ECO3 Innovation Demonstration Action

Energiesprong retrofits – Nottingham and Sutton

Jason Palmer, Nicola Terry, Emily Braham, Matt Wood, Zack Gill, Jon Warren, Richard Jack

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ECO3 Innovation Demonstration Action - Energiesprong

Executive Summary

Eleven dwellings underwent significant ‘deep’ retrofits including super-insulation of walls, roof and floor, and installing whole-house ventilation and heat pumps to provide space and water heating. Dwellings were recruited from two different regions of the UK: Sutton in south London – representing Southern England – and Nottingham to represent the North of England. Six concrete and timber frame terraced houses were recruited in Nottingham, with five of them retrofitted, and six two- or four-in-a-block cottage brick cavity homes were recruited in Sutton – all six undergoing deep retrofit.

One of the 11 upgraded dwellings was vacated during the retrofit work, so this could not be used in analysis. For the remaining set of 10 retrofits, the improvement in Heat Transfer Coefficient was statistically significant[1], and the average (mean) improvement in HTC was 33 W/K (minimum 5 W/K, maximum 61 W/K), or a 21% reduction in heat loss. There were technical problems with the heat pumps and ventilation system installed in Sutton homes, so actual bills savings were disappointing there. Including the very weak performance of the Sutton heating system, the average bill saving was still £201 (minimum a cost rise of £6, maximum saving of £408) a year, or a 22% saving (-0.6%/+45%). However, if the Sutton heat pumps had performed at the same efficiency as those installed in Nottingham, the average bill saving would have been £426 (minimum £292, maximum £555) a year, or 46% (31%/60%).

The mean internal temperature increased from 19.2°C before to 20.0°C after the retrofits, but this was not statistically significant. However, the change is biased by the fact that the external temperature was higher during the post retrofit phase. Adjusting for this, we estimate internal temperatures increased from 19.6°C to 20.0°C. Changes in quantitative scores for occupant comfort reflected this improvement, and the changes in scoring comfort were statistically significant. One home with very low pre-retrofit temperatures (14°C) increased them to by 3°C, bringing a meaningful improvement in comfort, and potentially health, wellbeing and fuel poverty. Properties with higher initial temperatures tended to witness a smaller change. Generally, there were also more even temperatures between rooms and over time once the retrofit work was complete.

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[1] The Student T-test with paired samples was used for statistical comparisons before and after retrofit, for group data. Using this test there is no minimum sample size. This assumes that the observations are normally distributed. We cannot prove this with such small samples but there is no reason to believe they are not. For the significance test of HTC across the whole cohort, p=0.02.

The Ventive Home heating and ventilation system used in Sutton was innovative, and in retrospect perhaps not sufficiently tested in the field. This led to problems with controls, and the heat pump was not used, which increased energy use for the Sutton homes.

In Occupant Satisfaction surveys, all residents in the Nottingham homes were more comfortable overall, and all were happier with winter temperatures. However, residents in Sutton were either less comfortable or gave the same rating after the work was complete than they were previously. This may have been because they were dissatisfied with delays and technical problems with the heating system.

Nottingham households generally reported improved ventilation after the work. Results were a little more mixed in Sutton, but most households said either that ventilation improved or it stayed the same. Regarding energy bills, most of the Nottingham residents thought their bills fell as a result of the work, whereas in Sutton all households though energy use was too high after the retrofits.

Taking all of the Occupant Satisfaction survey questions together, quantitative responses showed a statistically significant result for the Nottingham households, but not for those in Sutton. Similarly, the interventions had a statistically significant impact on perceived comfort and warmth in Nottingham (where the mean rating rose from 2.5 to 4.25, on a scale from 1 to 5), but not in Sutton.

Factoring up annual savings in energy costs over 15 years for these 10 dwellings to give a conservative estimate of Lifetime Bill Savings, based on the actual performance of the Sutton heating systems, suggests that these retrofit interventions could save between -£90 and £6,110 (central estimate: £3,020). If the Ventive heating system in Sutton were repaired or replaced with a heat pump that runs as efficiently as those installed in Nottingham, Lifetime Bill Savings would rise to between £4,390 and £8,320 (central estimate £6,390). These estimates do not capture the full benefit of fabric upgrades, which could last for 60 years or more, but it reflects the likely service life of heat pumps.

1.0 Introduction

Energiesprong is a Whole-House Retrofit (WHR) system that aims to deliver net-zero energy, warm, affordable to heat and comfortable homes. The system integrates low-carbon technologies including heat-pumps, a super-insulated wrap system including new windows, doors and roof, solar PV, and energy storage. To enable investment and financing, suppliers provide a 30-year performance and maintenance warranty.

The Energiesprong model takes a different approach to contracting. A performance outcome is specified, and the 'Solution Provider' (which is a new role in the UK) is responsible for designing and installing - and evidencing - the real-world performance of the outcome specified. This means the Solution Provider can provide the required long-term (30-year) performance guarantee. It is hoped this focus on outcomes enables the Solution Provider to innovate to reduce cost.

Offsite manufacture is also required, with homes needing to be retrofitted in less than 15 days on site. This drives solutions such as energy modules, with all of the M&E systems fitted into the module in the factory, which is hoped to improve quality, and façade solutions which can be craned-on in a day.

A summary of the performance warranty follows:

- The tenant will not receive an energy bill of greater than, typically, c2,000 kWh/year of electricity. This is confirmed by the Solution Provider at the outset, including the PV contribution.
- The tenant receives a guarantee that they can heat to 21°C, draw off 140 litres hot water per home per day, and use 2,300 kWh a year for appliances. Tenants can use more electricity and/or water if they wish and their energy bill will only increase slightly, as they will benefit from the efficiency and technologies provided by the solution.
- The aim is that solutions achieve net-zero consumption. For this Demonstration Action the net-consumption can be up to 1,500 kWh/yr. This is roughly a 90% energy/CO_2 saving.
- Other factors, including, noise, overheating, visual appeal, humidity, will be designed and managed.
- Housing providers benefit as maintenance costs are guaranteed not to exceed those stated in the maintenance plan.

The home also receives a full 'makeover', which contributes to estate regeneration and general resident satisfaction.

The first Energiesprong homes outside the Netherlands were in Nottingham (note that the homes in this Demonstration Action looked different, both before and after the retrofits):

Before:

After:

Ordinarily Energiesprong retrofits move tenants onto a 'Comfort Plan', where they pay a fixed monthly charge for energy services that includes the cost of maintaining energy systems. This gives them more certainty about energy costs, and good visibility of future charges. However, at Ofgem's request, the Comfort Plan does not apply in these retrofits. (Energiesprong is compensating tenants for any change to energy bills.)

Because an Energiesprong solution is outcome focussed, the Solution Provider can use different approaches which suit the property. In this demonstration action two different approaches have been taken. Both were signed off by Ofgem following receipt of the design proposals. The next sections detail the two different specifications.

1.1 Context for work and upgrades in Nottingham

Six non-traditional 'William Moss' cross-wall homes were selected in Nottingham for the demonstration action All six properties were ECO-eligible homes. One home dropped out of the scheme during the design stage due to health reasons and a second home became void in February, after initial monitoring which took place from December to early Feb. It would have been impractical to move a tenant in during the work, so this home served as a heated office until early April 2022, at which point it was re-let. This home was not used in any of the analysis below.

The properties were built in the 1960s. They have structural concrete cross walls, and timber frames and facades spanning between. Four of the five retrofitted homes are terraces, while the fifth ('Notts 4') is an end-of-terrace house. All five have garages, which were insulated and turned into useful living space as part of the work. This increased the useable internal floor area from 82m^2 to 102m^2.

The work was contracted between Nottingham City Council and contractor Melius Homes Ltd.

The technical solution included:

- Below-ground insulation around concrete floors using 600mm wide polar walls and 150mm XPS insulated board, aqua panels and aqua paint, to a depth of up to 650mm.
- Factory produced timber and mineral wool facades with weather boarding, factory fitted windows, doors and flashing, craned into place on the front and rear elevations in one day.
- Cold roofs with improved air tightness and insulation installed at ceiling level.
- Roof tiles stripped and replaced with solar PV and flashings
- Targeted air tightness of better than 5.0 m^3/h.m^2, which was achieved with combination of membranes, airtightness tapes, and a Passive Purple vapour-control layer.
- Aereco's demand-controlled whole house ventilation, using products that work together to respond to the presence of occupants, humidity, and CO_2 levels. The system includes humidity-controlled trickle vents for windows, which open wider as humidity rises, and include acoustic attenuation to reduce noise coming in from outside. It also has Aereco's 'BXC^2' room extract units in kitchens and bathrooms. These can be set to increase or reduce the airflow according to humidity, CO_2 concentrations, or occupancy, and reportedly make commissioning much easier than standard room extracts. These are linked to a centralised fan, which runs quietly and with low energy consumption (33dBA and <13W @40m^3/h).
- Solar PV array of 18 x 335W panels with a 3.6kW inverter
- Battery - 5kW
- ASHP - Vaillant KIWA 00016/018 5 kW capacity, with Flow Temp of 55 and SCOP of 3.06
- DHW Cylinder - Vaillant Unistor with 150l capacity

The new U-values for the solution are detailed in Table 1 below.

Table 1: New U-values for Nottingham homes

	W/m^{2}K
Walls new facades & gable fill	0.15
Floor front & rear	0.52
Floor gable	0.21
Roof	0.1
Door	1.3
Windows Double Low-E Soft. 0.05	1.3

Unlike most other Energiesprong schemes, the Nottingham homes did not include 'energy pods' located outside the dwellings, which ordinarily make installation easier and less disruptive for residents. External space constraints and concerns about noise risks during planning meant that energy pods could not be used in the Nottingham homes.

The heat pumps were sized for space heating demand after the insulated facades and roofs were installed – so arguably they were under-sized for the period between heat pumps being installed and the facades and roofs being added, see below.

Before

During panel install

Completed

As often happens, installation work on site did not go entirely to plan. There was a significant delay between installing the heat pumps in Nottingham homes in October-November and then insulating the walls, roof and floor in February. The Energiesprong contract requires work to be completed in 15 active days on site at each dwelling. As a result, the contractors do everything they can to sequence work in a way that reduces time on site and time for any scaffolding. For modest schemes like this one with relatively few homes, site work becomes squeezed (in a scheme of 100 homes the contractor would have 1500 days on site, but for the five homes here the contractor had only 75 days). There are also fewer dwellings to move on to when one step of work is complete, so the programming becomes less efficient, with more gaps between each element being installed.

An additional problem affecting sequencing of work was due to gas meters needing to be removed prior to the facades being installed. Gas company Cadent's notice period and timing meant that the heat pumps had to be installed well in advance of the fabric works. Then gas meters had to be decommissioned and removed before the wall panels could be installed. This time off site brought benefits in enabling the wall panels to be manufactured in the factory, which in most cases were installed subsequently in one day per property, but it also slowed down the process of retrofit.

There were additional delays caused by the weather affecting the façade installs (craning had to be delayed due to bad weather), which had knock-on effects on the roof because roofs can only be installed after the walls are complete. The Solar PV is the last thing to be installed and commissioned.

One of the properties dropping out during the design period also contributed to delays because sequencing and manufacturing had to be re-programmed. There were further delays due to difficulties getting access to some of the properties to take photographs for party wall consents between the contractor and occupants, and in one instance (Notts 4), difficulties agreeing consent led to a 3-week delay. There were also several failed access attempts.

Taking two weeks off for Christmas and two weeks off for bad weather, the total period came out at 80 days, which is close to the target of 15 x 5 days (75). Energiesprong view this as a success, and they emphasise that the limited number of days on site makes a big difference to tenant satisfaction.

Did Nottingham homes achieve the heating demand target?

SAP calculations for the Nottingham homes during design indicated that the mid-terrace homes would achieve 31 kWh/m^2, while the end terrace homes would achieve 40 kWh/m^2 – i.e. exactly on the Energiesprong target for heat demand. Our analysis of monitoring data (in Section 2, below) indicated that two of the four Nottingham homes achieved this target, and two did not.

1.2 Context for work and upgrades in Sutton

Two of the Sutton homes, pre-retrofit

The houses selected in Sutton are as shown above. ‘Cottage’ homes were built in significant numbers by London County Council in 1930s and there are estimated to be 2,700 on Sutton’s St. Helier estate (another c25,000 on the Becontree estate, and over a million in the UK).

Sutton Housing Partnership selected six homes to be included in the Demonstration Action, all of which were retrofitted. The homes had cavity walls and suspended timber floors. The retrofit works were contracted between London Borough of Sutton and contractor Bow Tie Construction.

The technical solution included:

- Standardised, integrated energy modules that were manufactured to include the key energy provision and distribution components (exhaust-air heat-pump, MVHR, hot-water and electricity storage, control and monitoring equipment). The module is optimised to maximise efficiency through use of a phase-change heat battery which is charged by the exhaust-air heat pump. Heat is distributed around the home via the existing wet radiator system and a plate heat exchanger provides hot water on-demand. Ventilation rates are adjusted according to CO_2 levels and to maintain stored thermal energy in the heat battery. The heat battery can also be topped up using an immersion heater. Further optimisation of the system is possible using predictive algorithms and diverting exported energy to the heat battery, but these features were not deployed in this pilot. PV was deployed on all homes and batteries were installed on two homes in order to meet the Energiesprong performance standard.
- Bow Tie Construction’s “Zip-UP” continuous insulation system provides an in-situ ‘wrap’. Existing cavity fill was extracted and the cavities were cleaned to minimise thermal bridging. Lintels which form thermal bridges were also replaced. Polyurethane foam was installed from the outside to completely fill the 65mm cavity and form a complete air-tight layer.
- Good airtightness and continuous insulation was maintained between the new wall solution and loft insulation at eaves level, with careful attention to detailing of thermal bridging. A deck was constructed over the loft insulation to protect it during roof construction.
- Air is extracted from the kitchen and bathrooms and supplied to the living room and bedrooms. Air is returned to the MVHR unit via the sub-floor to reduce heat losses from the room above. This

> also brought benefits during construction by avoiding disruption to residents and the need to replace floor coverings. The soil from surface level to 20cm below ground under the house dries in the long term and forms an insulating layer. Theoretically, the sub-floor void remains dry without the usual ingress of cold unheated air. This space is also monitored to ensure there is no risk of rising damp or joist decay as the space is no longer externally vented.

The new U-values for the Sutton homes (see Table 2 below) are less ambitious than those in Nottingham: the floor U-value in particular is more than four times that in Nottingham, and the wall U-value is also more than double the Nottingham value. However, the glazing has a higher specification: roughly 0.7 W/m^{2}K in Sutton versus 1.3 W/m^{2}K in Nottingham.

Table 2: New U-values for Sutton

Element	U-value (W/m^{2}K)
Cavity Walls	0.341
Floor timber	2.278
Floor concrete	2.436
Roof	0.129
Entrance door:	0.99 frame // 1 glazing
Patio Door	0.82 frame // 0.70 glazing
Windows	between 0.8 and 0.82 frames // 0.60 glazing

There was an evolution during design and construction relating to heat loss for the Sutton homes, compared to the original Energiesprong target of 40 kWh/m^2/year, see Table 3 below. Window U-values and heat recovery performance remained constant during design and construction, but wall U-values, thermal bridging and especially the effective floor U-values did not live up to the original expectations.

Table 3: Summary of how thermal performance at Sutton evolved during design and construction (provided by Energiesprong UK)

In Design		Expected Construction		Achieved On Site	
40 kWh/m^2/yr	**Energiesprong thermal fabric performance target (best practice assumptions for original outline design)**	**55 kWh/m^2/yr**	**Expected thermal fabric performance making allowances for real-world material performance and design detailing / site conditions**	**74 kWh/m^2/yr**	**Estimated thermal fabric performance based on HLP and air tightness measurement and estimated U-values that would lead to the measured HLP**
HLP	**1.25 W/m^2.K**	HLP	**1.46 W/m^2.K**	HLP	**1.88 W/m^2.K +0.45/-0.46 (i.e. between 1.42 and 2.33 W/m^2.K)**
Walls: U-value Walls: 0.318 W/m2.K	Continuous PU foam filled 65 mm cavity fully adjoined to new windows, doors and loft insulation system with no voids. Walls bonded with PU foam rather than wall ties.	U-value Walls: 0.334 W/m^2.K	Continuous PU foam filled 65 mm cavity adjoined to new windows, doors and loft insulation system with no voids. Walls bonded wall ties.	U-value Walls: 0.40 W/m^2.K	Equivalent to 30% underperformance of PU foam material
Windows:	U-value 0.938 W/m^2.K				
Roof/loft U-value 0.103 W/m^2.K	Loft insulation system 400 mm insulation with deck	U-value 0.142 W/m^2.K	Loft insulation system 300 mm insulation with deck	U-value 0.142 W/m^2.K	As per 55 kWh/m^2/yr design model
Floor U-value 1.045 W/m^2.K	Estimated best-case performance of encapsulated under floor space (using MVHR to treat air)	U-Value 2.187 W/m^2.K	Estimated performance of encapsulated under floor space (using MVHR to treat air)	U-Value 3.109 W/m^2.K	Most sensitive unknown with biggest scope for under-performance and further investigation
Thermal bridges	U-value equivalent: 0.037 W/m^2.K			U-value equivalent: 0.137 W/m^2.K	Potential reality of thermal bridges and onsite construction practices
Party wall losses	Zero. Original intention was to treat two whole blocks (two semi's and terrace of four)			Zero. Potential significant losses that haven't been modelled / estimated. One mid-terrace replaced with end-of-terrace.	
Airtightness (n50)	1.0 ACH			1.5 ACH (measured)	Measured post-retrofit air tightness (n50)
MVHR Efficiency	79.6% heat recovery efficiency				

Pre-retrofit, the average airtightness across the Sutton homes was 7.7m^3/h.m^2@50Pa. The target after the work was a very demanding 1.0m^3/h.m^2. Only two dwellings had an airtightness test after the work, and on average they achieved 1.45m^3/h.m^2 – not quite meeting the target, but very good test results nonetheless.

Completed home

Energy module

As for Nottingham, the Sutton retrofits were not without problems. First, the energy modules for all six homes arrived later than expected (the first units were due in early January but they did not actually arrive until late February). This was due to delays in obtaining materials and components which were on unusually long lead times, and also difficulties in securing labour for installation, due to Covid. As a result of the delay, the energy module was installed into the porch pod on site rather than in the factory.

Given this was a first of a kind application of an energy module in a porch pod, and the complexity of monitoring the air returning to the MVHR/heat pump, in retrospect the plans were ambitious. The MVHR/heat pump treats the void under the suspended floor as a plenum to channel return air. Ordinarily, the return-air sensor would be installed a short distance from the energy module. However, Energiesprong were interested not only in the temperature and relative humidity of return air, but also the temperature and relative humidity of air in the plenum – to ensure there was no condensation/moisture risk.

Ultimately the sensor was installed just inside the plenum – some distance from the energy module – but then some adjustment was necessary for it being further from the unit. There were also technical challenges with the control algorithm for the energy module, which relies on an exhaust-air heat pump. The algorithm takes data from many sensors (input, output, and multiple rooms) and tries to apply multiple set points and humidities at the same time as optimising air flow, coefficient of performance and the use of PV.

In the end the algorithm did not deliver the basic functions of heating water and keeping the homes warm. It had to be reprogrammed temporarily, and very simplistically ("if the heat battery falls below 50°C, turn on immersion, if room temperature falls below 20°C, run the radiator circulator pump").

As a result of this, although all units were operational in the period 7th-10th March, it became apparent in the following week that electricity costs were excessive. The monitoring issues were resolved in the period 17th-22nd March and analysis of the data identified that the standard control software was not activating the heat pump. (This would have come to light even without the ECO Demonstration Action, although possibly not as fast.) This is when the alternative, simple control algorithm was applied – to ensure tenants were not without heating and hot water, while also completing monitoring for the Demonstration Action. The HTC calculation had to be finished before Ofgem's 31st March deadline.

Although residents were reimbursed for any change in energy bills during the study, they were still aware of high energy consumption, and naturally they were concerned. The delays, inconvenience and interruptions to heating and hot water provision left residents with a negative impression and they probably contributed low scores in the Occupant Satisfaction Questionnaire (see 'Interview Data' in Section 2 below). They may also explain what is reported as "poor workmanship".

There was also a shortage in components which meant the only high-performance windows available for Sutton within the project timeframe were windows which opened inwards instead of outwards. This caused some resident complaints and required replacement of blinds.

One Sutton tenant sadly withdrew from the trial late in the day and Energiesprong UK had to recruit another tenant in close proximity, and then repeat the engagement process from scratch.

1.3 Report Aims

This report aims to provide an accurate assessment of the energy savings generated by applying an Energiesprong whole house retrofit solution. It presents the key insights from the data gathered during the trial, including the improvements in heat loss (HTC), changes in internal temperatures, Occupant Satisfaction surveys, energy bill savings, and Lifetime Bill Savings.

1.4 Who did what?

Table 4: Team members and their roles

Project Delivery	Sutton	Nottingham
Sponsoring supplier	British Gas	British Gas
Client	Sutton Housing Partnership on behalf of London Borough of Sutton	Nottingham City Homes on behalf of Nottingham City Council
Solution Provider	Bow Tie Construction Ltd	Melius Homes Ltd

Project Support	Energiesprong UK	Energiesprong UK
Heat Transfer Coefficient Calculations	Elmhurst Energy/Build Test Solutions	Build Test Solutions
Energy Monitoring	Carnego	Carnego
Analysis	Cambridge Energy	Cambridge Energy

1.5 Monitoring Methods

SmartHTC is a technique developed by BTS (Build Test Solutions) for measuring the thermal performance of houses, defined by the 'Heat Transfer Coefficient', or HTC. This was carried out before and after works on 11 properties (including the site office, which is excluded from this analysis), using energy-meter readings and measurements of internal temperature. Energy bill data was gathered for 12 months for 10 homes, although there were some problems with the bills data, with some missing data and inconsistencies.

The HTC encompasses all of the heat lost from a dwelling during the winter, through the walls, roof, floor and windows, and by air movement from outside to inside the home. The metric is W/K, the rate of heat loss in Watts per degree in temperature difference between inside and out. The lower the number, the better the overall fabric is at retaining heat.

The HTC value taken in isolation does not identify the location of the heat loss paths or which elements of the fabric are worst performing, it is simply a measurement of the overall fabric heat loss. The SmartHTC algorithm has been built into an online web service. This allows automated data input at calculation of the HTC.

The method has been applied and compared to SAP results in over 200 dwellings over the past two winter seasons and reportedly shows good agreement when tested alongside conventional co-heating in 43 field trial properties.

Further information about the Smart HTC method can be found in "*ECO3_TAP_SHTC clarification note* " and "*SmartHTC Repeatability note*" documents, previously supplied to Ofgem as supporting evidence.

The BTS method of calculating an HTC requires several data inputs to be entered into their secure platform. An algorithm is then used to calculate the HTC. A minimum of three weeks of data[2] is required to use the platform, with the start and end reading for each dataset used to calculate the total consumption / output during that period. The inputs required are as follows:

- Electricity import
- Electricity generation (where relevant)
- Electricity export (where relevant)
- Gas consumption (where relevant)
- Heat pump output (where relevant)
- Heat pump electrical input (where relevant)
- EV charging consumption (where relevant)
- Temperature data inside the property from a minimum of one room but up to ten taken at half hourly intervals
- External weather data

In addition, information about the property is entered into the platform. Some of this is essential to calculating the HTC and other elements are non-essential and used to improve the confidence in the result. Property inputs include property type (house or flat), wall type, attachment (detached etc), floor area, party wall area, window sizes, directions and materials, overshading level, heating fuel, boiler type (where relevant), and whether secondary heating is used. The number of occupants is also entered into the system, where known. For this demonstration action, accurate property inputs have been included.

The input data has been accessed through a variety of methods across the Demonstration Action. The methods of collecting the data are detailed in the tables below.

Table 5: Sutton & Nottingham monitoring

Measurement	Equipment	Logging Frequency	Responsible Party
Internal temperature and relative humidity (RH)	ALTA Wireless Humidity & Temperature Sensor - Coin Cell Powered Elitech RC-4HC Temperature ±0.6°C, RH ±5%	15 minutes in each room 10 minutes	Energiesprong UK
Manual Meter Readings	N/A	Start and end of monitoring periods	Energiesprong UK

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[2] An HTC can be calculated with the same inputs over a shorter period, but this cannot be carried out through their platform.

Energy Bills	N/A	Collected for 12 months pre works	Energiesprong UK
Comfort surveys	Undertaken by Energiesprong UK, Sutton Housing Partnership and Nottingham City Homes	At 2 points: - Pre-works - Post-works	Energiesprong UK
External temperature data for calculating Heating Degree Days	Weather data for the BTS calculation is accessed from the Weatherbit.io weather API which has a resolution of 15-25km depending on location. The Nottingham weather centre is just under 6 miles from the site. The Sutton weather centre is 6.5 miles away from the site. The system also corrects for altitude and shading (based on satellite images of cloud cover) to the particular location.	Half hourly averages	Build Test Solutions as part of the HTC calculation
Installed monitoring	Sutton: Ventive Home energy module, LuxPower battery/ inverter (2 homes), PV inverter (4 homes) Nottingham: Multi-circuit electricity meter (Class 1 –MID certified). Heat meter on the output of the ASHP(MID certified). Temperature and humidity sensors. Hot water meter.	At least hourly Half hourly data, based on data logging every 2 – 3 mins.	Bowtie (Ventive subcontractor) Melius Carnego systems (monitoring solution for both projects)

Table 6: Sutton monitoring

Measurement	Dates installed/monitored	Issues and resolution
Internal temperature and relative humidity	w/c 28th Feb – 20th Apr	Data recorded, no issues
Manual Meter Readings	Multiple meter readings pre- and during monitored period.	Only limited smart-meter data was available
Comfort surveys	Pre and post-retrofit	Data recorded, no issues
External temperature data	30th April 2020 to 31st March 2022	Purchased postcode-level satellite data from Solcast
Installed monitoring	Battery/inverter (2 properties) – 1st and 10th Mar onwards. Import/Export/PV generation Inverter (4 properties) – 11th Mar onwards. PV generation Ventive Home pod – 18th Mar onwards. Import/Export/PV generation. Heating system electrical input, total heat output (derived).	PV/import/export data for some properties was lost before 11th March due to technical issues with the metering on site. Ventive Home pod monitoring was installed from around 18th March. Total heat output cannot be measured directly due to the system setup, so has been derived from the temperature data recorded (see below).

Table 7: Nottingham monitoring

Measurement	**Dates Installed / Monitored**	**Issues and Resolution**
Internal temperature and relative humidity	Pre-Works December 2020. Post works 22nd to 26th February 22 until 30th – 31st March for Elitech sensors. 3 – 4 sensors per property. 22nd February 11 ongoing for Carnego sensors. 1 – 2 sensors per property.	No issues with Elitech sensors. Carnego systems temperature & humidity sensors not working in Notts 5 until 18th March 2022.
Electrical Import and Export	Carnego 8, 14, 18 from 21st February 2022. Carnego 38 from 18th March 2022. Daily readings for imported electricity from September 21 to March 22 from Smart meter for Notts 4.	In Notts 4 and 5 the electricity meters were not working correctly. This was spotted whilst reviewing data early March, and a site visit took place on 18th March to resolve. The actions taken resolved issues in Notts 5 so data is available from that point. The HTC calculation in this report used the period from 18th March to 31st March. The visit on 18th March did not resolve the issues with Notts 4. Electrical import and export meters not working correctly. Further analysis shows these have been wired incorrectly so the readings are not correct. Import readings have been gathered from Utilita. Smart meter data is expected to follow. This does not record Export readings so this has been derived based on the average of the other similar properties.
Electricity Generation	Carnego from 21st January 2022	No issues.
Heat Pump Electricity Input	Carnego from 21st Jan 2022	No issues

Heat Pump Output	Carnego from 21st Jan 2022	Notts 3 had a faulty heat meter. Carnego tried to rectify this on 18th March but it continued to be faulty. The heat output has been calculated based on the minimum, maximum and mean COP of the other heat pumps (taking out Notts 2, which was the site office and used minimal hot water). The HTC calculations were carried out based on each scenario.
Manual Meter Readings	Meter readings taken to support HTC calculations before works and after works.	Meter readings were taken before works and used to calculate HTCs. There are some challenges with the reliability of post completion meter reads due to smart meters having an inconsistent approach to access full data (Rate 1, Rate 2, Import / Export). Smart meter data is being sought on one property. Carnego data has been used instead of meter reads for post completion HTCs.
Energy Bills	Energy bills collected for 12 months before the works were carried out.	One of the properties (Notts 2) became void before works started, and then was used as a site office for the duration of the works. Energy bill data has been gathered for all other properties, although in some cases they are based on estimated readings.
Occupant Comfort Surveys	Collected before and after works	Due to one property being void, only four before / after comfort surveys are available for the Nottingham part of the DA.

2.0 Data Analysis

This analysis of data from the study is divided into five sections:

- heat loss savings from the retrofits
- comparing estimated heat loss with the design HTC
- internal temperatures and thermal comfort
- energy use
- savings
- interview data (Occupant Satisfaction surveys).

Heat loss savings from the retrofits

Heat loss was estimated by Elmhurst Energy based on weather data, energy use, internal temperatures, meter readings and solar gain estimates from window type, size and orientation. Using this data and BTS's Smart HTC algorithm, they estimated the Heat Transfer Coefficient (HTC, W/K, which is heat loss per unit temperature difference to outside). However, since the usable floor area increased in Nottingham, this makes comparisons difficult. Subsequently, we normalised the HTC per unit floor area to give the Heat Loss Parameter (HLP, in $W/K/m^2$).

In Nottingham there were three successful HTC estimates using the standard approach, but the fourth home needed more care and a tailored approach because of problems with data collection (technical problems with the heat and electricity meters on the heat pump).

In Nottingham the work increased the heated space from $81m^2$ before the retrofit to $102m^2$ afterwards. This also increased the area of the fabric envelope, and hence the HTC. We have reported the Heat Loss Parameter (HTC per m^2) as well as the HTC so that this impact is reflected.

For the Sutton homes, the HTC (and HLP) estimates post retrofit, using the BTS algorithm, were based on data from the 19th to the 31st of March. (Energiesprong has since carried out further HTC work, using data from April, but this is not reported here. The longer period generated estimates that were on average 8% lower (better).)

Note that all HTCs and HLPs used data from a heat meter, so they were unaffected by COPs of the heating equipment, either in Nottingham or Sutton. This means the results were not distorted by problems with the heat pumps in Sutton.

Comparing estimated heat loss with the design HTC

Pre and post HTC and design HTCs are presented in Table 8 below. Coloured figures indicate a statistically significant difference. Design HTCs were calculated using the Passivhaus Planning Package, PHPP, for Sutton; and SAP for the Nottingham homes. Comparing actual performance against the design specification is important because a large difference means that predictions of energy savings – and hence actual value for money for the interventions – are incorrect.

Table 8: Pre and post HTC and design HTC for all homes*

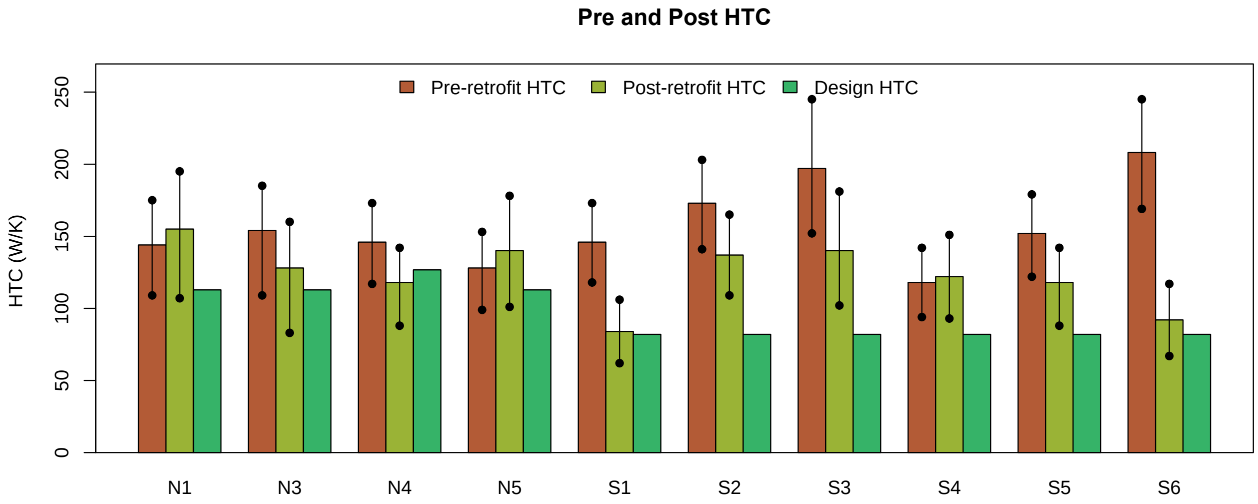
Code	Pre-HTC W/K	Post-HTC W/K	Design HTC W/K	Reduction pre to post	Difference design to post
Notts 1	144 +31/-35	155 +40/-48	113	-8% +29/-42%	37%
Notts 3	154 +31/-45	128 +32/-45	113	17% +53/-12%	13%
Notts 4	146 +27/-29	118 +24/-30	127	19% +45/-28%	-7%
Notts 5	128 +25/-29	140 +38/-39	113	-9% +45/-28%	24%
Sutton 1	146 +27/-28	84 +22/-22	82	42% +67/-19%	2%
Sutton 2	173 +30/-32	137 +28/-28	82	21% +45/-3%	67%
Sutton 3	197 +48/-45	140 +41/-38	82	29% +60/-3%	71%
Sutton 4	118 +24/-24	122 +29/-29	82	-3% +29/-35%	49%
Sutton 5	152 +27/-30	118 +24/-30	82	22% +48/-1%	44%
Sutton 6	208 +37/-39	92 +25/-25	82	56% +78/-34%	12%

**Note that six homes were recruited in Sutton and six in Nottingham. However one household dropped out and another moved away before the plan was complete, leaving only four.*

The fabric upgrades improved thermal performance in all-but-two cases, but the reductions in heat loss were not as large as expected in design estimates. Standard deviations for the reductions in heat loss (the 'Reductions pre to post' column in Table 8) were 15% for Nottingham, 20% for Sutton, and 21% in total. Standard deviation is higher in total, across the whole sample, because it includes variation between the two cohorts.

Figure 1 below also compares post retrofit performance with the design value. There is a statistically significant difference between design estimate and measured HTCs in four of the Sutton homes, but none of the Nottingham homes. Considered as groups, the difference between the post retrofit HTC and the design is not significant for the Nottingham homes but is for Sutton homes. This suggests that the retrofit measures applied in Nottingham were a more reliable way to reduce heat loss – or perhaps that the design estimates for Nottingham were more robust.

Figure 1: Pre and Post HTC and design HTC for all homes



Optimism in the design calculations for Sutton could be partly explained by party walls with non-Energiesprong properties: Sutton 2 to 5 all shared one party wall with homes that were not retrofitted, whereas the other two Sutton homes, which had better results, were all adjoined to other retrofit properties. It is likely that thermal bridging around the wall, roof and floor insulation undermined part of the heat loss benefits.

Energiesprong UK explained that there were no special measures to reduce thermal bridging to under-insulated neighbouring dwellings. The usual strategy of returning internal wall insulation back across the part of the party wall nearest the external wall was difficult because they endeavour to complete work from outside to minimise disruption. Ideally, Energiesprong UK would much rather recruit continuous blocks of homes rather than pepper pots of homes scattered across an estate, and this would avoid the party wall problem.

Looking for clues as to why Sutton 4 has such a disappointing increase in HTC, and comparing against other Sutton properties, it seems likely that the pre-retrofit HTC estimate was too low. (It was easily the lowest of all pre-retrofit HTCs.) The true pre-retrofit value is likely to lie close to the top of the error bar for this case – more like the other Sutton pre-retrofit HTCs. There are no obvious explanations as to why the pre- HTC estimate was so low. Internal temperature was around 18.5°C, and pre-retrofit gas consumption was around 6,000kWh a year – so this was low, but not ridiculously so. Nor was there evidence of overheating from the neighbouring dwelling that could have warmed the home and distorted findings. Energiesprong UK plan to repeat the HTC estimate in Winter 2022-3 to see if there is any change in findings then.

HTCs and hot water use

If energy use for providing domestic hot water is not available separately from energy use for space heating, the SmartHTC algorithm calculates an assumed hot water consumption based on a mix of the energy use, number of occupants (if this is known), building type, and floor area. It is typically in the range of 60-200l/day, and for these houses the calculated consumption came out around 90l/day for those with lower occupancy and 160l/day where there were more occupants. The measured hot water consumption was above the normal range in three cases: Notts 1 (340l), Sutton 5 (269l) and Notts 5 (230l). It was also *well* below the normal range at Sutton 4 (20l).

Where hot water consumption is significantly higher than this calculated value, the SmartHTC result is higher than the actual thermal performance – because there is actually less heat input into the dwelling than calculated. Conversely, where hot water consumption is lower than calculated, the SmartHTC result under-estimates the true HTC. This is accounted for in the calculation of confidence intervals, but it could cause a variation in the central SmartHTC result of up to 5% in extreme circumstances. BTS say that it is always more accurate to input disaggregated data where possible, but this seldom happens in practice because the data collection equipment required is expensive.

The large uncertainties in estimated HTCs (shown in the table above as relatively large +/- values, and in the figure as tall black uncertainty bars) are mainly due to the short timeframe for post retrofit testing. As well as increasing the uncertainty in HTC tests, this also forced us to use a model for estimating actual bill savings, rather than using actual meter readings. We have incorporated uncertainty into this model for the most important parameters, namely fabric efficiency (HTC) heating efficiency (SCOP) and self consumption for the energy from the solar panels.

Heat loss normalised by floor area

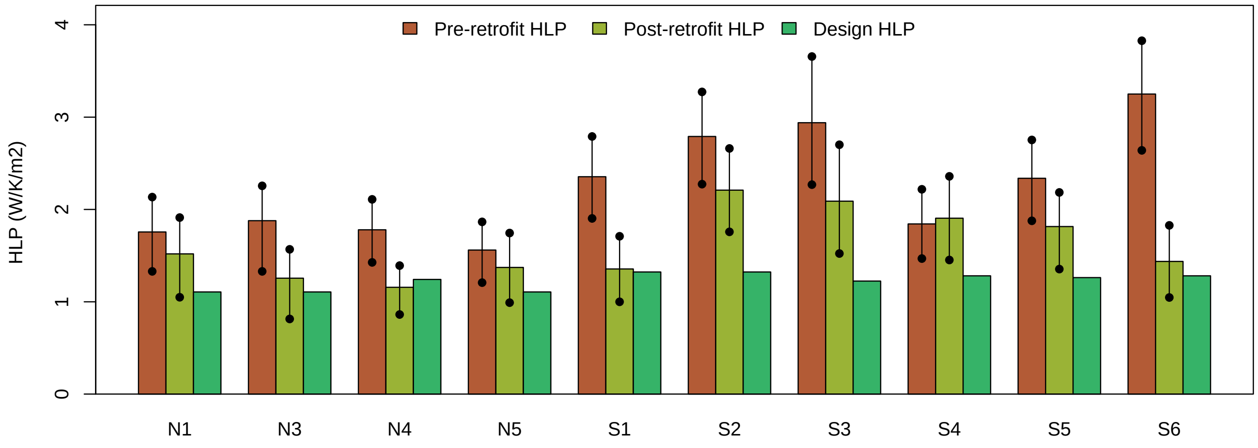
Another way to compare before and after performance is using the Heat Loss Parameter (HLP), which is the heat loss normalised by floor area. Table 9 and Figure 2 below illustrate the results. Again, coloured figures in the table indicate statistically significant differences. HLP has improved (decreased) in all but one case, but there are only three cases where the improvement is significant. Note that HLPs in Nottingham are affected by the increased floor area resulting from converting garages to heated living space, so they are slightly better than the equivalent HTC figures reported above.

Table 9: Pre and post retrofit HLP and design HLP for all homes

Code	Pre-HLP W/m²K	Post-HLP W/m²K	Design HLP W/m²K	Reduction pre to post	Difference design to post
Notts 1	1.76 +0.38/-0.43	1.52 +0.39/-0.47	1.11	13%	37%
Notts 3	1.88 +0.38/-0.55	1.25 +0.31/-0.44	1.11	33%	13%
Notts 4	1.78 +0.33/-0.35	1.16 +0.24/-0.29	1.24	**35%**	-7%
Notts 5	1.56 +0.30/-0.35	1.37 +0.37/-0.38	1.11	12%	24%
Sutton 1	2.35 +0.44/-0.45	1.35 +0.35/-0.35	1.32	**42%**	2%
Sutton 2	2.79 +0.48/-0.52	2.21 +0.45/-0.45	1.32	21%	**67%**
Sutton 3	2.94 +0.72/-0.67	2.09 +0.61/-0.57	1.22	29%	**71%**
Sutton 4	1.84 +0.38/-0.38	1.91 +0.45/-0.45	1.28	-3%	**49%**
Sutton 5	2.34 +0.42/-0.46	1.82 +0.37/-0.46	1.26	22%	**44%**
Sutton 6	3.25 +0.58/-0.61	1.44 +0.39/-0.39	1.28	**56%**	12%

Considering each group in turn, for Nottingham homes the mean reduction in HLP is 0.42 W/m²K and this is statistically significant ($p=0.02$). For Sutton the difference is larger: 0.78 W/m²K, and again significant ($p=0.01$).

Figure 2: Pre and post retrofit HLP and design HLP for all homes



2.1 Internal temperatures

Internal temperatures were monitored in four rooms pre-retrofit and in three or four rooms post-retrofit. The table below shows the periods when this occurred. Post retrofit monitoring was in the spring of 2022 and Pre-retrofit monitoring was sometimes also in the spring but often earlier in the year.

Table 10: Monitoring periods for Sutton and Nottingham homes

House	Pre-retrofit	Post-retrofit
Sutton 1	03/Mar/21 - 09/Apr/21	02/Mar/22 - 17/Apr/22
Sutton 2	03/Mar/21 - 09/Apr/21	02/Mar/22 - 17/Apr/22
Sutton 3	15/Dec/21 - 28/Jan/22	02/Mar/22 - 17/Apr/22
Sutton 4	03/Mar/21 - 07/Apr/21	02/Mar/22 - 24/Apr/22
Sutton 6	-	02/Mar/22 - 25/Apr/22
Notts 1	17/Dec/20 - 01/Feb/21	22/Feb/22 - 29/Mar/22
Notts 3	17/Dec/20 - 17/Mar/21	26/Feb/22 - 14/Apr/22
Notts 4	17/Dec/20 - 17/Jan/21	22/Feb/22 - 05/Apr/22
Notts 5	17/Dec/20 - 17/Mar/21	22/Feb/22 - 01/Apr/22

Internal temperatures are often partly dependent on external temperatures, therefore to allow a fair comparison between internal temperatures pre-and post-retrofit, we have used statistical analysis to determine what the temperature would be when it is 8°C outside. Note that this analysis includes all days where data was available.

The impact of external temperatures on room temperature has a delay due to the thermal mass of the building. Therefore we have applied a thermal lag of 12 hours. Figure 3 below shows how the lagged temperature varies over a week in Nottingham.

Figure 3: External temperature, hourly average and with 12-hour lag, for Nottingham, one week in March

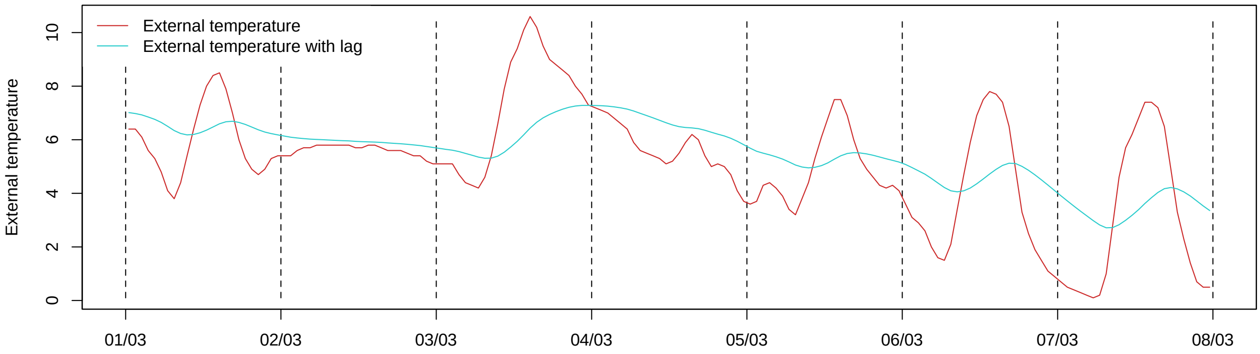


Figure 4 below shows the relationship between internal and external temperature, averaged over whole days, for one house (Sutton 1). The lagged external temperature has a stronger relationship – on average, the dots are closer to the trend line. (R-squared, which is a measure of correlation between variables, increases from 0.33 without the thermal lag to 0.44 with thermal lag.)

Figure 4: Daily mean room temperature against external temperature, with and without thermal lag

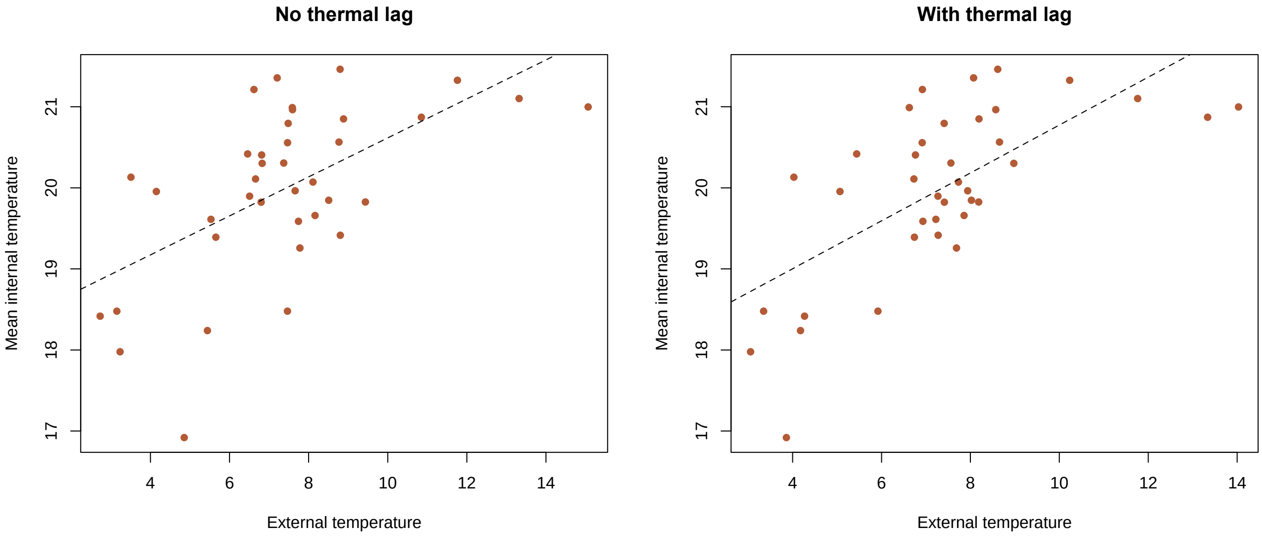
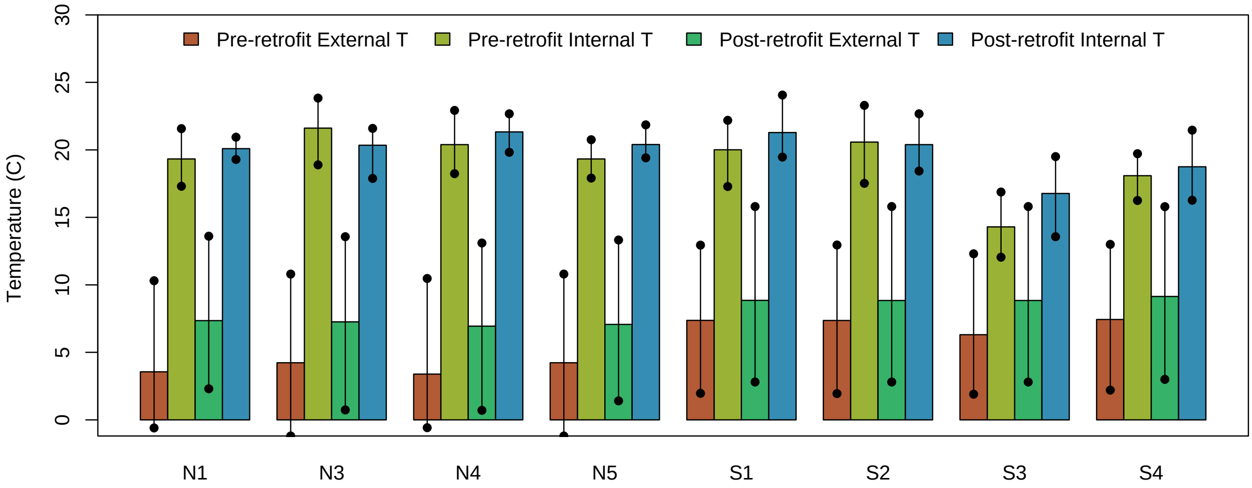


Figure 5 below shows average internal and external temperatures for all cases, based on daily averages with all data pre and post retrofit. The black range lines indicate temperature variation: the temperature was between these points 90% of the time. Sutton 6 is not shown because there was no monitoring pre-retrofit.

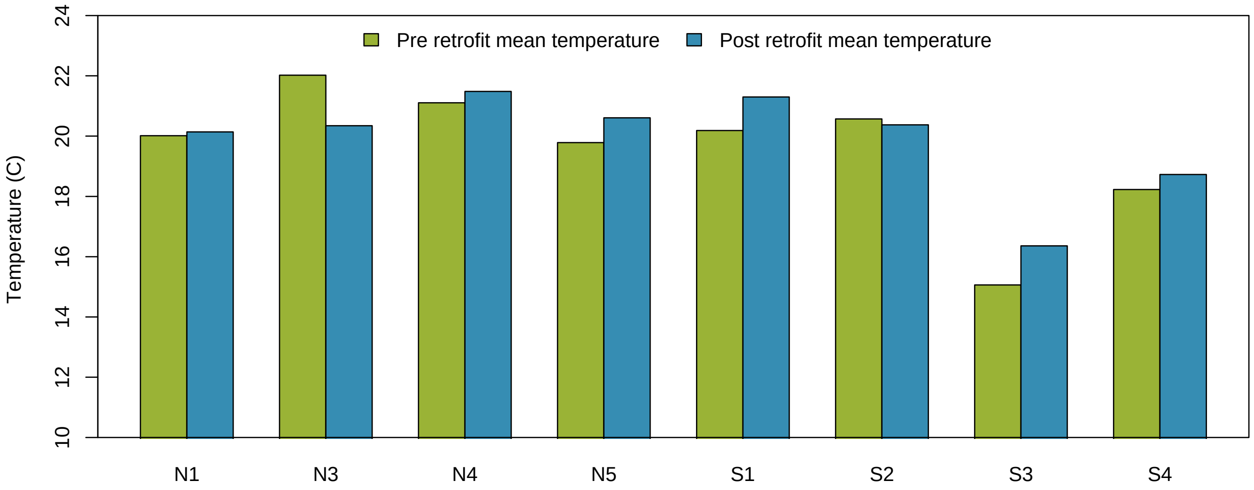
Figure 5: Temperatures and temperature ranges for internal and external temperatures pre and post retrofit



Considering all the homes shown in the chart, the mean temperature has increased from 19.2°C pre retrofit to 20.0°C post retrofit. The difference is not statistically significant.

However, the external temperatures during pre-retrofit monitoring for the Nottingham homes were considerably colder than in the post retrofit period. The difference is much less for Sutton homes. This means that, for the Notts homes, where there is an increase in room temperature this could be due to external conditions rather than the retrofit. Accordingly, we have taken an additional approach – using linear regression analysis to estimate the typical room temperatures that would be seen at 8°C outside, see Figure 6 below. The methodology is the same as was used to generate the trend lines in the chart above, using lagged thermal temperatures. There is a notable decrease in temperature for Notts 3, although the new mean temperature is still above 20°C. In S3 and S4 the mean temperatures were low before and have increased.

Figure 6: Estimated mean room temperature pre and post retrofit, when it is 8°C outside



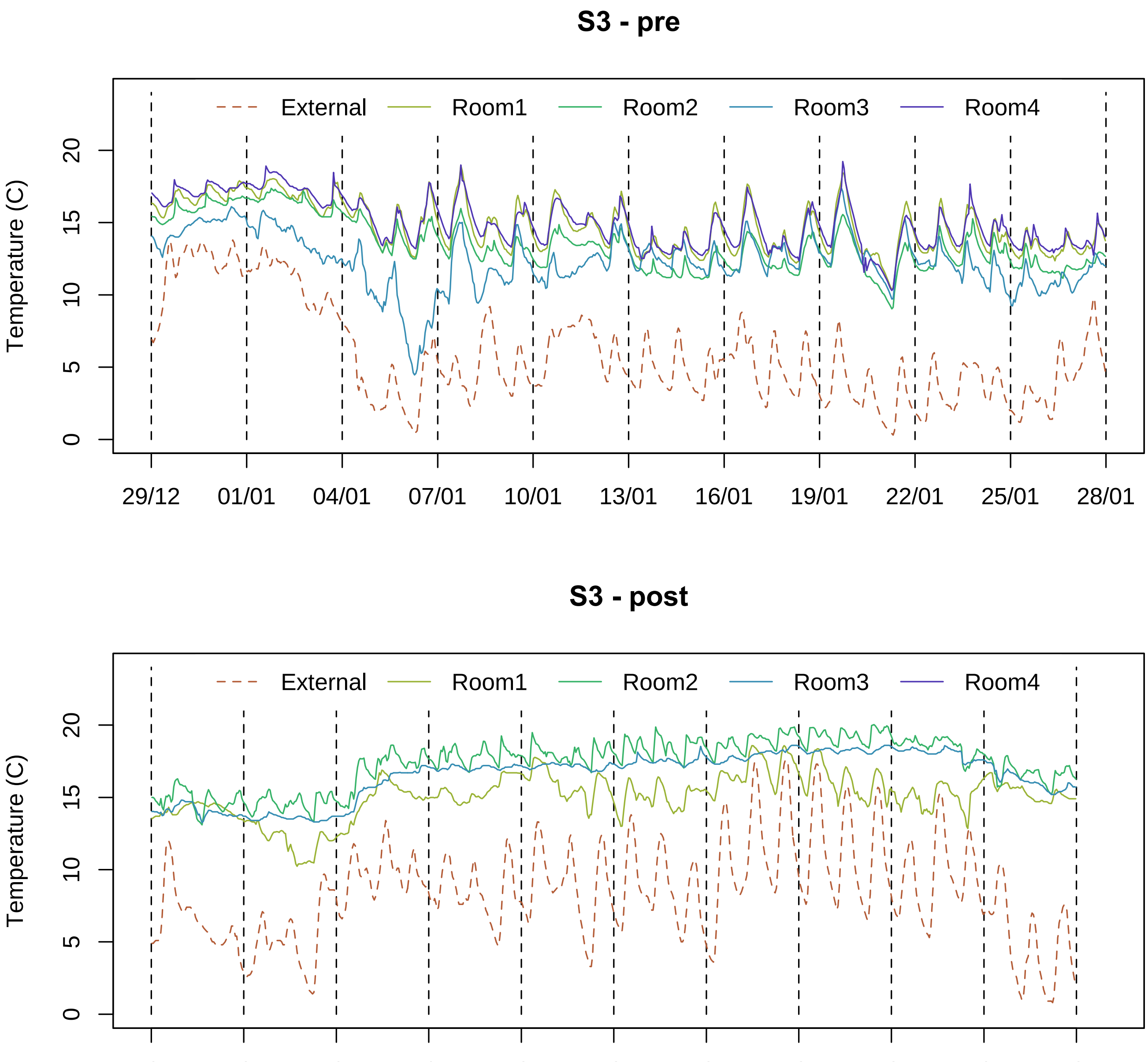
Considering all cases together, the mean internal temperature (corresponding to 8°C outside) increased from 19.6°C pre-retrofit to 19.9°C after the upgrades were complete. This change is small and not statistically significant.

Some of the homes have lower temperatures than before. A lower mean temperature does not necessarily lead to reduced comfort. Draughts and cold spots in a house can trigger discomfort in the occupants, which are partially rectified by raising the internal temperature. In contrast, when a house is air-tight and energy efficient without cold spots, the occupants can be comfortable at a lower thermostat set-point and mean temperature.

There are two outliers, Sutton 3, which was rather cool before the work and is now a little warmer, and Notts 3, which was rather warm and is now cooler.

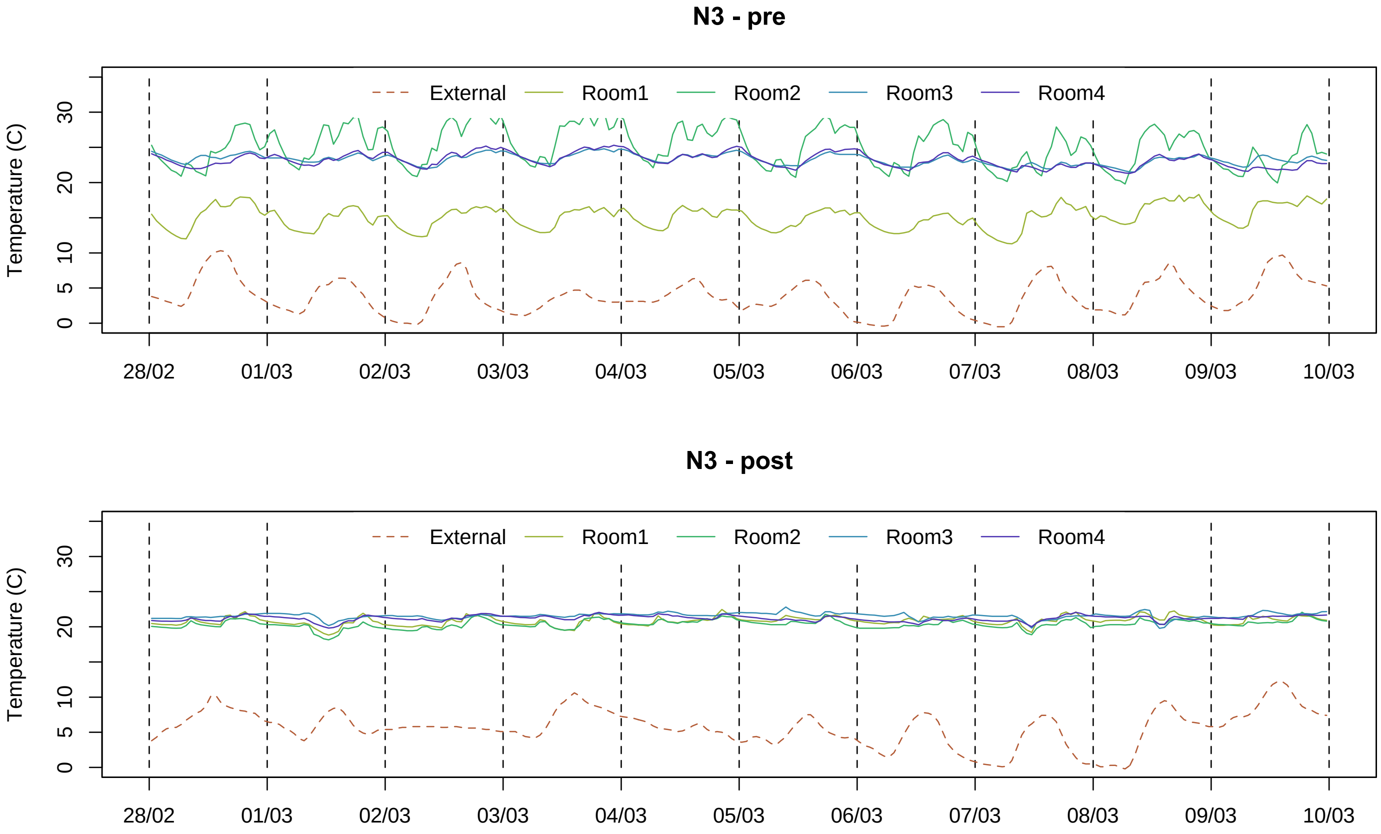
Figure 7 below shows room temperatures in more detail in Sutton 3. Unfortunately, we do not know which rooms are which and the numbers are not consistent in the two monitoring periods. However, one room was heated much less than the others; pre-retrofit the temperature in the unheated room dropped to below 5°C at one point (!). That was in January, but there were similar temperatures in the post-retrofit period during early March, and at the end of March, when that room was warmer. This suggests that heat loss was reduced in that room and it stayed closer to the house average even when the heating was off.

Figure 7: Pre and post retrofit temperatures in Sutton 3



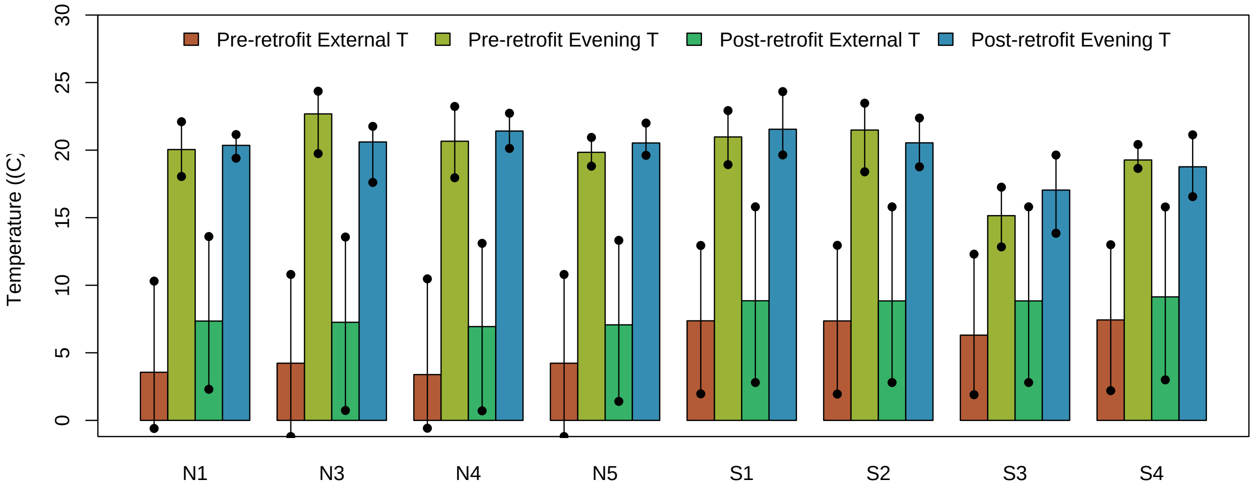
Readers should note that the chart above shows there is less day-to-day variation in temperature. This is partly because of the reduced heat loss, but also because of nearly constant heating, as is usual with heat pumps. This is also clear in the chart below showing temperatures in Notts 3.

Figure 8: Pre and post retrofit temperatures in Notts 3 over 10 days



Occupants are usually most interested in comfort in the day when they are in the house. The chart below compares evening temperatures (6-9pm) pre- and post-retrofit. It shows that after the work, four homes had higher evening temperatures, four had lower evening temperatures, and one had virtually the same evening temperature, on average.

Figure 9: Pre and Post retrofit mean temperatures in the evening (6-9pm) in all homes



For the sample as a whole, there is no statistically significant difference between evening temperatures pre- and post-retrofit. However, temperature changes are driven by a number of factors including fabric, heating regime and household behaviour, so sample means tell us little about the range of experiences. In Notts 3 (shown previously) before the retrofit, heat was concentrated in one room, whereas after the work, all the rooms had a similar temperature. This is a change in heating regime, possibly triggered by (an expectation of) greater affordability. The interview data (below) revealed improved satisfaction with thermal comfort in this house.

Table 11: Summary of internal temperatures

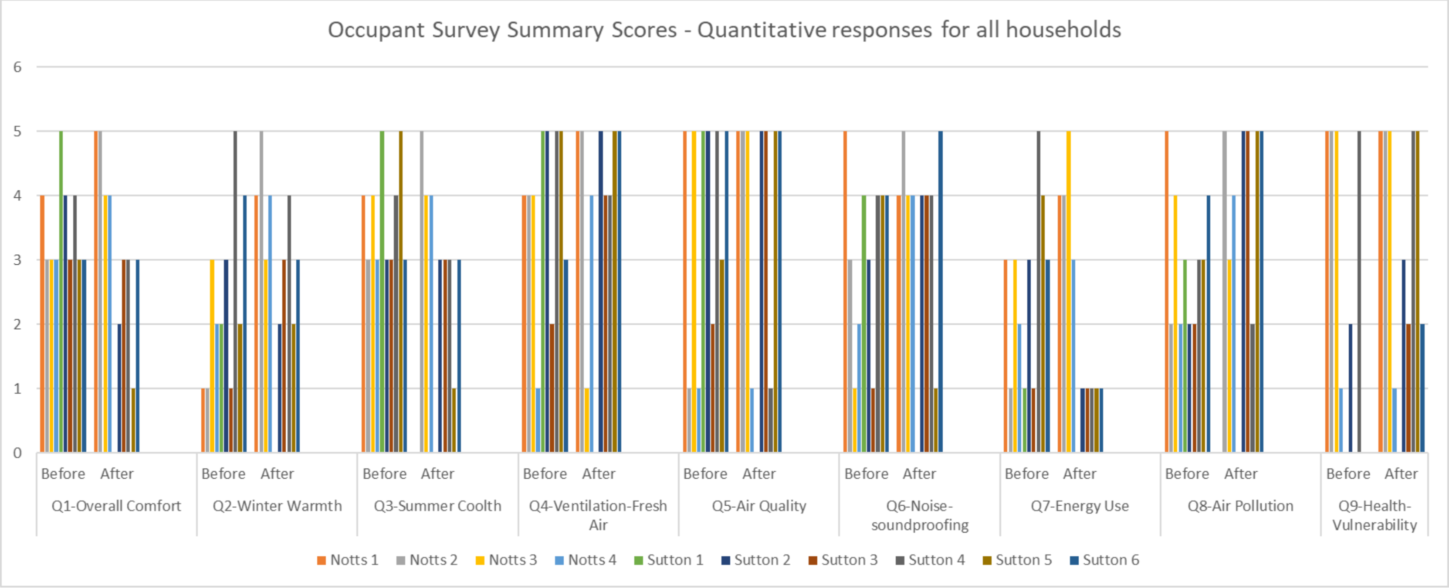
House	Pre retrofit	Post retrofit	Pre retrofit	Post retrofit	Pre retrofit	Post retrofit
	Mean temperature and 5%, 95% quantiles		Mean evening temperature 6-9pm and 5%, 95% quantiles		Estimated mean temperature for 8°C external temperature	
N1	19.3 +2.3/-2.0	20.1 +0.9/-0.8	20.0 +2.1/-2.0	20.4 +0.8/-0.9	20	20.1
N3	21.6 +2.2/-2.7	20.3 +1.2/-2.5	22.7 +1.7/-2.9	20.6 +1.2/-3.0	22	20.3
N4	20.4 +2.5/-2.2	21.3 +1.3/-1.5	20.7 +2.6/-2.7	21.4 +1.3/-1.3	21.1	21.5
N5	19.3 +1.4/-1.4	20.4 +1.4/-1.0	19.8 +1.1/-1.0	20.5 +1.5/-0.9	19.8	20.6
S1	20.0 +2.2/-2.7	21.3 +2.8/-1.8	21.0 +1.9/-2.0	21.5 +2.8/-1.9	20.2	21.3
S2	20.6 +2.7/-3.1	20.4 +2.3/-2.0	21.5 +2.0/-3.1	20.5 +1.8/-1.8	20.6	20.4
S3	14.3 +2.6/-2.2	16.8 +2.7/-3.2	15.2 +2.1/-2.3	17.0 +2.6/-3.2	15.1	16.4
S4	18.1 +1.6/-1.8	18.8 + 2.7/-2.5	19.3 +1.1/-0.6	18.8 +2.4/-2.2	18.2	18.7
S6	-	21.1 +3.0/-4.7	-	21.7 +2.7/-5.1	-	21.1

2.2 Interview data

All residents in Sutton and Nottingham were interviewed using the Occupant Satisfaction Survey questions in the Appendix. Each household carried out an interview both before and after the retrofits. The survey schedule has paired quantitative and qualitative questions on different aspects of comfort and health, with quantitative questions rated on a scale from 1 (low/poor) to 5 (high/very good). This allows straightforward comparisons between perceived comfort and performance before and after the upgrade work was carried out.

Quantitative questions for all homes in Sutton and the occupied homes in Nottingham are summarised in the chart below, which shows Questions 1 to 9 along the bottom, and each of the 10 occupied dwellings shown in a different colour. The top-level summary is that ratings generally improved for Questions 2, 4, 5, 6 and 8; but they deteriorated for Questions 1, 3 and 7. (Question 9 was about occupant health, and changes here are unrelated to the retrofit work.) The trend is more positive (i.e. more increases) for homes in Nottingham, with lower scores after the retrofit more common in Sutton. This part of the report drills into each question in turn and compares ratings and comments from residents before and after the retrofits.

Figure 10: Summary of Occupant Survey – quantitative responses



Question 1: How comfortable are you overall in your home?

The mean score for this question across the 10 households before work was carried out was 3.5, which fell to 3.33 when the work was complete. (Note that in Nottingham mean score rose from 3.25 to 4.5.) All households in Nottingham gave higher ratings after the retrofit. However, in Sutton three households gave lower ratings and two gave the same score for overall comfort. In qualitative comments prior to the work, all four households in Nottingham said their homes were cold in winter. Two examples are:

“The house is cold all the time, I can feel the wind coming through the windows as well it’s not good.”

“It’s comfortable but it does get cold and I use my heating a lot. On a regular day to day basis my property is more on the cold side.”

After the work, qualitative responses were much more positive. All four said they were now comfortable, and two said they now felt warm in their homes:

“I’m very comfortable. It looks good and I’m warmer.”

“Now the house has become warmer and I really like the modern look. The transformation with the windows. Modern feel.”

In contrast, none of the Sutton residents said that they were cold prior to the retrofit work. Their comments in reply to this question related to other issues they thought were important, for example:

“The walls are poor and the garden floods [in heavy rain].”

"I would prefer a walk-in shower."

After the work in Sutton, there was only one qualitative response to this question:

"I am not happy with workmanship and standard of works."

It is possible that Sutton households' dissatisfaction with the workmanship of the retrofit coloured their scoring of overall comfort for this question.

Question 2: Are you warm enough in winter?

The mean score for this question from all residents before work was carried out was 2.4, rising to 3.33 when the work was complete. (For Nottingham households the mean rose from 1.75 to 4 – a much greater improvement.) All-but-one Nottingham resident recorded a higher rating after the retrofit. This household, Notts 3, gave the same score, but this is explained partly by their pre- comment:

"I am warm enough in winter but that's because my heating is constantly on full otherwise it's not nice."

Other households in Nottingham gave similar comments pre-retrofit:

"Winter is horrible in this house and we have to constantly keep the heating on and even then it's still not perfect."

"Because winter here is not good and we can feel the cold a lot and it's rare we ever switch our heating off."

Post-retrofit, the comments in Nottingham were divided. Two households (Notts 1 and Notts 3) expected winter comfort to be better:

"It's still kicking in and we still need the heating on."

"Because I feel I should be warmer all rooms don't get that hot. It's mainly the small rooms like the bathroom and box room that get more heat."

However, the other two households (Notts 2 and Notts 4) gave very positive comments, and said they felt warmer:

"I'm very warm when it's cold outside and it's not too stuffy."

"I'm much warmer during the cold periods."

In Sutton, three households gave lower ratings for winter warmth after the work than they had beforehand. Only two of them had provided qualitative comments before the work:

"The windows are not great."

"[It's warm enough] when we put the heating on."

After the work, the Sutton residents generally felt that they hadn't had the opportunity yet to fully test the winter comfort, saying:

"I have not been able to control heating at times when cold, [and] not had a chance to really judge [the heating]"

"We haven't had a winter yet."

"We have not had winter [yet] but it has been cold and we had to use additional heating."

The last comment suggests that the heat pump is not able to provide as much heating as the occupants want – or at least, not with their current settings. The periods of heating could have been too short to achieve the temperature they wanted.

Question 3: Are you cool enough in summer?

The mean score for this question fell after the work: from a mean of 3.7 down to 3.25. (In Nottingham alone the mean rose from 3.5 to 4.33.) As with Question 2, Nottingham households all gave the same score or better after the retrofit, whereas Sutton households all gave the same score *or worse* and in one case (Sutton 5) the score fell from 5 down to 1. This household did not provide any qualitative explanation as to why summer comfort was so much worse.

There was a range of qualitative responses from the Sutton households before work took place – from positive to negative. These are the extreme comments:

"I'm comfortable in the summer it doesn't get to hot and we keep the windows open so we have a nice temperature."

"[I give a rating of 3] because sometimes the reflection from the sun on to the windows makes the property very stuffy."

After the upgrade work, Sutton residents were more positive in their comments:

"Yes, It used to get too hot and stuffy. Now it's a nice heat."

"I'm very comfortable in the summer especially when it's hot outside my house, it's nice inside."

Again, there were only minimal qualitative responses to this question from Sutton households. Before the work, one said:

"[It is comfortable] only if we open the windows and doors." (This household did not provide comments in response to this question after the work.)

After the retrofit, another household said:

"We have not had a summer to judge."

Question 4: Is there adequate ventilation and fresh air in your home?

The mean rating for this question improved from 3.8 before work to 4.22 afterwards. All-but-one household in Nottingham reported better ventilation after the retrofit – with Notts 3 the exception, giving a score of 4 before the project and only 1 afterwards. Meanwhile, in Sutton, two households gave a higher rating and one gave a lower rating (the others said ventilation was the same).

Three of the four Nottingham households said that ventilation was good before the work took place, but the fourth (Notts 4) said:

"No because otherwise we wouldn't have so much mould. We also have to keep our windows open regularly so we can get nice fresh air inside as we have hardly any ventilation."

This household gave a more positive comment about ventilation after the work:

"There is [good ventilation] but not in the bathroom."

The Nottingham household that reported worse ventilation (Notts 3) said after the work:

"Ventilation is not too great and don't work too good so not getting loads of fresh air. I think I should have more vents."

The Sutton households provided more limited comments about ventilation, but three of them said that they normally opened windows for ventilation before the work:

"I tend to open windows."

"We normally open windows."

After the work, the only household in Sutton to provide a comment said:

"Windows are opened [to provide ventilation]."

Question 5: Are you aware of air quality problems, like mould or solvent fumes?

For this question a '5' rating means they are not aware of any problems, while a '1' means they are aware of problems. The mean score before the work was 3.7, while after the work this rose to 4.11, indicating better perceived air quality. One of the Nottingham households gave a much higher rating for air quality (Sutton 2's score rose from 1 to 5), but the other Nottingham homes gave the same score before and afterwards. In Sutton, two households gave a higher score for air quality after the work, one lower, and the others the same score.

For the Nottingham homes, two (Notts 2 and Notts 4) had damp issues to begin with, and gave a rating of 1, but the two others reported no problems. The two with damp said:

"There is a lot of damp especially in my child's bedroom."

"We have so much mould in the property especially in the bathroom and the kitchen and top floor, there is not enough ventilation to stop the mould keep coming back."

After the retrofit, one of these (Notts 2) reported no damp, so gave a 5 rating, while the other (Notts 4) still had problems with mould. Respectively, they said:

“I don’t have any damp in the property which is good.”

“I have a lot of mould in the property. But I have reported to NCH repairs to fix.”

Turning to Sutton, two pre-work comments were:

“We have no [air quality] issues.”

“The windows steam up.”

The latter quote (from Sutton 5) reported no window-condensation problem after the work was complete, which probably explains their improved rating from 3 to 5. The other household in Sutton that had reported a pre-existing mould problem (Sutton 3) also gave a higher rating after the work, but they did not give any comment about this.

Question 6: How do you rate the noise and soundproofing of your house?

The mean rating for noise and soundproofing improved from 3.1 to 3.88 after the retrofit work. In Nottingham three households gave a higher rating, while one (Notts 1) gave a lower rating. Similarly, in Sutton, all-but-one household (Sutton 5) gave a higher rating or the same after the work.

The Nottingham household that gave a lower score for noise (Notts 1) said this before the work:

“[I’m giving a 4] because its good and we can only hear outside noise if people are shouting.”

After the work, this household said:

“We can still hear neighbours - not changed. Outside noise less. Can't hear if people are knocking.”

This suggests that they gave a lower score not because their home became noisier, but because they had trouble hearing people knock at the door after the work was complete.

All three of the other Nottingham households said that they could hear what was happening in the street in their homes before the work took place. Afterwards, all three said this was less of a problem:

“It’s good as I don’t hear next door or cars outside.”

“[Soundproofing is] good because it’s actually quiet and I don’t hear noise from others.”

The Sutton household that gave a lower score for noise offered no explanation as to why they thought noise or soundproofing had deteriorated. However, two said before the work:

“You can hear [the neighbours] through the walls.”

“I can hear next door.”

The latter reported after the work:

“[Noise from next door] is better since the work was completed.”

Question 7: How do you rate your home’s energy usage?

The mean rating for this question across all households fell after the retrofit, from 2.6 down to 2.33. (However, the mean rating in Nottingham rose from 2.25 up to 4.) In Nottingham, all households gave a higher rating, but in Sutton all-but one gave a lower rating. After the work, all Sutton respondents scored their homes only 1 out of 5.

Before the work, a majority of Nottingham households said they thought their bills were high, especially electricity:

“My bills are so expensive I am currently in debt of £450, they said I’m using a couple of hundred pound every month and I don’t understand why.” [Tenant gives actual meter readings]

“The gas usage is ok but I often have to keep topping up my electricity as runs out quick.”

After the work, three of the four Sutton households reported savings, and the fourth had not yet received a bill:

“Big change. Saving from before. In winter we saw a change and in summer we expect to see more.”

“Already costs have been going down between £3-£4 a day.”

In Sutton, before the retrofit, comments were mixed:

“We are topping up [the meter] too often.”

“Pretty good - it costs £107 a month.”

But after the work they were negative – very likely because of the problems with the heat pumps discussed above:

“We are now spending too much on electric [bills].”

“Electric bills are very high.”

Question 8: How do you rate air quality, including traffic pollution/secondary tobacco smoke?

Arguably, this question is not relevant to the Energiesprong retrofit, because retrofit work has a limited effect on air quality, but it was included because housing associations and local authorities are concerned about the health of their residents. Nevertheless, the mean rating for this question rose after the work: from 3 to 4.25. In Nottingham two households gave a higher score, while one gave a lower score (the other did not answer). In Sutton four households gave a higher rating and one lower (again, one did not answer).

In Nottingham, before the work, views on air quality were rather mixed:

“The air quality is good and things such as others peoples smoke don’t enter my property.”

"[I rated a 2] because the fact I have to keep my windows open when I want fresh air this means I get pollution and neighbours' smoke and also spiders in the property, so it's not good."

After the work, qualitative responses were similarly mixed in Nottingham:

"Tobacco smoke is so bad. That hasn't changed. Neighbours smoke from the windows so it comes in when windows are open. Using next door as B&B. Smell which has been coming. Pipes. Is it outside. Mostly in the passages. I used to think it's the toilet. Bad some days and not others. We didn't have it before the retrofit."

"The only issue is I can smell next doors tobacco through the bathroom vent."

There was just one comment from Sutton respondents before the work:

"Smells come through from our neighbours."

There were no comments at all after the retrofit, and this respondent (Sutton 3) raised their rating for air quality from 2 to 5, suggesting that the work helped to improve air quality for the home.

Question 9: Are members of your family more vulnerable than average to poor air quality or temperature?

This question is about the baseline health of participants in the study. It is not affected by the retrofit, so it is no surprise that ratings hardly changed from before to after the retrofit. For this question, a '5' rating means residents are not vulnerable, while a '1' means they are more vulnerable. The mean rating across all households fell from 3.83 to 3.66, indicating a very slight worsening of health and vulnerability.

In Nottingham, three of the households did not have any vulnerable residents, but the fourth did: an elderly person. In Sutton, two households included people with both anxiety and breathing problems, while a third (Sutton 6) had no health problems before work started but had been diagnosed with cancer (with treatment starting) after work was completed. It is not clear whether this change had any impact on the other comfort ratings.

Significance testing

We used the Kruskal-Wallis rank sum test[3] [4], which can be used for comparing groups of ordinal data (like the Likert scale used in the quantitative part of the occupant surveys) to test for statistical significance of the Energiesprong intervention. This works by sorting all the values into a single list, keeping track of what groups they came from, and then comparing the ranks (positions in the list, allowing for equal places) of each group instead of the values. It is similar to the Wilcoxon test.

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[3] https://statistics.laerd.com/spss-tutorials/kruskal-wallis-h-test-using-spss-statistics.php

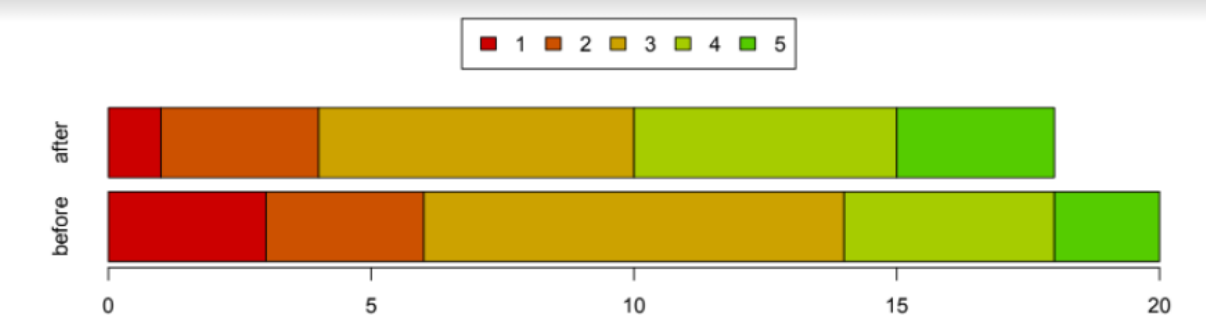
[4] https://users.sussex.ac.uk/~grahamh/RM1web/Kruskal-Wallis%20Handoout2011.pdf

The Kruskal-Wallis test applied to each question comparing before and after found that the only significant question (i.e. the results before and after are significantly different) is Question 8, on air pollution. The probability of getting this result through chance is only 0.033 (p=0.033), so it passes the 95% confidence test.

There were too few Nottingham responses to carry out individual question tests for that group. However, combining Questions 1 and 2 (on comfort and warmth), Nottingham alone gave a statistically significant result (p=0.0033) and Sutton was not significant.

Figure 11 below shows the before and after results for the comfort and warmth questions combined for Nottingham. Scores of 5 (good) are coloured green; scores of 1 (poor) are coloured red, and other scores in between. The more 5s - i.e. the larger the green part of the bars and the fewer 1s - i.e. the smaller the red part, the better.

Figure 11: Before and after ratings for comfort and warmth combined, Nottingham



Considering all questions together by the location, all Nottingham responses yielded p=0.0002094 - so there is a statistically significant result – but Sutton is not significant. This means that overall, the Energiesprong interventions had a statistically significant result on the whole occupant survey responses for Nottingham, but not for Sutton. Similarly, the interventions had a statistically significant impact on perceived comfort and warmth in Nottingham, but not in Sutton.

2.3 Comparing energy bills pre and post retrofit

Pre and post retrofit meter readings

Table 12 below shows the bills data that is available pre-retrofit. Whole years of data were used where possible to avoid bias due to seasonal trends. Where this was not possible, annual energy use was estimated by scaling up. For electricity we assume that usage is the same across the whole year, so it is a simple scale for the number of days. For gas, we assume a proportion is for hot water consumption and this is assumed constant for the year. In most cases this is 40%, but 50% for N1 as this was a low gas use household. The rest is for space heating and this is scaled by the number of degree days in the period. This more complex approach is important for N1 and N5, where the meter data is for a period much less than a year.

We have not performed a sensitivity analysis on this data because there is much variation from year to year. These figures are only indicative.

Table 12: Pre retrofit bills data

House	Dates	Days	Electricity (kW)	Gas (kWh)	Annual Electricity (kWh)	Annual Gas (kWh)
Notts 1	01/12/20 to 01/02/21 (E) 01/12/20 to 01/11/21 (G)	62 E 335 (G)	441	4,155	2,596	4,572
Notts 3	1/12/20 to 1/10/21	304	2,047	6173	2,458	7,427
Notts 4	01/12/20 to 01/02/21 (E)	62	479	-	2,820	-
Notts 5	01/12/20 to 01/06/21	182	1,479	4,720	2,966	7,832
Sutton 1	21/07/19 to 21/07/21 (E) 27/07/19 to 04/07/21 (G)	731 (E) 708 (G)	7,871	20,864	3930	10,756
Sutton 2	03/03/21 to 03/03/22 (E) 03/03/21 to 21/02//22 (G)	365 (E) 358 (G)	2,898	12,207	2,988	12,445
Sutton 3	09/09/19 to 09/09/21	731	4,703	9,854	2,348	4,920
Sutton 4	02/12/18 to 11/12/20 (E) 08/11/18 to 11/12/20 (G)	740 (E) 764 (G)	4,860	14,381	2,397	6,871
Sutton 5	04/03/21 to 23/11/21 11/03/21 to 03/03/22 (G)	264 (E) 357 (G)	1,366	113	1,889	115
Sutton 6	14/05/19 to 14/05/20 (E) 07/05/19 to 15/07/21 (G)	366 (E) 800(G)	2,059	26,581	2,053	12,128

From this table it seems that Sutton 5 did not use their gas for heating at all during the year before retrofit – if these readings are valid it can only have been used for cooking. (Though during the period of monitoring for the SmartHTC, the household definitely did use heat and also hot water). Since we do not have temperature data for Sutton 5 we cannot confirm this. However, we have excluded Sutton 5 from the analysis in this section, since a meaningful before/after bills comparison cannot be achieved.

Gas meter data was also missing for Notts 4. We have estimated gas use based on the temperature data we have for that house, see below.

Post retrofit, there is less than a month of heating season available. This data has not been used but the table below shows what limited data is available.

Table 11: Post retrofit bills data

Code	Dates	Days	Usage (kWh)	Mean usage (kWh/day)	Pre retrofit mean (kWh/day)
Notts 1	-	-	-	-	7
Notts 3	18/03/22 to 29/03/22	11	81	7	7
Notts 4	18/03/22 to 29/03/22	11	105	10	8
Notts 5	-		-	-	8
Sutton 1	19/03/22 to 31/03/22	12	231	19	11
Sutton 2	11/02/22 to 31/02/22	20	781	39	8
Sutton 3	10/02/22 to 31/02/22	21	406	19	6
Sutton 4	10/02/22 to 31/02/22	21	-643	-31	7
Sutton 5	[Excluded because heating is omitted from pre data]	-	-	-	-

Sutton 6	11/02/22 to 31/02/22	20	472	24	6

There was no valid data for Notts 5 and the meter for Sutton 4 seemed to be running backwards (possibly due to a malfunction because of the solar panels). The other readings are plausible. The increases in use are large for the Sutton homes, as discussed below.

The very short period of post retrofit energy data available – just 11 to 21 days – means it would be inappropriate to use these figures to attempt to estimate cost savings.

Sutton heating bills

Because of problems with the MVHR/heat pump reported earlier, heating costs for Sutton homes during the trial were very high, and probably not representative of performance once they are working properly.

(Regarding actual energy bills in Sutton, residents were reimbursed for their additional electricity usage during the trial. Happily, mild sunny weather when the trial finished means that residents are now benefitting from PV generation, so bills are reportedly similar to pre-retrofit bills. The exhaust-air heat pumps have now been fully commissioned in one house and contractors are rolling out the solution to the other five homes imminently. Energiesprong UK will check they are performing later in the year, and they also wish to repeat the HTC calculations next winter.)

Estimating cost savings

We performed a simplified heat balance calculation to disaggregate energy demand before the retrofit, calibrated to the bills, and then we modelled the post-retrofit energy demand and hence the energy bill. We then compared the cost of heating the homes pre- and post-retrofit, using the current SAP energy prices. The basic model for the energy bill is described below.

Pre-retrofit

- Gas is required for heating hot water and for space heating. Hot water consumption is calculated based on hot-water demand (in litres) during the post-retrofit monitoring period, with a 35°C temperature uplift for delivering hot water.
    - In one case (Notts 1), the monitored hot-water use was so high that it more than accounted for the *entire* annual gas bill. Either the monitored value was incorrect or the hot water consumption at that time was greater than usual. We capped hot water consumption to no more than half the gas bill (this only applies to Notts 1).
- Gas boiler efficiency is assumed to be 85%.
- Space heating demand is based on the measured HTC pre-retrofit, the measured internal temperature during monitoring, and external temperatures based on the weather between May 2020 and May 2022.

  - For Sutton 6 there was no pre-retrofit internal temperature data. We assumed a mean of 19.6°C as this is the average of all the others (Sutton and Nottingham).
- Heat gains other than from gas are based on use of lights and appliances (i.e. the entire electricity bill), solar gains through windows (during the heating season) and metabolic gains from the occupants (using the standard SAP assumption of 60W per occupant; lower than 100W actual gain from adult occupants to reflect the fact that they are out for part of the time).
- The total heating demand and heating supply should match.

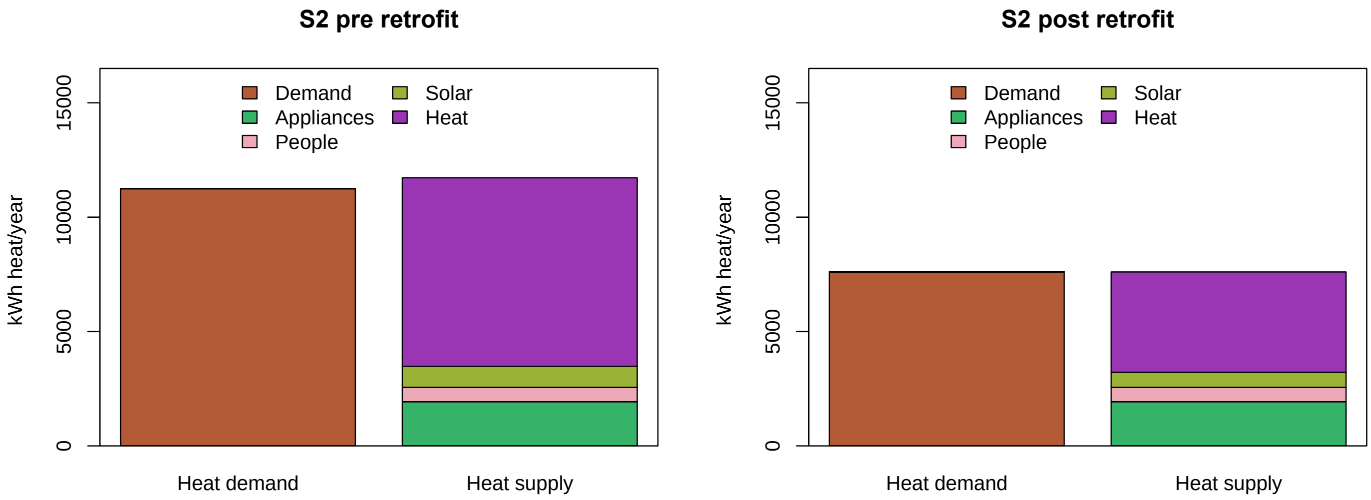
Post-retrofit

- The space heating demand is recalculated using the measured HTC and the measured internal temperature post-retrofit.
- Gains from the occupants, lights and appliances are assumed to be the same. Solar gains through windows are reduced based on the upgrade to the windows (which reduces thermal transmittance through the glass).
- The electricity required to deliver this heating is calculated based on heat-pump efficiency, using the actual coefficients of performance for each dwelling.
- We also calculated confidence ranges for the energy bills by varying parameters: the post-retrofit HTC varies between the ranges reported; the heat pump efficiency is varied between 2.3 and 3.0 (the normal ranges for air-source heat pumps, and the monitored efficiencies in Nottingham), and self-consumption for PV from the solar panels from 20% to 50%. We calculated the overall confidence ranges by summing the variances generated by each of these parameters.

For some homes the mean internal temperature varied depending on the external temperature. (This was particularly common where some rooms were unheated and strongly affected by the external weather.) We estimated parameters for this relationship from the temperatures during the monitoring periods. In cases where there was a significant variation, these results were used to estimate mean temperatures varying based on external temperature through a typical year, and so the annual heating demand. Otherwise, the mean internal temperature was used throughout.

Electricity and gas bill data for at least 12 months were sourced for all the homes except: Notts 4 (where only 2 months of data were available); and for Notts 1, Notts 3 and Notts 5, where fewer than 12 months of data were scaled up appropriately. For the homes with only two months of gas bills, the bill was estimated from the calculated demand for heat. Figure 12 below illustrates the heat balance that arises pre- and post-retrofit.

Figure 12: Results of heat balance analysis to disaggregate energy use



In a number of cases the supply and demand in the initial pre-retrofit balance were rather different. In the worst case (Sutton 4), the initial estimates of heat demand and supply differed by 50%. There are a variety of potential causes for this, including:

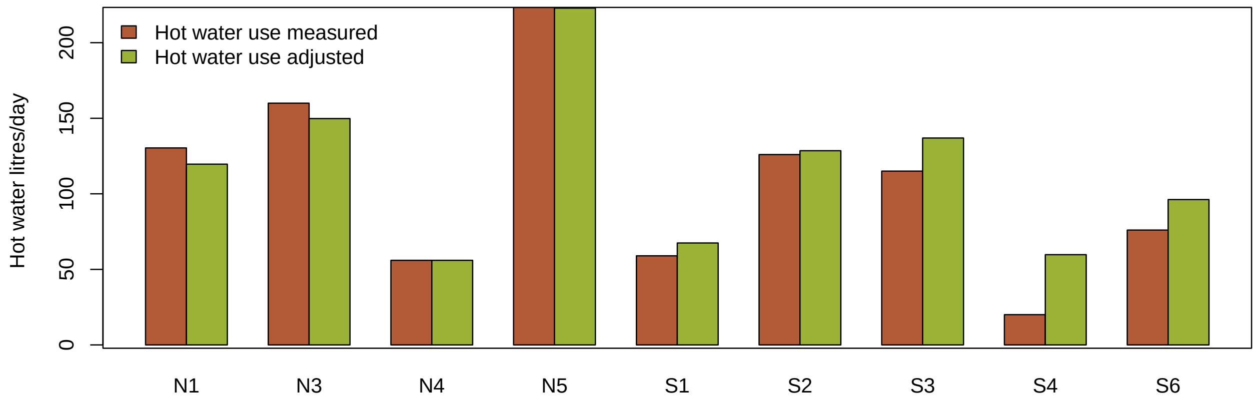
- The assumed gas boiler efficiency is incorrect.
- The internal temperatures during the monitoring period are not typical of the whole period behind the bills.
- The hot water demand during the monitoring period was not typical of the whole period behind the bills.
- The HTC estimate is inaccurate.
- The occupant behaviour is such that the metabolic gains do not match the SAP standard assumption.

We subsequently adjusted some of the parameters to improve the fit (see chart below). This adjustment was performed by using the statistical technique, ‘Maximum Likelihood Estimation’. The six parameters allowed to vary were: boiler efficiency, hot water consumption, HTC (using the known confidence range), metabolic gains, solar gains and internal temperature. After adjustments, the worst-case difference between supply and demand was 12%.

- Boiler efficiency varied between 76% and 90%.
- Hot water consumption was in all cases closer to the norm (illustrated in Figure 13 below).

- Space heating demand varied between 96% and 104% of the expected – reflecting changes in internal temperature patterns.
- Metabolic gains and solar gains varied: between half and double the expected gains. However, there is more uncertainty around these values than others, because of potential shading and occupant behaviour. In any case, they are a relatively small part of the heat balance in most cases.

Figure 13: Adjustments to hot water consumption



The two charts below show the balance between heat supply and demand before and after the adjustments – the first shows the heat balance without adjustments, the second after adjustments were applied.

Figure 14: Heat balances before and after adjustments

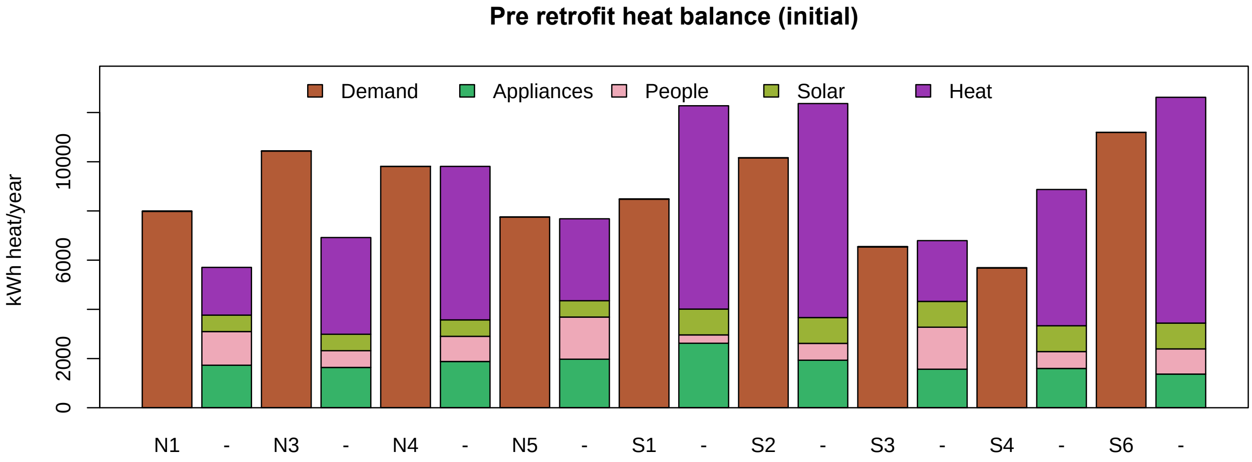
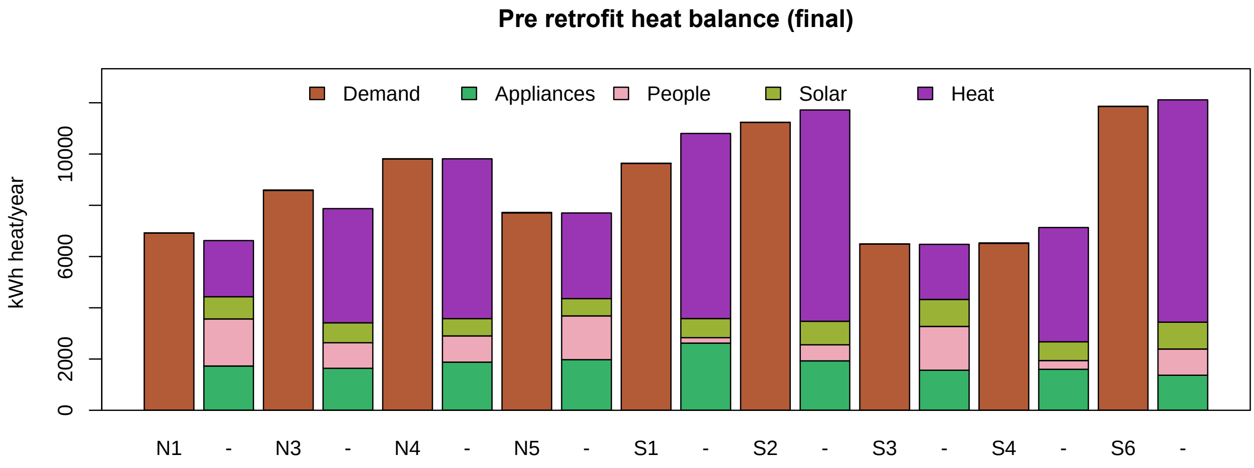


Figure 14 (continued): Heat balances before and after adjustments



Estimating pre and post retrofit bills

From the heat balance we estimated total energy use, and hence bills, using the tariffs in SAP 10.2[5] shown in the table below.

Table 12: SAP 10.2 prices for Gas and Electricity

	Gas standing charge/year	Gas price/kWh	Electricity standing charge/year	Electricity price/kWh	Electricity export/kWh
SAP 10.2	£92.00	3.64	£81.00	16.49	5.9p

We also assumed that post-retrofit there is no gas use in the properties, so no gas fixed charge. This is consistent with the removal of gas meters from properties.

We compared the energy bills for these households with the old heating systems under SAP energy prices with the energy bills after retrofit with the same heating regime. We also considered the retrofits without the benefit of solar panels.

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[5] BRE (2022) The Government's Standard Assessment Procedure for Energy Rating of Dwellings: Version 10.2. Watford: BRE.

Comparison of bills with and without retrofit

Table 13 and Figure 15 below compare post-retrofit bills with and without PV with what the bills would have been assuming the same energy prices (electricity and gas) pre-retrofit. For the Sutton homes, the Ventive Home Module performed very poorly, with an effective COP of 1.0 compared to 2.7 for Nottingham.

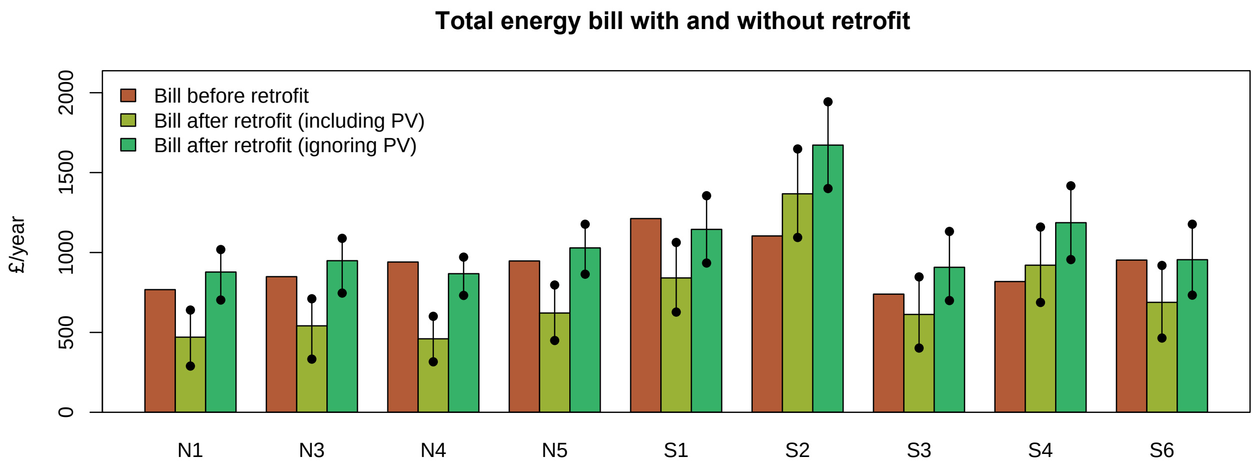
Overall, the mean heating bill for the pre-retrofit state is £926, compared to £725 after retrofit including the PV: a saving of £201 over the year. This change is statistically significant (p=0.04). Significance for individual cases is shown using green text in the table, as before.

Table 13: Pre and post bills, with and without PV

House	Pre retrofit bill	Post retrofit bill including PV	Reduction in bill (%)	Post retrofit bill ignoring PV
N1	£770	£470 +180/-170	**39%**	£880 +170/-140
N3	£850	£540 +210/-170	**36%**	£950 +200/-140
N4	£940	£460 +140/-140	**51%**	£870 +130/-110
N5	£950	£620 +170/-170	**34%**	£1,030 +160/-150
S1	£1,210	£840 +210/-220	**31%**	£1,140 +220/-210
S2	£1,100	£1,370 +270/-280	-24%	£1,670 +270/-270
S3	£740	£610 +230/-220	17%	£910 +220/-210
S4	£820	£920 +230/-240	-12%	£1,190 +230/-230
S6	£950	£690 +220/-230	**28%**	£960 +220/-230

Figure 15 below shows the same data.

Figure 15: Pre and post bills, with and without PV



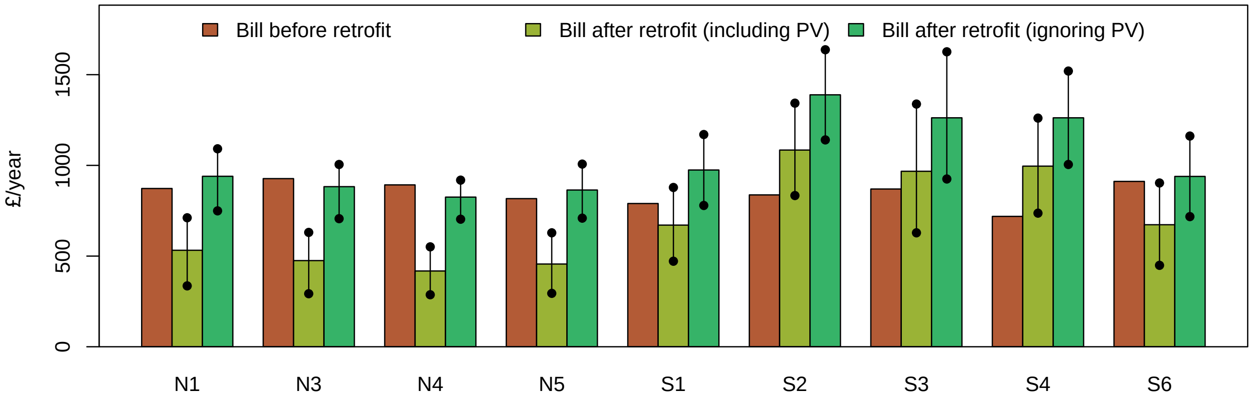
The most important factors in the relative change for heating bills are the difference between pre- and post- HTC (W/K) and the heating system efficiency. HTCs were reported in Section 2 above.

In the Nottingham homes, the HTC decreased in two homes and increased in two. The average change was only 8 W/K. However, the heat pumps performed well with good efficiency. Overall, savings were achieved but this was mainly due to the solar panels. With the solar panels, bills reduced by an average of £350/year and this was statistically significant, both at the group level and for each home.

In the Sutton homes, HTC decreased by an average of 50 W/K, however the Ventive Home Module performed very poorly. The heat pump was hardly activated and the overall efficiency was effectively 1.0 – pure resistive heating. Hence only two houses had statistically significant decreases in energy bill even with the solar panels. At the group level for the Sutton cohort the changes were not significant.

Figure 16 below shows expected bills with standardised occupancy patterns: number of occupants, appliances and cooking energy use, and hot water use estimated using SAP methods, and the mean internal temperature is 20°C for the whole dwelling both pre- and post-retrofit (this approximates to the standard SAP heating regime of 21°C in the living room and c. 19°C in other rooms (Zone 2). The mean bills are £848 pre retrofit, £697 post-retrofit including PV (not significant).

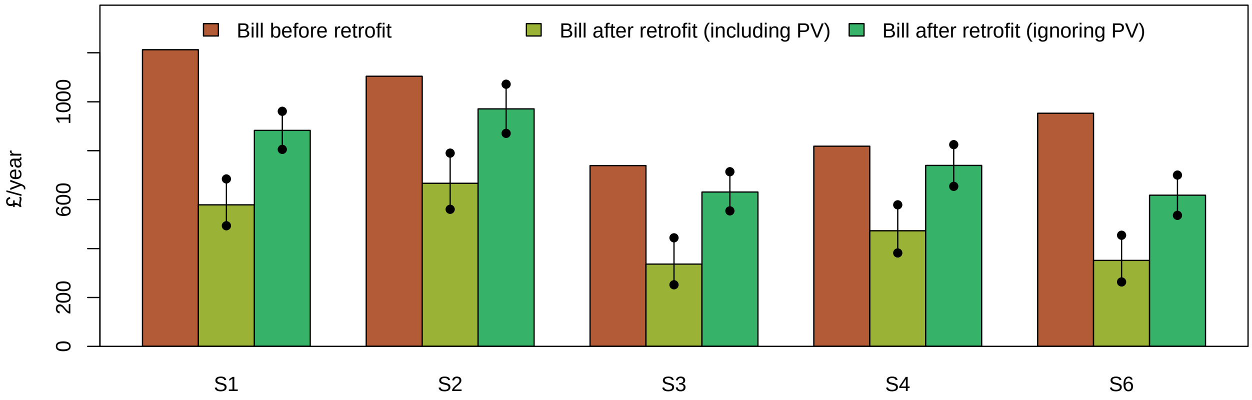
Figure 16: Total bills before and after retrofit, with standardised occupancy



Considering the homes one at a time, there are significant bill decreases in all Nottingham homes, but none of the Sutton homes. As before, the savings in Notts are mainly due to the solar panels.

If the heating system in Sutton had been working correctly, then there would have been bill savings for those residents as shown in the chart below, generated assuming heating efficiency the same as in Nottingham. The mean bill saving is £484, or 50% of the energy bill. Without the solar panels, savings are not statistically significant in every case, but overall there is a significant saving of £197, or 20%.

Figure 17: Total bills before and after retrofit, if Sutton heat pumps were working correctly



2.4 Lifetime Bill Savings

Realistically, the fabric upgrades carried out in Nottingham and Sutton would last at least 30 years. However, the heating and ventilation systems have an expected service life of 15 years, and they would probably need to be replaced at around this time. We are therefore taking a conservative estimate of the 'Lifetime' of the Energiesprong interventions, 15 years. This does not capture the full benefit of fabric upgrades, which could last for 60 years or more. Conversely, we are not taking into account the technical problems with the heating system in Sutton, so this is a pragmatic approach.

Assuming standard SAP heating regimes and including PV, along with the weak performance of the Sutton exhaust-air heat pumps, the average annual bill saving is £201 (-£6 to £408). This calculation uses the actual occupancy of all 10 homes in the study. This translates into Lifetime Bill Savings over 15 years of £3,020 (a minimum of -£90 and a maximum of £6,110).

Table 14: Lifetime Bills Savings over 15 years

	Cost
Mean energy bills before upgrades	£926
Mean energy bills after upgrades (heat pump COP of ~2.7 for Nottingham, ~0.9 for Sutton, and including PV)	£720 (£520-£930)*
Annual saving	£201 (-£6 [i.e. cost *rise* of £6] to £408)
Lifetime Bills Saving (15 years)	£3,020 (-£90 to £6,110)

*This is a pessimistic estimate of Lifetime Bill Savings, because Energiesprong is working to fix the installed heat pumps at Sutton, and it would not use the Ventive system again without resolving controls issues.

However, assuming that the heat pumps installed in Sutton can be repaired or replaced with heat pumps with the same efficiency as those in Nottingham, Lifetime Bills Savings rise considerably: to £6,390 (£4,390 to £8,320), see Table 15 below.

Table 15: Lifetime Bills Savings over 15 years if Sutton heat pumps were working

	Cost
Mean energy bills before upgrades	£926
Mean energy bills after upgrades (HP COP of 2.7 throughout, and including PV)	£500 (£370-£630)
Annual saving	£426 (£292 to £555)
Lifetime Bills Saving (15 years)	£6,390 (£4,390 to £8,320)

Savings with higher energy prices, or over 60 years

Gas and electricity prices have already risen substantially compared to the SAP energy prices listed on page 46 above. The Ofgem price caps introduced in April 2022 increased gas prices by 103% (i.e. more than double) compared to the SAP prices, and electricity prices by 78%. This means the cost savings today would be substantially higher than those in Tables 14 and 15. It also seems likely that energy costs will continue to rise – above background inflation – so the true savings over 15 years could be more than double those shown.

In addition, extending the savings beyond 15 years, to the 60-year likely lifetime of fabric upgrades, would dramatically increase the potential savings – even if we continue to use the current SAP energy prices. Table 16 below shows indicative savings over 60 years if the achieved efficiency of installed heat pumps was half-way between the two tables above: a coefficient of performance of 2.7 in Nottingham and 1.85 in Sutton. (This is a cautious estimate because Sutton heat pumps will be fixed and likely to achieve a similar efficiency to Nottingham heat pumps, and also because heat pump efficiencies are likely to rise over time as the UK gains experience of installing and using heat pumps, and the technology improves.)

Table 16: Indicative Lifetime Bills Savings over 60 years if Sutton heat pumps were working half as well as those in Nottingham (SAP energy prices)

	Cost
Mean energy bills before upgrades	£926
Mean energy bills after upgrades (HP COP of 2.7 Nottingham, 1.85 Sutton, and including PV)	£610 (£445 to £780)
Annual saving	£316 (£146 to £481)
Estimated replacement costs of heat pump after 15, 30, 45 years*	£8,000*
Lifetime Bills Saving (60 years)	£10,960 (£760 to £20,860)

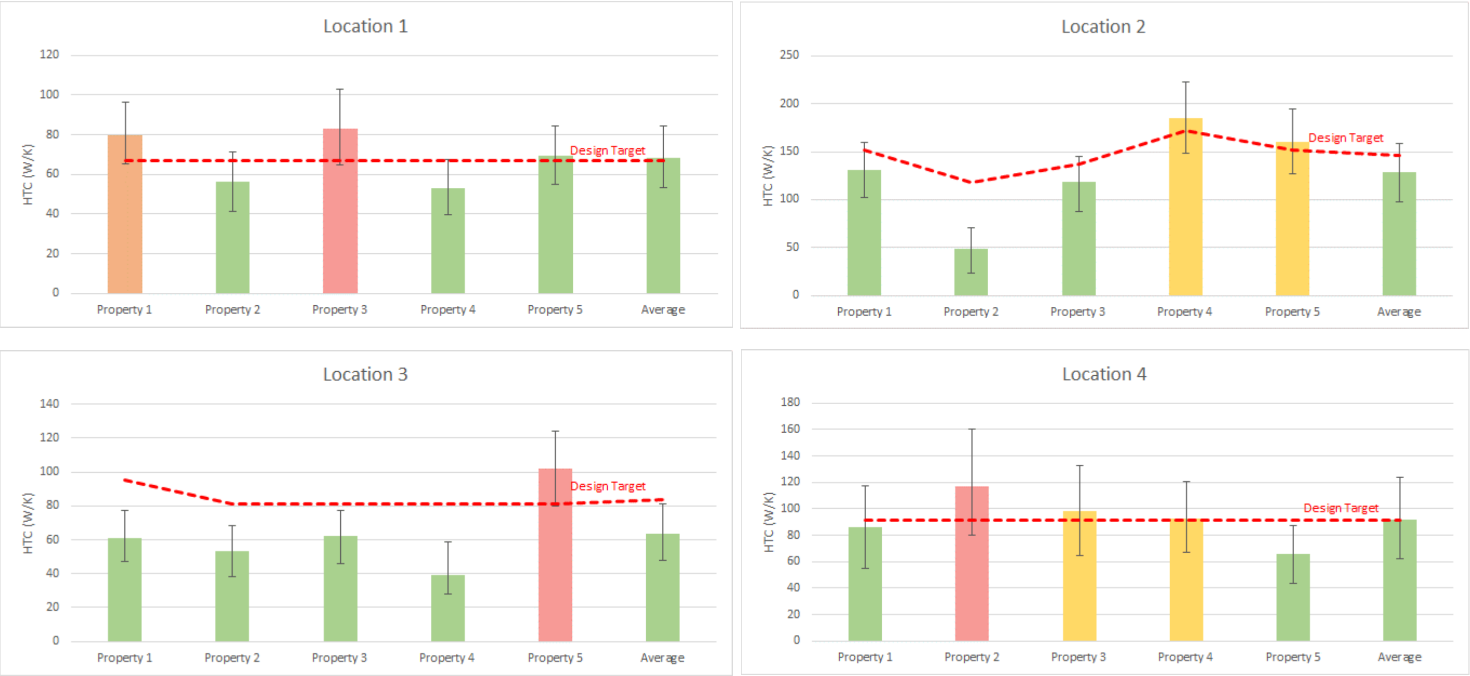
*This assumes the heat pump will need new fans, pump and refrigerant after 15 and 45 years, and an all-new heat pump after 30 years. There is no discounting or assumed reduction in heat pump replacement costs resulting from learning effects over 45 years. Nor is there any allowance for counterfactual costs of replacing standard boilers every 15 years.

2.5 Comparing against other Energiesprong retrofits

Energiesprong UK routinely assess the post-retrofit HTCs of projects using SmartHTC, and they compare these against the Design HTCs to identify any potential problems. However, they do not normally carry out pre-retrofit HTC calculations. The mean HTC across 20 other properties that underwent Energiesprong retrofits, was 90 W/K (Confidence Interval: 78-113 W/K). (These HTCs are from a mixture of semi-detached houses, terraces and bungalows, and are plotted in the charts below.) In five of these cases the central estimate for HTC was higher (worse) than the design estimate, but for all the other 15 the central estimate was the same or better than the design estimate.

This compares to the mean HTC after retrofit work in this Demonstration Action of 123 W/K (CI: 90-154 W/K). In this study fully nine out of 10 properties had central estimates of HTC that were higher (worse) than the design estimates. Both of these suggest that the outcomes of this Demonstration Action were not as positive as previous Energiesprong retrofits – perhaps due in part to having a less experienced contractor for the Sutton retrofits.

Figure 18: HTCs from Energiesprong retrofits outside of this trial



Columns are colour-coded so green is a 'good' Heat Loss Parameter, amber is 'fair', and red is 'disappointing'.

3.0 Limitations of the work

This research was complex, and faced some challenges, but the work brings learning and insights that can feed into the design of future trials of whole-house energy efficiency interventions. This section of the report summarises the limitations of this field-based research and discusses likely impacts. Overall, 11 limitations can be identified:

1. The regulations for Demonstration Actions state that samples should be "no more than necessary" to demonstrate cost savings (ECO3 Order 2018, 20(4)(d)). In line with this, Ofgem steered Energiesprong UK to recruit a very **small sample** of dwellings into the study, which did not reflect the technical complexity of the Energiesprong measures. This means it is much harder to achieve a sample that is representative of different house types and household types. It also means that there is a limited number of replacement dwellings to fall back on if households withdraw or if there are technical problems with monitoring equipment or building services equipment installed in the dwellings. However, Energiesprong did manage to replace one household that dropped out at a late stage with limited impact on the study, and also to collect data from one dwelling where the household moved out, by working creatively (in the latter case, by heating the dwelling and using it as a site office).
2. The HTC estimates **rely on SmartHTC**, which is economical and does not force occupants to move out, but is arguably less accurate than a co-heating test. SmartHTC can have high uncertainties,

especially as here when there are only short periods of data available. The uncertainties have two implications: first, they make it more difficult to achieve statistically significant changes; and second they mean that all results can only be presented with large uncertainty bands. Realistically, it would not have been possible to carry out co-heating tests for all these dwellings because the households living there would all have been forced to move out and find alternative accommodation for three weeks or more. This itself runs counter to the Energiesprong ethos, and the idea that retrofit work should avoid disrupting residents as much as possible, as well as minimising time on site.

3. Ideally, an intervention study like this would have included 12 months' monitoring before the retrofit work and 12 months' monitoring afterwards. However, the time required to design innovative solutions, obtain funding approval, engage residents/landlords and deliver/monitor meant the **programme was too tight to allow monitoring for 12 months** after the homes were improved. Energiesprong UK does intend to continue monitoring after the Demonstration Action is complete, so a fuller and more detailed account of impacts should be available next spring.
4. **Variations in external temperature** between the pre- and post-retrofit weather. This was adjusted for in the HTC estimates, and in the comfort/internal temperature analysis presented here. There is also an unknown impact of wind variations and solar gain – which can both affect HTC estimates – but these are likely to be small, notably because the post-retrofit airtightness was very good.
5. **Comfort-taking by residents** may also have affected results, and this demonstrably happened in Nottingham, where average internal temperatures rose. This underestimates efficiency savings in bills (which would have fallen further in Nottingham if mean internal temperatures had stayed the same). However, this very likely reflects what would happen in other social housing homes that undergo similar deep retrofits, so in some respects this is useful.
6. Interview responses showed that many householders in the study were concerned about high energy costs. This means that **energy-price rises** in December may have resulted in more frugal heating and appliances use, which could have distorted energy practices somewhat between pre- and post-retrofit monitoring. It is possible, if energy prices had remained the same, that households would have taken still more of the benefit from improved efficiency as improved thermal comfort. However, these price rises (especially after the end of the study) are outside Energiesprong's control.
7. The **defective heating system controls in Sutton** homes is very obviously a limitation in the study. If the exhaust-air heat pumps had worked as intended, the heating coefficients of performance could have been better or worse than those achieved in Nottingham. It would be much better to rectify the controls problem and use the new COPs to calculate cost savings in Sutton, and Energiesprong UK intends to do this next winter.
8. A further limitation to this study, but which does not apply to many other ECO Demonstration Actions is the fact that Energiesprong combines together **multiple upgrades**, all carried out together. This is a strength in achieving very significant energy savings, but it also brings a weakness because it is impossible to separate savings attributable to each of the fabric efficiency measures – which might be useful in other contexts.
9. **Delays and the short window for HTC** calculations meant that the usual three-week minimum that is needed to run SmartHTC was not always available. However, Energiesprong UK and BTS intervened to carry out special treatment, with a manual HTC calculation, so HTCs could still be generated for 10 out of 11 cases. The shorter periods of data in some cases increases the

confidence intervals somewhat for these cases, but this was unavoidable to meet Ofgem's deadline at the end of March.

10. HTC estimates in the North were also distorted by **combining energy efficiency upgrades with extensions** to living/heated area. HTCs would doubtless have been lower if the useable floor area had remained the same, and - this *reduced* the measured savings in Nottingham homes. However, reporting the Heat Loss Parameter (per m^2) adjusts for this, and this approach partly eliminates this problem.
11. **Different upgrade measures in the North and South** also complicates analysis and represents a limitation to the study. Had identical fabric and heating system upgrades been applied in both locations the empirical evidence would have been stronger. However, this does not reflect how Energiesprong works, with contractors permitted and encouraged to innovate to find their own ways to meet the performance outcome, and also varying the approach depending on the condition and circumstances of the specific homes to be upgraded. Arguably, it would be misleading to suggest that Energiesprong retrofits are uniform and always achieve the same results. In this study, some of the true diversity of Energiesprong retrofits is reflected.

4.0 Conclusions

This trial of deep retrofits on 11 dwellings in Sutton and Nottingham (10 with usable data) achieved statistically significant reductions in heat loss and Heat Transfer Coefficient. The mean improvement was 33 W/K (confidence interval 5 to 61 W/K), or a 21% reduction in heat loss. This improvement comes in spite of extending the heated space for the four Nottingham homes by $20m^2$ (24% of the floor area), which brings considerable extra benefit to the Nottingham households.

There were technical problems with the heating system installed in dwellings in Sutton, and difficulties with the algorithm controlling heating meant that electricity use there was disappointingly high after the retrofit. This was partly due to the innovative Ventive heating system used in Sutton, which was one of the first times the system had been installed in the field. However, if the Sutton heat pumps had performed at the same efficiency as those installed in Nottingham, the average bill saving would have been £640 (minimum £390, maximum £890) a year, or 40%. This was also statistically significant. Again, these bills savings would have been even greater if the garages in Nottingham had not been converted to heated rooms.

Average internal temperature for all dwellings also increased from 19.6°C before to 20.0°C after the retrofits (adjusted for higher outdoor temperature after the retrofit work, and excluding the Nottingham garages/rooms, which were much cooler prior to retrofit). This change was not significantly significant.

The Sutton contractor, Bow Tie Construction, was new to Energiesprong retrofits, and this may have been a contributing factor to problems on site. This was particularly apparent with regards to communication with residents and keeping householders on side. In contrast, the retrofit work in Nottingham by Melius Homes – which is Melius's fourth Energiesprong project – was relatively straightforward. Even in

Nottingham, however, there were some delays in site work, largely due to removing Cadent's gas meters before the wall panels could be installed.

Delays across both sites emphasises how difficult it is to carry out deep energy retrofits – even with experienced support from Energiesprong UK and an experienced contractor. These delays were exacerbated because of the rigid deadline to complete the Demonstration Action by 31st March, which in turn squeezed the time available to collect monitoring data.

The small sample for this trial, and the requirement to carry out work in two different regions, also complicated data collection and analysis. The small sample meant that technical problems with retrofit equipment, and monitoring equipment, had disproportionate effects because there were very limited alternative dwellings to draw on for data.

Originally this Demonstration Action aimed to install and monitor a sample of 12 dwellings, which included 'oversampling' of two dwellings in case any dropped out. The fact that one household in Nottingham did withdraw at a late stage, and another was vacated and used as a site office, vindicated the decision to over-sample. Although the site office continued to be heated like a dwelling, it could not be used in analysis.

This work highlighted the problem of small samples (both number of homes and the duration of studies) producing high uncertainties. This is an argument for using larger samples when studying in-use data to evaluate retrofits. This is an important insight for government (and industry and academia).

Unlike other energy-saving trials where an 'elemental' approach is appropriate – e.g. measuring the savings from a single insulation measure, such as wall insulation, a smart heating controller, or a ventilation device – Energiesprong is based around a Performance Outcome. How this is met is left to the market (i.e. property owners and contractors) to decide. In this instance the solutions chosen in Sutton and Nottingham were different, so inevitably the outcomes were different.

The major benefit from installing a package of measures together is that, even if some parts of the package did not perform as expected, other parts partly compensated. Here, good returns from the installed PV on both sites in Spring 2022 helped to soften the blow of high energy bills in Sutton.

There is a statistically significant difference in four cases between the expected fabric performance in Design HTCs (based on u-values and expected airtightness at design stage), and the Measured HTCs generated from internal and external temperatures, heating and energy use. In all four cases the Measured HTCs were higher (i.e. weaker thermal performance). This appears to be due to a combination of optimistic estimates of HTC at the design stage (especially in Sutton), high hot-water use (which biases the HTC estimate), and properties sharing party walls with poorly-insulated neighbours, leading to thermal bridging at the edges of the walls, floor and roof.

The Nottingham Heat-Loss Parameters (HTC normalised to floor area, which incorporates the impact of extended heated space in Nottingham) were generally lower (better) before retrofit work than those in Sutton. Although there was greater variation between the HLP improvements in Sutton – and for one house the post-retrofit HLP was virtually the same – on average homes in both locations improved by just over a quarter third (26%). For both the Nottingham and Sutton groups the improvement in HLP was statistically significant.

After adjusting for different weather between monitoring periods, internal temperatures rose on average across all homes in the study, but only by 0.4°C, and this was not a statistically significant change. In two homes the average post-retrofit temperature actually fell, but this may have been because heating was controlled more effectively (i.e. reducing unnecessary heating), or because occupants were content with lower air temperatures once they had warmer internal surfaces and reduced draughts.

There were also more even temperatures between rooms and over time after the retrofits – partly because of the new heating systems, because heat pumps are designed to be used for longer periods than boilers. Temperatures across all homes also converged in the evening (6-9pm) after the work, with homes that had been cooler before the retrofit generally becoming warmer afterwards, and warm homes becoming cooler after the retrofit. Again, this could be a reflection of improved control over heating.

4.1 Occupant surveys

There were mixed messages coming from occupant surveys in Nottingham compared to those in Sutton, with generally more positive responses in Nottingham. On comfort, all residents in Nottingham said they were more comfortable overall, after the retrofits, and all were happier with indoor temperatures in winter. However, Sutton households said they were either less comfortable or gave the same rating after the work. Ratings in Sutton may have been affected by dissatisfaction with what one termed ‘workmanship’ (but this was likely a catch-all to describe delays during the retrofit, as well as technical problems with the heating system).

Specifically on winter comfort, three-quarters of residents in Nottingham said they were more comfortable in winter, but two said they expected even better indoor temperatures in winter after the work. The Sutton households generally felt that there had not been sufficient time to test winter comfort of their retrofitted homes.

Turning to summer comfort and the risk of overheating, all Nottingham households said they experienced the same summer comfort or better after the work was complete. Conversely, two of the Sutton households gave lower scores after the retrofit, and some said it was too soon to say because they had not yet experienced a summer.

Nottingham households generally experienced improved ventilation after the work. Results were a little more mixed in Sutton, but most households reported either than ventilation improved or it stayed the same.

Regarding humidity and condensation, one resident in Nottingham with a pre-existing damp problem said it got better after the retrofit, but the other did not, and still reported mould. In Sutton, the two homes with pre-existing damp or condensation problems both gave higher ratings, suggesting that the retrofit helped with air quality.

On noise and sound issues, generally perceptions improved as a result of the work in both Nottingham and Sutton. In Sutton, one household gave a lower rating (down from 4 to 1), but they did not explain why.

There was another clear divergence between the two locations in relation to energy bills: most of the Nottingham households thought their energy bills fell as a result of the work, but in Sutton the outcome was quite different, and all households thought energy use was too high.

The one Occupant Survey question where Sutton residents gave more positive answers than those in Sutton was linked to indoor air quality. There were mixed views from the Nottingham households, with some perceiving better air quality and others worse. However, there was generally a positive perception of air quality in Sutton, with most giving a higher rating after the work.

Significance testing

Overall, the Energiesprong interventions had a statistically significant result on the whole occupant survey responses for Nottingham, but not for Sutton. Similarly, the interventions had a statistically significant impact on perceived comfort and warmth in Nottingham, but not in Sutton.

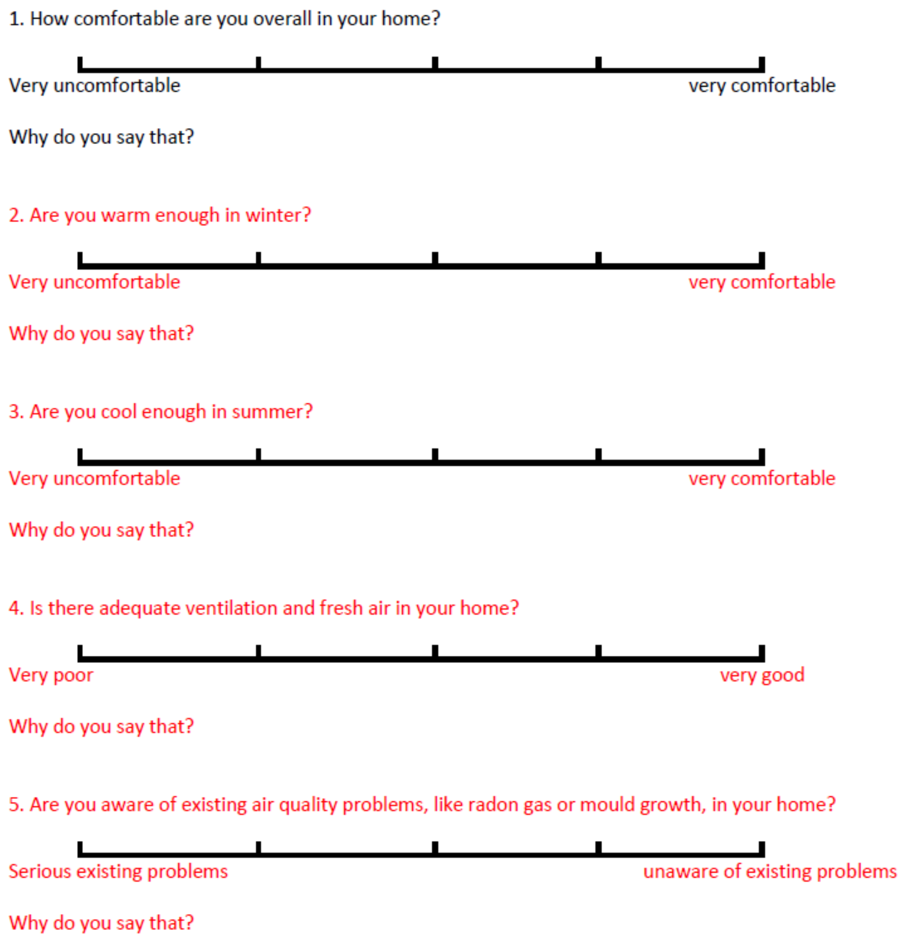
Lifetime savings

Factoring up annual savings in energy costs over 15 years for these 10 dwellings to give a conservative estimate of Lifetime Bill Savings, based on the actual performance of the Sutton heating systems, suggests that these retrofit interventions could save between -£90 and £6,110 (central estimate: £3,020). If the Ventive heating system in Sutton were repaired or replaced with a heat pump that runs as efficiently as those installed in Nottingham, Lifetime Bill Savings would rise to between £4,390 and £8,320 (central estimate £6,390). These estimates do not capture the full benefit of fabric upgrades, which could last for 60 years or more, but it reflects the likely service life of heat pumps.

Extending the analysis to a 60-year period could bring Lifetime Bill Savings of £10,960 (£760 to £20,860), even allowing for the cost of replacing heat pumps, and making conservative assumptions about the performance of the heat pumps.

Appendix: Occupant Satisfaction Survey

Survey questions used in Sutton and Nottingham are listed below. Questions shown in red have a bearing on health issues, which were highlighted by housing associations as being important. Health-related questions reflect important themes identified in Hamilton et al's 2015 paper in the British Medical Journal.[6]



1. How comfortable are you overall in your home?

Very uncomfortable — very comfortable

Why do you say that?

2. Are you warm enough in winter?

Very uncomfortable — very comfortable

Why do you say that?

3. Are you cool enough in summer?

Very uncomfortable — very comfortable

Why do you say that?

4. Is there adequate ventilation and fresh air in your home?

Very poor — very good

Why do you say that?

5. Are you aware of existing air quality problems, like radon gas or mould growth, in your home?

Serious existing problems — unaware of existing problems

Why do you say that?

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[6] Hamilton I, Milner J, Chalabi Z, *et al (2015)*Health effects of home energy efficiency interventions in England: a modelling study *BMJ Open* 2015; 5:e007298. doi: 10.1136/bmjopen-2014-007298

6. How do you rate the noise and soundproofing of your home?

Very poor very good

Why do you say that?

7. How do you rate your home's energy usage?

Very poor very good

Why do you say that?

8. How would you rate air quality in your home? (including traffic pollution entering the home, and secondary tobacco smoke)

Poor air quality good air quality

Why do you say that?

9. Are members of your family more vulnerable than average to poor air quality or extreme temperature? (Because of poor physical or mental health, or being very young or old)

More vulnerable less vulnerable

Why do you say that?