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# Meta-analysis of European heat pump field trial efficiencies

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ABSTRACT

A meta-analysis of seasonal performance for ground to water and air to water heat pumps based on eight European trials for over 600 installations from five countries provides thirteen different descriptors of performance. Seven of these trials have previously been publish but no overview of their results has been attempted in terms of system boundary analysis. Trial boundaries are rationalised to four values of seasonal performance providing the opportunity to reassess the UK EST heat pump trial results and identify two boundary conditions directly relevant to the interpretation of the Renewable Energy Sources Directive. What is apparent is the wide range in performance at all boundaries and in all trials indicating that heat pumps are sensitive to design and installation practice. The overarching theme of the paper is the need for a unified framework for reporting heat pump performance and its applicability to the re-analysis of existing data. The task of building such a framework has proved beyond the present author, but the work presented here represents an attempt to scope the potential value and combination of analytical and practical difficulties that would need to be faced by those undertaking such a task.


## 1. Introduction: heat pumps and the low carbon agenda

With some 40% end-use carbon dioxide emissions attributable to buildings, the EU 20/20/20 targets [1] are particularly relevant to the heat pump sector. To achieve the "nearly zero emissions" requirements for all new and retrofitted buildings, the Energy Performance of Buildings Directive (EPBD) [2] specifically refers to heat pumps as among "high-efficiency alternative systems" whilst the Renewable Energy Sources Directive (RES) [3] focuses on the annual efficiency, or the seasonal performance factor (SPF), of heat pumps.

For the purposes of the RES Annex VII: "Only heat pumps for which SPF > $1.5 \times 1/\eta$ shall be taken into account, where $\eta$ is the ratio between total gross production of electricity and the primary energy consumption for electricity production and shall be calculated as an EU average based on Eurostat data." Currently the EU ratio of primary to delivered energy for electricity is approximately 0.4 [4]. Under these circumstances, for heat pumps to begin to produce renewable heat, they will require a minimum SPF of greater than 2.88.

However, there is, as yet, no definition of 'as installed' SPF and whether this includes just the heat pump and its seasonal efficiency in converting source energy and compressor electricity to heat, the heat pump and any system circulation pumps required for heat transfer to emitters or the heat pump and any backup heating required during annual performance – quite clearly different things. The use of backup heating will depend on whether the heat pump has been sized for maximum winter space heating load and any domestic hot water (DHW) boosting. Many heat pumps include an electric resistance heater controlled to automatically provide backup heat and DHW pasteurisation as necessary. The RES states that the Commission will establish guidelines on how Member States are to estimate the "value" of SPF and the associated renewable heat values for the different heat pump technologies and applications. This paper reviews historic European practice for assessing SPF, the values obtained at various boundary conditions in heat pump field trials and discusses their relevance to the RES (Table 1).

### 1.1. COP, SPF and trial comparisons

Heat pump coefficient of performance (COP) is a laboratory test based on EN 14511 [5] at steady flow conditions for a set temperature of source and sink and where the heat pump is loaded until it reaches the manufacturer's maximum output. Measured inputs consist of compressor energy and the circulation pump/fan requirements to overcome the frictional resistance of the evaporator and condenser at that output. When testing at low source temperature,

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**Table 1**
Nomenclature adapted from SEPEMO.

| COP | Heat pump coefficient of performance | Dimensionless |
|---|---|---|
| $SPF_H$ | Heat pump seasonal performance factor for heating | Dimensionless |
| SEPEMO | $SPF_{H1} = \frac{QH_{hp}+QW_{hp}}{EHW_{hp}}$ | Dimensionless |
| SEPEMO | $SPF_{H2} = \frac{QH\_hp+QW\_hp}{ES\_fan/pump+EHW\_hp}$ | Dimensionless |
| SEPEMO | $SPH_{H3} = \frac{QH\_hp+QW\_hp+QHW\_bu}{ES\_fan/pump+EHW\_hp+EHW\_bhu}$ | Dimensionless |
| SEPEMO | $SPH_{H4} = \frac{QH\_hp+QW\_hp+QHW\_bu}{ES\_fan/pump+EHW\_hp+EHW\_bhu+EB\_pump}$ | Dimensionless |
| JAZ | $JAZ1 = \frac{QH\_hp+QW\_hp+Qbt\_pump}{ES\_fan/pump+EHW\_hp+Ebt\_pump}$ | Dimensionless |
| JAZ | $JAZ2 = \frac{QH\_bt+QW\_hp}{ES\_fan/pump+EHW\_hp+Ebt\_pump}$ | Dimensionless |
| JAZ | $JAZ3 = \frac{QH\_bt+QW\_hp+QHW\_bu+Qsh\_pump}{ES\_fan/pump+EHW\_hp+Ebt\_pump+Esh\_pump}$ | Dimensionless |
| JAZ | $JAZ4 = \frac{QH_{bt}+QW_{hp}+QHW_{bu}+Qsh_{pump}}{ES\_fan/pump+EHWhp+EB\_pump}$ | Dimensionless |
| SPTRI | $SPFps = \frac{QH\_hp+QW\_hp+QB\_pump}{ES\_fan/pump+EHWhp+EB\_pump}$ | Dimensionless |
| SPTRI | $SPFhs = \frac{QH\_hp+QW\_hp+QB\_pump+QB\_bu}{ES\_fan/pump+EHWhp+EB\_pump+EHW\_bu}$ | Dimensionless |
| EST | $System\ efficiency = \frac{QH\_hp+Qdhw\_tap+QB\_pump+QHW\_bu}{ES\_fan/pump+EHW\_hp+EB\_pump+EHW\_bu}$ | Dimensionless |
| EST | System Efficiency may be described as $SPF_{H5}$ | Dimensionless |
| QH_hp | Quantity of heat of the heat pump in space heating (SH) operation | Wh or kWh |
| QW_hp | Quantity of heat of the heat pump in domestic hot water (DHW) operation | Wh or kWh |
| QHW_bu | Quantity of heat of the back-up heater for SH and DHW | Wh or kWh |
| QH_bt | Quantity of heat from the SH buffer | Wh or kWh |
| Qsh_pump | Quantity of useful heat from the SH pump downstream of the buffer tank | Wh or kWh |
| Qdhw_tap | Quantity of heat in DHW draw off (tapped hot water) | Wh or kWh |
| ES_fan/pump | Electrical energy use of the HP source: fan or brine/well pump | Wh or kWh |
| EB_pump | Electrical energy use of the heat sink (building) pumps for DHW and SH | Wh or kWh |
| EHW_hp | Electrical energy use of the heat pump for SH and DHW | Wh or kWh |
| EHW_bu | Energy use of back-up heater(s) for SH and DHW | Wh or kWh |
| Esh_pump | Electrical energy use of the header circuit pump | Wh or kWh |
| Esh_pump | Electrical energy use of the SH pump downstream of the buffer tank | Wh or kWh |

the input includes a defrost cycle should one or more occur during a test equilibrium or measurement period. The COP is not comparable to the annual operating conditions experienced in a real installation with its start/stop running conditions, variable source and sink temperatures and load, the full energy demand for system fans and circulation pumps plus electrical resistance backup where it is needed to meet all system requirements; thus its seasonal performance factor (SPF).

EN 15316-4-2 [6] defines SPF as: "the ratio of the total annual energy delivered to the distribution subsystem for space heating and/or domestic hot water to the total annual input of driving energy . . .. plus the total annual input of auxiliary energy." It identifies the system boundary of "the heat pump generation subsystem" at these "distribution subsystems" as the heat flow to the space heating system and the heat flow in the tapped domestic hot water. As the recognised existing standard, it has been applied to testing multifunctional heat pump systems by the International Energy Agency, see for example, Wemhoener et al. [7].

However, field trial reports have been presented with no specific reference to EN 15316-4-2 and usually in isolation, without comparisons drawn between other trials and their boundary protocols. Studies that have focused on an overview of these various trial reports, a meta-analysis, have presented the results as either COP or SPF and, whilst recognising the impact of backup heaters and circulation pumps, have generally not compared them against a set of clear boundary definitions. Staffell [8] provides a review of published trial efficiencies ranging from those for over 40 ground source installations through to individual units as well as heating season-only trials. These are presented with results quoted as either COP or SPF where COP values, "do not take into account any additional energy used on the backup heater" and where SPF is described as: "including any energy required and produced by the backup immersion heater". Colbourne's review [9] of performance of electric heat pumps includes Staffell's work and adds a large trial by the Swiss Federal Office of Energy, as well as smaller studies from Austria, Sweden and France. Colbourne specifically refers to the impact of backup heaters in lowering seasonal efficiency whilst describing all results as SPF. Colbourne's work provides the air source heat pump efficiency data for Johnson's HFC impact study [10] where SPF is defined as: "heat delivered/electrical energy input".

The first report to comment on the difference in boundary conditions between European trials is from Delta Energy and Environment in 2010 [11]. Focusing on the UK Energy Saving Trust trials between 2008 and 2010, it compares the results to those of the Fraunhofer Institute and the Swiss Federal Office of Energy. Delta comment: "Throughout the paper we refer to Seasonal Performance Factor (SPF) – effectively the average COP (co-efficient of performance) measured throughout the trial period. Note that due to differences in methodology between trials, the results are not completely comparable – due to the wider system boundary used in the EST trial, the UK results are likely to be lower (possibly by a SPF of around 0.1) than the other trials."

Other published comments on the EST trials include: "relatively poor results from UK installations compared to European experience", and "heat pump performance in the UK is on average worse than in continental Europe", Boait et al. [12]. In the same vein: "evidence is emerging that heat pumps may be underperforming in the UK compared with other European countries", Stafford and Lilley [13], and, "In particular, issues relating to the consistent definition of system boundaries are likely to prove difficult to resolve." [14].

What is apparent from cross-European studies is the need to compare performance against a consistent boundary analysis. Provided that the implications of boundary identification are recognised, existing data should enable the assessment of the current mean for ground and air source heat pump installations and, importantly, the range of performance experienced in these trials. This requires an investigation into boundary conventions and assessment of appropriate boundary conditions to represent heat pump performance.

## 2. System boundaries

European field trials can be broadly classified into two main boundary schemas based the German *Jahresarbeitzahlen* (JAZ) model, effectively in English, "seasonal performance factor" and the recent European model developed by SEPEMO-Build for seasonal performance factor classifications.

### 2.1. Jahresarbeitzahlen

Baumgartner et al. [15] provide a block diagram, later adapted by Wemhoner (Fig. 1), representing three efficiency boundaries with the JAZ monovalent boundary *WPA-Wärmepumpenanlage* "heat pump system", comprising the source, the heat pump, circulation pump for the hydraulic header circuit and a buffer vessel, historically considered a necessary component for efficient heat pump operation. JAZ is measured at this boundary as the ratio of heat energy out (therefore minus any buffer vessel losses) to

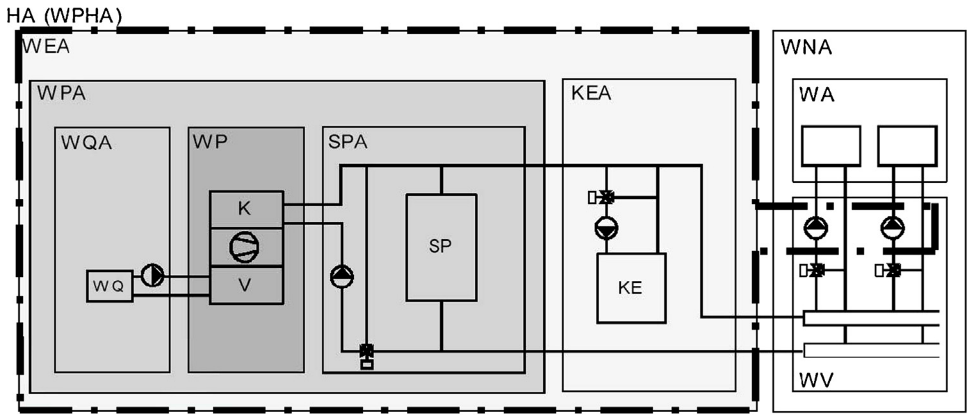


**Fig. 1.** IEA Annex 28 JAZ definition ([16] – after Baumgartner et al. [15]).

electrical energy in. Bivalent systems, again historically a boiler system, provide the next boundary. Finally, the inclusion of the space heating system and its circulation pumps provides a total system analysis. Wemhoner and Afjai [16] take this analysis and provide a JAZ boundary definition for IEA Annex 28 which includes all system circulation pumps, effectively including all energy inputs and outputs.

The current German standard for assessing heat pump performance, VDI 4650 [17], is the latest iteration in Jahresarbeitzahlen methodologies. A typical graphical depiction of Jahresarbeitzahlen is shown in Fig. 2 where four separate JAZ boundaries have been defined which clearly relate to the Baumgartner/Wemhoner boundaries and where the higher index numbers indicate more components, greater complexity and progressively lower SPF efficiencies for the same heat pump installation.

JAZ 1: *Erzeuger JAZ* or "after the heat pump" with source fans or pumps, controls and compressor plus what could be described as a header pumps – the circulation pump(s) to the distribution header feeding a buffer vessel and hot water cylinder.

JAZ 2: *System JAZ* or JAZ 1 plus space heating buffer storage losses, Baumgartner's JAZ.

JAZ 3: *Anlagen JAZ* or "installation", comprising JAZ 2 plus any backup/boost heating and the space heating circulation pump; therefore Wemhoner's IEA Annex 28 definition.

JAZ 4: JAZ 2, minus the circulation pump. JAZ 4 may be applied where comparison is made with conventional boiler performance. Since the energy demand for space heating circulation pumps depends on system size factors such as volume flow and resistance, this is excluded in any comparison of heat source efficiency.

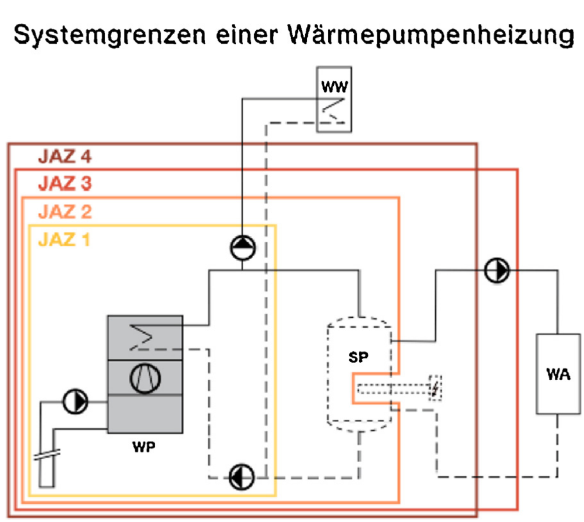


**Fig. 2.** Jahresarbeitzahlen boundaries [18].

Where there is a single circulating pump or no buffer vessel, only the energy fraction used to circulate primary water to the domestic hot water cylinder should be included in JAZ 1 and JAZ 2 making monitoring programmes more complicated to set up. Similarly, it is apparent that header pump energy is dependent on circuit mass flow rate and resistance through the pipework and valves, condenser, buffer vessel and hot water storage cylinder, all functions of the individual installation and not of the heat pump itself. Jahresarbeitzahlen boundaries are reported for two field trials, the largest European trial from FAWA, Switzerland and a Local Agenda 21 programme from Lahr in Germany.

### 2.2. FAWA, Switzerland

The Swiss Federal Office of Energy report [19] on their *Feldanalyse von Wärmepumpenanlagen* project "Field Analysis of Heat Pump Installations" or FAWA, is based on field trial data collated between 1995 and 2004 for 221 heat pumps at the JAZ 2 boundary. Some 50% of the installations included domestic hot water with 22% relying on the heat pump only. The trials cover both new build and existing housing with some 60% new and 40% of what is described as "*Sanierungsobjekten*" or renovation projects. The range of building heat loss is from 28 to 208 kWh/m$^2$ pa with a mean of 75 kWh/m$^2$ pa due to the dominance of new build and low energy refurbishment. FAWA combine the data for both new and existing housing, with and without domestic hot water, to present a single JAZ 2 value (Table 2).

### 2.3. Lahr, Germany

The Lahr trial in the Black Forest region of Germany, undertaken through the Local Agenda 21 programme, collected data on 32 heat pumps including 12 air source, 7 water source and 13 ground source; the results published on a dedicated website, http://www.agenda-energie-lahr.de. The report write-up [20] provides results for "*Erzeuger JAZ*", JAZ 1, and "*System JAZ*", JAZ 2 (Table 3).

## 3. SPTRI, Sweden 2007

Early Swedish trials from 2007 by SP Technical Research Institute [21] provide a model with two boundaries, SPFhps and SPFhs. SPFhps refers to the seasonal efficiency of the heat pump system, the source pump and central heating sink pump at boundary A (Fig. 3). SPFhs is the seasonal efficiency of the whole heating

**Table 2**
FAWA JAZ 2 mean and range.

| Ground source heat pumps | Mean | Range | Air source heat pumps | Mean | Range |
|---|---|---|---|---|---|
| JAZ 2 | 3.4 | 2.3–5.3 | JAZ 2 | 2.6 | 1.5–4.0 |

**Table 3**
Lahr Agenda 21 heat pump trial results.

| LAHR | | No. | JAZ 1 | JAZ 2 | JAZ 2 All | | JAZ 2 All | |
|---|---|---|---|---|---|---|---|---|
| | | | Mean | Range | Mean | Range | Mean | Range |
| ASHP | Underfloor | 7 | 2.8 | 2.3–3.2 | 2.4 | 1.9–2.8 | 2.3 | 1.7–3.0 |
| | Radiators | 5 | 2.4 | 1.9–2.8 | 2.2 | 1.7–2.6 | | |
| GSHP | Underfloor | 11 | 3.4 | 2.0–4.4 | 3.1 | 2.3–4.2 | 3.1 | 2.3–4.2 |
| | Radiators | 2 | | | | | | |
| WSHP | Underfloor | 6 | 3.2 | 2.0–4.2 | 2.9 | – | 2.9 | – |
| | Radiators | 1 | | | | | | |

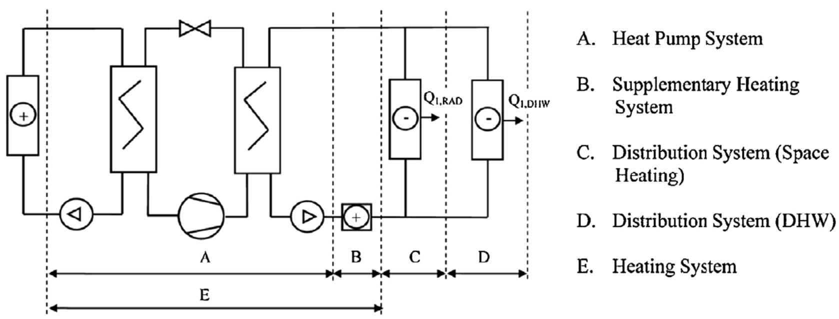


**Fig. 3.** SPTRI GSHP boundary definition [21].

**Table 4**
SPTRI GSHP trial results [21].

| GSHP | Mean | Range |
|---|---|---|
| SPFhps | 2.9 | 2.5–3.1 |
| SPFhs | 2.6 | 2.4–2.9 |

**Table 5**
EST field trial system efficiencies [24].

| System efficiency | Ground source | Air source |
|---|---|---|
| Number | 49 | 22 |
| Average | 2.39 | 1.82 |
| Range | 1.55–3.37 | 1.2–2.2 |

system including any backup heating at boundary E. The trial results are for 5 ground source heat pumps only (Table 4).

The Association of Austrian Electricity Companies funded Arsenal Research to develop, test and evaluate a “standardised monitoring methodology” for heat pump systems [22]. The resulting SPF is the ratio of heat energy out (heat sink) to energy in (compressor, source and sink circulation pumps), the same SPFhps boundary defined by SPTRI (Fig. 4). Unfortunately published results are for direct expansion ground loops only and thus not directly comparable with brine filled ground source heat exchangers or air source heat pumps.

## 4. UK EST Trials

The UK Energy Savings Trust [23] has uniquely applied the concept of “System Efficiency”, with the inclusion of hot water draw off within the overall SPF heating system boundary. The UK Department of Energy and Climate Change (DECC) have published an

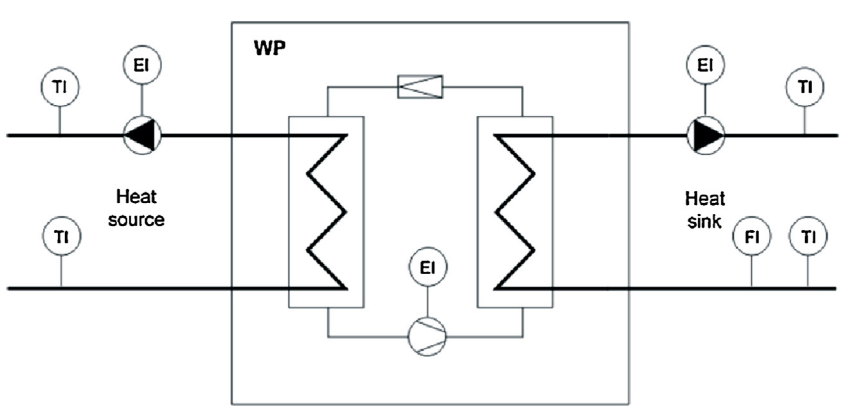


**Fig. 4.** Arsenal research standardised monitoring methodology [22].

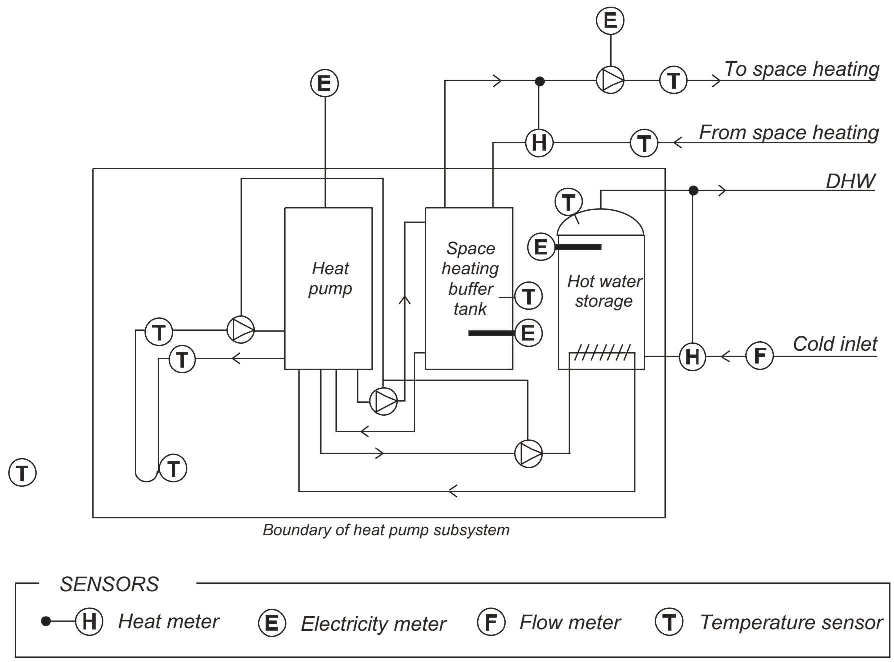


**Fig. 5.** System efficiency [24].

updated report on the EST trial [24], which includes a both a boundary image (Fig. 5), and updated results for 71 installations (Table 5).

Whilst the Fig. 5 boundary from DECC excludes the space heating circulation pump, this pump was included as an energy input in published results. There are advantages and disadvantages to measuring hot water draw off when comparing the efficiency of regular boilers to combination boilers or instantaneous water heaters. However, the heat pump is heating a hot water cylinder and cylinder heat loss is dependent primarily on volume of storage, insulation, temperature difference between stored water and ambient and the rate of hot water use, none of which are related to the efficiency of the heat pump. Where hot water is heated but not used, cylinder losses are included in the denominator whether useful or not. The EST condensing boiler trials [25] included draw off within the system boundary and, it is assumed that in accordance with this historical precedent, the EST heat pump trials also included draw off. The EST approach to heat pump monitoring, using "System efficiency", has raised some concerns regarding comparability with other heat pump trials although there was at the time no internationally agreed trial methodology. However, the "System efficiency" approach is in the spirit of EN 15316-4-2 and therefore has much to recommend it.

## 5. SEPEMO boundaries

The profusion of monitoring methodologies and the confusion over appropriate boundary setting is the subject of the European Union Intelligent Energy Europe research project: "SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector" (SEPEMO-Build) [26]. The earliest published report specifically aimed at considering field trial system boundaries from a common European approach was published in 2010 by SP Technical Research Institute, Sweden (SPTRI) [27], the lead partner for SEPEMO. The SEPEMO project published a detailed analysis in 2011 [28] providing four boundary definitions and their equations. The SEPEMO methodology consists of the heat pump only ($SPF_{H1}$), with expanding boundaries covering fan or pump power into the heat pump ($SPF_{H2}$), back up heaters ($SPF_{H3}$) and finally, system circulators or pumps ($SPF_{H4}$) and is shown in Fig. 6. Note again the relationship between the higher index number and lower SPF efficiency for the same installation. Extending the SEPEMO boundary approach, the inclusion by the EST of tapped hot water, "System efficiency", rather than heat into the hot water cylinder, could be defined as $SPF_{H5}$.

$SPF_{H1}$ is entirely theoretical since there is no means to drive heat into or out of the heat pump, therefore, practical measurements must take place at any of the boundaries defined as $SPF_{H2}$, $SPF_{H3}$ or $SPF_{H4}$. SEPEMO boundaries have been applied to field trials by the Fraunhofer Institute in Germany, the Danish Technology Institute (DTI) and SPTRI Sweden. The boundary definitions for the Fraunhofer and DTI trials differ from those of SEPEMO only by boundary numbering. Where SEPEMO define the heat pump alone as $SPF_{H1}$, Fraunhofer and DTI describe this as SPF 0, the expanding boundaries therefore differ by 1. Fraunhofer results are generally quoted for SPF 2 ($SPF_{H3}$), whereas DTI publish only SPF 3 ($SPF_{H4}$).

### 5.1. SPTRI Sweden 2010

The SPTRI 2010 [27] report on seven ground source heat pumps is important due to its direct link to the SEPEMO director, Nordman, and its use of the SEPEMO boundary methodology; results are given for $SPF_{H1}$ and $SPF_{H3}$ (Table 6).

$SPF_{H1}$ shows the impact of sink temperature is reflected in the drop in efficiency of 18% between heating only and heating and DHW. An $SPF_{H3}$ drop in efficiency of 23% is associated with the inclusion of DHW.

**Table 6**
SPI Sweden GSHP SPF.

| SPTRI 2010 GSHP | Heating and DHW $SPF_{H1}$ | Heating and DHW $SPF_{H3}$ | Heating only $SPF_{H1}$ | Heating only $SPF_{H3}$ |
|---|---|---|---|---|
| Mean | 3.7 | 3.26 | 4.6 | 4.2 |
| Range | 2.7–4.1 | 2.6–3.6 | 3.9–5.4 | 3.4–5.1 |

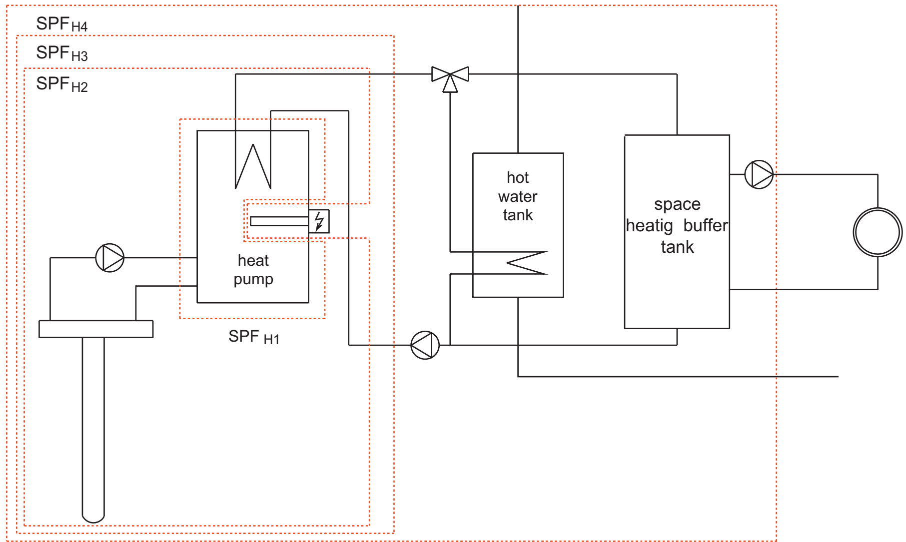


**Fig. 6.** SEPEMO system boundaries [28].

**Table 7**
Fraunhofer existing buildings mean SPF.

| GSHP | Mean | Range | ASHP | Mean | Range |
|---|---|---|---|---|---|
| $SPF_{H3}$ | 3.3 | 2.2–4.8 | $SPF_{H3}$ | 2.6 | 2.1–3.4 |

### 5.2. *Fraunhofer existing buildings trial*

The Fraunhofer Institute report [29] on 72 heat pump systems in existing buildings, "*Gebaeudebestand*", all with domestic hot water (Table 7). The trial investigates 36 ground, 34 air and 2 water source heat pumps. These are further subdivided into 10 ground collector (ground loop) and 26 borehole, 21 air source and 13 exhaust air source. The house sizes range from 90 to 360 $m^2$ with a mean of 181 $m^2$. The range of heat losses are from 85 to 340 kWh/$m^2$ pa.

### 5.3. *Fraunhofer new buildings trial*

The Fraunhofer Institute report [30,31] on field trials in new buildings for space heating and domestic hot water, carried out between 2005 and 2010, on 110 heat pumps with a final report on 56 ground to water, 18 air to water and 3 water to water. Underfloor heating was installed in all installations but one and weather compensation was used throughout. Applying SEPEMO definitions, results are published for mean performance at $SPF_{H1}$, $SPF_{H2}$, $SPF_{H3}$ and $SPF_{H4}$, with the means referred to by Delta at SPF 2 or SEPEMO $SPF_{H3}$. Fraunhofer 'new build' results at $SPF_{H3}$ are 3.9 for ground source and 2.9 for air source (Table 8).

Comparing Fraunhofer ground and air source from the "existing" buildings to those of the "new" provides means in existing buildings of 3.3 and 2.6, compared to the values for new build at 3.9 and 2.9, a percentage reduction of 10 and 13% respectively; a result partially explained by the use of radiators for 71% of the existing building heating systems.

**Table 8**
Fraunhofer new build mean SPF.

| GSHP | Mean | Range | ASHP | Mean | Range |
|---|---|---|---|---|---|
| $SPF_{H1}$ | 4.19 | | $SPF_{H1}$ | 3.17 | |
| $SPF_{H2}$ | 3.93 | | $SPF_{H2}$ | 2.95 | |
| $SPF_{H3}$ | 3.88 | 3.1–5.1 | $SPF_{H3}$ | 2.89 | 2.3–3.4 |
| $SPF_{H4}$ | 3.75 | | $SPF_{H4}$ | 2.74 | |

### 5.4. *Danish Technological Institute*

The Danish Technological Institute (DTI) report [32] on 170 field trials monitored between the period May 2010 and July 2011 on both new and existing dwellings. The final results included 138 ground and 12 air source, some 20 heat pumps being excluded from the final report due to, "data reliability and their analysis", including the exclusion of heat pumps whose "COP" exceed 5.5 (4 units) or fell below 1.5 (8 units). The trial results are based on the Fraunhofer SPF designations and given for SPF 3 ($SPF_{H4}$), that is, a boundary including backup heater and circulation pump. As would be expected from the sample size, the data for the ground source heat pumps is instructive, with a 17% reduction in SPF between radiators and underfloor. Whilst less instructive, the air source data provides a similar pattern relating SPF to emitter type (Table 9). Importantly, the DTI data provides a difference in SPF between air and ground source heat pumps operating on mixed emitters of 23%. Weighted averages for all emitters provide means of 3.03 and 2.33 with ranges of 3.1–5.1 and 2.3–3.4 for ground and air source respectively (Table 9).

## 6. Analysis of reported boundary conditions

Thirteen boundary descriptors are met in eight heat pump trials lasting for a minimum of one year and consisting of over 600 heat pump installations. The review of these methodologies indicates that seven of these boundaries are unique: JAZ 1, JAZ 2, SPFhps, $SPF_{H1}$, $SPF_{H2}$, $SPF_{H3}$, $SPF_{H4}$ and $SPF_{H5}$ with six descriptors being redundant. The highest practical SPF is achieved by $SPF_{H2}$ followed by JAZ 1, the inclusion of the header circulation pump. JAZ 2 takes into account both the header pump and any losses from any buffer vessel should one be installed. $SPF_{H3}$ includes only the backup heater and not the sink pump. SPFhps includes the total energy demand of the sink circulation pump, whereas JAZ 3, SPFhs and $SPF_{H4}$ are identical and include both integrated backup heating

**Table 9**
DTI $SPF_{H4}$ for radiators, mixed radiators and underfloor, underfloor.

| GSHP | Mean | Range | ASHP | Mean | Range |
|---|---|---|---|---|---|
| $SPF_{H4}$ Radiators | 2.72 | | $SPF_{H4}$ Radiators | 2.14 | |
| $SPF_{H4}$ Underfloor | 3.04 | | $SPF_{H4}$ Underfloor | 2.34 | |
| $SPF_{H4}$ Mixed | 3.27 | | $SPF_{H4}$ Mixed | 2.87 | |
| $SPF_{H4}$ All | 3.03 | 3.1–5.1 | $SPF_{H4}$ All | 2.33 | 2.3–3.4 |

**Table 10**
Trial boundary analysis.

| Boundary | FAWA | Lahr | SPTRI 2007 | SPTRI 2010 | EST | Fraunhofer existing | Fraunhofer new | DTI |
|---|---|---|---|---|---|---|---|---|
| JAZ 1 | | √ | | | | | | |
| JAZ 2 | √ | √ | | | | | | |
| SPFhps | | | √ | | | | | |
| SPF 0/$_{H1}$ | | | | √ | | | √ | |
| SPF 1/$_{H2}$ | | | | | | | √ | |
| SPF 2/$_{H3}$ | | | | √ | | √ | √ | |
| SPFhs/SPF 3/$_{H4}$ | | | √ | | | | √ | √ |
| System Efficiency/$SPF_{H5}$ | | | | | √ | | | |

and all circulation pumps. Finally, "system efficiency" provides the resulting $SPF_{H5}$ for all loads including domestic hot water cylinder losses.

Arguments may be made for the exclusion of backup heaters where installation issues such as undersizing of the heat pump or poor heat distribution, neither of which are directly associated with heat pump efficiency, will require additional heating. However, it should be considered legitimate to include the backup required for heat pumps incapable of reaching domestic hot water pasteurisation temperatures, a situation exemplified by most domestic HFC-based units. The inclusion of hot water cylinder losses is an extension of the logic that includes buffer vessel losses and is entirely dependent on size, insulation and demand. To compare a heat pump driven wet central heating system to, for example, electric storage heaters or warm air heating, JAZ 3 or $SPF_{H4}$ is the logical choice since these boundaries capture all system energy inputs including the circulation pump to the space heating.

The bulk of the data is from five trials: FAWA, EST, Fraunhofer 'new' and 'existing' and the DTI. Since the boundaries used by the Fraunhofer Institute, the Danish Technical Institute and SPTRI 2010 are identical they may all be renamed using SEPEMO terminology. SPFhs is identical to $SPF_{H4}$, that is, all system electrical inputs. The boundaries applied to the different trials are shown in Table 10, the total number of installations in Table 11 where all SEPEMO-based boundaries comply with SEPEMO nomenclature.

### 6.1. Further boundary compression

For a meta-analysis of heat pump performance we may wish to re-analyse the significant work of FAWA, Lahr or the EST in SEPEMO terms, or, for example, to recalculate DTI results from $SPF_{H4}$ to $SPF_{H3}$, in order to compare all data in the same boundary category. Even if we assume 100% heat transfer into the system from header pumps, buffer vessels, backup and circulation pumps, there is no mathematical approach that will separately identify these impacts from the reported arithmetic mean efficiencies since each additional input introduces an unknown quantity of heat into the efficiency equations. In reality these electrical inputs will not provide 100% useful heat transfer and the resulting equations introduce yet more unknowns. Some grasp of the challenge may be apparent from the equations representing Fraunhofer New [31] and Lahr [20] GSHP trials, Eqs. (1) and (2). $SPF_{H2}$ differs from JAZ1 solely due to the header circuit pump. This pump consumes an unknown quantity of electricity, Ebt_pump, and transfers an unknown fraction of the electricity as heat to the installation water, Qbt_pump. Similarly, QH_bt, the useful output from the buffer vessel is an unknown fraction of QH_hp, the heat energy entering the buffer vessel. Without access to the trial raw data, it is not mathematically possible to transpose trial arithmetic means in order to recalibrate between trial results either in JAZ or SPF units; of necessity, a qualitative approach would be required.

**Comparison of SPF means**

$$
\begin{aligned}
SPF_{H2} &= \frac{QH\_hp + QW\_hp}{ES\_fan/pump + EHW\_hp} = 3.93 \\
SPF_{H3} &= \frac{QH\_hp + QW\_hp + QHW\_bu}{ES\_fan/pump + EHW\_hp + EHW\_bu} = 3.88 \\
SPF_{H4} &= \frac{QH\_hp + QW\_hp + QHW\_bu}{ES\_fan/pump + EHW\_hp + EHW\_bu + EB\_pump} = 3.75
\end{aligned}
\tag{1}
$$

**Comparison of JAZ means**

$$
\begin{aligned}
JAZ1 &= \frac{QH\_hp + QW\_hp + Qbt\_pump}{ES\_fan/pump + EHW\_hp + Ebt\_pump} = 3.4 \\
JAZ2 &= \frac{QH\_bt + QW\_hp}{ES\_fan/pump + EHW\_hp + Ebt\_pump} = 3.1
\end{aligned}
\tag{2}
$$

### 6.2. EST re-analysis

The EST trial results have caused some consternation in the UK where this field trial has provided evidence, for some observers, of poor 'as-installed' heat pump performance. However, the trial was carried out to assess the state of heat pump installation in the UK and, positively, has proven to be the catalyst for critical reflection on installation practice and the production of extensive guidance through the Microgeneration Certification Scheme heat pump design guide MIS 3005 [33] and other supporting documents.

Due to data logger/meter location, the some of the trial raw data can provide SEPEMO or SPFhps related outputs. Differentiating between boundaries requires, in some instances, allowances for integrated central heating pumps and hot water cylinder heat losses. Most of the heat pumps used in the EST trials had integrated circulation pumps and would therefore most closely emulate either

**Table 11**
Total numbers of heat pump at the various boundaries.

| TRIAL | No. | JAZ1 | JAZ2 | SPFhps | $SPF_{H1}$ | $SPF_{H2}$ | $SPF_{H3}$ | $SPF_{H4}$ | DHW |
|---|---|---|---|---|---|---|---|---|---|
| FAWA | 221 | | 221 | | | | | | 50% |
| Fraunhofer new | 74 | | | | 74 | 74 | 74 | 74 | 100% |
| Fraunhofer existing | 70 | | | | | | 70 | | 100% |
| DTI | 150 | | | | | | | 150 | 100% |
| LAHR | 25 | 25 | 25 | | | | | | Unknown |
| SPTRI 2007 | 5 | | | 5 | | | | 5 | 100% |
| SPTRI 2010 | 6 | | | | 6 | | 6 | | 86% |
| EST | 71 | | | | | | | | 77% |
| Total | 622 | 25 | 246 | 5 | 80 | 74 | 150 | 229 | |

**Table 12**
EST GSHP field trial.

| GSHP | No. | Mean | Range |
|---|---|---|---|
| $SPF_{H2}$ | 9 | 2.6 | 1.9–3.3 |
| SPFhps | 10 | 2.4 | 1.9–3.2 |
| $SPF_{H4}$ | 17 | 2.5 | 1.4–3.3 |
| $SPF_{H5}$ | 41 | 2.3 | 1.5–3.4 |
| DECC | 49 | 2.4 | 1.6–3.4 |

the SPFhps, no back up, and $SPF_{H4}$, all inputs. The following analysis is based on raw data only and, since no heat balance has been carried out, the results are therefore provisional and unconfirmed.

Many of the EST installations are space heating only and readily fit into boundary categories other than System Efficiency, $SPF_{H5}$. A review of the EST raw data for 52 ground source installations provides SPF values for 9 heat pumps at $SPF_{H2}$, 10 at SPFhps, 17 at $SPF_{H4}$ and 41 at $SPF_{H5}$ which can be compared to the DECC results where the efficiency of all installations is described as System Efficiency (Table 12).

The same analysis of 24 air source installations provides SPF values for 4 heat pumps at $SPF_{H2}$, 9 at SPFhps, 7 at $SPF_{H4}$ and 12 at $SPF_{H5}$ (Table 13).

This analysis casts a somewhat different light on the EST trial results indicating that trial mean SPF is dependent on system boundary definition. If the trial results constitute a sample, we now have sub-samples corresponding to each system boundary that is present in the sample. For very small sub-samples, such as $SPF_{H2}$, the calculated mean is vulnerable to the impact of possible outliers. The Energy Savings Trust's use of System Efficiency is unique and its reclassification, where possible, as SPFhps and $SPF_{H4}$ is certainly more useful when comparing trial outputs.

### *6.3. Combining all trial results*

$SPF_{H1}$ excludes the source fan/pump, sink pump and any backup and therefore, since it is not indicative of 'real world' operation, may be removed.

Lahr alone provides JAZ 1, with values for 23 heat pumps, 13 ground and 12 air source. EST alone provide "system efficiency" and since the objective is to compare trial results these may be omitted.

JAZ 2 and SPFhps are similar in that that JAZ 2 includes the header circulation pump and buffer losses whereas SPFhps includes the full sink pumping requirements only; SPFhps may be reclassified as JAZ 2 without any great loss of accuracy. JAZ 2 from FAWA, Lahr, SPTRI 2007 and EST provides 274 heat pumps, the largest classification.

Removing JAZ 1, $SPF_{H1}$, SPFhps and $SPF_{H5}$ reduces boundary classifications from eight to four: JAZ 2, $SPF_{H2}$, $SPF_{H3}$ and $SPF_{H4}$. The boundaries may now be analysed by source to provide number, weighted mean and range (Tables 14 and 15).

### *6.4. Discussion*

Changes to heat pump manufacture and quality of installation are crucial in understanding, in particular, the range of

**Table 13**
EST ASHP field trial.

| ASHP | No. | Mean | Range |
|---|---|---|---|
| $SPF_{H2}$ | 4 | 2.9 | 2.2–4.0 |
| SPFhps | 9 | 2.3 | 1.9–2.6 |
| $SPF_{H4}$ | 7 | 1.9 | 1.2–2.3 |
| $SPF_{H5}$ | 12 | 1.9 | 1.5–3.0 |
| DECC | 22 | 1.8 | 1.2–2.2 |

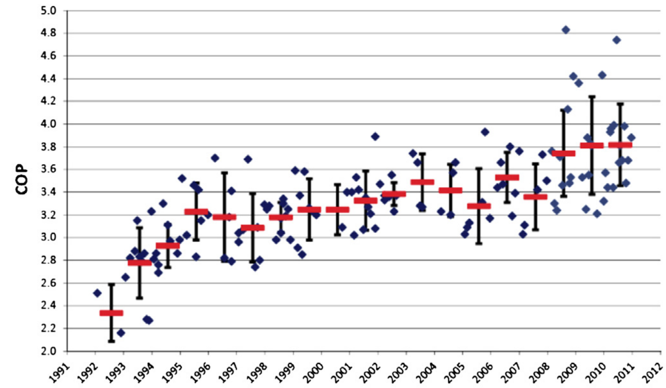


**Fig. 7.** COP historical improvement [35].

performances. Because of its historical overview, the FAWA report provides evidence of the increasing efficiency of heat pumps [34]: "Between 1995 and 2003, the SPF improved by approximately 20% for both groups. Since the start of the project, the SPF data for 59% A/W [air to water, i.e., ASHPs] and 41% B/W heat pumps [brine to water, i.e., GSHPs], plotted against the total installed Swiss heat pump capacity, show an increase of around 23% (from 2.5 to 3.1)."

This increased efficiency may be partly ascribed to the increased efficiency of manufacturers' heat pump units, evident from the laboratory COP test data from WPZ, Buchs, Switzerland [35] (Fig. 7), allied to improvements in system design as Swiss knowledge of the technology has matured. The general improvement in heat pump design would imply that recent installations should be more efficient.

Tables 14 and 15 show that Fraunhofer new building installations have the highest efficiencies. This is due to designing, wherever possible, for minimal use of backup heaters, for low temperature space heating with weather compensated control and variable speed circulation pumping, all of which produce the lowest energy input to output ratio. Combining both Fraunhofer New and Existing results allows for comparison with a contemporary study of both new and existing buildings in a mature market, that of Denmark. The combined Fraunhofer trials produce weighted $SPF_{H3}$ mean values of 3.7 and 2.7 for ground and air source respectively. Although not directly comparable to the DTI $SPF_{H4}$ values of 3.03 and 2.33, they do indicate that even when adjusted for circulation pump, about a 10% reduction, the Fraunhofer installations still outperform the Danish.

In addition to their comments on SPF boundary, of "System Efficiency", Delta [11] raise the following points concerning the EST field trials:

"Other important differences to note, which may contribute to lower SPFs in the UK, are:

- The German and Swiss heating systems are typically of higher quality than those in the UK (in terms of the quality of components and control system).
- UK and German installations were providing a higher proportion of DHW than in Switzerland.
- UK buildings were (broadly) of lower quality in terms of insulation/rate of heat loss.

These issues may have reduced achievable SPF in the UK by a few percentage points, but these factors alone are not sufficient to explain the UK trial's poorer results."

We may offer the following comments supported by Tables 14–16:

**Table 14**
GSHP meta-analysis.

| GSHP | JAZ 2 | | | $SPF_{H2}$ | | | $SPF_{H3}$ | | | $SPF_{H4}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TRIAL | No. | Mean | Range | No. | Mean | Range | No. | Mean | Range | No. | Mean | Range |
| FAWA | 100 | 3.4 | 2.3–5.3 | | | | | | | | | |
| LAHR | 25 | 3.1 | 2.3–4.2 | | | | | | | | | |
| SPTRI 2007 | 5 | 2.9 | 2.4–2.9 | | | | | | | 5 | 2.6 | 2.4–2.9 |
| EST | 10 | 2.4 | 2.4–3.5 | | | | | | | 17 | 2.5 | 1.4–3.3 |
| SPTRI 2010 | | | | | | | 6 | 3.26 | 2.6–3.6 | | | |
| Fraunhofer Existing | | | | | | | 36 | 3.3 | 2.2–4.8 | | | |
| Fraunhofer New | | | | 56 | 3.93 | | 56 | 3.88 | 3.1–5.1 | 56 | 3.75 | |
| DTI | | | | | | | | | | 138 | 3.03 | 3.1–5.1 |
| No, mean, range | 140 | 3.3 | 2.3–5.3 | 56 | 3.9 | | 98 | 3.6 | 2.2–5.1 | 216 | 3.2 | 1.4–5.1 |

**Table 15**
ASHP meta-analysis.

| ASHP | JAZ 2 | | | $SPF_{H2}$ | | | $SPF_{H3}$ | | | $SPF_{H4}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TRIAL | No. | Mean | Range | No. | Mean | Range | No. | Mean | Range | No. | Mean | Range |
| FAWA | 100 | 2.6 | 1.5–4.0 | | | | | | | | | |
| LAHR | 25 | 2.3 | 1.7–3.0 | | | | | | | | | |
| EST | 9 | 2.3 | 1.9–2.6 | | | | | | | 7 | 1.9 | 1.2–2.3 |
| Fraunhofer Existing | | | | | | | 34 | 2.6 | 2.1–3.4 | | | |
| Fraunhofer New | | | | 18 | 2.95 | | 18 | 2.89 | 2.3–3.4 | 18 | 2.74 | |
| DTI | | | | | | | | | | 12 | 2.33 | 2.3–3.4 |
| No, mean, range | 134 | 2.5 | 1.5–4.2 | 18 | 3 | | 52 | 2.7 | 2.1–3.4 | 37 | 2.4 | 1.2–3.4 |

- Heat pumps are subject to the same market conditions as any other commodity leading to the use of similar manufacturing techniques, materials, components and international marketing strategies. Some of the manufacturers in the UK trials also appear in the German and Danish trials. A significant difference is in system design where weather compensation control in particular and variable speed pumps have a far higher market penetration in continental Europe than in the UK.
- Swiss installations have a 50% DHW load, EST have around 70% whereas all Fraunhofer installations produce DHW. If DHW has a significant impact on SPF then the UK results should lie between the two. Apart from ASHPs at JAZ 2, all UK heat pumps underperform by at least 20% of the boundary group means.
- The DTI state that their installations encompass both new and existing buildings although there is no information on the actual heat losses. FAWA describe both new and refurbished with a mean of 75 kWh/m$^2$ pa and a range between 28 and 208 kWh/m$^2$ pa. Fraunhofer Existing provide a mean of 177 kWh/m$^2$ pa with a range between 85 and 340 kWh/m$^2$ pa. There is no heat loss overview in EST trial publications, however, some 20% of the dwellings are built post-2000. To put this in context, the average space heating load for UK dwellings was about 90 kWh/m$^2$ pa in 2004 [36] and thus the Fraunhofer trials of existing buildings, with higher SPFs than those of the EST, cannot be said to focus on low energy refurbishments.
- Mean SPF is a ratio of output to input and whilst high heat losses will result in higher fuel input (as with any space heating system), SPF is fundamentally dominated by Carnot source and sink absolute temperatures. There is a practical limit to output from underfloor heating due to floor surface temperature leading to high loss buildings requiring radiators. 20% of UK buildings used underfloor heating alone, 16% of Danish and only 3% of Fraunhofer existing.

High envelope heat losses cannot explain the low SPF results from the UK when compared with higher losses in the Fraunhofer existing buildings trial. High heat losses impact on system design, requiring higher temperatures from emitters, yet the EST trials have more underfloor systems than both DTI and Fraunhofer existing. If the issue is not the heat pump model, envelope losses or emitters then perhaps it is the quality of installation, a general underachievement in praxis. The wide range of performance identified in Tables 14 and 15 indicates the need for in-depth individual system analysis. The interpretation of measurements for heat pumps will depend on factors other than system boundaries, for example, monitoring intervals, completeness of datasets and treatment of errors. Unfortunately such detailed information on monitoring specifications is not available for several of the field trials referred to in this paper. It has therefore not been possible to include consideration of these questions in our comparison of heat pump performance across field trials. However, the inconsistency in performance does raise the issue of design and installation competency and therefore an opportunity to readdress vocational education and training (VET) including design, matching heat pump to load, system installation, installation controls, the quality of system monitoring and the monitoring and analysis protocols.

**Table 16**
Comparison of Trial installation data.

| TRIAL | UFH | Mixed | Radiator | DHW | New build | Mean heat loss (kWh/m$^2$ pa) | Range (kWh/m$^2$ pa) |
|---|---|---|---|---|---|---|---|
| DTI | 16% | 70% | 14% | 100% | N/K | N/K | N/K |
| EST | 21% | 14% | 64% | 73% | 19% | ≈90 | N/K |
| Fraunhofer existing | 3% | 26% | 71% | 100% | 0% | 177 | 85–340 |
| FAWA | 93% total, 53% refurb* | N/K[a] | N/K[a] | 50% | 60% | 75 | 28–208 |

[a] FAWA state: "92% of cases of buildings have underfloor heating that is partially complemented by radiators. In renovation projects, the proportion of underfloor heating systems is 53%." K/N not known.

## 7. Conclusions

This paper is an exploration of the importance of system boundaries in the measurement and reporting of heat pump performance data. It begins by describing the system boundaries that have been used by major heat pump trials over the last 20 years. It goes on to demonstrate the impact of choice of boundary on the values of SFP that are quoted in the different studies.

The paper then shows that a combination of analytical and practical redundancy allows considerable reduction (by roughly half) in the set of boundary conditions that need to be considered in analysing data but that, in the absence of trial raw data, significant, irreducible, differences remain between the four historical and contemporary definitions of JAZ 2, $SPF_{H2}$, $SPF_{H3}$ and $SPF_{H4}$.

The paper presents a short exploration of the possibility of introducing corrections to allow data for these remaining system boundaries to be mapped onto each other. The conclusion of this exercise is that uncertainties around the physical properties of sub-systems (heat stores, circulation pumps and electric resistance heaters) which are either unmeasured or unreported in most of the studies examined, mean that such corrections are unreliable and, in the view of this author, of little value.

The final section of the paper is an attempt to reconcile one recent study of heat pumps, the EST field trial undertaken in the UK between 2009 and 2010, with the body of work undertaken in continental Europe. This exercise shows how careful analysis of boundary conditions can impact significantly on the conclusions from such comparisons.

The meta-analysis indicates that, when evaluating the RES 2009 demand that $SPF > 1.15 \times 1/\eta$, $SPF_{H2}$ is the most relevant metric for heat pump efficiency since it includes only the source fan/pump, compressor and control electrical energy inputs and is directly comparable to alternative heat sources such as condensing gas boilers. However, $SPF_{H2}$ applies only to monovalent designs where the heat pump is sized to provide all necessary heat demand rather than rely on resistance backup for either space heating or domestic hot water. Where bivalent heat pump systems are installed, $SPF_{H3}$ is the relevant metric for direct comparison to other forms of wet central heating and therefore RES 2009.

Given that manufacturers provide similar heat pump technologies the extreme ranges of performance, even in recent trials, confirms the sensitivity of heat pump performance to technical context. Heat pumps are particularly sensitive to poor design, installation and operation. The current mean for air source heat pumps provides reasonable evidence that this technology will not meet the expectations of RES 2009 to provide renewable heat unless there is a significant change in electricity grid fuel mix, an increase in renewables to raise the value of $\eta$ (eta), or significant inroads are made across Europe to raise the standards of design, installation and operation in order that the mean reflect the higher range values identified.

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