Heat pumps and UK's decarbonisation: lessons from an Ofgem dataset of more than 2,000 domestic installations.

Context – Methodology – Analysis – Discussion – Recommendations

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Spring 2021

Abstract

The decarbonisation of heat in the UK represents an urgent and colossal challenge. Most homes use mains gas which is relatively cheap and easy to use. When demand for heat peaks at 300GW it is five times greater than the peak for electricity (Ofgem, 2016). Heat pumps are cited as a crucial tool for decarbonisation but uptake has been slow compared to market growth in other countries. UK heat pump field trials completed in 2010 and 2015 have reported disappointing results with many installations failing to deliver benchmark efficiencies. Little new evidence about performance is available, yet UK consumers are given optimistic messages about heat pump efficiency.

It is against this backdrop that the Government wants to boost installation rates from 30,000 per year to 600,000 by 2028 (Prime Minister's Office, 2020). To investigate actual heat pump performance, a dataset was obtained from the Office of Gas and Electricity Markets (Ofgem) for a sub-set of installations that is subject to strict monitoring under the Renewable Heat Incentive (RHI). A methodology was developed to interrogate the dataset and calculate efficiencies and these actual SPF results were compared to the installer forecast efficiencies that were included in the dataset.

Although there are important limitations, the overall results are sobering. More than one quarter of the main sample and 28% of ASHPs were found to have an SPF below 2.5. The average SPF was found to be 2.76 for all installations analysed (2.71 for ASHPs and 3.07 for GSHPs). The analysis found no discernible improvement in performance after the UK standard for heat pump installation was changed in 2017. The analysis of installations since that date found the average ASHP SPF to be 2.69 and the average GSHP SPF to be 2.98. No correlation between the installer performance forecasts and the actual performance was found in the main sample.

Overall, these results raise significant questions about installation design and execution and about the methodology used for the provision of consumer performance estimates. Further modelling found that the consumer financial value case for heat pump installation was highly sensitive to heat pump efficiency and that the Government's plans to replace the RHI with a £4000 one-off grant will severely weaken the value case for most heat pump installations. A CO_2e mitigation model (described in detail in a *companion paper*) found that the installer forecast efficiencies overestimated potential CO_2e mitigation by some 5% over a 12-year period.

The results are considered within the context of the quality of UK housing. It is concluded that information asymmetries may damage consumer confidence in heat pumps and that this represents a challenge to market growth.

List of Abbreviations and Acronyms

ASHP	**Air Source Heat Pump**
BEIS	**Department for Business Energy & Industrial Strategy**
CCC	**Committee on Climate Change**
CoP	**Coefficient of Performance** (See Appendix A)
DRHI	**Domestic Renewable Heat Incentive**
EST	**Energy Saving Trust**
GSHP	**Ground Source Heat Pump**
GHG	**Greenhouse Gas Emissions**
MCS	**Microgeneration Certification Scheme**
Ofgem	**Office of Gas and Electricity Markets**
RHI	**Renewable Heat Incentive**
RHPP	**Renewable Heat Premium Payment**
SCOP	**Seasonal Coefficient of Performance** (See Appendix A)
SEPEMO	**Seasonal Performance factor and Moninotoring**
SPF	**Seasonal Performance Factor** (See Appendix A)

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1.0: Context: Introduction

1.1: The Policy Context

The decarbonisation of heat is, according to the Office of Gas and Electricity Markets (Ofgem): "arguably the biggest challenge facing UK energy policy over the next few decades (Ofgem, 2016)."

There are two over-arching reasons why this challenge is so intractable. Firstly, the task is urgent. According to the Committee on Climate Change (CCC), the UK must eliminate the CO_2e associated with the energy used for heating and hot water in UK buildings by 2050 if the UK is to meet its legally binding targets under the *Climate Change Act* and its obligations under the *Paris Agreement* (CCC, 2016b). Yet UK's efforts to decarbonise heating has stalled since 2013 and emissions from buildings are higher now than they were in 2015 (CCC, 2020, page 106)(CCC, 2016b).

Secondly, the task of decarbonising heat in the UK is colossal. Heat makes up nearly half of all the final energy consumed in the UK and nearly 60% of that is used in UK homes as space and water heating (Ofgem, 2016). When energy demand for heat is at its aggregate peak (300GW), it is around 5 times greater than the peak for electricity (Ofgem, 2016). 23 million residential buildings (85%) use mains gas (CCC, 2016a, page 3).

UK Governments have grappled with decarbonisation options and heat pumps have consistently been advocated as a critical alternative to conventional fossil fuels. In 2010 the CCC said heat pumps were crucial for the UK to meet its energy targets (CCC, 2010) and Government policies since then have sought to reinforce support for heat pumps through direct and indirect subsidy (DECC, 2016)(BEIS, 2018a). The Government's strategy of using the Renewable Heat Incentive (RHI) as its key mechanism to drive the uptake of renewable heat has had limited success. UK heat pump installation rates lag far behind those of similar economies. For every one heat pump installed in the UK in 2016, 11 were installed in France (Greater London Authority, 2018).

The year 2020 brought a step change in Government Policy. The Government reaffirmed its commitment to the mass roll-out of low carbon heat technologies through the 2020s (Department for Business Energy & Industrial Stratergy, 2020b). It has decided to extend the life of the RHI to March 2022 when it is proposed a capped £100m budget will fund Clean Heat Grants to consumers of £4000 to be used for low carbon heating (Department for Business Energy & Industrial Stratergy, 2020b).

The UK Government set itself the target of 600,000 heat pump installations per year by 2028 (Prime Minister's Office, 2020). More than 5% of Scottish homes will have a renewable heat installation under Scottish Government plans for a cumulative total of 126,000 installations by 2025 (Scottish Government, 2020).

In 2019, the CCC observed: "The low uptake of heat pumps is symptomatic of low awareness, financing constraints, concerns around disruption and difficulty in finding trusted installers with the right skills (CCC, 2019b, page 11)." The UK Government itself has said the current market in the UK remains small because renewable alternatives are: "largely unable to compete on cost with conventional heating options, such as natural gas, oil and direct electric heating (Department for Business Energy & Industrial Stratergy, 2020b)." Mains gas is recognised as being well understood by consumers, cheap compared to other fuels such as conventional electric heating, reliable, quiet and can provide on-demand hot water without the need for storage tanks (Broad, Hawker and Dodds, 2020). As a result, consumers may (at least in the short term) be reluctant to switch to a low-carbon alternative.

A further challenge is that a heat pump's SPF depends on the thermal efficiency of the building in which it is installed (Flower, Hawker and Bell, 2020). Critically, the energy efficiency of UK's housing is among the worst performing in Europe (Broad, Hawker and Dodds, 2020).

It is within the above context that the issue of pump performance plays a critical role. Results from field trials (described in **2.1** and **2.2**) carried out in the UK have been described as poor and disappointing (Gleeson and Lowe, 2013)(Frontier Economics, 2013)(Dunbabin and Green, 2013)(Griffiths, 2018)(DECC, 2014).

Very little new evidence about heat pump performance in UK homes has emerged since the publication of the RHPP field trial. Consequently, there is a lack of reliable evidence that describes recent heat pump performance in UK dwellings and policy decisions related to the mass roll-out of heat pumps are based on dated intelligence.

UK consumers are exposed to confusing information. For example, it remains widely assumed (MacKay, 2009; page 71 and page 147) and advertised that heat pumps generally perform with a "Coefficient of Performance" of between 3 and 5 even though the term "COP" is not always explained. Gleeson argues that the term "CoP" used by manufacturers leads to misunderstandings about performance because factory-based efficiency tests may not mirror in-situ reality (Gleeson, 2014). In 2010 the CCC forecast that performance would improve from a baseline of between 2.0 to 2.5 and "increase to a plateau in the 2020s, with space heating CoPs in the range 3.5 – 5.5 (up to 4.5 in residential applications and 5.5 in non-residential)" (CCC, 2010). Yet, more recently, the CCC said that it was expecting average SPFs to increase by just 0.5 from 2.5 to 3.0 "by 2030" (CCCa, 2019, page 87).

The corollary of the above is that consumers have poor access to information based on recent 'real world' (field trial) data rather than demonstration projects. Consumers using MCS Certified installers are given formal 'performance estimates' but these are currently based on the Seasonal Coefficient of Performance (SCOP) metric; a measurement of product efficiency (Griffiths, 2018) that has been criticised as being inappropriate for predicting the performance of a whole heating system.

The above context places heat pumps at the heart of UK and international efforts to decarbonise energy and, therefore, of key relevance to the analysis of climate change mitigation. However, it is also clear that there is sparse recent information available about the actual performance of heat pumps in UK dwellings and, in the UK, the installation industry places emphasis on the SCOP metric to estimate the potential performance of heat pumps within dwellings.

This paper will scrutinise current suppositions about heat pump performance through the analysis of a dataset provided by Ofgem and will seek to answer the following main question:

1. **How efficiently do heat pumps operate in UK households?**

Additionally, the paper will:

2. **Contrast the heat pump actual efficiencies calculated with the performance forecasts provided to consumers and critically assess current performance forecasting methods used for consumer installation proposals.**

Further modelling on the results from 1 & 2 is used to:

3. **Examine the consumer financial value case for heat pump installation.**

A *Companion Paper* has also examined the CO_2e mitigation and the results are also discussed in **5.0**.

1.2a: The Technology

Like most forms of renewable energy production, heat pumps require some electrical energy to function. However, because a heat pump is a *reverse heat engine,* significant work is required (driven by electricity) to transfer heat from the cold reservoir.

Furthermore, like all heat engines, the efficiency cannot exceed that set out by Carnot using the following equation:

$$COP_{MAX} = \frac{T_1}{T_1 - T_2}$$

Where COP_{MAX} is the theoretical maximum coefficient of performance that can be delivered (in units of heat per unit of electricity), T_2 (the source) is the outside temperature (Kelvin) and T_1 (the sink) is the inside temperature (Kelvin) (Klein, Huchtemann and Müller, 2014)(Dunbabin and Wickins, 2012). For example, where a flow temperature of 45°C is required and the outside temperature is 5°C, then the maximum possible COP is 7.95. That maximum is impossible to achieve in practice, but the equation demonstrates that the smaller the gap between the source and sink temperatures, the higher the COP. Additionally, a heat pump's performance depends on the thermal efficiency of the building (Flower, Hawker and Bell, 2020).

Electricity is essential for the compressor and all pumps used for circulation (and fans needed for ASHPs) and the coefficient of performance (COP) is the ratio of electricity needed in relation to the amount of energy generated.

$$COP = \frac{total\ energy\ output\ (kWh)}{total\ input\ electricity\ (kWh)}$$

Unless a heat pump sources the electricity it needs from a renewable electricity generator then its indirect consumption of fossil fuel via the national grid will be significant. Overall, however, there is widespread consensus that heat pumps can reduce GHG emissions. In 2009 the EU's *Renewable Energy Directive* formally recognised this potential by stating that the energy heat pumps generate can count towards a member country's renewable energy target, provided they meet a minimum benchmark for efficiency (EU, 2009; Article 5).

1.2b: The European Context

The UK Government uses that efficiency benchmark as the minimum allowed for RHI eligibility (Ofgem, 2015). Under the EU's *Renewable Energy Directive*, the energy generated by a heat pump can be renewable where the energy output is "significantly" greater than the primary energy input needed for the process (EU, 2009) provided that:

$$SPF > 1.15 * \frac{1}{\eta}$$

Within the context of this legislation, laboratory measurements and climate data averaged over one year are used to forecast the seasonal performance factor (SPF) of the heat pump (Dunbabin and Green, 2013) and η is the ratio of EU's total gross production of electricity to the primary energy consumption (EU, 2013). In 2010 η=45.5% (European Commission, 2018), which is described as "the average ratio of the efficiency of the EU electricity grid" (Dunbabin and Green, 2013). The above threshold therefore implies a minimum SPF of 2.5.

The formula for calculating the proportion of energy generated that is renewable is:

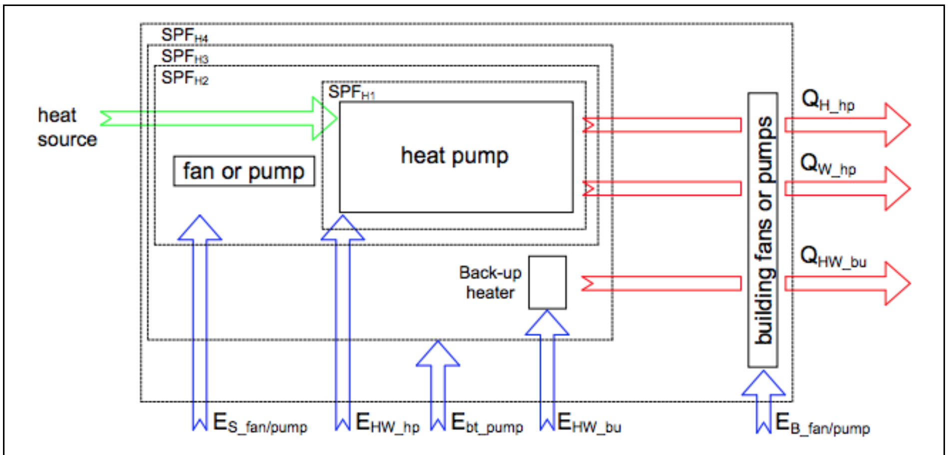
$$E_{RES} = Q_{usable} * \left(1 - \frac{1}{\mathrm{SPF}}\right)$$

Where E_{RES} is the renewable portion of the energy captured and Q_{usable} is the total usable heat delivered by the heat pump in kWh.

1.2c: System Boundaries

It is difficult to compare and evaluate heat pump efficiencies without defining the system boundaries that apply. The SEPEMO boundaries developed initially by SP Technical Research Institute in Sweden (Gleeson, 2014) are now used as the standard established methodology (in Europe at least)(Lowe *et al.*, 2017) and are illustrated below. SPFH1 includes only the core heat pump components and the boundaries extend to SPFH4 which also incorporates the air fan or ground loop pump power, backup heaters such as electric immersion and system circulation pumps. A further 'H5' boundary has been described which includes heat losses associated with any domestic hot water cylinder (Gleeson and Lowe, 2013)(Lowe *et al.*, 2017).

Of critical importance is that the boundary set in the EU methodology is $SCOP_{net}$ (Lowe *et al.*, 2017; page 6) which is equivalent to the SPFH2 boundary as indicated in *Figure 2* below.



$E_{S\_fan/pump}$	Energy used to run fan and/or pump that circulates the refrigerant
E_{HW_hp}	Energy used to run the heat pump itself
E_{bt_pump}	Energy used to run pump that circulates the medium that absorbs the ambient energy (not relevant for all heat pumps)
E_{HW_bu}	Energy used to run supplementary heater (not relevant for all heat pumps)
$E_{B\_fan/pump}$	Energy used to run fan and/or pump that circulates the medium that supplies the final usable heat
Q_{H_hp}	Heat supplied from the heat source via the heat pump
Q_{W_hp}	Heat supplied from the mechanical energy used to drive the heat pump
Q_{HW_hp}	Heat supplied from the supplementary heater (not relevant for all heat pumps)

Figure 1. *System boundaries for measurement of SPF and* Q_{usable}. (Kleefkens *et al.*, 2012)

As *Figure 2* shows, SPFH2 includes only the energy needed to drive the actual heat pump (compressor and refrigeration circuits) and the fan (in ASHPs) or the brine/refrigerant circulation pump (in GSHPs). According to the European Commission the calculation of *renewable energy supplied* should depend on the heat pump alone and should not include parts of the heat distribution system (European Commission, 2013a). It is therefore argued that $SCOP_{net}$ is a laboratory forecast of product efficiency, not an estimate of in-situ performance (Dunbabin and Green, 2013; page 24).

This has important implications. Boundaries such as SPFH4 obviously reflect the actual efficiencies achieved in homes more accurately because they include more of the actual losses incurred. But there are other potential problems related to the use of SPFH2 for forecasting in-situ system efficiency. In 2015, the Ecodesign and energy labelling regulations No *811/2013* and *812/2013* came into force providing a heat pump efficiency estimate for space heating based on SCOP (European Commission, 2013b)(European Commission, 2013c)(Griffiths, 2018)(Nolting, Steiger and Praktiknjo, 2018). The way these regulations have been used to provide consumers with information about heat pump efficiency have been criticised (Griffiths, 2018)(Nolting, Steiger and Praktiknjo, 2018). For example, Griffiths argues that, because these regulations provide an estimate of efficiency as a product, and excludes criteria that are essential for assessing heat pump performance within homes, the methodology is not suitable for forecasting the performance of an in-situ heat pump (Griffiths, 2018). The missing criteria include (for example):

- The plant size ratio (PSR) (the design output divided by the design heat load);
- Provision of domestic hot water; and
- Operating hours (such as intermittent heating).

The authors of the DECC analysis of the EST field trials contend that, from the consumer's point of view, only a 'whole system' boundary captures the efficiency losses needed for an indication of overall costs (Dunbabin and Green, 2013) and they maintain that SPFH4 is the most appropriate boundary for heat pump design.

Of key relevance to this discussion is that the current Microgeneration Certification Scheme (MCS) heat pumps standard (MIS 3005)(MCS, 2017) requires installers to provide performance estimates that are based on the SCOP metric. Yet, an estimate of product efficiency is likely to overestimate in-situ performance. This paper will return to this issue in **5.0** and **6.0.**

See *Appendix A* – a note on terminology, for more on definitions.

1.3: Taxes and Levies

The UK energy tax and levy regime is often blamed for the slow uptake of heat pumps. There is no question that the absence of a carbon price on mains gas, combined with the various taxes and levies imposed on electricity, has an obvious impact on the value case for low carbon heating fuelled by electricity. But there is evidence to show that other factors are more likely to have a decisive impact within a complex market. For example, in their recent analysis published in *Energy Policy*, Barnes and Bhagavathy agree that a plethora of UK Government policies have both inflated electricity prices and kept mains gas prices relatively low and the combined effect has disincentivised the electrification of heat (Barnes and Bhagavathy, 2020). However, the model used by Barnes and Bhagavathy demonstrates that, although the overall impact of taxes and levies imposed on electricity bills is significant, it is not critical to the affordability of heat pumps compared to gas boilers (Barnes and Bhagavathy, 2020). The Barnes and Bhagavathy analysis is discussed in more detail in **Appendix C**.

2: Context: Literature Review

2.1: UK Field Trials

Given the emphasis being placed on heat pumps as a potential solution to the GHG emissions associated with domestic heating it is surprising that there is not more robust, recent field trial research on the performance of heat pumps in UK dwellings.

One of the most widely publicised trials was organised by the Energy Saving Trust (EST) and carried out in 2009 and published in the form of two EST reports (Roy, Caird and Potter, 2010)(Energy Saving Trust, 2013) and the results for *Phase 1* of the research is detailed in *Table 1* (Gleeson and Lowe, 2013).

Table 1: Results from EST Field trial 2009-2010 (Gleeson and Lowe, 2013)

	Number of Installs	**Mean SPF**	**Range**
Boundary	**Ground Source**		
SPFH2	9	2.6	1.9-3.3
SPFH4	17	2.5	1.4-3.3
SPFH5	41	2.3	1.5-3.4
DECC (Whole System)	49	2.3	1.6-3.4
	Air Source		
SPFH2	4	2.9	2.2-4.0
SPFH4	7	1.9	1.2-2.3
SPFH5	12	1.9	1.5-3.0
DECC (Whole System)	22	1.8	1.2-2.2

The trial, conducted in a wide variety of public and private housing, used a 'system efficiency' boundary that included the energy associated with domestic hot water use rather than simply assess the energy (heat) supplied to the DHW tank. This methodology therefore incorporated cylinder heat loss (Gleeson and Lowe, 2013) and are indicated as *DECC – Whole System* in *Table 1* (Dunbabin and Wickins, 2012).

Given the mean ASHP efficiency was found to be less than 2 (for ASHPs), the EST Phase 1 results attracted widespread concern about UK heat pump installation (Gleeson and Lowe, 2013). However, the unusual system boundary employed made direct comparisons with other trials difficult (Gleeson and Lowe, 2013). In 2013 data for a portion of the EST sample was re-analysed using the standard SEPEMO boundaries (as indicated in *Table 1*, SPFs 2,4 and 5) but some of the sample sizes are very small. SPFH5 corresponds closely with the EST whole system efficiency boundary (Gleeson and Lowe, 2013)(Lowe *et al.*, 2017).

Phase 2 of the EST research involved an assessment of the 83 installations included in Phase 1 and upgrades to improve the performance of 38 of those (Dunbabin and Green, 2013). The results of that phase fall outside the intended scope of this review.

The largest European field trial carried out so far was funded by UK's Department for Energy & Climate Change (DECC) and carried out in the UK from 2013 to 2015 (Lowe *et al.*, 2017). The results used a range of SEPEMO boundaries and are shown in *Table 2.* SPFH5 was included to enable a direct comparison with the EST trial described above. The research team described extensive and important limitations to the analysis that mostly relate the monitoring technology and resulting metering errors and that, as a consequence, the results cannot be assumed to be representative of heat pumps generally (Lowe *et al.*, 2017; pages 4 and 7).

Table 2. The DECC RHPP Field Trial

Results from the RHPP Field Trial			
	Number of Installs	**Mean**	**% with SPFH2 greater or equal to 2.5**
Boundary	**Ground Source**		
SPFH2	92	2.9	80%
SPFH4	92	2.8	
SPFH5	76	2.5	
	Air Source		
SPFH2	292	2.6	62%
SPFH4	292	2.4	
SPFH5	223	2.2	

(Lowe *et al.*, 2017)

The SPFH2 results are shown in *Figure 3* below. The benchmark SPF 2.5 is indicated in red.

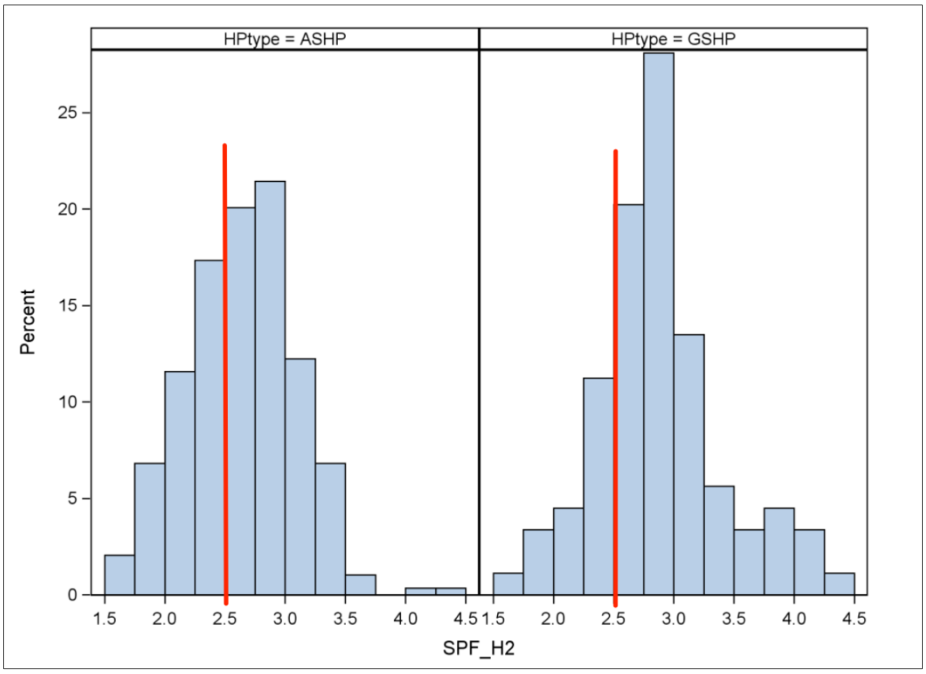


Figure 2: *Histogram showing % failing to achieve SPFH2 of at least 2.5. ASHP, left. GSHP, right. Source: (Lowe et al., 2017)*

The authors concluded that around one in three of ASHPs and one in five GSHPs did not meet the EU's Renewable Energy Directive SPF 2.5 threshold for renewable energy.

The study also covered wider compliance with MCS standards and compared the actual SPFs achieved with the installer's efficiency estimates. The installer estimated efficiencies were (at the time) confusingly termed 'SPFs' (by the MCS 'Heat Emitter Guide' – the compulsory method then in place used to calculate efficiency for installation proposals). Overall, *Table 3* shows that the actual SPFs achieved (measured SPFs) were significantly lower than the installer estimates.

Table 3. RHPP Field Trial: SPFs versus installer estimates (Gleeson *et al.*, 2017)

SPF Value	ASHPs	GSHPs
Median measured SPFs (H2 boundary)	2.65	2.78
Median installer estimated SPFs (H2 boundary)	3.4	4.1

One recent systematic review (Carroll, Chesser and Lyons, 2020) identified 34 papers on trials of ASHPs in real world settings including the EST research described above. The papers report results from a wide variety of settings with most located in China, however, a small number of other relevant UK-based studies were included:

- Kelly and Cockroft used field trial data from eight homes retrofitted with ASHPs replacing solid fuel stoves (Kelly and Cockroft, 2011). The results are difficult to compare with other field trials because the monitored data was combined with simulations for performance assessment.
- Underwood et al,. proposed a model based on two datasets, one of which was obtained from field monitoring of one ASHP installation in Leeds. This modelling exercise is described in more detail in **Appendix C**.
- Sweetnam et al,. describe a field trial of heat pump control devices involving 76 properties in England (Sweetnam *et al.*, 2019). The primary focus of the trial was to test the performance of the heat pump *control mechanisms* rather than assess the efficiencies.
- A small number of other papers identified by the review reported results from single dwellings.

Two other detailed reports refer to field trials designed to assess the performance of hybrid heat pumps: where a combination of ASHPs with conventional heating is used to provide space and water heating in domestic properties. Neither are directly comparable to the UK field trials noted above or to the analysis carried out for this paper. They are described in **Appendix B**.

2.2: European field trials

The meta-analysis (Gleeson and Lowe, 2013) included results from a range of other European trials; the most significant are in **Table 4** (Miara *et al.*, 2014) (Gleeson and Lowe, 2013):

Table 4: Results from other Major European Field Trials (Germany unless specified)

	Number of Installs	**Mean**	**Range**
Boundary	**Ground Source**		
Fraunhofer new build SPFH2	56	3.9	
Fraunhofer new build SPFH4	56	3.7	
Fraunhofer existing build SPFH3	36	3.3	2.2-4.8
DTI SPFH4 (Denmark)	138	3.0	
SPI (Sweden) SPFH3	7	3.3	2.6-3.6
	Air Source		
Fraunhofer new build SPFH2	18	2.9	
Fraunhofer new build SPFH4	18	2.7	
Fraunhofer existing build SPFH3	34	2.6	2.1-3.4
DTI SPFH4 (Denmark)	12	2.3	

These results reflect widespread experience that GSHPs tend to perform with higher efficiency as do those installed in new buildings. While direct comparisons are not always possible (Gleeson and Lowe, 2013), there is concern that UK field trial results generally indicate that UK heat pump installations do not perform as well as those in other European countries (Underwood, Royapoor and Sturm, 2017)(Gleeson and Lowe, 2013).

2.3: Modelling: the Value Case for Heat Pumps and Heat Pump Performance

There is a lack of *recent* and definitive field trial evidence regarding heat pump performance in the UK and a resulting lack of evidence related to the consumer value case for heat pump installation. As a consequence, a range of relevant models have been developed to explore the potential benefits and challenges of heat pump roll-out. The suppositions that underpin these studies are important because they are often based *assumed* SPF values. **Appendix C** explores models that examine the value case for extensive heat pump roll-out.

UK's Standard Assessment Procedure (SAP) has incorporated heat pump performance data using EN14511:2007 and a modified version of the calculation method EN15316-4-2:2008. This was superseded by the Ecodesign regulations as all heat pumps must be tested in accordance with EN14825 which introduced SCOP (as described in **1.2c**). SCOP is an estimate of product efficiency and is not an estimate of heating system efficiency (Griffiths and Abnett, 2017). Research carried out by BRE has sought to resolve this problem using a model called the Domestic Annual Heat Pump System Efficiency (DAHPSE) that offers a forecast of the annual efficiency of the generator system – not just the product. This is achieved using a combination of a modified version of EN15316-4-2:2017 and EN14825 test data for individual heat pumps. The work uses heat pump test data incorporated with an annual combined space and hot water heating duty cycle using hourly space and hot water heat load and temperature assumptions using average UK weather data and the SPFH4 boundary (Griffiths, 2018)(Griffiths and Abnett, 2017). The methodology used for the DAHPSE model is described in **Appendix D**.

Results using the DAHPSE model, have been tested against findings from the RHPP field trial (described above) with reasonable agreement. The authors also state that the model indicates that the SCOP metric over-predicts performance (Griffiths, 2018)(Griffiths and Abnett, 2017). Authors describing other models also describe a "performance gap" between modelled in-situ performance compared to values from manufacturers' technical literature (Underwood, Royapoor and Sturm, 2017; page 586).

3: Methodology

3.1: Secondary Data Obtained from Ofgem

3.1.1: The dataset

A dataset containing anonymised information from over 2200 domestic heat pump installations was obtained from Ofgem. The installations are a sub-set of those eligible for the Domestic Renewable Heat Incentive (DRHI) and are all subject to the rules for 'metering for payment' including compulsory metering as a condition for RHI eligibility. Heat pumps eligible for the DRHI are subject to 'metering for payment' when:

- the domestic consumer needs back-up heating such as a fossil fuel boiler or where a hybrid heat pump is used (for example, a heat pump combined with a gas boiler in the same unit);
- the property uses more than one renewable technology for space heating; or
- the property is occupied for less than 183 days per year (Ofgem, 2018a).

See **Appendix E** for more information.

The information in the dataset includes:

- heat generation in kWh or MWh;
- electricity consumption in kWh or MWh;
- the data on heat generation and electricity consumption is provided for each heat meter and each electricity meter used for each installation separately;
- the period of time each data point covers (usually quarterly);
- unique identifiers for each installation;
- the installer's prediction of efficiency present in the form of a coefficient of performance provided at the time of the install (the SCOP is essential for the calculation used to assign the RHI).

The dataset contains some 24,000 lines of data with consumption and generation values starting in 2016 for some installations with final meter readings provided in 2019. A typical entry in the data for one installation is indicated below as *Figure 4*. The column headed 'SPF' refers to the installer *forecast* performance.

Reference no	App Status	TechType Label	ElectricMeter Label	ElectricMeter SubmissionDate	ElectricMeter Reading	ElectricMeter UnitsLabel	HeatMeter Label	Heat_Meter_DateofReading	Heat_Meter_UnitsLabel	Heat_Meter_Reading	Spf
A1033	Accredited	Air Source	EM1	30/03/2016	4397	kWh	HM1	30/03/2016	kWh	9921	3.4
A1033	Accredited	Air Source	EM1	19/05/2016	5457	kWh	HM1	19/05/2016	kWh	12320	3.4
A1033	Accredited	Air Source	EM1	19/08/2016	6099	kWh	HM1	19/08/2016	kWh	14147	3.4
A1033	Accredited	Air Source	EM1	19/02/2017	11549	kWh	HM1	19/02/2017	kWh	28369	3.4
A1033	Accredited	Air Source	EM1	19/05/2017	13224	kWh	HM1	19/05/2017	kWh	33398	3.4
A1033	Accredited	Air Source	EM1	19/08/2017	13584	kWh	HM1	19/08/2017	kWh	34190	3.4
A1033	Accredited	Air Source	EM1	19/08/2018	21312	kWh	HM1	19/08/2018	kWh	53121	3.4
A1033	Accredited	Air Source	EM1	16/11/2018	22385	kWh	HM1	16/11/2018	kWh	55988	3.4
A1033	Accredited	Air Source	EM1	19/02/2019	25589	kWh	HM1	19/02/2019	kWh	64240	3.4
A1033	Accredited	Air Source	EM1	19/05/2019	27298	kWh	HM1	19/05/2019	kWh	69032	3.4
A1033	Accredited	Air Source	EM1	19/08/2019	27610	kWh	HM1	19/08/2019	kWh	69587	3.4

Figure 3: *Typical entry for one installation in the Ofgem dataset*

The earliest meter readings occur at the start of the dataset and the installations with the fewest readings are situated at the end of the dataset, however, the installations are not in strict chronological order.

The standard methodology for evaluating the actual performance of an installed heat pump is to relate the heat output to the energy input (electricity)(Nordman *et al.*, 2010). Although calculating the efficiency ratio is therefore straightforward, the data provided for a significant number of installations had entries for more than one heat meter and/or more than one electricity meter. Where this occurs, the cumulative totals for each meter must be combined before the simple efficiency calculation can be completed. The dataset was therefore provided in a form that necessitated the development of relatively complex spreadsheet strategies for the efficiency calculations.

3.1.2: Pilot Findings

The Excel strategy developed and described in **3.1.5** was based on a pilot analysis of 50 installations and then a preliminary analysis of 400 installations was used to test the process used for the calculations. The pilot stage found that eight installations included obviously incorrect or impossible values. In most cases, however, the data anomalies could be mitigated without excluding all the data for those specific installations (by, for example, removing rows of data at the start or end of installation entries). The data for installations with multiple meters was examined and a manual method for resolving this issue was developed.

3.1.3: Preliminary Analysis

The pilot analysis was used to develop the methodology described in detail below (**3.1.5**) and modified and verified using a preliminary analysis of one in every 5 installations. The process confirmed the spreadsheet methodology was viable but it was not possible to differentiate installations that took place before or after the implementation of a compulsory change to the MCS MIS 3005 heat pumps standard which is compulsory for RHI eligibility. The process was therefore modified as described below.

3.1.4: Samples

Two contiguous sub-samples were used for the final analysis:

Sub-set 1 included installations numbered from 1000 to 1499 of the original full dataset and ***Sub-set 2*** the installations numbered from 1500 to 1999. These sections of the dataset were chosen for the following reasons:

- The vast majority of installations in *Sub-set 1* occurred *before* the important change to MIS 3005 became optional (from May 2017) and then became compulsory from October 2017 (see section **4.1.3** for more on the change to the certification standard). The full process below identifies installations that occurred after May 2017 allowing this sample to be filtered to include only those installations carried out *before* Version 5.0 of that standard became optional in May 2017 or compulsory in October 2017.
- The installations in *Sub-set 2* included a significant number that occurred *after* the MIS 3005 Version 5.0 became compulsory. This sample could then be filtered to *include* only those installations carried out *after* that version standard became compulsory in October 2017.
- Almost all the most recent installations in the full dataset from numbers 2000 to 2200 do not include meter readings for one full year (and therefore had to be excluded).
- The combined contiguous set of 1,000 installations represents the best portion of the full dataset to represent a large sample for statistical certainty and also allows a comparison of performance between installations carried out *before* and *after* MIS 3005 Version 5.0 became compulsory.

3.1.5: Conditional Analysis and Efficiency

Conditional Analysis

Erroneous data was highlighted using conditional formatting and additional formulae that identified:

- dropping values; and
- values that exceeded previous values by a specified amount.

The methodology also ensured that the period used for the analysis for each installation was always a minimum of at least one year. The conditional formatting used is described in more detail in **Appendix F**.

Excel strategy and Efficiency Calculations

The Excel pivot table process can be summarised as follows:

1. After conditional analysis and removal of erroneous data, unique identifiers were given to all installation meters and readings. In *Sub-set 1*, all installations were identified as carried out either before or after the certification standard MIS 3005 Version 5.0 was defined as optional or

compulsory. In *Sub-set 2*, all installations were identified as carried out either before or after the certification standard MIS 3005 Version 5.0 was defined as compulsory.

2. The data was divided, and two separate spreadsheets created: one for electricity consumption and another for heat generation.
3. Robust values were obtained for consumption/generation by identifying the first (minimum) values for both consumption and generation for each installation and subtracting those first meter readings from subsequent values. This stage is described in more detail in **Appendix G**. Any readings provided in mega-watt hours (MWh) were converted to kilo-watt hours (kWh). **Note:** An alternative method was tested which calculated total consumption and total generation using the final meter reading only without subtracting minimum values. This approach (as also described in **Appendix G**) was tested on a sub-set of installations. There was no significant difference in the actual efficiencies calculated using the two methods.
4. Pivot tables were used to obtain total consumption/generation figures for each install (by combining values provided for multiple meters).
5. The two separate spreadsheets were then recombined and checked to verify perfect alignment whereby each reading of electricity consumption matched the equivalent generation reading for each installation.
6. After alignment was confirmed a final pivot table was used to allow filtering by variables such technology (ASHP or GSHP) and RHI status.
7. Performance efficiency was calculated by relating the heat output to the energy input (electricity). That is: the ratio of heat delivered to the system (distribution or emitters) to the electricity needed to run the heat pump (Nordman *et al.*, 2010)(Lowe *et al.*, 2017; page 6) using the methodology for calculating the coefficient of performance (COP), (which is a measure of efficiency at any one time)(Boyle, 2012, page 434). Total generation was divided by total consumption for the installation Seasonal Performance Factor (SPF) (Element Energy, 2017; page 49)(Gleeson, 2014; page 83).
8. When the analysis was complete, and installations designated ‘cancelled’ or ‘rejected’ by OFGEM were excluded, a small number of heat pumps were found to have very high or very low SPF results. For example, of the 353 installations remaining in *Sub-set 1*, nine had SPF values below 1.5 and 11 values above 4.

3.1.6: Identification Outliers and Data Cleaning

As described above, installations must be removed for a number of reasons:

- Those without a whole year of contiguous clean data.
- Those identified as ‘cancelled’ or ‘rejected’ by OFGEM.

Additionally, outlying results are likely to be to be influenced by data monitoring anomalies (Lowe *et al.*, 2017, page 11) and various methods can be used to filter and remove installations from field trial results. Wide filter limits can encompass genuine results and reduce sample size while narrow limits may incorporate anomalous results. The RHPP field trial (as described in **2.2**) excluded all installations below SPF 1.5 and above SPF 4.5 (Lowe *et al.*, 2017, page 12). However, a simple upper and lower SPF boundary fails to accommodate the fact that GSHPs tend to perform better than ASHPs and have a higher proportion perform with SPFs above 4. There is a risk, therefore, that this approach may exclude genuine GSHP results.

For this research, the outliers were therefore identified using the standard Tukey definition applied to ASHPs and GSHPs *separately*. Installations were therefore identified as outliers where the result was 1.5 times the interquartile range either over Q3 or below Q1. The results of the Tukey analysis is described in **Appendix H.** In summary, 15 outliers were removed from sub-set 1 to create *Sample 1 Tukey* containing 338 installations and 21 outliers were removed from sub-set 2 to create *Sample 2 Tukey* containing 260 installations. The final *Combined Set* included 598 installations. Significantly more installations were removed from *Sub-set 2* because a greater proportion did not have a whole year of contiguous clean data.

3.2: Economic Value Case Model

A heat pump's SPF has a profound impact on the financial case for an installation (Barnes and Bhagavathy, 2020). It is important, therefore, to examine the potential financial impact of discrepancies between installer performance forecasts and the actual calculated efficiencies observed. Any shortfall in performance can, for example, postpone or eliminate the installation 'payback': a key consumer driver for adopting microgeneration. The 'payback' is the point in time when any cumulative financial benefit adds up to more than the capital cost.

The methodology used for this study was based on the Microgeneration Certification Scheme's *Heat Pump System Performance Estimate* (HPSPE) (MCS, 2018); an Excel-based calculator that is used to support the MCS information provided to domestic consumers by MCS-certified installers. The HPSPE was implemented by MCS as part of the certification changes made compulsory in 2017 (MCS, 2017) and its rationale is to provide robust estimate of performance and likely financial outcome. The HPSPE document in the form it is presented to domestic consumers is set out in **Appendix J.**

The HPSPE was adapted for use in this study to track the *cumulative annual* net benefit (or detriment) to allow a comparison between the installer forecast performance and the actual efficiency as calculated in **4.1** and provide a lifetime value case assessment. Both of those outcomes are tracked for the assumed lifetime of the heat pump (16 years) by combining:

- the annual RHI Income (where applicable);
- the metering and Monitoring Service Package incentive (upfront and annual) (where applicable); and
- the annual fuel saving or additional spend (if applicable).

A range of factors have an important influence on the financial argument for installing or not installing a heat pump and the key variables used for the methodology are described in *Table 5*. As shown, estimates of total installation cost (Energy Saving Trust, 2020a)(Energy Saving Trust, 2020b) were incorporated into the calculation to provide a 'payback' analysis.

Table 5: Important Variables Used in Financial Analysis

Value	Source Used for HPSPE	Source Used for this Research
Energy required for space heating and hot water (kWh)	Energy Performance Certificate (EPC) or heat loss survey of property.	The average generation per installation (17624kWh) using *Sample 2 Tukey* was used (See *Appendix F)*. The *proportion* of hot water to space heating used was obtained using the average UK household consumption: 1460kWh (BRE, 2019) for the medium UK total domestic heat consumption value (Ofgem, 2020b) (12,000kWh) and calculated on a proportional basis giving 15480kWh allocated to space heating and 2144kWh allocated to DHW.
The RHI Incentive Tariff (p/kWh)	The RHI Tariff Rate Applicable at time of contract agreement	The current RHI Tariff for the technology is used in the case studies below for the seven-year eligibility period (Ofgem, 2020a).
The Metering Monitoring and Service Package	The MMSP default grant and annual allowance are included when MMSP is selected	This optional incentive is available for eligible domestic consumers and includes a one-off grant of £805 in the first year of the RHI and £115 per year for the duration of the RHI (Ofgem, 2018a).
Cost of Displaced Fuel **Oil and LPG (p/litre)** **Electricity (p/kWh)**	Recent cost of displaced fuel paid by domestic consumer.	Typical current fuel prices are sourced from the EST (Energy Saving Trust, 2020c) and the exact prices used are specified in the commentary with the case studies (below).
Cost of Electricity p/kWh	Current cost of electricity paid by domestic consumer.	Typical current electricity prices were sourced from the EST (Energy Saving Trust, 2020c) and the exact prices used are specified in the commentary with the case studies (below).
MCS SCOP (Installer Estimate)	The MCS SCOP for the heat pump design flow temperature obtained from the MCS Product Directory.[1]	The installer forecast (SCOP) and actual SPFs obtained from the results in 4.1

The HPSPE includes a number of other important calculations and default values that impact on the financial estimate of performance. Those are described in *Table 6* (below).

Table 6: Other Assumptions Used in Financial Analysis

Default SPF Value for Hot Water	The methodology used to estimate heat pump SCOPs is based on space heating only. As a higher heat pump flow temperature is required to deliver domestic hot water, (MCS, 2020) the SPF achieved (for hot water) is typically significantly lower than that for space heating. The HPSPE therefore uses default SPF value allocated to the energy required for DHW. Those are 1.75 for ASHPs and 2.24 for GSHPs.
Hot Water Immersion Use	Pasteurisation at temperatures above 60 ºC is needed to kill harmful bacteria such as legionella pneumophila. This is usually carried out on a weekly basis (MCS, 2020). The HPSPE assumes that the immersion raises the temperature once per day or once per week to 60ºC (from 50 ºC). For this study, weekly pasteurisation was selected using a 150ltr cylinder.
Efficiency of Displaced Heating	And, the total amount spent annually on fuel depends on the assumed efficiency of the displaced boiler. Default efficiencies are allocated to the displaced technologies the HPSPE method. For this

[1] https://mcscertified.com/product-directory/

	research, electric heating is assumed to be 100% efficient while gas, oil and LPG heating is assumed to have been installed prior to 2007 and operate with an efficiency of 87%.
The RHI calculation	The RHI is calculated as specified by Ofgem (Ofgem, 2015) using the following formula to calculate the eligible heat demand: $\mathrm{RHI} = Heat\ Demand * 1 - \left(\frac{1}{SCOP}\right)$
Inflation	The RHI is index linked and the cases studies set out below assume inflation of 2.3%. Inflation is not included for any other variable such as fuel prices.

The UK Government's approach to the incentives made available to domestic consumers is of key significance to the financial context. For example, UK Government has confirmed that the RHI will remain available to new applicants until March 2022 (Department for Business Energy & Industrial Stratergy, 2020a). The RHI and associated incentives are therefore incorporated into the case studies below at the current tariff rate of 10.85p/kWh for ASHPs and 21.16 for GSHPs (Ofgem, 2020a).

However, there is a complex relationship between the RHI and the installer's performance estimate. In practice, the RHI is paid only on the renewable portion of the heat generation which in turn is either 'deemed' (based on the estimated heat generation minus electricity input) or based on the actual measured heat generation (actual metered generation minus electricity input).

The installer estimates the RHI as part of the MCS performance estimate given to the consumer and that is based on the heat demand and the SCOP using this formula:

$$\mathrm{RHI} = Heat\ Demand * 1 - \left(\frac{1}{SCOP}\right)$$

In practice (as the results in **4.1** will show), the SCOP often differs from the SPF actually achieved. When the RHI is 'deemed' (not metered), the money is allocated to renewable heat using only the SCOP. If there is a discrepancy, and the actual SPF is lower than the estimated SCOP then the consumer will save less in fuel costs (or may make no fuel savings at all) but that loss is partially compensated because the RHI is based on the higher SCOP.

The outcome is not as positive for consumers who are 'metered for payment'. In these cases, the RHI is paid only for the metered renewable portion of the generation: the *actual* heat generation minus the electricity energy input (Ofgem, 2018a). In these circumstances, if there is a discrepancy and the SPF is lower than the estimated SCOP, then the consumer will save less in fuel costs than expected *and* receive a lower than expected RHI. These issues are described in further detail in ***Appendix K***.

To examine the financial impact, a number of scenarios were plotted (see **4.2**), where the average generation, average SCOP and average SPF from *Sample 2 Tukey* were used to test heat pump installations replacing oil, electricity and gas. The scenarios were tested assuming two different incentive regimes.

4: Results

4.1: Data Analysis

4.1.1: Overview

Two batches of data were analysed:

- *Sample 1 Tukey*
- *Sample 2 Tukey*

The *Combined Set* includes all the installations in both Samples irrespective of whether they were carried out before or after Version 5.0 of MIS 3005 was introduced. **4.1.2** describes the results for *Combined Set Tukey* with separate results for GSHPs and ASHPs. **4.1.3** compares results before and after Version 5.0 of MIS 3005 became compulsory. **4.1.4** gives a correlation analysis. **4.1.5** explores technology sub-samples, gives a standard deviation and provides a further analysis on the comparison between the installer estimates and the SPF efficiencies. **4.1.6** provides a summary.

4.1.2: Combined Set Tukey

Table 7: Results for the Combined Set

Total in Sample (ASHPs and GSHPs)(Tukey Outliers Removed)	598
Average Actual Efficiency SPF	2.76
Average Installer Forecast Efficiency	3.31

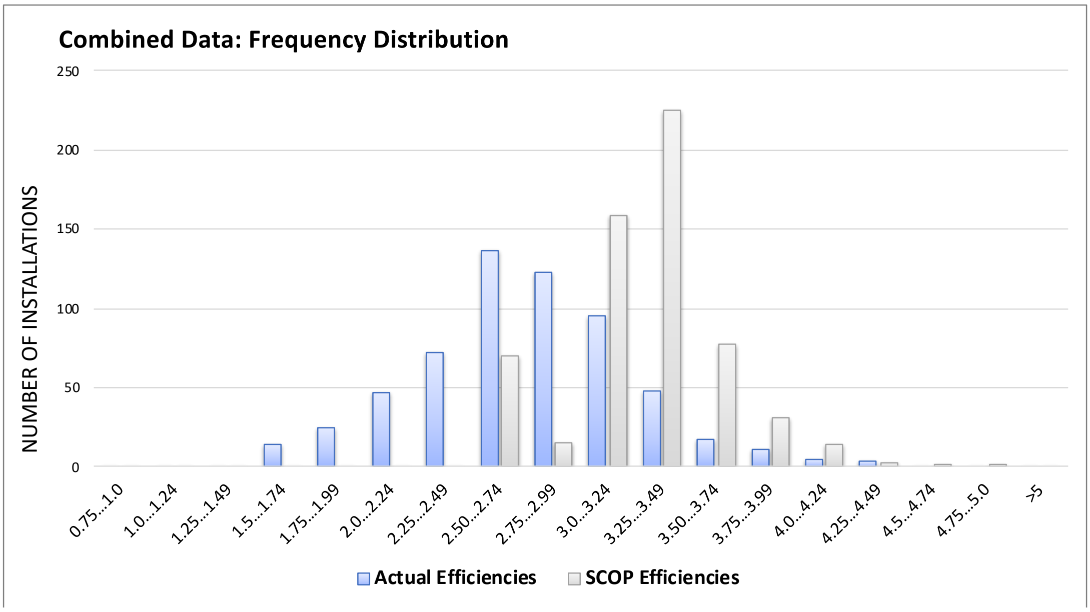


Figure 4: *Frequency Distribution for Combined Set*

Figures 6 and *7* (below) show that GSHPs provide significantly higher performance than ASHPs.

Table 8: Results for the *Combined Set* GSHPs Only

Total in Sample GSHPs only	88
Average Actual Efficiency SPF	3.07
Average Installer Forecast Efficiency	3.65

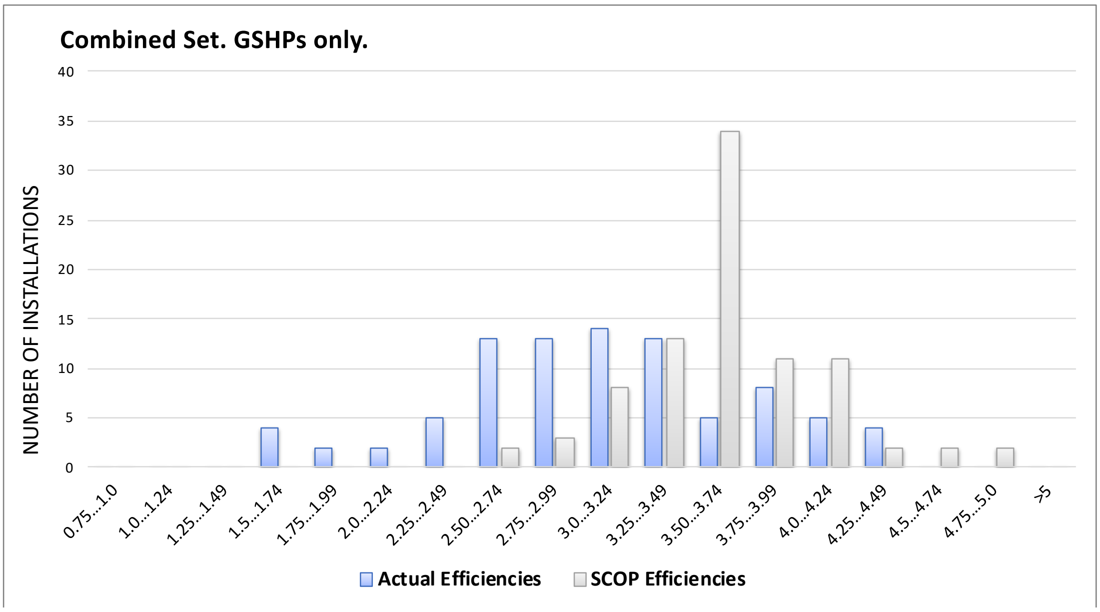


Figure 5: *Frequency Distribution for Combined Set GSHPs Only*

Table 9: Results for the *Combined Set* ASHPs Only

Total in Sample ASHPs only	510
Average Actual Efficiency SPF	2.71
Average Installer Forecast Efficiency	3.25

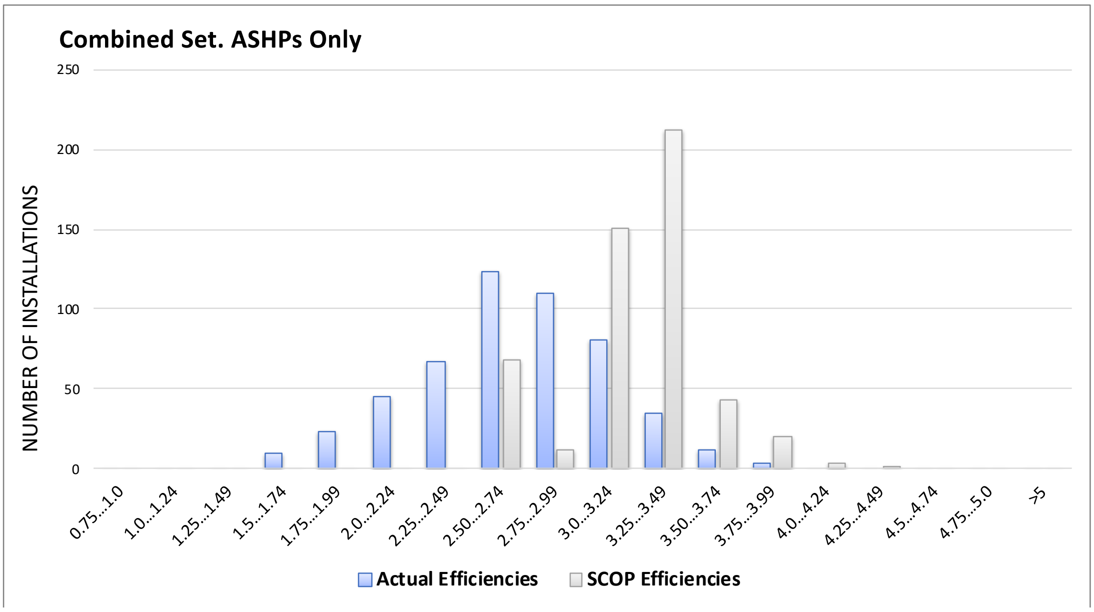


Figure 6: *Frequency Distribution for Combined Set ASHPs Only*

4.1.3: Before and after MIS 3005 Version 5

Important changes to MIS 3005 were introduced in 2017 when Version 5.0 of the standard became compulsory in October that year. It is therefore important to compare performance before and after those changes were made. As described above, *Sample 1 Tukey* was filtered to include only those installations carried out *before* Version 5.0 of that standard became optional in May 2017. That filtered version of *Sample 1 Tukey* therefore functions as a benchmark to assess whether Version 5.0 of MIS 30005 has had any discernible impact on performance.

Sample 2 Tukey includes a significant number of installations carried out *after* the MIS 3005 Version 5.0 became compulsory (October 2017) and can be filtered to include only those installations.

Table 10: Results for the *Sample 1 Tukey* (Whole Sample)

Total in Sample	338
Average Actual Efficiency SPF	2.75
Average Installer Forecast Efficiency	3.27

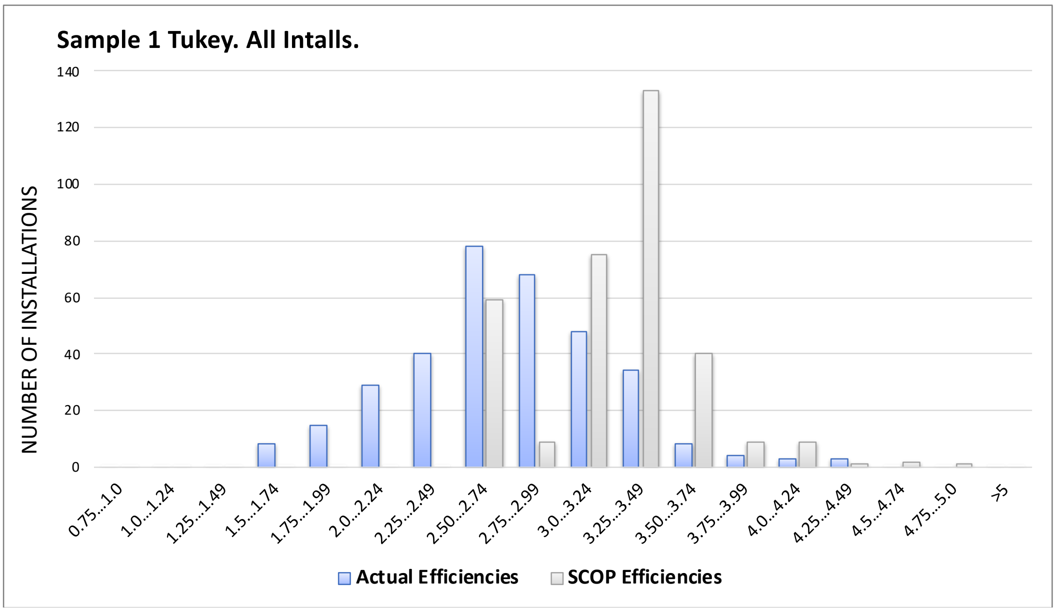


Figure 7: *Frequency Distribution for Sample 1 Tukey*

A small number (24) of installations within *Sample 1 Tukey* were installed after Version 5.0 of the MIS 3005 certification standard became optional in May 2017. Those installations were removed and the results were almost identical to the whole sample:

Table 11: Results for *Sample 1 Tukey* (V5 Option Removed)

Total in Sample	314
Average Actual Efficiency SPF	2.74
Average Installer Forecast Efficiency	3.27

Sample 2 Tukey includes installations from before MIS 3005 V5 became optional (May 2017) and also a significant number of installations that were carried when V5 became compulsory (October 2017).

Table 12: Results for *Sample 2 Tukey* (Whole Sample)

Total in Sample	260
Average Actual Efficiency SPF	2.77
Average Installer Forecast Efficiency	3.37
Correlation coefficient (r value)	0.14 (see 4.1.4)

The above sample was filtered to include only those installations carried out *after* Version 5.0 of MIS 3005 became compulsory in October 2017.

Table 13: Results for *Sample 2 Tukey:* V5 installations only

Total in Sample	85

Average Actual Efficiency SPF	2.75
Average Installer Forecast Efficiency	3.44
Correlation coefficient (r value)	0.14 (see 4.1.4)

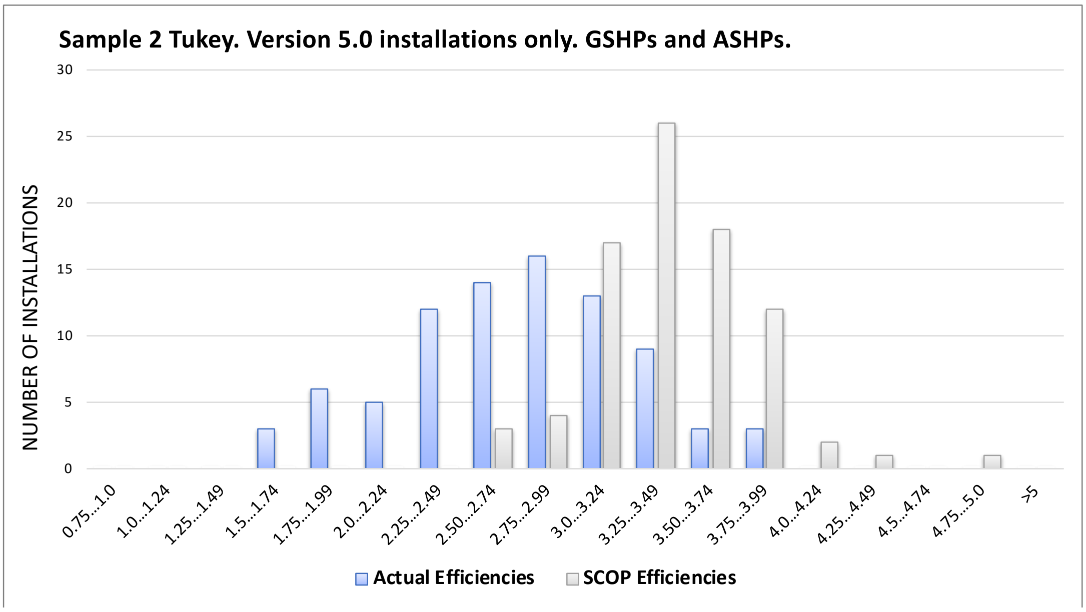


Figure 8: *Sample 2 Tukey: V5 installations only.*

4.1.4: Correlation analysis

A correlation analysis was used to explore the relationship between the SPF results and the SCOP efficiencies in *Sample 2 Tukey* using the formula for the Pearson correlation coefficient:

$$r = \frac{n\Sigma xy - (\Sigma x)(\Sigma y)}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]}}$$

where:
n = the number of installations
Σxy = the sum SCOP values multiplied by the SPF values
Σx = the sum of SCOP values
Σy = the sum of SPF values
Σx² = the sum of squared SCOP values
Σy² = the sum of squared SPF values

The r value was calculated to be 0.14 (*Table 14*) (for *Sample 2 Tukey* – Whole Sample) and therefore no correlation was found between the installer forecasts and the actual SPFs.

Table 14: Correlation coefficient (r values)

Correlation coefficient (r value) for different samples	
Sample	r value
Sample 2 Tukey – Whole Sample	0.14
Sample 2 Tukey: V5 Only	0.14
Sample 2 Tukey: ASHPs Only	0.06
Sample 2 Tukey: GSHPs Only	0.25
Sample 2 Tukey: V5 ASHPs Only	0.14

Sample 2 Tukey: V5 GSHPs Only	-0.30

The r values indicate that there is almost no correlation between the installer efficiency estimates and the actual SPFs. *Sample 2 Tukey: GSHPs Only* was the only sample in which a very weak correlation was evident.

4.1.5: Technology sub-samples and further analysis on the comparison between the installer estimates and the SPF efficiencies

This section uses a number of visualisations to compare the installer estimated SCOPs with the actual SPFs calculated. Overall, the actual efficiencies were found to be lower than the installers' efficiency estimates for 85% of the installations in the *Combined Sample*. A small divergence between an installer estimated efficiency and the actual calculated SPF may not necessarily result in significant consumer harm. However, *Figures 9 and 13-17* indicate that many divergences are significant and some extreme. All of the installer *forecast* estimates provided are above 2.5 (the minimum allowable under the RHI) yet a large proportion of actual efficiencies fall below that benchmark.

Overall, the standard deviation calculated for the *Combined Sample* was found to be 0.49 almost exactly the same as that reported for the EST field trial (0.50)(Gleeson, 2014).

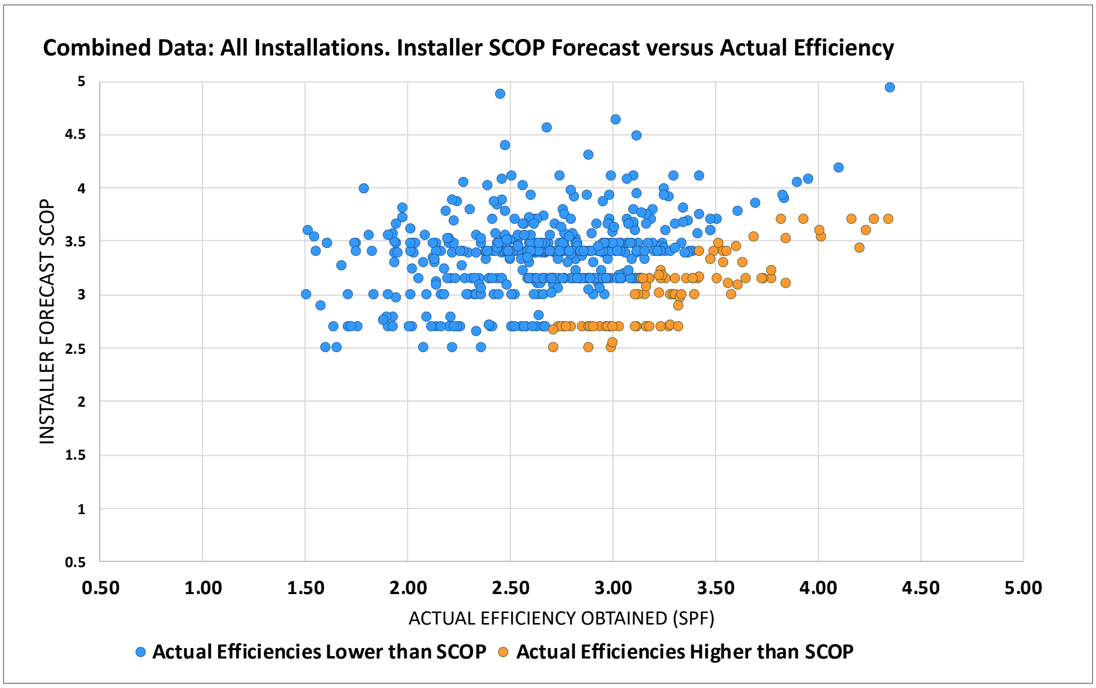
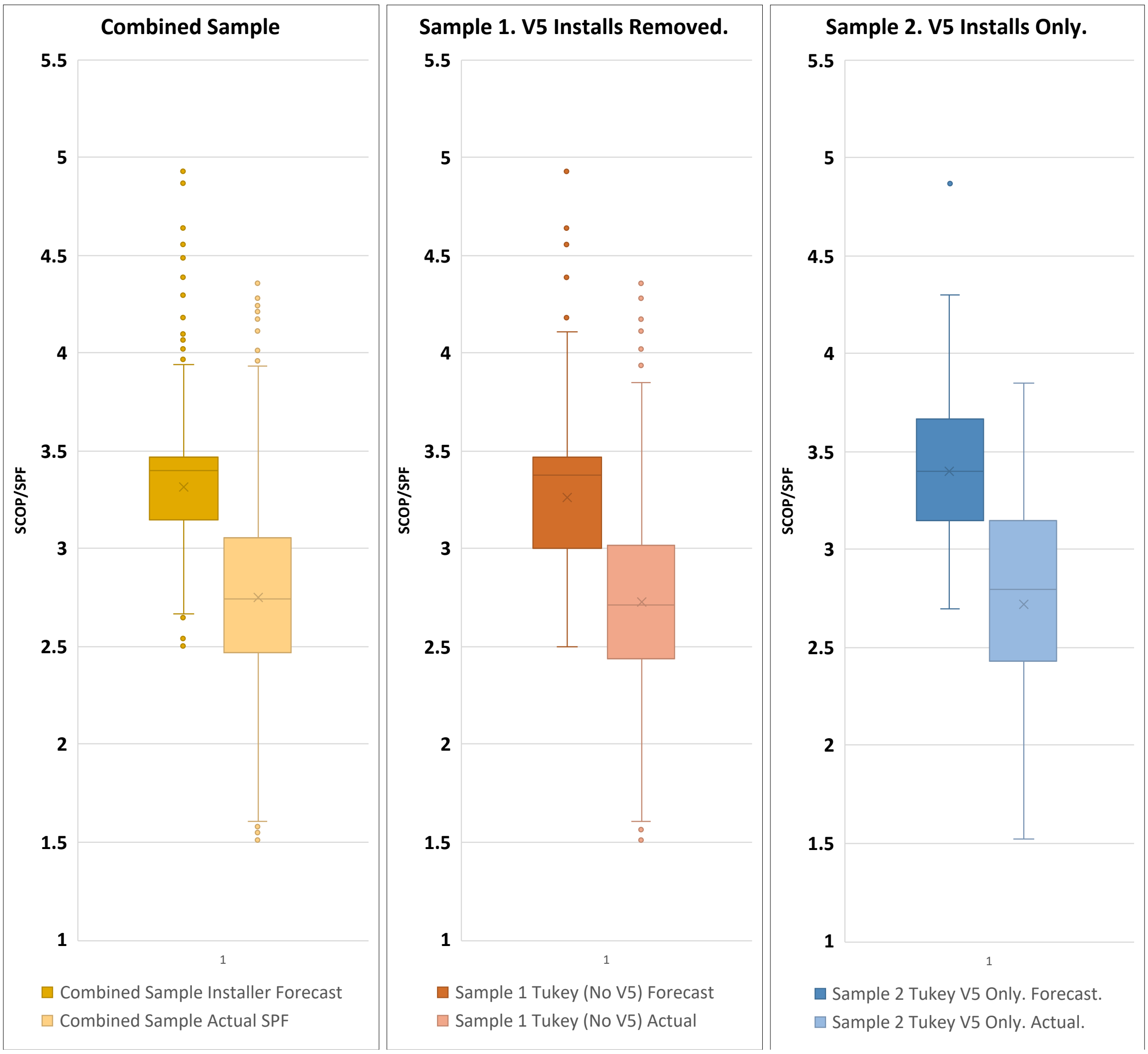


Figure 10*: Scatter Plot: Installer Estimates Versus Actual Efficiencies*

The box and whisker charts, *Figures 10* to *12*, summarise the divergence by comparing installer estimates versus actual efficiencies for three main data samples.



Figures 10, 11 and 12: *Figure 10, (Combined) gives results for all heat pumps in both Samples. Figure 11, (Sample 1: V5 Installs Removed) gives results for all installations carried out after May 2017 excluded. Version 5 of the heat pump installation standard MIS 3005 became optional from May 2017 and compulsory from October 2017. Figure 12, (Sample 2: V5 Installs Only) gives results for all installations carried out after October 2017.*

Figure 10 to *12*, above, and *Table 19* show that the divergence between the installer estimates and the actual efficiencies have *amplified* for *Sample 2: V5 Installs Only*. As *Table 19* shows, when the Before V5 sample is compared to the V5 Installs Only, the installer average estimated SCOP has increased but the actual SPF has decreased (for both GSHPs and ASHPs). The standard deviation (SPF) for *Sample 2: V5 Installs Only* was found to have increased slightly to 0.52.

Table 15: Results for *Sample 2 Tukey* (ASHP installations only):

Total in Sample	219
Average Actual Efficiency SPF	2.72
Average Installer Forecast Efficiency	3.32
Correlation coefficient (r value)	0.06

Figure 13 below gives the results for all ASHPs only for the whole of *Sample 2 Tukey*. The installations are ordered by installer forecast (blue, starting lowest left) and the corresponding actual efficiency provided for each installation (orange). Very few ASHPs achieve or exceed the installer performance forecast.

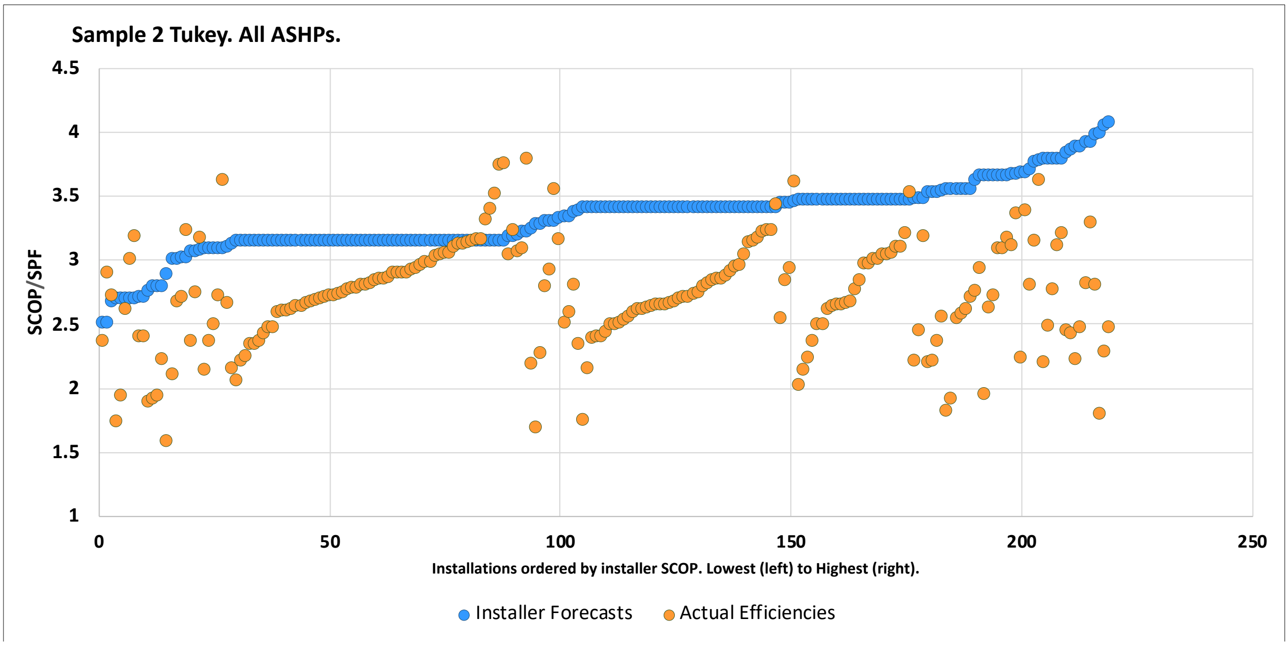


Figure 13: *Sample 2 Tukey (ASHPs Only).*

The same analysis was carried out for GSHPs only:

Table 16: Results for the *Sample 2 Tukey* (GSHP installations only):

Total in Sample	41
Average Actual Efficiency SPF	3.19
Average Installer Forecast Efficiency	3.57
Correlation coefficient (r value)	0.25

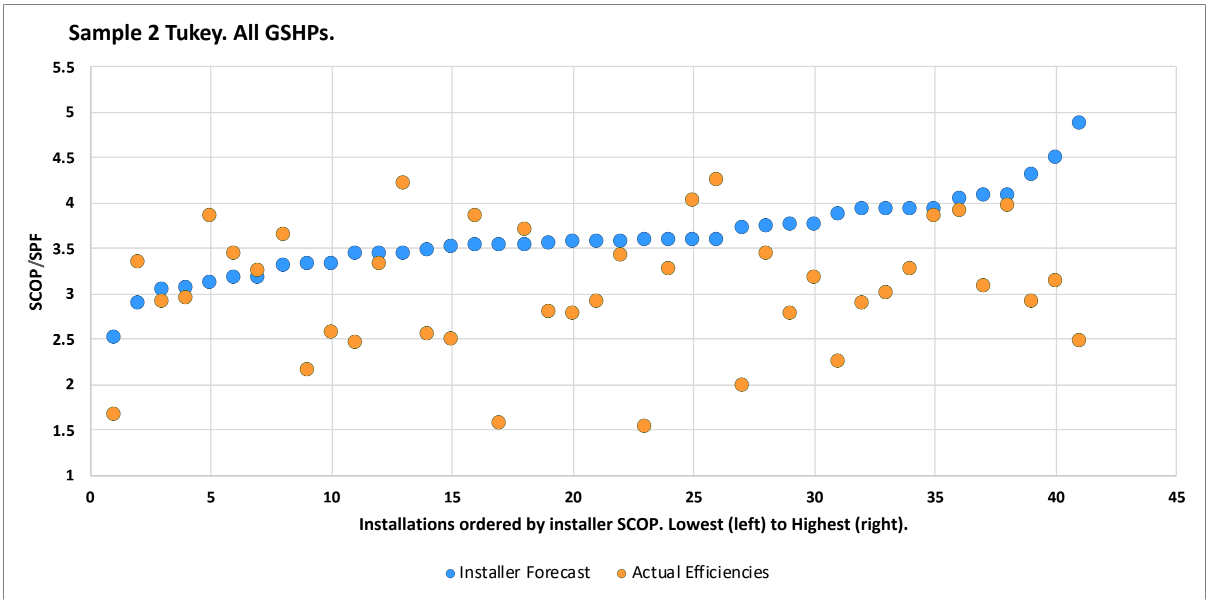


Figure 14: *Sample 2 Tukey (GSHPs Only).*

Sample 2 Tukey was filtered to include the MIS 3005 Version 5.0 installations only for each technology.

Table 17: Results for *Sample 2 Tukey*: V5 ASHPs Only

Total in Sample	66
Average Actual Efficiency SPF	2.69
Average Installer Forecast Efficiency	3.39
Correlation coefficient (r value)	0.14

Table 18: Results for *Sample 2 Tukey*: V5 GSHPs Only

Total in Sample	18
Average Actual Efficiency SPF	2.98
Average Installer Forecast Efficiency	3.60
Correlation coefficient (r value)	-0.30

Figure 15, provides another analysis of *Sample 2: V5 Installs Only*. The installations are ordered by installer forecast (blue, starting lowest left) and the corresponding actual efficiency provided for each installation (orange). Only a small fraction achieve or exceed the installer performance forecast.

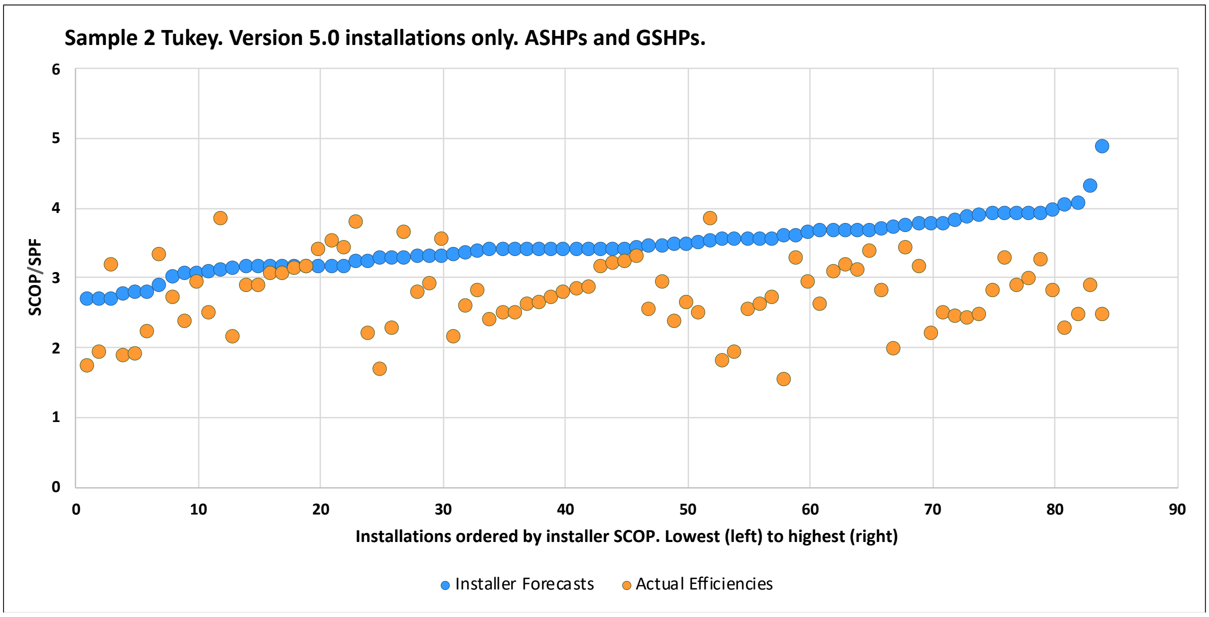
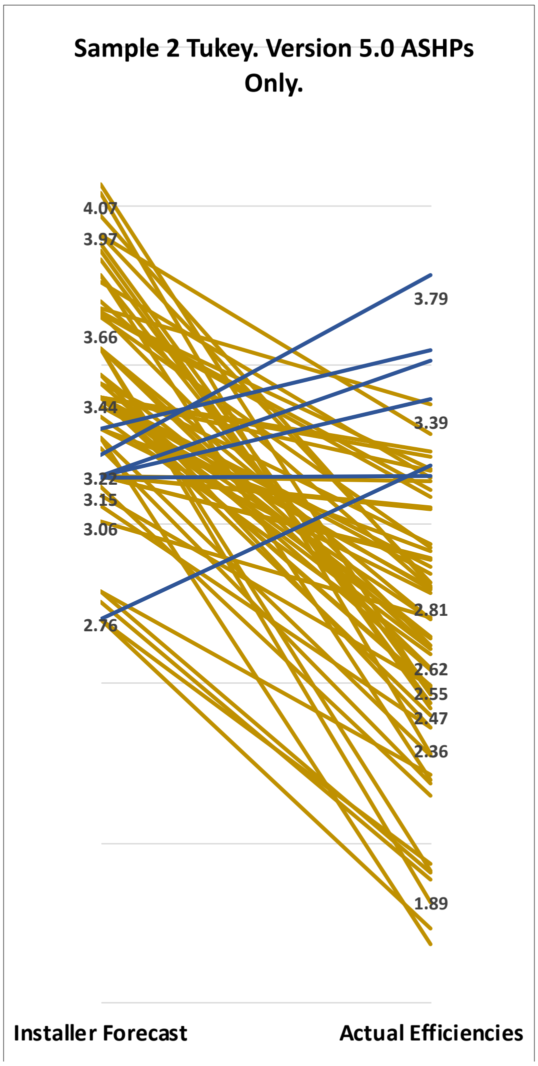


Figure 15: *Sample 2 Tukey (V5 Installs only GSHPs and ASHPs).*

The slope graphs below provide the same information separated by technology. In only eleven installations (*Sample 2 Tukey: V5 Installs Only*) did the installer estimate match or exceed the actual efficiency. Those installations are highlighted in *Figures 17* and *18* (in blue).



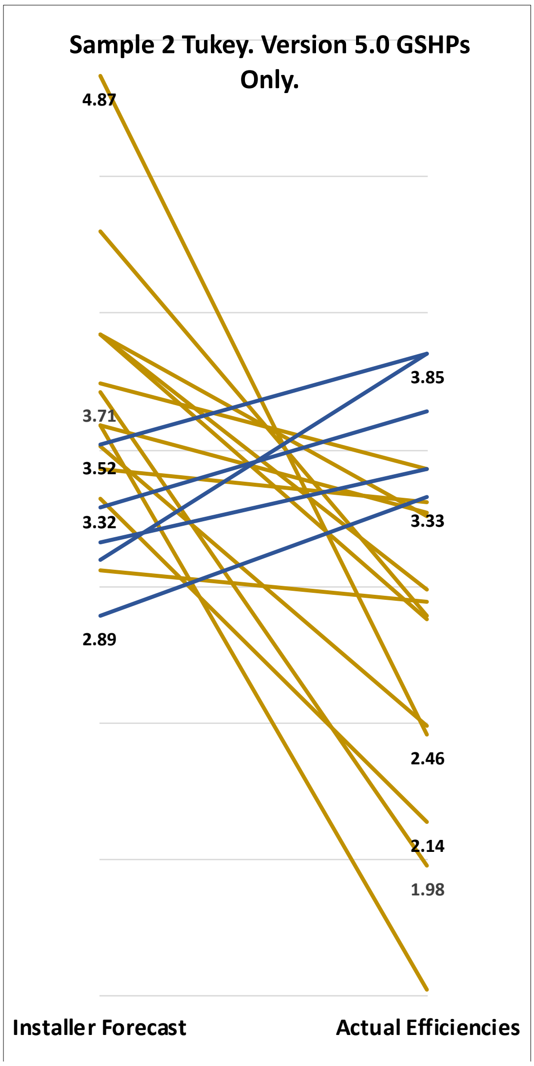


Figure 16: *Sample 2 V5 ASHP Installs Only,* and ***Figure 17***: *Sample 2 V5 GSHP Installs Only*

4.1.6 Summary Giving Comparison with Other Field Trials

Table 19, below, compares the results for the *Combined Sample* and *Sample 2 Tukey* with results from the two main UK field trials described in **2.1**.

Table 19: Results Compared to UK Field Trials

Combined Sample Results Compared to EST and RHPP Field Trial Results: ASHP				
Data	**Boundary**	**Number of Installs**	**SPF (Mean)**	**Installer Forecast**
Combined Sample	Ofgem[1]	510	2.71	3.35 Mean 3.38 Median
Sample 2 Tukey (Before V5)	Ofgem[1]	219	2.72	3.32 Mean 3.40 Median
Sample 2 Tukey (V5 Only)	Ofgem[1]	66	2.69	3.39 Mean 3.40 Median
EST[2]	SPFH2	4	2.9	
EST[2]	SPFH4	7	1.9	
EST[2]	SPFH5	12	1.9	
EST[2]	DECC (Whole System)[2]	22	1.8	
RHPP[3]	SPFH2	292	2.6	3.4 Median[4]
RHPP[3]	SPFH4	292	2.4	
RHPP[3]	SPFH5	223	2.2	

Combined Sample Results Compared to EST and RHPP Field Trial Results: GSHP				
Data	**Boundary**	**Number of Installs**	**SPF (Mean)**	**Installer Forecast**
Combined Sample	Ofgem[1]	88	3.07	3.65 Mean 3.65 Median
Sample 2 Tukey (Before V5)	Ofgem[1]	23	3.21	3.54 Mean 3.56 Median
Sample 2 Tukey (V5 Only)	Ofgem[1]	18	2.98	3.60 Mean 3.12 Median
EST[2]	SPFH2	9	2.6	
EST[2]	SPFH4	17	2.5	
EST[2]	SPFH5	41	2.3	
EST[2]	DECC (Whole System) [2]	49	2.4	
RHPP[3]	SPFH2	92	2.9	4.1 Median[4]
RHPP[3]	SPFH4	92	2.8	
RHPP[3]	SPFH5	76	2.5	

Table Notes:
1: See *Appendix K* and *Limitations* regarding the boundary for the Ofgem dataset.
2: (Gleeson and Lowe, 2013)
3: (Lowe *et al.*, 2017)
4: Only median results provided (Gleeson *et al.*, 2017)

4.2: Economic Value Case Model

The four scenarios below demonstrate how the consumer financial value case for a heat pump installation is extremely sensitive to the actual SPF achieved. This is partly explained by the impact of the RHI (as detailed in **3.2).** To examine the financial impact, four scenarios were plotted, where the average generation, average SCOP and average SPF from *Sample 2 Tukey* were used to test heat pump installations replacing oil, electricity and gas. The four scenarios were tested assuming two different incentive regimes.

Scenario 1: ASHP displace oil under the RHI
In the example below the total lifetime outcome is predicted for an ASHP replacing oil under the RHI. The assumed heat generation is 17624kWh (*Sample 2 Tukey* average*)* all other assumptions provided in the table below.

- The ***Cumulative Forecast Benefit*** represents the likely outcome where the performance matches the installer SCOP estimate of 3.32 (the *Sample 2 Tukey* average).
- The ***Actual Benefit (Deemed RHI)*** represents the likely outcome where the SCOP is 3.32 and SPF is 2.72 (the *Sample 2 Tukey* average). The RHI is paid on the basis of the SCOP. This is what occurs normally under the RHI.
- The ***Actual Benefit (Using Actual SPF)*** represents the likely outcome for RHI 'metered for payment' installations where the SPF outcome is 2.72 (the *Sample 2 Tukey* average). The (metered RHI) is paid on the basis of the SPF.

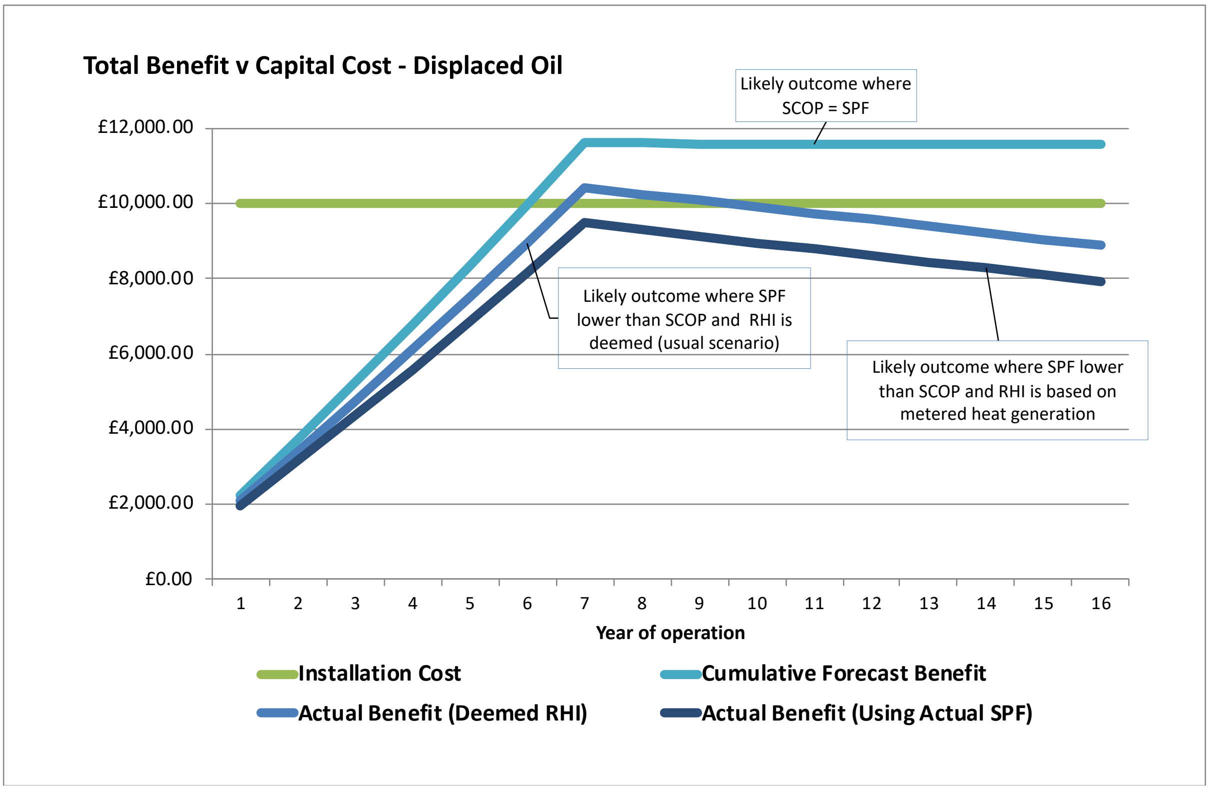


Figure 18: *Oil displaced by ASHP Under RHI*

Electricity Cost	16.36 pence/kWh for displaced fuel and heat pump consumption
Oil Cost	47.14 pence/litre (4.81 pence/kWh assuming 9.8 kWh/litre)
Sample	*Sample 2 Tukey* for ASHPs only
Installer SCOP Estimate	3.32
Calculated SPF	2.72
Incentives	RHI and MMSP included
Installation Cost	£10,000

It is currently the Government's intention to replace the RHI (tariff-based incentive) with one-off grants set at £4000 for all eligible technologies such as heat pumps (BEIS, 2020). Such a grant effectively lowers the capital cost. The following scenario therefore explores the potential consequences of replacing the RHI with a single one-off grant.

Scenario 1: ASHP displaces oil under one-off grant

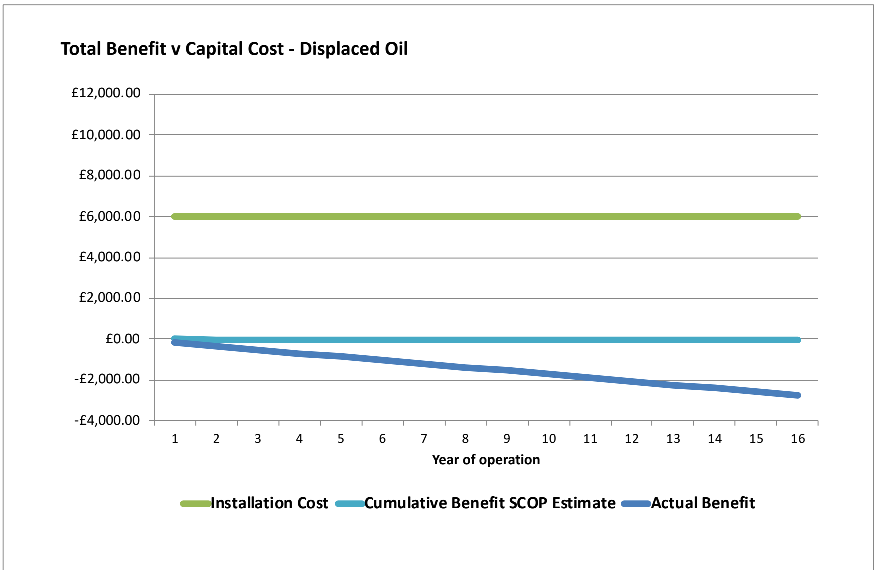


Figure 19: *Oil displaced by ASHP Under One-Off Grant*

Electricity Cost	16.36 pence/kWh for displaced fuel and heat pump consumption
Oil Cost	47.14 pence/litre (4.81 pence/kWh assuming 9.8 kWh/litre)
Sample	*Sample 2 Tukey* for ASHPs only
Installer Forecast	3.32
Calculated SPF	2.72
Incentives	One-off £4000 Grant
Installation Cost	£10,000 minus £4000 Grant

Scenario 2: GSHP displaces oil under RHI. As GSHPs tend to be more efficient than ASHPs and receive a much higher RHI tariff, net savings are more likely

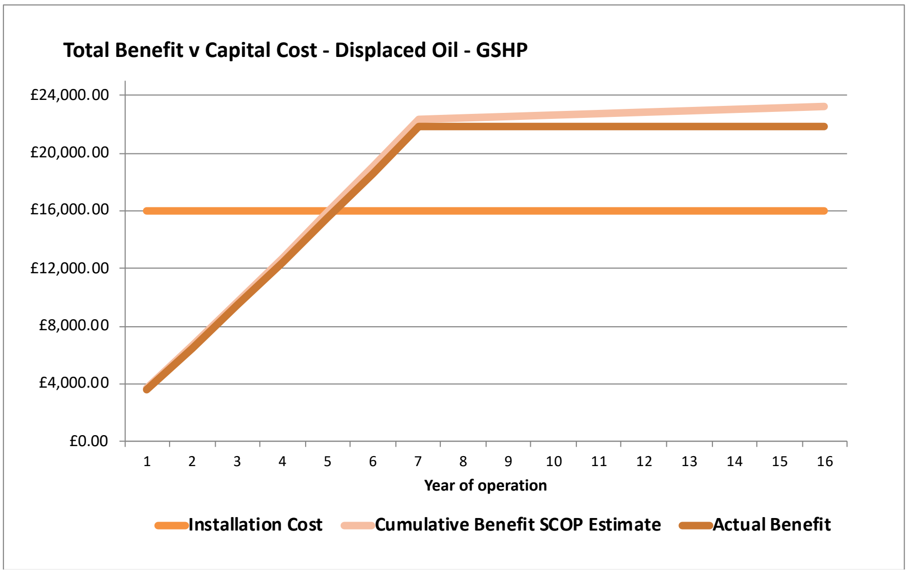


Figure 20: *Oil displaced by GSHP Under RHI*

Electricity Cost	16.36 pence/kWh for heat pump consumption
Oil Cost	47.14 pence/litre (4.81 pence/kWh assuming 9.8 kWh/litre)
Sample	*Sample 2 Tukey* for ASHPs only
Installer Forecast	3.57
Calculated SPF	3.19
Incentives	RHI and MMSP included
Installation Cost	£16,000

Scenario 2: GSHP displaces oil under one-off grant. No net savings are likely where the RHI is replaced with a one-off grant.

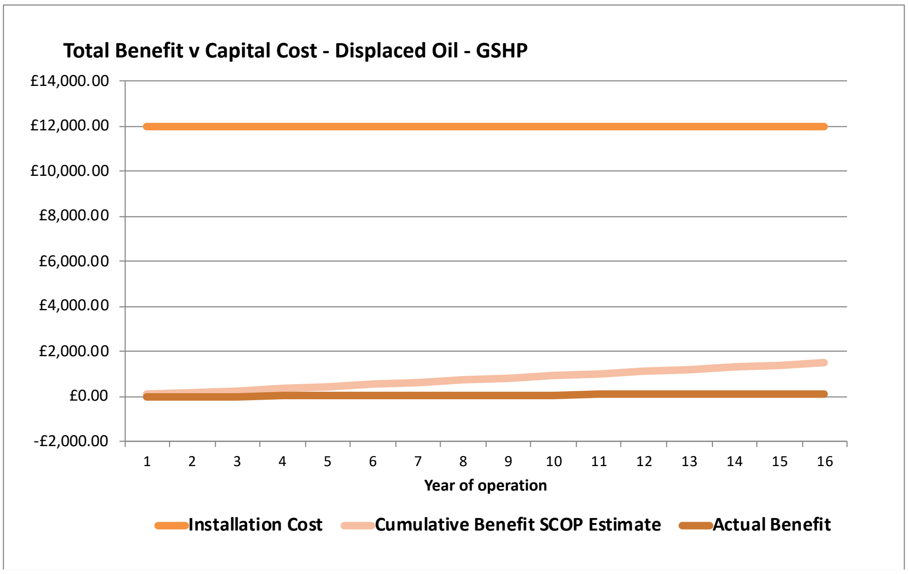


***Figure 21:** Oil displaced by GSHP Under One-Off Grant*

Electricity Cost	16.36 pence/kWh for displaced fuel and heat pump consumption
Oil Cost	47.14 pence/litre (4.81 pence/kWh assuming 9.8 kWh/litre)
Sample	*Sample 2 Tukey* for GSHPs only
Installer Forecast	3.57
Calculated SPF	3.19
Incentives	One-off £4000 Grant
Installation Cost	£16,000 minus £4000 Grant

Scenario 3: ASHP displaces electric heating under RHI. As electric heating is so expensive, substantial savings are likely. In this scenario no allowance is made for lower 'Economy 7' tariffs used with storage heating. Even so, ASHPs are also normally cheaper than Economy 7.

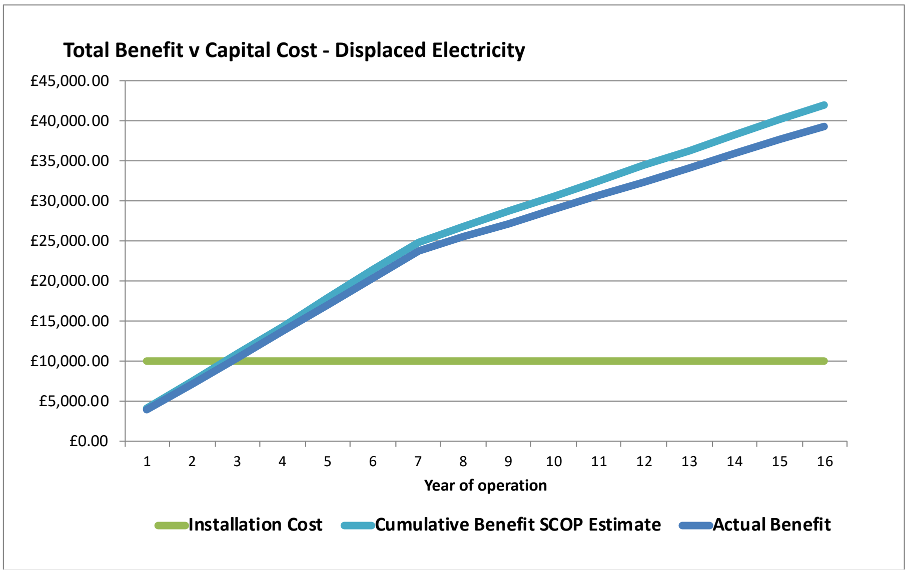


Figure 22: *Electric heating displaced by ASHP Under RHI*

Electricity Cost	16.36 pence/kWh for displaced fuel and heat pump consumption
Sample	*Sample 2 Tukey* for ASHPs only
Installer SCOP estimate	3.32
Calculated SPF	2.72
Incentives	RHI and MMSP included
Installation Cost	£10,000

Scenario 3: ASHP displaces electric heating under one-off grant

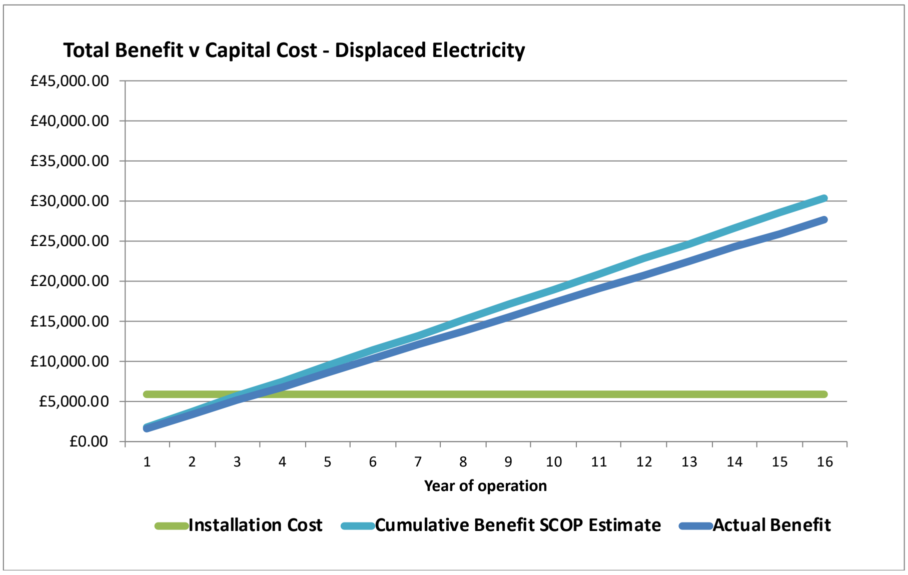


Figure 23: *Electric heating displaced by ASHP Under One-Off Grant*

Electricity Cost	16.36 pence/kWh for displaced fuel and heat pump consumption
Sample	*Sample 2 Tukey* for ASHPs only
Installer SCOP estimate	3.32
Calculated SPF	2.72
Incentives	One-off £4000 Grant
Installation Cost	£10,000 minus £4000 Grant

Scenario 4: ASHP displaces mains gas under the RHI
The vast majority of UK homes are heated by gas. Again, the average SPF and average installer estimated SCOP from *Sample 2 Tukey* were used for *Figure 24*, below.

The ***Cumulative Forecast Benefit*** indicates a net financial benefit up to point at which the RHI payments cease and then a slight net financial cost over the lifetime of the installation because (if prices remain static) the heat pump will be more expensive to run than mains gas. The ***Actual Benefit (Deemed RHI)*** indicates there would be an increase in fuel costs of more than £300 per year and the consumer would not recoup the cost of the installation.

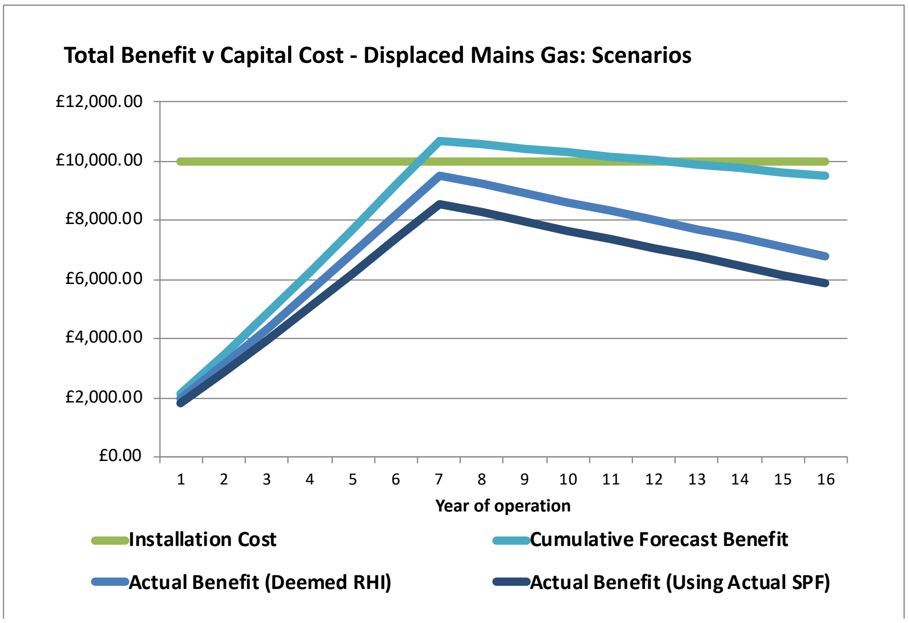


Figure 24: Mains Gas displaced by ASHP Under RHI

Electricity Cost	16.36 pence/kWh for heat pump consumption
Mains Gas	4.17 pence/kWh
Sample	*Sample 2 Tukey* for ASHPs only
Installer Forecast	3.32
Calculated SPF	2.72
Incentives	RHI and MMSP included
Installation Cost	£10,000

Scenario 4: ASHP displaces gas under one-off grant.
Under an incentive regime based on a one-off grant of £4000, and using current average prices, the financial case for a heat pump installation replacing mains gas falls away. The total *net loss* or *detriment* is the difference between the Installation Cost and the (negative) financial impact of the heat pump running costs: around £11000 if the SPF is 2.72 (and £8000 if the heat pump achieves the installer estimated SCOP: 3.32).

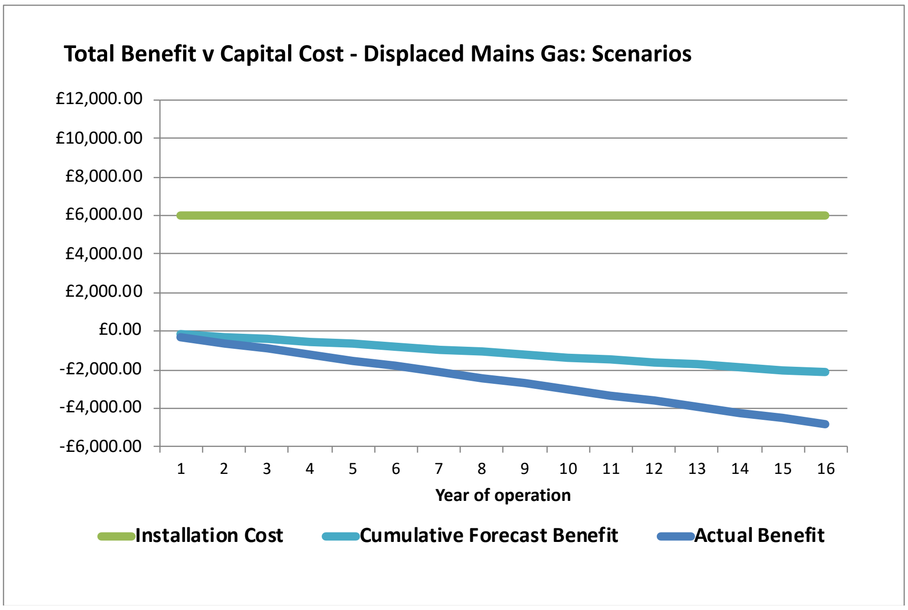


Figure 25: Mains Gas displaced by ASHP Under One-Off Grant

Electricity Cost	16.36 pence/kWh for heat pump consumption
Mains Gas Cost	4.17 pence/kWh
Sample	*Sample 2 Tukey* for ASHPs only
Installer Forecast	3.32
Calculated SPF	2.72
Incentives	One-off £4000 Grant
Installation Cost	£10,000 minus £4000 Grant

5. Discussion

This section addresses the three research questions set out in **1.1**.

5.1. Heat pump efficiency.
How efficiently do heat pumps operate in UK households?

As explained in **7.0** (Limitations), the Heat Pump installation metering used for RHI purposes may not replicate the SEPEMO H2 boundary exactly (as described in **1.2c**) therefore a direct comparison with, for example, the RHPPH2 results described in *Table 19* may not be possible. However, while the conclusions that can be assimilated are subject to the limitations set out here and in **7.0,** the results related to performance are obviously disappointing and are broadly consistent with previous UK field trials.

More positively, the average GSHP SPF was above 3 in two samples including the whole *Combined Sample*. The frequency distribution charts in **4.1** illustrate that very high SPFs are possible. Out of the 88 GSHPs in the Combined Sample, 22 (25%) had SPFs above 3.5. Within the same sample, fifteen ASHPs out of the total 510 (3%) were found to have SPFs above 3.5.

Of significant concern, however, is the proportion of installations found to have SPFs below 2.5. Out of the 510 ASHPs (in the Combined Sample) 145 (28%) had SPFs below 2.5 and 33 of those were below 2.0. Out of the 88 GSHPs, 13 (15%) had SPFs below 2.5. In the whole of *Sample 2 Tukey* (ASHP and GSHP combined), 66 installs out of 260 (25%) had SPFs below 2.5. It is critical to make a distinction between the results 'Before V5' and 'V5 Only'. As explained in **3.1** and **4.1**, these labels differentiate the installations that took place before and after important changes were made to the MCS heat pumps standard: MIS 3005. This paper has focused on *Sample 2 Tukey* for this reason. As *Table 19* shows, the V5 Only samples for both GSHPs and ASHPs show a slight *fall* in actual SPFs calculated compared to the samples 'Before V5'.

While the drop in average SPFs between 'Before V5' and 'V5 Only' are relatively small (and in the case of GSHPs relate to a sample of only 18 installs) the results are sobering and may indicate that installation practice has not improved as expected since the compulsory changes to MIS 3005 were introduced in October 2017. Those changes sought to simplify the standard, but the main change introduced revamped the way installers were instructed to provide performance estimates to consumers. Under the previous version (MIS 3005 V4.3) installers used a *Heat Emitter Guide* (Gleeson *et al.*, 2017) that gave installers guidance on selecting emitters, flow temperatures and heat pump sizing. This was replaced with a simpler method using the *Heat Pump System Performance Estimate* (**Appendix J**) to present a SCOP estimate of efficiency (MCS, 2017).

5.2. SCOP and SPF Consistency.
Are the actual efficiencies consistent with the installer performance estimates?

Only one other study could be found that compared installer forecast performance estimates with actual results and those are summarised in *Table 3* which describes the median measured SPFs in the RHPP field trial compared to the median installer estimate. As *Table 19* shows, the RHPP median installer estimate for ASHP is the same as that reported for this paper (Sample 2 Tukey), and the RHPP median for GSHP is slightly higher (than the Sample 2 Tukey median).

The standard deviation calculated for the *Combined Sample* was found to be 0.49 (**4.1.5**); almost exactly the same as that reported for the EST field trial (0.50)(Gleeson, 2014). The results on consistency are summarised in the correlation analysis carried out on Sample 2 Tukey (**4.1.4**). The r value was calculated to be 0.14 (*Table 10*) and therefore no correlation was found between the installer forecasts and the actual

SPFs. The charts in Figures **13**, **14** and **15** are notable because they indicate that the SCOP estimates are most likely to match or exceed the SPFs where the installers provide *cautious* estimates of performance (lower SCOP estimates). The installers who provide the most optimistic estimates (above 3.5) are almost never correct.

This absence of correlation is likely to be the source of considerable consumer harm because large discrepancies between the installer estimates and the actual SPFs can have obvious financial consequences Consumers have little access to objective, recent information and they are likely to trust information provided as part of MIS 3005 certification.

The question as to whether the actual efficiencies are consistent with the installer performance estimates is of key significance for several reasons. Not only do consumers base contractual decisions on the installer estimated SCOP but, given the absence of reliable, recent data on heat pump efficiency, the industry is placing increasing emphasis on SCOP estimates as a proxy measure of actual performance. As described in **2.0**, the *Heat Pump System Performance Estimate* (**Appendix J**) is based on the SCOP product metric (MCS, 2018) and as detailed in **Appendix C** other stakeholders are using the installer estimates as a proxy for actual performance to model both the CO_2e mitigation of heat pumps and the value case for Government investment.

5.3 The financial value case
What impact do the results have on the consumer financial value case for heat pump installation?

As section **4.2** shows, while an installer *estimated* performance using SCOP may indicate a net benefit under the under RHI, the likely financial impact using the average SPF calculated for this paper indicates a net financial cost in some situations (no payback over the lifetime of the system assuming prices remain static). That financial discrepancy is due to the difference in assumed heat pump efficiency. For example, *Figure 20* shows that where an ASHP has an efficiency of 3.32 it costs roughly the same to run as an oil system: 16.36pence/kWh for electricity compared to oil priced at 4.81pence/kWh (*16.36 ÷ 4.81=3.40*). But with efficiency assumed to be 2.72 the heat pump is £172 more expensive to run than oil per year. But, where the RHI is 'deemed', that loss is (partially) cushioned through the influence of the RHI. *Figures 19* (ASHP) and *21* (GSHP) demonstrate that there is no realistic 'payback' possible using current SPFs if the RHI is removed and grants set at £4,000. The same is true where heat pumps replace gas Figure *25* (ASHP).

The exception is where heat pumps replace electric heating. Even where the actual performance is significantly lower than the installer estimated SCOP, considerable fuel cost savings are still likely.

Table 20, below, indicates that the model used for this paper (and assuming SPF 3.32) returns results that are broadly consistent with likely financial outcomes described by the EST (Energy Saving Trust, 2020a).

Table 20: Annual Fuel Costs: Thesis Model Compared to EST Information

Potential Financial Result – Annual Fuel Costs using ASHP[1] Thesis Model Compared to EST "Potential Annual Fuel Bill Savings"		
Displaced Technology	EST Estimates[2]	Thesis Estimate (Mains Gas and Oil Boilers assumed to have been installed before 2007)
Mains Gas	-£95 to £100 (A-Rated Gas Boiler)	-£133 (SPF 3.32)
		-£302 (SPF 2.72)
Oil	-£80 (A-Rated Oil Boiler)	-£4 (SPF 3.32)
		-£172 (SPF 2.72)
Electric Heating	£920 to £1000	>£1000

Table notes:
1: Negative values indicate fuel spend increases (no savings).
2: The EST figures relate to a standard ASHP in an average-sized four-bedroom detached home.

5.4 CO_2e mitigation

Is there a shortfall in CO_2e mitigation due to any discrepancy between the actual efficiencies calculated and the performance forecasts?

The CO_2e mitigation analysis is the subject of a *companion paper* but the overall results are described here. Where the carbon mitigation is calculated using the installer SCOP estimates, the average CO_2e saving per annum was found to be 3.50t per install (with an average demand of 17624kWh). The equivalent figure using the calculated SPF was found to be 3.19t per annum and this is broadly in line with the EST's estimates (Energy Saving Trust, 2020a). This analysis demonstrates that there is a carbon mitigation shortfall but, importantly, that shortfall is not proportional to the difference between the installer efficiency forecast and the actual SPF. Any CO_2e mitigation shortfall will relate to the carbon intensity of the heat pump's electricity consumption and, as the grid decarbonises, heat pump generation becomes less carbon intensive.

The CO_2e mitigation shortfall related to the total cumulative generation of all *Sample 2 Tukey* installations from 2018 to 2029 was calculated to be nearly 500 tonnes (CO_2e). The analysis indicates that the shortfall in carbon mitigation based on a comparison between the installer forecast efficiency and the actual SPF was approximately 5% (over the 12 year period assessed).

In 2018, the total number of domestic heat pump installations under the RHI was 44411. In order to determine the potential impact of the disparity between actual and forecast performance on a larger number of installations, the CO_2e saved by those 44411 installations in 2018 was calculated using the *Sample 2 Tukey* average generation: 17624kWh per install. The generation was found to be **782699 MWh** and the CO_2e saving (net) using the installer forecast efficiency **(3.37)** is **1721916 tonne** and the CO_2e saving (net) using the actual calculated efficiency **(2.77)** is **1640669 tonne:** a *shortfall* of **81,247 tonnes** CO_2e for just one year. As the roll out of heat pumps scales up to millions, the shortfall in CO2e mitigation will obviously be amplified. *This demonstrates why the SCOP metric should not be used as a proxy for in-situ efficiencies for forecasting purposes as often occurs.*

It is instructive to also examine the ratio of MWh to tonne CO_2e saved. The chart below demonstrates how the ratio of MWh to tonne CO_2e saved is significantly higher when the calculations are based on actual performance instead of installer forecast performance. For example, in 2018, 5.5 MWh was required for every tonne of CO_2e saved when using SPF 2.77 compared to 5MWh when using the installer forecast. That gap then narrows as the carbon intensity of the grid is forecast to fall.

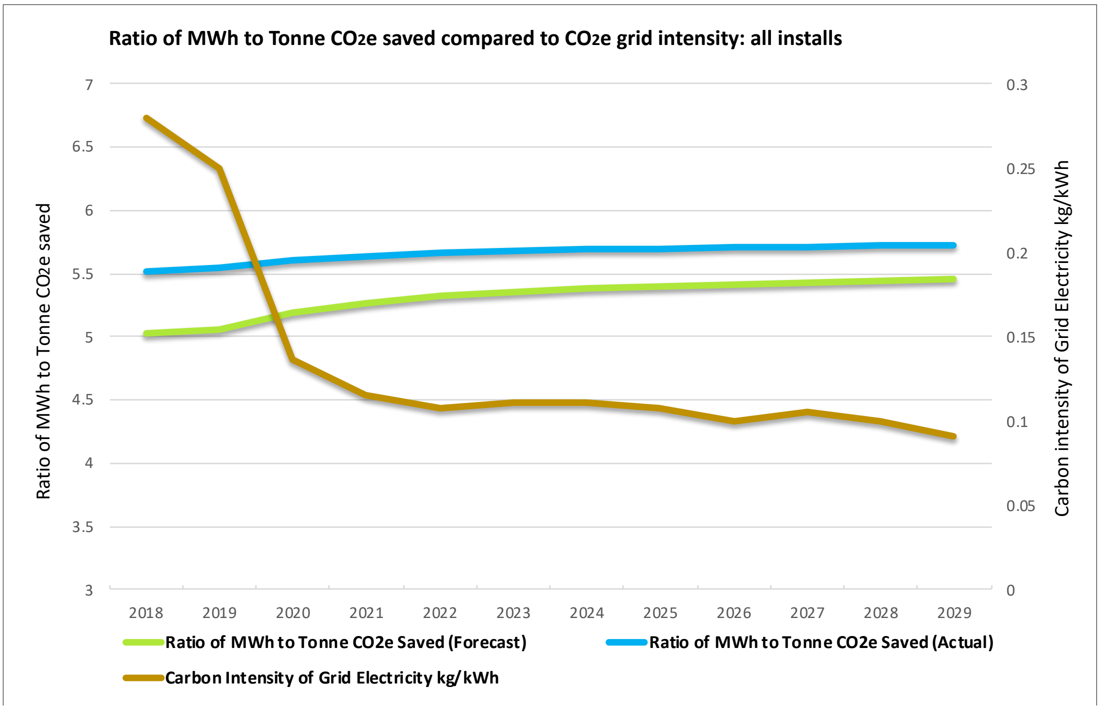


Figure 26: *Ratio of MWh to Tonne CO_2e saved versus CO_2e grid intensity – all installs*

6: Conclusion and Recommendations

The conclusions and recommendations described in this section are qualified by the limitations described in **7.0** (Limitations) which note that a direct comparison with, for example, the RHPPH2 results described in *Table 19* may not be possible because the heat pump installation metering used for RHI purposes may not replicate the SEPEMO H2 boundary exactly (as described in **1.2c**). Nevertheless, this analysis provides a valuable insight into:

- in-situ heat pump performance;
- the gap between SCOP estimates and actual SPFs; and
- performance before and after the MIS 3005 heat pumps standard was changed in 2017.

5.0 also acknowledges that the results fall within the logical parameters of already published work. In other words, while research evidence on the in-situ performance of heat pumps is lacking, the results described in **4.0** are broadly consistent with previous field trials and this consistency strengthens the existing body of evidence on in-situ performance.

While it cannot be assumed that the Ofgem dataset is representative of heat pumps more generally, the following observations are based on all the available research on performance including the results from this paper.

As previous field trials have shown, the analysis of the Ofgem dataset shows that some heat pumps are performing with good efficiency. The average GSHP SPF for the *Combined Sample* was 3.07 and in the more recent *Sample 2 Tukey*, GSHPs had an *average* SPF of 3.19. Three per cent of ASHPs and 25% per cent of GSHPs in *Sample 2 Tukey* had a SPF above 3.5. These results are encouraging and demonstrate that high levels of efficiency for extended periods are possible in the UK.

Of particular concern, however, is that there was no discernible improvement in installation performance since the MCS heat pump certification standard changed in 2017. This study was designed to enable a comparison between installations carried out before and after that new standard became compulsory and, as described in 5.2, not only has the divergence between the installer estimates and the actual SPF efficiencies widened, average installation SPFs have deteriorated slightly.

As noted in Section 1.0, there is widespread agreement that heat pumps in the UK do not match the performance observed in many European countries (Gleeson and Lowe, 2013) and it has been speculated that mainland European efficiencies may be higher because dwellings are more likely to use compensating heating controls, have higher quality heating systems, and have better insulation while also using less domestic hot water and less back-up heating (Underwood, Royapoor and Sturm, 2017).

Gleeson argues that the inconsistency in SPFs found in UK field trials does raise questions about design and installation competency that could be addressed through improved training, standards and compliance monitoring (Gleeson and Lowe, 2013)(Gleeson, 2016). There are likely to be many reasons why SPFs in the UK appear to be low but one critical factor was identified in 2010 immediately after the first phase of the EST field trial. The fact that UK's housing stock is particularly old and inefficient was, according to the EST, the "major difference" between the UK and European field trial findings at that time (Roy, Caird and Potter, 2010). Broad et al,. point out that the UK's housing has among the worst energy efficiency in Europe (Broad, Hawker and Dodds, 2020).

The issue of UK's building fabric thermal efficiency is of key importance. As described in **1.1**, over the last 10 years a consensus has emerged that heat pumps will play an important role in the decarbonisation of domestic heating. For example, in 2018 the CCC placed emphasis on the need for heat pumps in new build properties and those off the gas grid (CCC, 2018). In its 2020 Progress Report to Parliament, however, it said the deployment of heat pumps must "scale up to be able to replace the majority of current gas boiler demand by the early 2030s" a target it says represents around 1.5 million installations per year (CCC, 2020, Page 177).

Inevitably, these CCC calculations and targets mean that that vast majority of heat pump installations will be retrofit. If, as is suspected, old and poor-quality housing stock is at least partly to blame for the comparatively low performance of heat pump installations, then these targets represent a considerable challenge. For example, it is widely argued that the potential for energy saving benefits through heat pump installation can be reduced if dwelling efficiency improvements are not carried out at the same time (Flower, Hawker and Bell, 2020)(Broad, Hawker and Dodds, 2020). Flower et al., conclude that, as heat pumps operate with flow temperatures that are significantly lower than conventional fossil-fuelled systems, they are better suited to homes that are thermally efficient. They conclude that the value case for both heat pumps and supportive policy is: "interdependent with interventions taken to increase building energy efficiency" (Flower, Hawker and Bell, 2020).

These are not arguments against the installation of heat pumps, but they are a warning that the mass retrofit campaign should be coordinated with building fabric upgrades where needed in retrofit situations. These points relate to the basics of heat pump design with the Carnot equation explained in **1.2a**: the smaller the gap between the source and sink temperatures, the higher the COP. Higher flow temperatures are needed in buildings with poor thermal efficiency and higher flow temperatures result in lower SPFs.

It is argued that meeting the challenge of rolling out millions of heat pump installations depends on consumer confidence. Flower et al., have said that reducing the costs and improving the performance of low carbon heating together with building public confidence is critical if heat pumps are to compete with mains gas (Flower, Hawker and Bell, 2020).

Of key significance here is the *performance gap* that has been identified between design and as-installed heat pump performance (Underwood, Royapoor and Sturm, 2017). Underwood et al., found that their modelling confirmed a gap between UK field trial findings and values expected for the heat pump products (Underwood, Royapoor and Sturm, 2017, page 586) and that gap is obvious given the large proportion of heat pumps that failed to reach the SPF 2.5 threshold in UK field trials and as reported here using the Ofgem dataset. These installations very clearly challenge consumer confidence.

Of additional concern is that the problems related to the performance gap are compounded by current methods used to forecast design performance. As explored in **1.2c**, it is known the SCOP metric is a measure of product efficiency. When used as a tool to predict the efficiency of the heating system the SCOP metric will most likely exaggerate performance. Commenting directly on SCOP forecasts, Griffiths said: "If reasonable confidence in performance estimates – namely the annual efficiency – cannot be guaranteed, then the long-term uptake of heat pumps also cannot be assured" (Griffiths, 2018).

A very weak correlation was found between the installer performance estimates and the SPFs in one small sub-sample of GSHPs, but no correlation was found in the wider population of installations, in the ASHP sub-samples or in other samples of GSHPs (*Table 14*). These result raise significant questions about the methodology used for the provision of performance estimates in the MCS Standard 3005 Version 5 (MCS, 2017).

Both Griffiths and Nolting et al,. have critiqued the European Ecodesign and energy labelling regulations because the methodology used is only suitable to estimate heat pump product efficiency and is unlikely to provide a robust estimate of heat system efficiency (Griffiths, 2018). Nolting et al,. have concluded that consumers need precise information if they are to overcome information asymmetries and choose more efficient products (Nolting, Steiger and Praktiknjo, 2018).

The evidence related to the consumer financial value case for installation is stark. The modelling described in **4.2** shows that while it is certainly logical to displace electric heating with a heat pump, when displacing gas or oil the value case under the RHI depends on the SPF. The results detailed in **4.2** demonstrate how SCOP estimates can forecast a net financial benefit when a net financial loss can be more likely using average SPF results. When using the Government's preferred option for future incentives (a one-off £4000 grant) the financial value case for replacing oil or gas with a heat pump is severely weakened because typical consumer scenarios suggest a significant net detriment.

As explained in section **5.4**, the performance gap does lead to a shortfall in carbon mitigation implied by the SCOP estimates. The shortfall was significant but not dramatic. This shortfall is *not* proportional to the gap between the SCOP and the SPF because most of the CO_2e mitigation relates to the displacement of the fossil fuel boiler irrespective of the efficiency of heat pump. These findings on forecast versus actual CO_2e mitigation are important for several reasons. Section **1.1** reports how the assumptions about performance that underpin policy can sometimes be opaque and **2.3a** and **Appendix C** detail examples where research papers on both CO_2e mitigation and the UK Government value case for incentivising heat pump installations have used installer estimates drawn from the RHI database as a proxy for heat pump performance. Proxies based on SCOP are likely to overstate performance and a shortfall in CO_2e mitigation of some 5% when related to millions of heat pumps is clearly of some concern.

This paper demonstrates that profound information asymmetries exist in the UK market for domestic heat pump installation and that these asymmetries risk the consumer confidence that is essential if current targets are to be met. Since the new MIS 3005 heat pumps standard was made compulsory, the *average* installer efficiency *forecast* provided (using the V5 only sample) has been just under 3.50. By contrast, the CCC said in a 2019 technical report that it is expecting average SPFs to increase by just 0.5 from 2.5 to 3.0 "by 2030" (CCCa, 2019, page 87). This disparity between what consumers are told, and what policy experts expect, is not sustainable.

The evidence presented shows that there is concern about heat pump performance and performance forecasting in the UK and the Government has proposed increasing the *minimum* SCOP necessary for Government incentive support from 2.5 to 2.8 (Department for Business Energy & Industrial Stratergy, 2020, page 33). This focus on performance is to be welcomed, however, simply raising the minimum SCOP threshold is unlikely to have much effect unless there are parallel strategies in place to improve SPFs and improve the estimates of performance provided to consumers. As this paper shows, all the installer SCOP estimates included in this analysis were *above* 2.5 and the vast majority were 2.7 or above, yet 26% of all SPFs and more than 28% of ASHPs fell below the 2.5 benchmark.

Recommendations:

1: There is an urgent need for more research on the performance of heat pumps in retrofit situations. This should be undertaken with the specific aim of understanding the improvements needed to the thermal fabric of buildings necessary to achieve SPFs of at least 3.0. The research should accommodate the heterogeneity of UK residential demand and housing stock and should place less emphasis on 'demonstration' projects.

2: Consumers should be given coordinated advice on both heat pumps and the likely minimum levels of thermal efficiency necessary for installation. Where necessary, the UK Government and Governments in the devolved nations should offer incentive support for fabric improvements as well as support for heat pump installation. Where significant fabric improvements are necessary, installations should be supported by retrofit coordinators.

3: All stakeholders, including the Government, should stop using SCOP-based forecasts (such as those carried in the RHI deployment database) as a proxy for in-situ performance.

4: A multi-stakeholder commission should review ways to improve consumer installation proposals, heat pump installation design and installation practice. The review should make recommendations to MCS for the next review of the MIS 3005 heat pump standard. The MCS should seek to broaden the membership of its technical Working Groups to include more non-industry stakeholders.

5: In order to improve the alignment between estimates of system performance and actual SPFs, the current methodology used for UK heat pump installation performance forecasting (MIS 3005) should be replaced by BRE's Domestic Annual Heat Pump System Efficiency (DAHPSE) described in 2.3 which forecasts the performance of the whole generator system. The MCS rules on installation practice should be changed to ensure that:

- The design survey is carried out *before* contracts are agreed.
- An estimate of performance based on the design survey and the DAHPSE calculation is provided to the consumer before the contract is agreed.

7: Commentary on Limitations

Analysis of Ofgem Data

Meter readings for installations subject to *Metering for Payment* are obtained by Ofgem via manual submissions to a dedicated website on a quarterly basis. While some entries are likely to be anomalous as a result, this issue of manual reporting will be of limited significance to the integrity of the results for a number of reasons. Firstly, the submission site flags 'unlikely' readings and the data entry system prevents unit errors, meter reading errors and errors where values are entered for the wrong meter (Ofgem, 2018a)(Ofgem, 2018b). Secondly, users have strict obligations under the RHI to enter accurate information. Thirdly, the methodology used for the analysis (described in **3.1**) means that only an error in the *most recent submission* would influence the calculation and, lastly, the data cleaning would identify anomalous values.

Aside from that issue, the limitations that apply here are similar to those described by Lowe et al,. for the RHPP field trial and that apply to many field trials of domestic energy generation (Lowe *et al.*, 2017, page 7). As with the RHPP field trial, this study was not a controlled experiment. Metering problems are common in many circumstances. The data cleaning identified a significant number of 'impossible' readings which were eliminated. However, as Lowe et al., have made clear: "there should be no expectation that the monitoring of data used in the analysis must be perfect", and the same would apply to the Ofgem data.

The Heat Pump installation metering used for RHI purposes may not replicate an exact SEPEMO boundary (as described in **1.2c**). While the normal metering arrangement used by Ofgem to establish the renewable energy generated (**Appendix L**) will match the SPFH2 boundary or be close to it, some of the metering deployed in different circumstances may reflect other SEPEMO boundaries. Installation arrangements are highly variable (Lowe *et al.*, 2017) and some of the metering used for RHI purposes may not conform the H2 boundary or to the rules set out by Ofgem. Given this limitation, a direct comparison with, for example, the RHPPH2 results may not be possible. The metering arrangements described by Ofgem for Metering for Payment installations is set out in **Appendix K**.

The Ofgem data relates to a specific sub-set of RHI installations and it is impossible to know if the performance assessed in that sub-set is representative of installations under the RHI or more generally. On the other hand, the sample size is very large compared to other field trials and the results are broadly consistent with results in already published studies and guidance as described in **5.0**.

Financial Value Case
The main limitation with the financial analysis is that the model does not attempt to build in either fuel price inflation or fuel price variability. Overall, the cost of annual maintenance is similar for all boiler types (Barnes and Bhagavathy, 2020) included in the analysis and has therefore been ignored.

Carbon Analysis
The estimate of CO_2e saved when displacing fossil fuel boilers does not take into account the emissions linked to manufacture, transport and installation and is therefore *not* a life cycle analysis. Instead, the analysis seeks to calculate the CO_2e saved related to energy generation only. The calculation depends on the accuracy of the Government's GHG Conversion Factors (Department for Business Energy & Industrial Stratergy, 2019) and includes forecasts of grid carbon intensity up to 2030 (Department for Business Energy & Industrial Strategy, 2019b).

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Appendix A: A note on Terminology

The **Coefficient of Performance** (**CoP**) of a heat pump denotes the efficiency at a *specific point in time* or over a defined period of time such as a week or a month. A **CoP** value of 3 means that 1 kWh of electric energy is being used in the generation of 3kWh of heat energy.

The **Seasonal Coefficient of Performance** (**SCOP**) is a factory-based assessment of efficiency using a limited system boundary (limited to the energy used to generate the heat). **SCOP** is combined with climate data to estimate renewable energy output.

The **Seasonal Performance Factor** (**SPF**) is the measured annual efficiency of a heat pump in a specific location. It can also be estimated using factory-based tests with a range of adjustments. It is used in this paper to describe the calculated performance of the installations.
Comparisons are difficult unless the electricity inputs and heat outputs are specified. This context is the system boundary described under **1.2c**.

Appendix B: Field Trials: Hybrid Installations

The Freedom Project (Freedom Project, 2018) was a demonstration venture organised by Western Power Distribution, Wales & West Utilities and PassivSystems and involved the installation of ASHP/gas hybrid systems in 75 homes in South Wales. No changes were made to the emitters in place and no thermal improvements were made to the properties. The organisers claimed the project successfully demonstrated that hybrid systems could be deployed in a wide range of housing types without the need for thermal upgrades. The authors reported a median SPF of 3.60 and said that the heat pump performance was significantly better than that reported in monovalent heat pump trials because smart controls used in the trial ensured that the heat pumps were only used when specific SPFs were possible (Freedom Project, 2018). However, while some participants were able to make cost savings (those displacing LPG), the authors found that it was rarely cost effective for the participants to operate the heat pump. They added that, given today's gas prices, the heat pumps were only able to provide between 1 and 20% of the heat required (where heat pumps were combined with mains gas).

In 2017, a report for BEIS referred to the Greater Manchester Smart Energy Project that installed and monitored 550 heat pumps and hybrid heat pumps between December 2015 and March 2017 (Element Energy, 2017). However, although the trial monitored electricity consumption and external temperatures, the study did not record metered heat output and therefore cannot be used to estimate performance reliably. The same report also referred to five other very small field trials designed to assess hybrid heat pump performance. Taken together, those results indicate that performance ranges from 2.5 to 4.0 with a mean value of 3.1. This result includes a mix of individual homes and multiple family homes with the latter tending to have higher SPFs (Element Energy, 2017).

Appendix C: Modelling - The impact of efficiency assumptions

As introduced in **1.3** above, Barnes and Bhagavathy sought to assess the impact of taxes and levies on the economic case for heat pumps through a comparison between the lifetime cost of heat pump options to the lifetime cost of conventional heating using mains gas or electricity (Barnes and Bhagavathy, 2020). Overall, they concluded that the financial competitiveness of heat pumps is "largely dependent" on the SPF achieved (Barnes and Bhagavathy, 2020).

The authors calculated the Net Present Cost (NPC) for all technology scenarios over a system lifetime of 15 years by incorporating fuel prices and the RHI incentive into the calculation including installation costs (based on data provided to BEIS in 2017)(Element Energy, 2017).

As this paper explores in **4.2** and **5.3**, an installation that performs with a very high SPF can compete on cost with mains gas where the RHI is available. However, an installation with mediocre or poor efficiency can cost significantly more. Barnes and Bhagavathy calculated the lifetime costs of ASHPs and reported them to be generally more expensive than gas boilers. However, they found that ASHPs operating with good efficiencies could be cheaper.

Of key relevance to this discussion however, is that the heat pump efficiency calculations used by Barnes and Bhagavathy are based on the installer efficiency *forecasts* sourced from the RHI deployment database (Department for Business Energy & Industrial Strategy, 2019a). Those values are the *performance estimates* based on the SCOP metric. The historical mean in that database is 3 for ASHPs and 3.3 for GSHPs and the range is 2.5 to 4.1. As this paper will go on to discuss, the installer performance estimates do not correlate with the actual performance of heat pumps in-situ. As a consequence, lifetime costs for heat pumps shown by Barnes and Bhagavathy are likely to be significantly higher.

Flower et al,. examine how the value case for heat pumps is influenced by the diversity of UK's housing stock and residential heat demand. The authors note that marginal abatement cost (MAC) of heat pumps is very sensitive to both the heat demand and the assumptions made about the technology including the SPF chosen to represent the heat pump efficiency. The MAC is determined by calculating the additional cost of obtaining specific GHG reductions over the lifetime of the heat pump. Lower MAC values represent lower costs in achieving GHG reductions and negative MAC values show that cost savings are possible as well as GHG reductions. The UK Government has defined abatement measures as affordable when the cost is below £200/tCO_2 (Flower, Hawker and Bell, 2020).

The assumptions used by Flower et al,. for their analysis are of key importance to this discussion. Firstly, the authors note that their study is focused on the potential impact of abatement in the retrofit of older properties in which it would frequently be difficult to achieve high SPFs without additional spend on energy efficiency measures. The authors refer to the SPFs obtained in the EST trial described in section 2.1 and assumed all ASHPs operate at SPF 2.5 (ASHPs deployed in a hybrid arrangement SPF 3.1). The authors describe this assumed SPF as conservative but argue it is justified given the disappointing efficiencies reported in field trials (as cited above). Using these efficiencies, the authors found that (assuming no rebound) the retrofitted ASHPs would fail to achieve negative MAC values and would not achieve the MAC values that fall within the Governments 'cost effective' threshold.

Secondly, in order to estimate the possible impact of improved installation practice over time, Flower et al., used a sensitivity analysis based on a range of higher SPF values obtained from the deemed SPF rating of heat pumps (installer predictions) sourced from the RHI deployment database (as used by Barnes et al., described above). The MAC results remained positive even when the *maximum* performance estimates included in the database are used (4.0 for ASHPs and 4.6 for GSHPs). However, when those highest installer forecasts were used, a significant proportion of installations in the model did achieve the Government's 'cost effective' threshold of £200/tCO_2 (Flower, Hawker and Bell, 2020).

As discussed in **1.1** and **6.0**, a heat pump's performance in terms of efficiency, depends on the thermal efficiency of the building (Flower, Hawker and Bell, 2020). Broad et al,. examined the decarbonisation of UK's residential heating using models that reflect the poor energy efficiency of a large proportion of UK's housing stock (Broad, Hawker and Dodds, 2020). The authors make reference to other studies that have used national-scale modelling to identify decarbonisation pathways and, as acknowledged by Flower et al., the authors argue that these models fail to reflect the heterogeneity of residential heat demand. The authors conclude that no one model can provide a single "holistic" method for exploring heat decarbonisation. To circumvent this problem, the authors use two local-scale exemplar models to critique the results from their own system-wide modelling. The authors conclude that, in order to achieve national GHG targets, residential heating must decarbonise through replacement of natural gas with end-used electrification (at household or heat network levels) and that this is preferable to 'alternate gases' such as mains supplied hydrogen.

Within the context of this paper, however, it is important to highlight specific assumptions used. Broad et al,. apply various technology scenarios to the local-scale exemplar models and coefficients of performance are applied by time of year. The coefficients used for ASHPs are drawn from a Government report published in 2012 and are within the following range: 298% to 335% (SPF 2.98 and 3.35) depending on the building age and ratio of space heating to hot water demand. For example, new builds are assumed to have seasonal efficiencies of between 313% to 317% (SPF 3.13 and 3.17) and those with cavity wall insulation between 307% and 331% (SPF 3.07 and 3.31) (DECC, 2012).

Appendix D – DAHPSE

The Domestic Annual Heat Pump System Efficiency (DAHPSE) offers a forecast of the annual efficiency of the generator system – not just the product. This is achieved using a combination of a modified version of EN15316-4-2:2017 and EN14825 test data for individual heat pumps. The method uses a 'virtual test' using an hourly time-step approach incorporating UK dwelling variables.

The method incorporates a range of criteria not used for SCOP calculations that the developers of DAHPSE consider essential for assessing domestic heat pump performance including the plant size ratio (the design output divided by the design heat load), backup heating and operating hours. Overall, the method is based on the SEPEMO H4 system boundary.

Appendix E – The Dataset

Ofgem meters a sub-set of heat pump installations that are eligible for the domestic Renewable Heat Incentive (dRHI). Some of those installations are metered under Ofgem's Metering and Monitoring Service Package (MMSP); an Ofgem administered service that gives domestic customers access to their own system performance data (Ofgem, 2018a). It allows householders to see:

- how much electricity is used by the heat pump; and
- how much heat energy is being generated.

Installations can be subject to *metering for performance* and/or *metering for payment*. Those subject to *metering for payment* are monitored as a condition of RHI eligibility and can choose to use MMSP for the compulsory metering required (Ofgem, 2018a).

In June 2019 a request was sent to Ofgem requesting access to data obtained by Ofgem for the monitored installations described above. Ofgem determined that the data related to the efficiency of heat pumps requested was environmental information under the *Environmental Information Regulations 2004* (ICO, 2019)(Durham University, 2019). OFGEM provided a formal response to the request in September 2019. In that correspondence, it said that it could not provide the data for all heat pumps using the MMSP scheme, but it did hold the required data for all heat pumps subject to compulsory metering: those subject to 'metering for payment'.

Appendix F – Conditional Formatting

The conditional formatting analysis used identified values that were, for example, unexpectedly high, low or out of context. *Figure Appendix F*, below, illustrates the formatting method used to identify errors. Conditional formatting was also used to identify installations with multiple meters.

A1588	Accredited	Air Source H	EM1	A1588-EM1	09/03/2017	2551	kWh	HM1	A1588-HM1	09/03/2017	0	kWh	3.47
A1588	Accredited	Air Source H	EM1	A1588-EM1	09/03/2017	2551	kWh	HM1	A1588-HM1	09/03/2017	311216	kWh	3.47
A1588	Accredited	Air Source H	EM1	A1588-EM1	03/09/2017	135	kWh	HM1	A1588-HM1	03/09/2017	177	[illegible]	3.47
A1588	Accredited	Air Source H	EM1	A1588-EM1	05/12/2017	341	kWh	HM1	A1588-HM1	05/12/2017	800	[illegible]	3.47
A1588	Accredited	Air Source H	EM1	A1588-EM1	06/03/2018	1142	kWh	HM1	A1588-HM1	06/03/2018	827	kWh	3.47
A1588	Accredited	Air Source H	EM1	A1588-EM1	07/06/2018	1170	kWh	HM1	A1588-HM1	07/06/2018	3267	kWh	[illegible]
A1588	Accredited	Air Source H	EM1	A1588-EM1	05/09/2018	1211	kWh	HM1	A1588-HM1	05/09/2018	3268	kWh	3.47
A1588	Accredited	Air Source H	EM1	A1588-EM1	07/12/2018	1589	kWh	HM1	A1588-HM1	07/12/2018	4447	kWh	3.47
A1588	Accredited	Air Source H	EM1	A1588-EM1	05/03/2019	2544	kWh	HM1	A1588-HM1	05/03/2019	7316	kWh	3.47
A1588	Accredited	Air Source H	EM1	A1588-EM1	04/06/2019	2926	kWh	HM1	A1588-HM1	04/06/2019	8546	kWh	3.47
A1588	Accredited	Air Source H	EM1	A1588-EM1	16/03/2018	910	kWh	HM1	A1588-HM1	16/03/2018	2489	kWh	3.47

Figure Appendix F: Conditional formatting.

Appendix G - Methodology Regarding the Allocation of Dates

As described in **3.1**, the first consumption and generation meter reading results were subtracted from the cumulative totals for each install.

For install A1528, for example, the method used is:
Total generation: 10901 minus 2413 = 8488
Total electricity consumption: 4153 minus 932 = 3221

This is necessary because no information is available regarding when the meters were started before the first readings and/or if they were started at the same time. In most installations the readings indicate that the meters were started at about the same time and close to the first reading. By subtracting the first readings:

- the period of time up to the specific date of the first readings is eliminated; and
- only the actual period beyond that data and up to the last meter is used to measure performance.

The Ofgem readings for A1528 are shown in Table 1 (below). Table 2 (below) illustrates the effect of removing the first quarter readings.

The calculation method uses the DATEDIF formula to calculate the difference between the two dates (A and B) in Table 2: **30 months** shown in red.
30 months divided by 12 = 2.5. So the generation per year is the cumulative generation 8488 divided by 2.5 = 3395kWh

Install A1528								
Table 1		Generation	Consumption		Table 2		Generation	Consumption
10/02/2017	Q1	2413	932	A	10/02/2017	Q1	0	0
08/05/2017	Q2	3783	1408		08/05/2017	Q2	1370	476
09/08/2017	Q3	4031	1510		09/08/2017	Q3	1618	578
10/11/2017	Q4	4308	1638		10/11/2017	Q4	1895	706
10/02/2018	Q5	6008	2288		10/02/2018	Q5	3595	1356
10/05/2018	Q6	7208	2739		10/05/2018	Q6	4795	1807
11/08/2018	Q7	7209	2780		11/08/2018	Q7	4796	1848
10/11/2018	Q8	7458	2894		10/11/2018	Q8	5045	1962
10/02/2019	Q9	9370	3589		10/02/2019	Q9	6957	2657
10/05/2019	Q10	10864	4102		10/05/2019	Q10	8451	3170
10/08/2019	Q11	10901	4153	B	10/08/2019	Q11	8488	3221
					30			

Another example is given below whereby the first meter readings for consumption and generation are subtracted from the cumulative totals to give 5573kWh and 12080kWh respectively. The green highlighted figures are the final results from the analysis. The period within which the consumption and generation occurs is the period from 16/12/2016 to 09/03/2019.

A1426	Accredited	Air Source H	EM1	A1426-EM1	16/12/2016	240	kWh	HM1	A1426-HM1	16/12/2016	640	kWh	3.4	
A1426	Accredited	Air Source H	EM1	A1426-EM1	11/03/2017	684	kWh	HM1	A1426-HM1	11/03/2017	762	kWh	3.4	
A1426	Accredited	Air Source H	EM1	A1426-EM1	17/06/2017	908	kWh	HM1	A1426-HM1	17/06/2017	2223	kWh	3.4	
A1426	Accredited	Air Source H	EM1	A1426-EM1	14/09/2017	946	kWh	HM1	A1426-HM1	14/09/2017	2224	kWh	3.4	
A1426	Accredited	Air Source H	EM1	A1426-EM1	11/03/2018	2926	kWh	HM1	A1426-HM1	11/03/2018	7855	kWh	3.4	
A1426	Accredited	Air Source H	EM1	A1426-EM1	03/07/2018	4922	kWh	HM1	A1426-HM1	03/07/2018	9149	kWh	3.4	
A1426	Accredited	Air Source H	EM1	A1426-EM1	11/09/2018	4922	kWh	HM1	A1426-HM1	11/09/2018	9150	kWh	3.4	
A1426	Accredited	Air Source H	EM1	A1426-EM1	09/03/2019	5813	kWh	HM1	A1426-HM1	09/03/2019	12720	kWh	3.4	
						5573					12080		SPF	
													2.167594	
A1426	**3.4**	Air Source H	Accredited	5573	12080									Final Pivot
A1426	3.4	Air Source H	Accredited	5573	12080	2.17								Data All 3 Row

A sub-set of installations was analysed without the first meter readings being subtracted from the cumulative totals. Those specific results were compared to the corrected results:

The sub-set included 59 installations whereby all the meter readings were included in the cumulative total. **The average actual efficiency for those installs – including the first meter readings – was 2.66.** Results for those 59 installations were then corrected and **the average efficiency for those installs – excluding the first meter readings – was 2.68**. In only a small number of installations did the actual SPF increase or decrease significantly.

Appendix H – Tukey Analysis

The Tukey analysis was applied to the technologies separately (as explained in **3.1**). For Sub-Set 1: ASHP only, the outliers were identified as SPF <1.49 and >3.90 and for GSHP only, SPF <1.36 and >4.79. The Tukey defined outliers for ASHPs and GSHPs (separately) were applied to *Sub-set 1* and the sample labelled as *Sample 1 Tukey*. Nine installations were removed with very low SPFs, five ASHP installations and one GSHP were removed with high SPFs. The final *Sample 1 Tukey* included 338 installations.

The same process was carried out for *Sub-set 2* and the outliers for ASHP only, SPF <1.49 and >3.96 and for GSHP only, SPF <1.15 and >5.04. 14 installations were removed with very low SPFs, six ASHP installations and one GSHP were removed with high SPFs. The final *Sample 2 Tukey* included 260 installations. Significantly more installations were removed from *Sub-set 2* because the data available did not extend to at least one year for each installation.

Appendix I – Actual Variables Used in Carbon Mitigation Model

The actual values used in the carbon mitigation model were as follows:
The *fraction* of total heat generation allocated to the various displaced fuel types was obtained from Ofgem figures for the fuel displaced by RHI approved installations (Department for Business Energy & Industrial Stratergy, 2020c):
22% Oil, 3% LPG, 6% Coal, 13% Gas, 30% Electricity, 26% Other. The 'other' were then distributed on a proportional basis.
The carbon intensity of displaced fuels was obtained from Government's GHG conversion factor reports (Department for Business Energy & Industrial Stratergy, 2019).
The assumed efficiencies of the displaced boilers were obtained from the *MCS Heat Pump System Performance Estimate*: Oil 87%, LPG 87%, Coal 75%, Gas 87%, Electricity 100%.
The carbon intensity of the grid supply was forecast up to 2030:

2018	0.28
2019	0.25
2020	0.136
2021	0.115
2022	0.108
2023	0.111
2024	0.111
2025	0.108
2026	0.1
2027	0.105
2028	0.1
2029	0.091

(Department for Business Energy & Industrial Strategy, 2019b)(ICAX, 2020).
The assumed efficiency of the heat pumps deployed was obtained from the Ofgem Dataset analysis as explained in **4.1**.

Appendix J – Heat Pump System Performance Estimate

Heat Pump System Performance Estimate

MCS

Optional Installer Logo

Installer Project Reference	
Client	
Installation Address Line 1	
Installation Address Line 2	
Installation Address Line 3	
Installation Address Line 4	

Energy Performance Certificate (EPC) Information

Is the building existing and not proposed to be extended or reduced in size? Yes

EPC No.

Energy required to heat property	15,480	kWh
Energy required for hot water	2,144	kWh
Potential RHI energy	17,624	kWh
Energy potentially eligible for RHI (Adjusted using SCoP where applicable)	12,687	kWh

Renewable Heat Incentive (RHI) info required: Yes

RHI Funding Stream: Domestic

Fuel Information

(where possible unit rate from customer bills inc. VAT)

Date on which prices found

Existing Fuel	*Cost*
Oil (p/litre)	47.14

	Cost
Electricity (p/kWh)	16.36

New Renewable System Information

Type of System	Ground Source Heat Pump	**This calculator is not designed to be used for Solar Assisted Heat Pumps*
Manufacturer Name	Manufacturer A	
Manufacturer Model	Model ABC	
Flow Temperature	40 °C	** Determined by the temp. of the water leaving the HP when supplying space heating at the external design temp.*
MCS SCOP Heating	3.57	** SCoP - Seasonal Coefficient of Performance. This value is based on the MCS HP SCoP Table below*
MCS SCOP Hot Water	2.24	** If DHW only, this should be calculated in accordance with Clause 4.3.2 d) of MIS 3005. If providing space heating and DHW, default value from SAP2012*
Renewable Sytem Provides	Heating and Hot Water	
Hot Water Immersion Use	Once per week	** based on 50C up to 60C, 3kW*
Size of Hot Water Cylinder	150 ltr	

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Existing Heating System

Existing heating system fuel	Oil
Hot Water heated by	Oil (see note * below)
Age of existing system	Post-2007
Efficiency of existing system	92 %

*If a different source of fuel is chosen for heating & hot water system, it is always assumed the hot water system is generated via direct electricity despite there appearing to be a choice

Renewable Heat Incentive (RHI)

0 p/kWh

RHI Tariffs can be viewed here

Metering and Monitoring Service Package (MMSP)

No *RHI Uplift*

Running Costs

Existing system annual running cost	£921	
Renewable System annual running cost	£881	*Includes Immersion*
Fossil Fuel Cost in new system	£0	
Annual fuel saving	£41	
Fuel saving over 7 years	£284	

RHI per year	£0	* Note: RHI funding stops after 7 years
Total RHI	£0.00	* Please note payments are based on deemed values
Total fuel saving, RHI & MMSP over 7 years	£284.45	

CPI linkd@ 2.30% * MMSP only applicable for Domestic RHI

Government CPI reference

Capital Cost for Installation

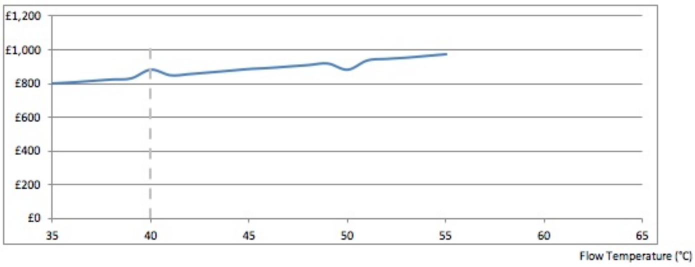
Cost for installation of new system £10,000 inc.VAT ** Breakdown of quote detail provided seperately*

Energy Requirement for the building

Energy required to heat property	15,480	kWh
Energy required for hot water	2,144	kWh

New System Running Info

Existing Annual Cost	£921	
Proposed Annual Cost	£881	
Electrical Energy consumed	5,293	kWh



Disclaimer

The performance of microgeneration heat pump systems is impossible to predict with certainty due to the variability of the climate and its subsequent effect on both heat supply and demand. This estimate is given as guidance only and should not be considered a guarantee.

Important Information: A technical variation to the specification could affect the performance of the Heat Pump System in which case the MCS Contractor MUST update and re-issue this document and advise the customer of their Consumer Rights. See CTSI

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Link to MCS Website SCoP values

Flow temperature	SCOP
35°C	4.02
36°C	3.98
37°C	3.93
38°C	3.88
39°C	3.84
40°C	3.57
41°C	3.74
42°C	3.7
43°C	3.65
44°C	3.6
45°C	3.55
46°C	3.52
47°C	3.48
48°C	3.44
49°C	3.4
50°C	3.57
51°C	3.32
52°C	3.28
53°C	3.25
54°C	3.21
55°C	3.17
56°C	0
57°C	0
58°C	0
59°C	0
60°C	0
61°C	0
62°C	0
63°C	0
64°C	0
65°C	0

SCoP Definition

SCoP = Seasonal Coefficient of Performance:

MCS SCoP is a theoretical indication of the anticipated efficiency of a heat pump aggregated over a year using standard climate data across Europe. It indicates the units of total heat energy generated (output) for each unit of energy (electricity) consumed (input). It is slightly different to ErP SCoP as it contains efficency losses due to controls and brine pumps (for a GSHP). As a guide a heat pump with a MCS SCoP of 3 generates 3 kWh of heat energy for every 1 kWh of electrical energy it consumes.

This also means that 2/3rds of the heat output could be eligible for RHI payments. MCS SCoP is based on stringent factory based tests for equipment but does not specifically include the energy consumption of heating circulating pump(s) nor does it model the transient conditions typically experienced in practice in the consumers home and hence the overall final system efficiency is likely to be different from the MCS SCoP.

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Appendix K – RHI

Figure 20 gives the likely financial outcome where an ASHP displaces an oil boiler. This Appendix provides a more detailed breakdown of value case related that scenario and the RHI in particular.

In *Figure 20*, all three scenarios include the RHI, fuel cost savings (or losses), and all other relevant variables as described in **3.3**. **Cumulative Forecast Benefit** shows the theoretical financial benefit – RHI plus any fuel cost savings - that would accrue where the installation performs according to the 'installer forecast' SCOP efficiency of 3.32. The RHI is usually 'deemed' – which means it is only payable 'renewable' portion of the heat demand: the *estimated* heat generation minus the electricity energy input. And calculated using:

$$\mathrm{RHI} = Heat\ Demand * 1 - \left(\frac{1}{SCOP}\right)$$

In *Figure 20*, the heat demand is assumed to be 17624kWh, therefore:

$$\mathrm{RHI} = 17624kWh * 1 - \left(\frac{1}{3.32}\right) = \ 12319kWh$$

That renewable portion is then multiplied by the RHI tariff (10.85pence/kWh) to give an annual income of £1336.

The **Actual Benefit (Deemed RHI)** is the financial result where the RHI is calculated using the installer forecast, but the installation *actually performs* with an SPF of 2.72. Under this scenario, the RHI will still be £1336, but any fuel savings will be less. In this case, the cost of electricity with an SPF of 2.72 works out significantly more expensive than the cost oil:

Oil = 47.14pence/litre = 4.81pence/kWh (assuming 9.8kWh/litre)

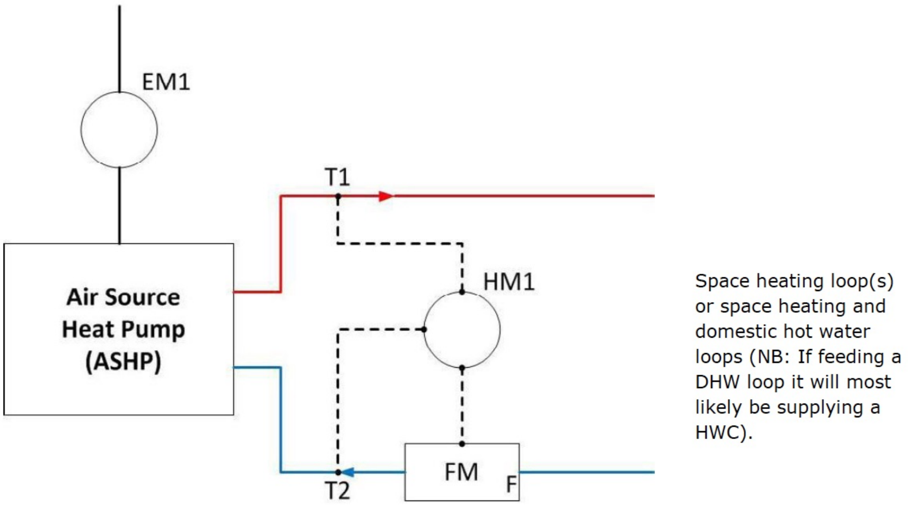
As the electricity cost is 16.36pence/kWh, the SPF must be 3.40 or better before savings can be made when oil is 4.81pence/kWh: (16.36 ÷ 4.81=3.40)

The **Actual Benefit (Using Actual SPF)** is the financial outcome when the RHI is metered. In these cases, the RHI is paid only for the metered renewable portion of the generation: the *actual* heat generation minus the electricity energy input (Ofgem, 2018a).

Assuming the actual SPF is 2.72, the renewable metered generated heat would be 11145kWh compared to 12319kWh where the RHI is calculated using the SCOP of 3.32 (as above). When the renewable heat is calculated using the SPF of 2.72, the RHI works out as £1209 instead of £1336.

Appendix L: The Ofgem Dataset Boundary

The standard arrangement for metering described by Ofgem for Metering for Payment installations is shown in the schematic below. A large a majority of installations in the dataset had one heat meter and one electricity meter as described.



NOTE: The pipes may diverge after they exit the ASHP to feed one (or multiple) space heating loops or a combination of space heating and domestic hot water heating loops. A minimum of one electricity meter is required to measure the input electricity required to run the heat pump compressor and any other electrical input (eg for hot water boosting, evaporator fans etc) that has gone into the generated heat output. Potentially more than one electricity meter may be required.

T1 = Temperature Sensor Flow Pipe

T2 = Temperature Sensor Return Pipe

FM = Flow Meter

HM = Heat Meter Digital Calculator

EM = Electricity Meter

Metering Payment Formulae

Renewable Heat Payment = Tariff rate x (HM1 - EM1)