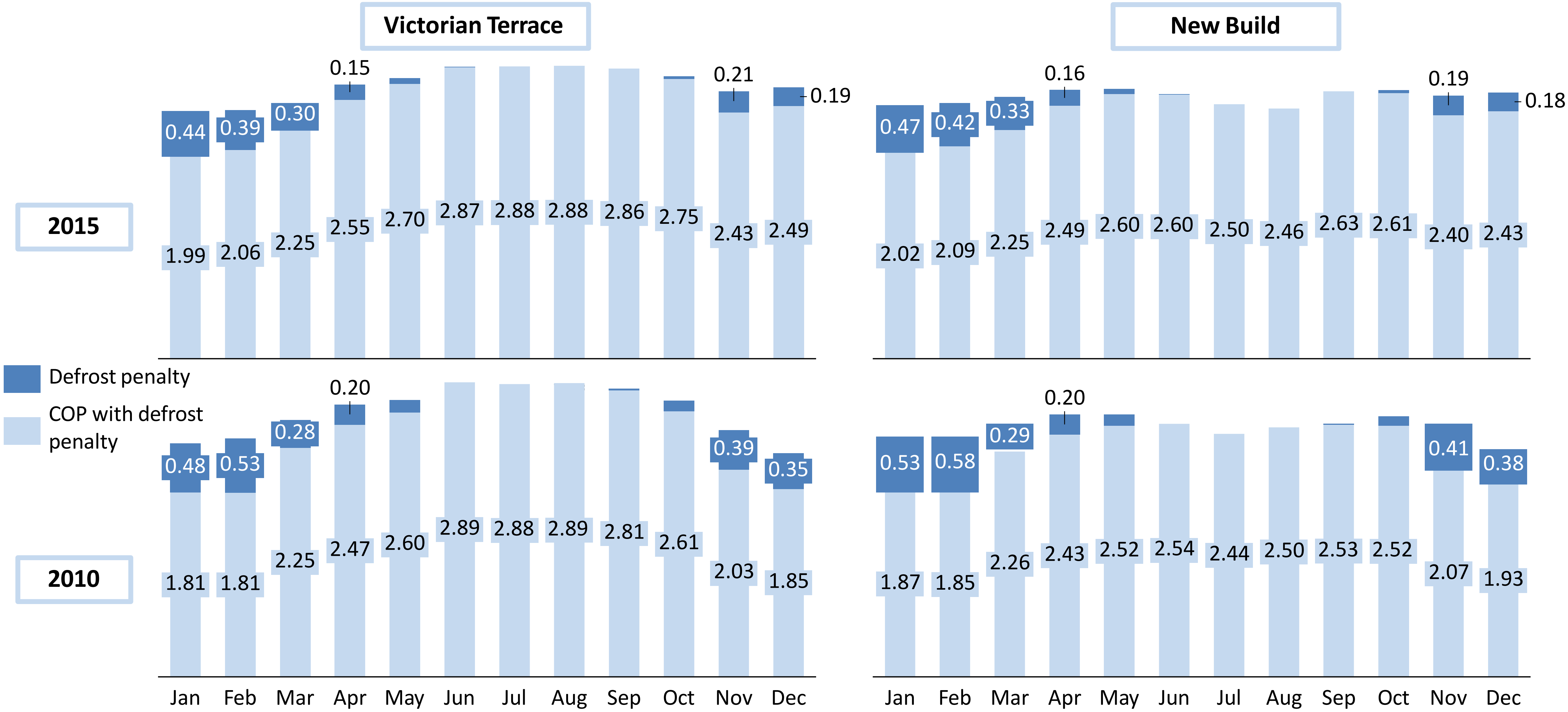
Additional Impact of Humidity

- ASHPs COPs are measured under standard test conditions with a humidity of 85%
- The Zhang et. al. data (shown right) shows the **negative impact of humidity on COP in weather conditions that would require defrosting**
  - These values are not as high as the defrost penalty but can provide a small, humidity dependant adjustment to ensure the COP values are adjusted to account for the local climate as well as possible.
- Based on the Bingley 2015 data, nearly 70% of hours in the heating season have humidity higher than 85%, rising to over 80% of the hours in the coldest months.
- While this humidity correction may even out across the year, humidity drops during the day so may affect the optimisation of flexibility.
- This **additional humidity correction was only applied in hours within the frost region.**

COP vs external temperature for various humidity values



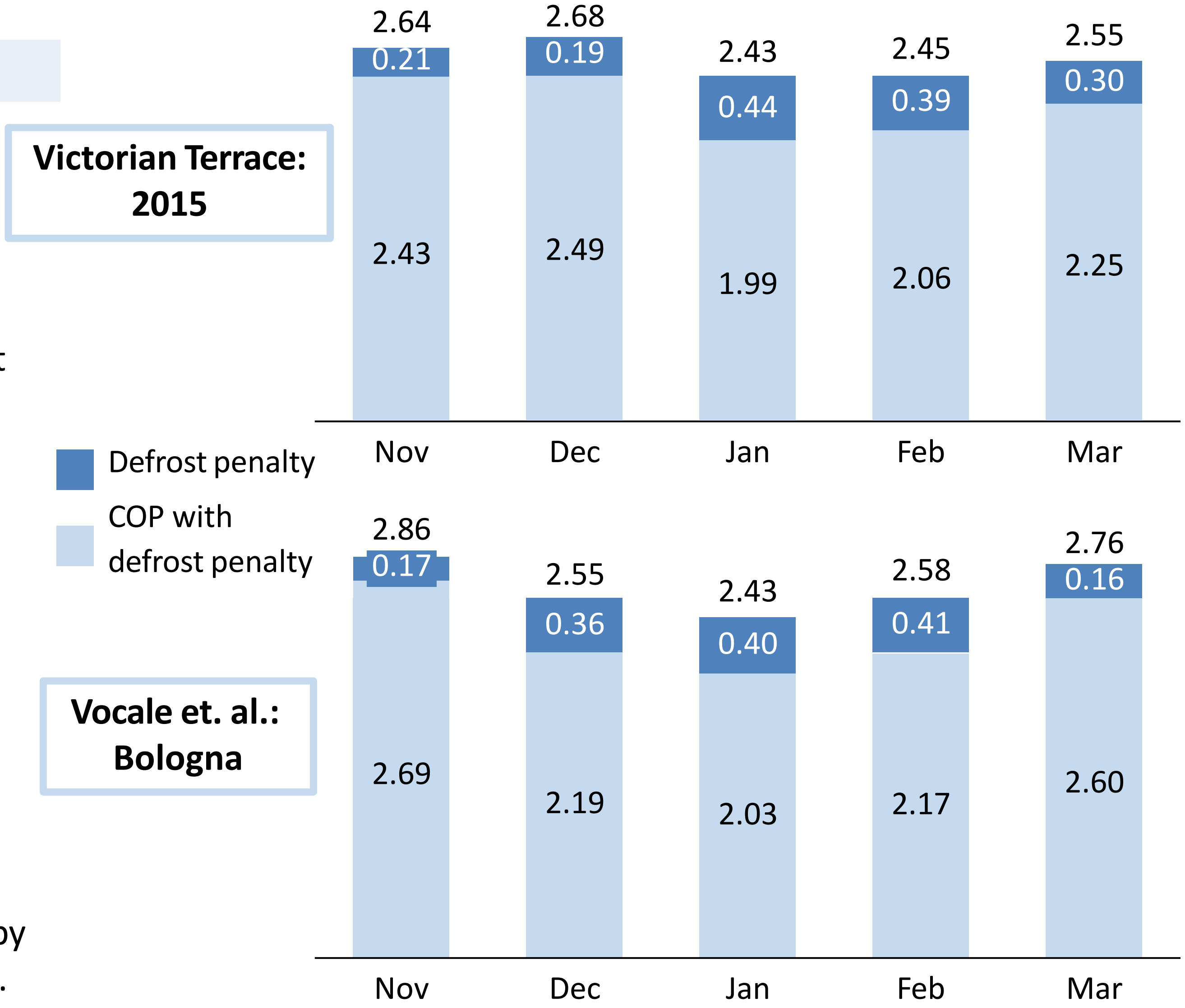
The lower COP values for hot water in the 4 kW system used for the new build compared to the 6 kW system used for the Victorian terrace lead to lower summer COPs for the new build



The COP values calculated by the described method are broadly in line with COP values reported in published studies

Comparison with Other Literature Sources

- The calculated values have been compared to literature
  - Vocale et. al. had performed calculations from first principles to understand the impact of defrost cycles in ASHPs in various Italian cities
  - The northern cities, Bologna and Milan had the highest COP penalties with winters characterised as cold and damp, most like the UK.
  - The monthly data for Bologna is shown in the lower figure, though is it not clear if the calculations are performed for a specific year or averaged across years.
- The figures obtained by our calculations are broadly in line with those reported by Vocale et. al.
  - The Vocale et. al. COP values climb more quickly as we move away from January as the Italian climate warms more quickly
  - The highest penalties are slightly lower than obtained by our calculations due to the higher humidity in our data.



Source: Vocale et. al https://www.sciencedirect.com/science/article/pii/S187661021400071X