Whitepaper

Underfloor Heating (UFH)

An Orbia business.

Executive Summary

The decarbonisation of residential heat is being delivered by improvements in the efficiency of existing heating systems as well as by a shift to low carbon energy sources. Technologies such as heat pumps (using low carbon electricity) will perform better if they deliver heat at a lower flow temperature.

In this respect, underfloor heating confers substantial benefits compared to radiator based central heating systems. It provides higher levels of thermal comfort, can provide a safer and healthier environment and all with considerable energy savings.

Although condensing boilers and heat networks also benefit from underfloor heating, savings are most pronounced in heat pump systems. Here, the relatively low flow temperatures result in higher seasonal performance factors. As heat pumps are expected to play an increasing role in residential heating over the coming decades, UFH represents a key enabler for this low carbon heating solution.

In contrast to UFH, the technical requirement for low flow temperatures imposes challenges on existing radiator-based heat distribution systems. These challenges arise in terms of performance, operating cost, disruption to the home, compatibility with piping systems and many other practical issues. All of these currently constrain the deliverability of efficient, low carbon heating systems.

Underfloor (hydronic) heating systems can overcome many of these issues and may also provide additional economic, thermal comfort and other benefits. This paper describes how efficiency gains are achieved using basic physics supported by laboratory and field trial data.

We start by describing thermal comfort and how humans respond to various factors such as radiant temperature, air temperature, and so on, to achieve personal comfort. We find that UFH can deliver superior thermal comfort at a lower air temperature than radiator-based systems resulting in a reduced heat input for a given level of comfort.

Secondly, we describe how this reduced heat demand can be provided more efficiently when appliances are allowed to operate at lower flow temperatures. It is shown that savings of around 10% can be achieved from the reduced air temperature with, in the case of heat pumps an additional 25% gain in appliance efficiency, resulting in potential total cost savings in excess of 30%.

In addition to these quantifiable benefits, UFH also offers:

- Avoidance of cold spots, hot surfaces, sharp/hard edges
- Increased space availability, particularly in modern homes with relatively small rooms
- Extended product life
- Thermal inertia and the potential for load shifting to periods when electricity is cheaper.

This document was produced by LCD Delta in March 2023. See more on pages 18-19.

Introduction

It is widely believed that UFH provides significant benefits in residential heating compared with conventional radiator-based emitters. These benefits include both quantifiable heating system efficiency, cost and environmental benefits as well as less tangible, qualitative benefits such as space saving and safety.

This study is intended to provide both a rationale for these claimed performance benefits and an evidence base of laboratory and field trials which support the rationale; it comprises two main workstreams.

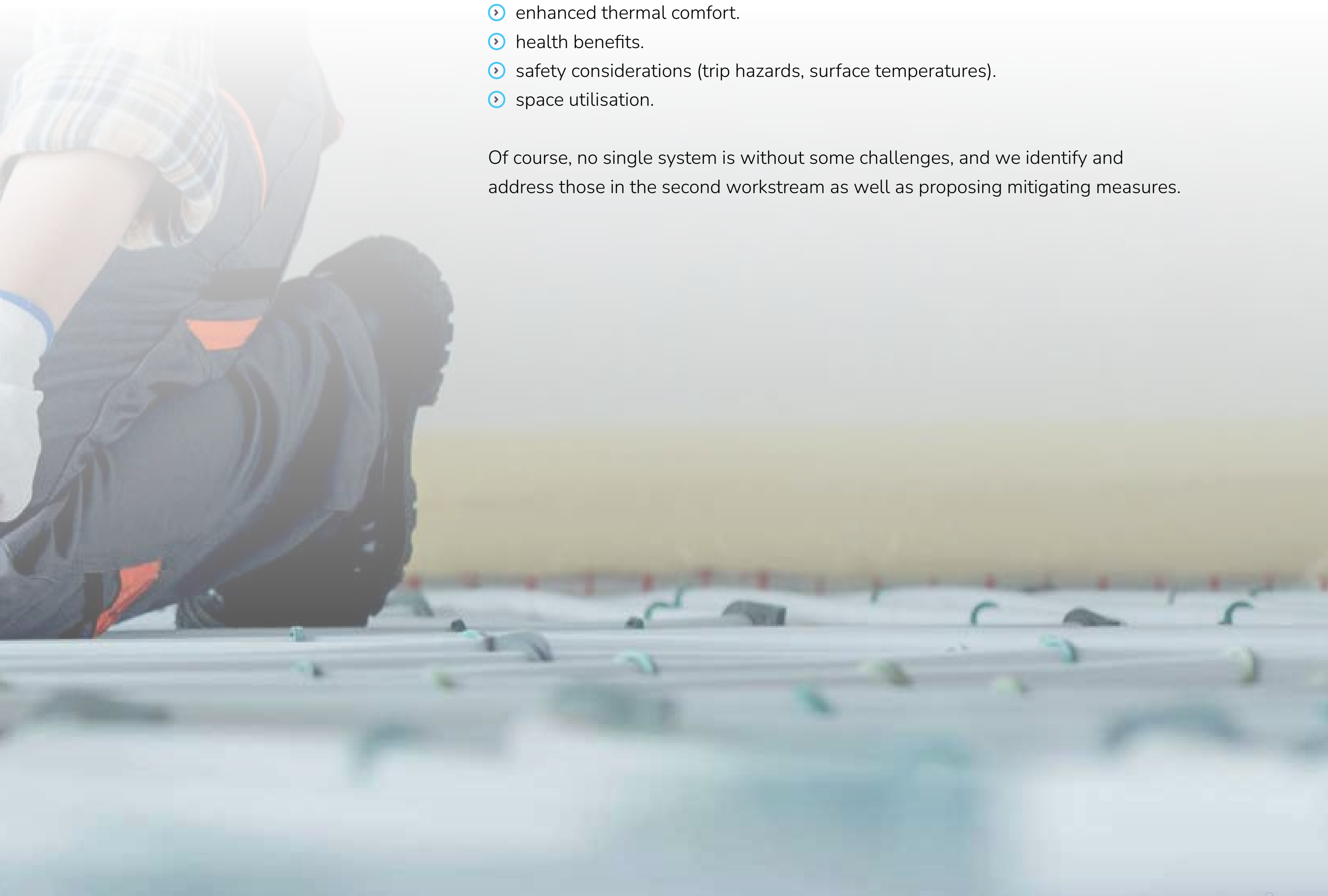
The first stream considers the performance and efficiency issues and sets out to describe how these benefits are achieved. The analysis is supported by fundamental physical laws, derived evidence and test results which, in broad terms, quantifies the benefits. Here we describe the rationale behind the efficiency benefits of UFH based on the following considerations:

- how people perceive thermal comfort.
- the ability of UFH to achieve an equivalent level of comfort as a radiator-based system with a lower room air temperature.
- the ability of UFH to deliver a given heat output with lower flow temperatures and the resulting impacts on appliance (boiler/heat pump) efficiencies.
- consequent efficiency gains from the combined benefits of improved appliance efficiency and reduced room heat loss due to the lower room air temperature.

The second workstream identifies the key issues from the literature regarding environmental physics as well as "soft" features from published case studies. Additionally, it considers the less readily quantifiable benefits such as:

- enhanced thermal comfort.
- health benefits.
- safety considerations (trip hazards, surface temperatures).
- space utilisation.

Of course, no single system is without some challenges, and we identify and address those in the second workstream as well as proposing mitigating measures.



Thermal Comfort

A warm, dry, safe living space is one of the most basic of human needs. It is not only a means of providing thermal comfort but is also essential for our health. It is the main reason we heat our homes; other reasons include maintaining the condition of our possessions and the building itself, but those are second order issues and outside the scope of this paper.

Thermal Comfort is an expression of the perceived (subjective) comfort of an individual within their environment. Although there are agreed metrics for thermal comfort which can be measured and replicated by accepted means, the main issue is that no two individuals respond in the same way to thermal conditions. We therefore tend to use statistical approaches to determining the level of thermal comfort which is being achieved. This can be either in the form of predicted mean vote (PMV) which rates the degree to which people feel too hot or too cold, or as a distribution of peoples' level of (dis)satisfaction with a given condition known as percentage of people dissatisfied (PPD) .

There are six key variables which affect our perception of thermal comfort as noted below; two of these are personal factors (relating to the individual) whilst the other four are environmental. Research into how each of these factors contribute to our overall experience led to the development of thermal comfort equations which allow us to compare the anticipated levels of thermal comfort of various heating solutions under standardised conditions.

Personal Factors

These factors are characteristics of the individual concerned:

1. **Metabolic rate.**
   It is well understood that an individual with a higher metabolic rate will feel warmer than one with a lower rate. It is therefore necessary to take account of whether the individual is for example, sitting, standing, moving around or sleeping.

2. **Clothing insulation.**
   Obviously, someone wearing more, better insulating clothing will feel more comfortable at a lower temperature than someone wearing lighter, less insulating clothing.

Environmental factors

3. **Air temperature.**
   Importantly this is only one of four environmental factors which affects our perception of comfort, yet it is the single parameter used to control the heating system in our homes. That is, a simple thermostat measuring the air temperature is used as a proxy for all the factors, leading to less-than-optimal heating in many instances.

4. **Mean radiant temperature.**
   This feature is a function of both the radiant temperature of a surface and the area over which it radiates. Although this factor is rarely used to control our heating systems it represents a significant impact on our overall comfort. It is often observed that someone can feel perfectly warm in snowy mountain conditions and very low air temperature if the sun is shining brightly. It is this aspect of UFH which imparts significant benefits due to the large radiant surface.

5. **Humidity.**
   The relative humidity of the air in the room has an impact on our ability to sweat and thus lose heat from our skin; this is particularly significant when considering cooling applications.

6. **Air speed.**
   The movement of air across our skin also affects heat loss from the body with higher air speeds, perceived as cold draughts.

If we consider the various factors applicable to UFH and radiator-based systems respectively, the key differentiator is that UFH provides a large surface area (the entire floor) compared with that of radiators. One consequence of this is that a similar level of comfort can be achieved by the UFH system even if the air temperature is slightly lower. This is of key importance as it is the air temperature, which is used to control the heating system, not the level of comfort being achieved. As we shall see, a higher air temperature than necessary results in higher heat loss from the home and consequently higher heating bills.

Building Physics

This section considers how we heat our homes to provide thermal comfort, and how that affects heat loss and consequent energy consumption, fuel bills and carbon emissions.

The majority of homes in the UK and other North European countries, are heated using hydronic heat distribution systems feeding hot water to so-called radiators. Although these have historically delivered relatively high levels of comfort, they do suffer from several drawbacks which limit their efficacy and efficiency when used in conjunction with low carbon appliances such as heat pumps as well as highly efficient modern condensing gas boilers.

The heat output from radiators is determined by the temperature at which hot water is delivered to the radiator, and the temperature drop across the radiator which is often regulated by a TRV and ultimately limited by the surface area and other physical characteristics of the radiator.

Heat loss from buildings

The room (air) temperature to which we heat our homes is the primary driver for heat loss from the home. For any given outdoor temperature, the higher the set temperature in the home the higher the resultant heat loss. It is generally assumed that the temperature on which this is based (the room thermostat setting) accurately reflects the temperature in the room. However, this is rarely the case.

When measuring air temperature, we need to consider the position of the temperature sensor (thermostat) and how that reflects the average air temperature for the space, for it is this which determines the amount of heat loss. That is, heat loss is directly proportional to the difference in temperature between the space and the outside air temperature.

In the case of radiators which tend to result in a fairly steep temperature gradient between floor level and ceiling, the thermostat set point may be unrepresentative of the room temperature. In practice, people tend to adjust the thermostat so that they achieve comfort, but in doing so may inadvertently be setting a significantly higher air temperature than the desired average room temperature with the inevitable consequence of higher energy consumption. It is not unusual to find a dT between floor and ceiling of more than 3K.

In contrast to this highly stratified situation for radiators, for UFH, the set point will better reflect the desired temperature. The temperature gradient is much less, resulting in heat loss more in line with that expected from calculation and lower than for the radiator system.

The level to which this discrepancy between set point and actual temperature impacts heat loss is further complicated by issues such as cold spots (particularly at foot level for radiator systems), drafts and so on related to perceived thermal comfort, but we would expect to see UFH achieving the same comfort level as radiators (based on this element alone) of the order of 1-2K . It is generally accepted that a reduction in set point of this level will result in a reduction in heat demand of around 10-20% .

Fig. 1: Heat distribution in a radiator heated room.
Induced convection results in high temperatures at ceiling height (increasing heat loss) whilst simultaneously allowing cold draughts at floor level.

Fig. 2: Heat distribution in room with UFH.
The predominant effect of radiant heat is to provide an even comfort level at all room heights.

Appliance efficiency

Having discussed the effect of UFH on the amount of heat required to achieve thermal comfort for the occupants, we now move on to the cost of producing this heat using UFH and radiators respectively.

The efficiency of a heat producing appliance will vary according to the temperature at which the heat is delivered. Here we will consider three main types of hydronic heating appliances which are expected to form the basis of most residential heating systems both today and in the future.

These are:

- electric heat pumps
- gas (possibly hydrogen in the future) boilers
- district heating

It is well known that the efficiency (COP) of heat pumps varies significantly with delivered water temperature, usually by well over 25% between flow of 50°C and 30°C respectively. Condensing gas boilers also benefit when operating in condensing mode, with a potential gain of just over 10% compared with operation in non-condensing mode. Achieving condensing mode is dependent on the return water temperature being below 55°C, the further below the better.

An important point to note is that efficiency data for both heat pumps and boilers tends to be quoted based on specified operating conditions which do not necessarily represent either real world conditions, or the operating conditions which are most critical to overall annual performance.

However, to begin with we need to examine the efficiency of each technology at these standard conditions.

The principal benefit of UFH in terms of its impact on appliance performance is that, due to the very large surface area of the floor compared to radiators, the required surface temperature and hence the primary flow temperature are very much lower than even the largest radiators for delivering the same amount of heat.

Flow temperature for UFH is typically 35°C with 25°C return, although it may be as low as 29/25°C on occasion. Radiators on the other hand, even when sized for low temperature heat sources tend to use 50°C and 30°C respectively.

It is this relative difference which provides such significant efficiency gains for UFH systems.

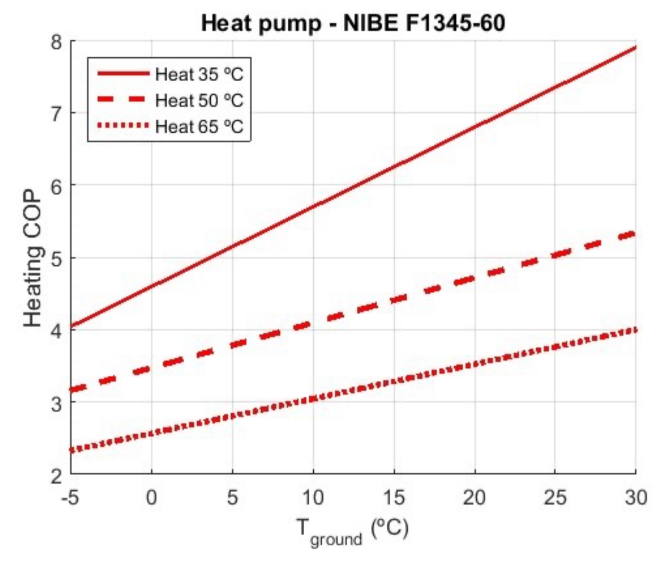


Fig. 3: Variation of heat pump COP with source and flow temperature.

Heat Pumps

It is widely understood that the performance of a heat pump is significantly affected by the difference in temperature between the heat source (for example ambient air) and the delivered temperature of the heat output. This temperature difference, often referred to as dT directly affects the coefficient of performance (COP) and is common to all heat pumps. The greater the dT, the lower the COP.

For any given system, if we assume a constant heat source temperature to make a comparison, then it is the output temperature which is the single parameter which affects the COP. Of course, for a given heat output, the output temperature will also determine the return temperature.

In figure 3 below it can be clearly seen that the COP varies between as low as 2 for a flow temperature of 65°C and as high as 4 for a flow temperature of 35°C. If we consider the design flow temperatures of a low temperature radiator system at 50°C and a UFH system at 35°C, we can see that the effective COP are 3 and 4 respectively. Although the actual COP will vary between different heat pump models, the same principles apply regardless. It should also be noted that these COP are instantaneous for the specific temperature conditions and do not take account of proportion of the year for which flow temperatures such as these are appropriate in assessing overall annual performance.

This demand weighted COP is referred to as the seasonal performance factor (SPF). The impact of this on the overall annual energy consumption is explored in greater detail in the following section on operating costs.

An additional incidental benefit of UFH in heat pump performance is the relatively high thermal inertia of the floor slab which helps to minimise cycling of the heat pump. Indeed, it is for this reason that many heat pump systems are equipped with buffer tanks to increase the primary flow volume and thus minimise cycling.

Condensing boilers

As noted above, condensing gas boilers also benefit when operating with a lower primary circuit temperature, except that in this case, it is the return water temperature which determines the efficiency gain. This is because the latent heat of evaporation can only be recovered if the heat exchanger operates at a temperature below the dew point. As shown on the graph below, this effect kicks in at around 55°C and increases up to a point at which the total boiler efficiency approaches 100%

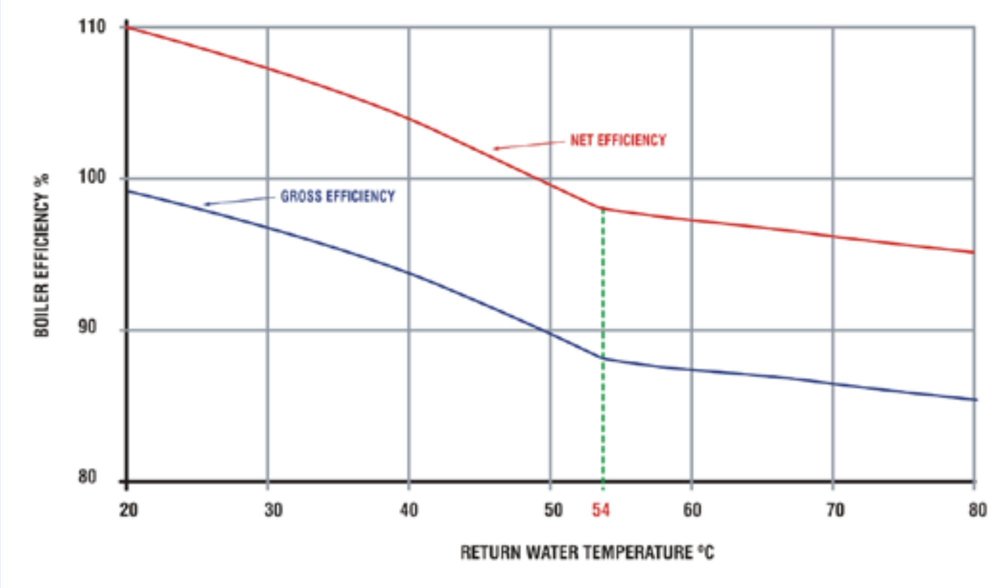


Fig. 4: Variation of condensing boiler efficiency with return temperature.

(GCV), rather than the lower limit of around 88% which applies to sensible heat alone, that is when not in condensing mode. For a well sized boiler, able to modulate efficiently and provided with weather compensation, it is possible to achieve the high efficiencies in condensing mode most of the time provided that the radiators have been sized to meet design output at a return temperature which results in condensation at the heat exchanger. However, at peak output in very cold weather, this condition may no longer fully apply and there will be some loss of efficiency. On the other hand, UFH operates well below the condensing threshold and thus tends to always operate at a relatively higher efficiency. The degree to which this is true depends on the individual installation. According to laboratory measurements undertaken by Professor Oschatz at the Technical University of Dresden, a variation of 0.4% efficiency change results for each degree change in return temperature. For the same 10K return temperature difference noted earlier, we would expect around 4-5% improvement in boiler efficiency. Whilst the efficiency gains for a low temperature radiator system are therefore relatively modest, it should be noted that the majority of radiator systems in existing homes are sized for a primary flow and return of 80/60°C respectively. For much of the year, (that is the coldest periods when most heat is required), these systems are unlikely to operate in condensing mode, particularly if they are not fitted with weather compensating controls. In this case, on the same basis we might expect to see a relative efficiency gain of around 10% for the UFH.

District Heating

District heating systems can also benefit from lower flow temperatures. These arise from the reduced losses in the distribution pipework as well as in the heat generating appliances.

Enhanced heat generating appliance efficiency

Perhaps the greatest benefit of district heating (DH) systems is their ability to capture heat from a wide variety of resources including waste heat, energy from waste and fuelled appliances. It is this incorporation of a wide range of technologies, including boilers, heat pumps or even resistance heaters which represents such a challenge to identifying benefits attributable in all cases. The relative complexity and the vast number of component permutations makes it almost impossible to produce precise figures for the benefits.

One exception is for more modern, (ultra)-low temperature (5th generation) distribution systems, where performance benefits will be in line with those for the heat pump values given earlier. This is because the ambient loop (as the name implies) distributes primary water at a relatively low temperature and is upgraded at the point of demand (the home) using a water-to-water heat pump. In some regards this aligns with the operation of systems such as the Kensa shared ground loop system.

Enhanced distribution network efficiency

In the case of existing DH schemes designed for high flow temperatures , it is not possible to reduce the primary flow temperature in the DH system. Even if the existing radiators were to be replaced with low temperature emitters, the flow temperature is determined not by the space heating demand, but by the need to deliver heat at a temperature suitable for the production of domestic hot water.

However, surface losses from the return pipework can be reduced if the return temperature is reduced. Furthermore, reduced return temperature results in a higher dT which means that a lower water flow rate is required. This can have a significant impact on the electrical energy required to circulate water in the DH network. Here, low temperature radiators can play a part in reducing the return temperature, and UFH can often provide a more reliable means of ensuring consistently lower return temperatures.

As the precise level of savings will be largely determined by how well the system is designed and operated, we do not specify a value for this in the following tables. However, it is common practice in Denmark for example, for financial incentives to encourage systems operating with larger dT between flow and return.

In the following tables, the range of potential savings is based on either zero (for the conventional DH systems) or the higher value based on the equivalent savings from enhanced COP for heat pumps upgrading ambient loop distribution temperatures. Of course, the efficiency benefits resulting from the improved thermal comfort conditions may still be captured, not to mention the other significant benefits described in the next section.

Operating costs

Combining the benefits of improved thermal comfort at any given air temperature with the appliance efficiency gains from lower flow temperatures associated with UFH, we see significant reductions in energy demand resulting in substantial annual fuel bill reductions. This calculation, based on fundamentals of building physics are largely substantiated by field trials. Here we illustrate the savings based on trials of heat pumps in the UK, Denmark and Germany.

In the analysis above we have taken a single set point for COP, although we recognize that the Seasonal Performance Factor (SPF) is a demand weighted aggregate of COP at various ambient and flow temperatures. However, over the course of a full year, SPF for UFH will be higher than that for the higher flow temperature radiator systems. This is evidenced by the fundamental characteristics of the heat pump as illustrated in the earlier graphs and is borne out by field trails in real homes as shown in the graphs below .

In this trial, the majority of installations demonstrated at least some performance benefits; those which showed lesser benefits were attributed to less-than-optimal installation practice. As with any energy saving solution, the maximum benefits are most likely to be achieved in well designed, sized and installed heating systems. In this context, the use of weather compensating controls will ensure flow temperatures are as low as possible to deliver the desired level of thermal comfort. It should also be noted that any field trial involving occupied homes will be subject to some variability in performance depending on user (ab)use of the system. This is particularly true for heat pumps which depend on control regimes with which many households are unfamiliar. The point here is simply to demonstrate the trend in performance benefits.

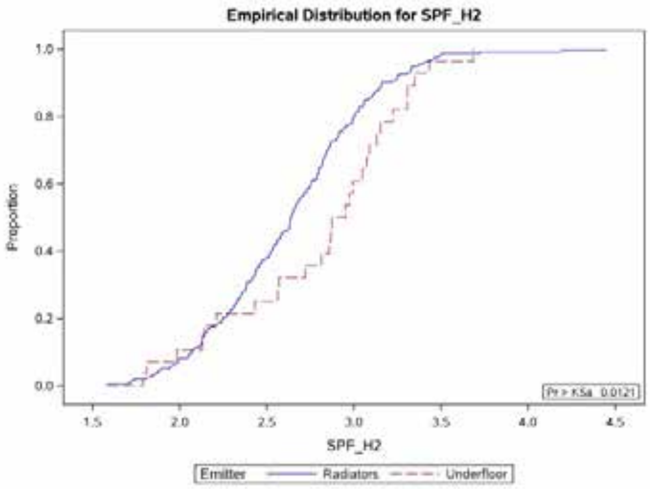


Fig. 5: Comparison of SPF by emitter type (radiators versus UFH).

Whilst the two graphs in Figure 6 above illustrate a range of values for both radiators and UFH in conjunction with both ASHP and GSHP, the flow temperatures recorded in all cases are significantly lower for UFH than for radiator-based installations.

Rather encouragingly, other trials which have built on learnings from this early pilot, have demonstrated further efficiency gains from well-designed and installed heat pump systems using low flow temperatures.

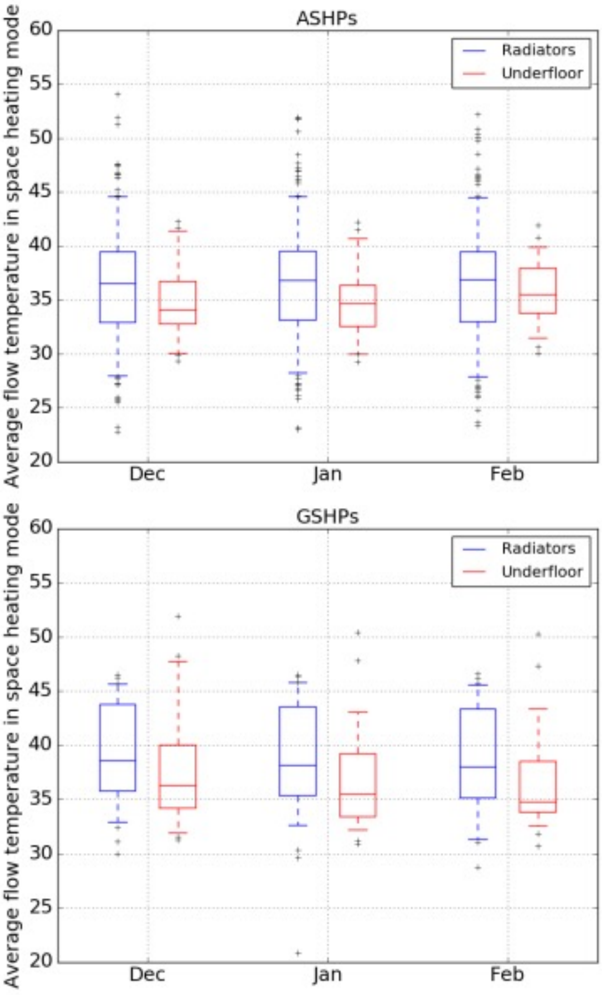


Fig. 6: Winter space heating flow temperatures (measured).

For example, trials undertaken by the Danish Technological Institute (2011) have demonstrated significantly higher savings (around 22%) resulting from flow temperature differences of around 10K up to as much as 17K.

Most recently (2023), published data from the extensive UK Electrification of Heat field trials illustrated in the figure below shows a wide range of savings dependent on the specific heat pump model and generically by refrigerant type.

In all cases the trial demonstrated significant performance benefits attributable to low flow temperatures. The figure below illustrates SPF variations (for refrigerant type R290) typically from 3.2 to 2.3 at flow temperatures of 35°C and 50°C respectively, a potential saving of 28%.

What this means in practice

Given the potential savings arising from the fundamental calculations, laboratory tested performance and validated by field trials described above, the following tables illustrate the potential savings as a percentage of the total efficiency and how that converts to annual savings.

This is expressed in both energy (kWh) and as economic savings expressed in money terms (£). The numbers given are for a typical UK home with an annual design heat loss of 12,000kWh, using current energy cap fuel prices.

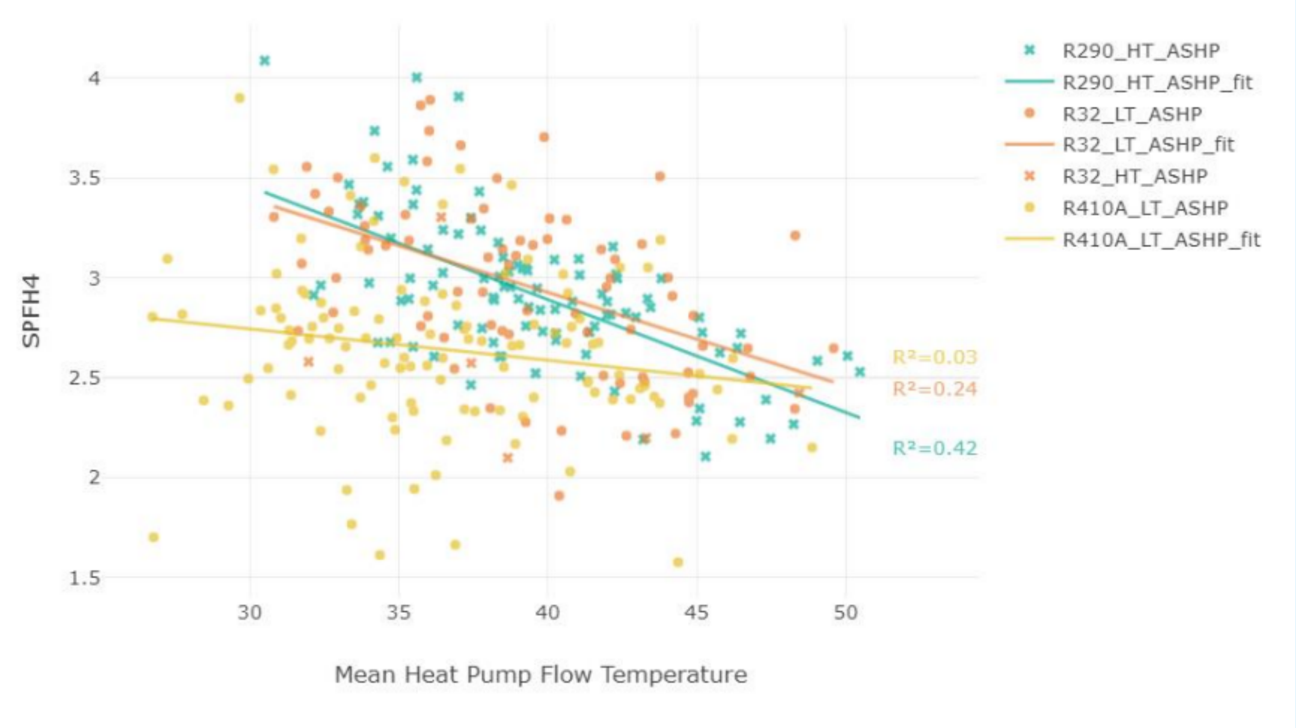


Fig. 7: Variation of SPF for a variety of refrigerant types at varying flow temperatures based on extensive UK Electrification of Heat field trial.

	Savings from reduced air temperature	Savings from improved appliance efficiency	Combined benefit
Gas boiler (50/30)	10-20%	4-5%	14- 24%
Gas boiler (80/60)	10-20%	5-10%	15- 28%
Heat pump	10-20%	25%	33- 40%
District heating	10-20%	Up to 25%	10- 40%

Fig. 8: Typical percentage efficiency gains achieved by underfloor heating compared with radiator-based systems (at 80/60°C and 50/30°C flow/return respectively).

As explained above, the actual savings achieved will vary by household even for identical homes and heating system configurations, but it can be clearly seen that significant performance gains can be achieved in all instances by using UFH rather than conventional radiator based central heating.

For heat pump systems in particular, total savings of over 30% seem realistically achievable, based on the mechanisms described in this study and evidenced from laboratory and field trials.

The table below (figure 9) illustrates the annual savings expressed in kWh, using the percentages noted above applied to a typical UK family home with an annual energy consumption (for space heating) of 12,000kWh.

	Savings from reduced air temperature (kWh)	Savings from improved appliance efficiency (kWh)	Combined benefit (kWh)
Gas boiler (80/60)	1,200 – 2,400	600 – 1,800	1,740 – 3,360
Heat pump	1,200 – 2,400	3,000	3,900 – 4,800
District heating	1,200 – 2,400	3,000	1,200 – 4,800

Fig. 9: Potential annual household energy savings, in kWh, by underfloor heating compared to radiator-based systems (at 80/60°C and 50/30°C flow/return respectively).

The table below displays the effect of the savings above in terms of monetary savings, using the United Kingdom price cap as a reference (set at 34 p/kWh for electric and 10.3 p/kWh for gas between January and March 2023 , the price for district heating used was 4.8 p/kWh)

	Savings from reduced air temperature	Savings from improved appliance efficiency	Combined benefit
Gas boiler (80/60)	£124 – £247	£62 - £124	£168 - £297
Heat pump	£408 - £816	£1,020	£1,326 - £1,632
District heating	£58 – £115	£0 - £144	£57 - £231

Fig. 10: Potential annual household energy bill savings by underfloor heating compared to radiator-based systems in the UK (at 80/60°C and 50/30°C flow/return respectively).

Although more substantial savings will be achieved in older homes with higher absolute energy demands, it is clearly significantly easier to deploy UFH in new build housing and this is where we would also expect to see a more rapid growth in heat pump installations as gas boilers are gradually phased out in this sector.

The figure below shows how savings vary depending on the thermal demand of the property indicating a range of values resulting from the percentage savings noted above. However, it should be noted that these savings will only be fully realised if the heat pump installation using UFH as its means of heat distribution, is designed, installed and operated correctly.

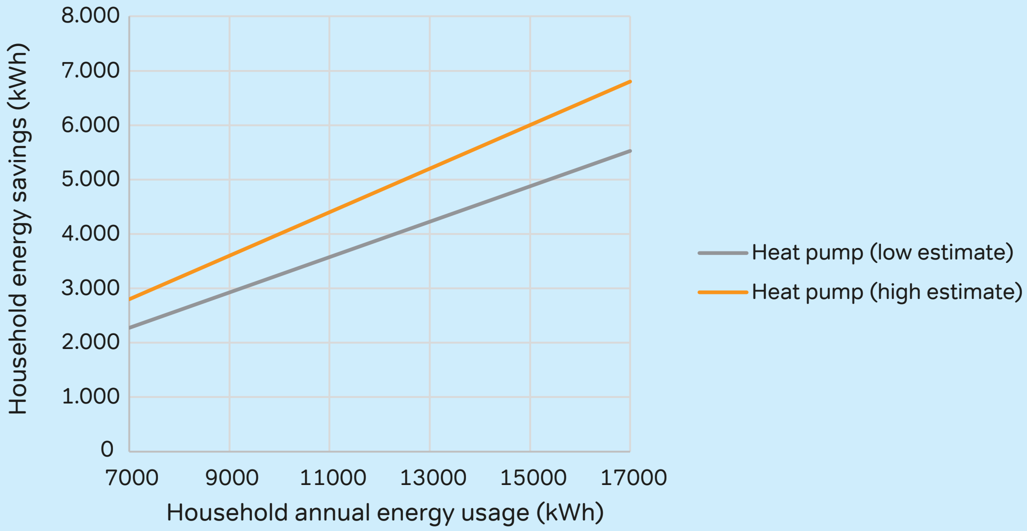


Fig. 11: Household annual energy savings as a function of annual energy usage.

Other Considerations

The previous section identified the potential economic and energy benefits of UFH, particularly in conjunction with electrically driven heat pumps. In addition to these quantifiable economic benefits, there are also many qualitative benefits. However, we should also recognise that there are other aspects which may not benefit to the same extent and still others which may present a negative impact. In some cases, issues which might be considered in this last category, often come about due to shortcomings in the way we currently design and build houses, not from UFH itself.

For example, disruption to the existing supply chain of installing heating coils in the concrete slab is as much a consequence of a sub-optimal construction process as of UFH per se. As with other construction innovations such as off-site construction which offers very substantial benefits in performance, quality control and cost, it may take some time for the building industry to adapt to best practice.

However, we do recognise that the disruption in introducing UFH to existing homes does present a challenge. It requires significant upheaval to replace or cover existing floors with UFH, although suitable solutions for most floor types are now available. But similar criticism can also be levelled at radiator systems where heat pumps are to be installed in existing homes. It is almost always necessary to add or replace radiators and, particularly where microbore piping has been installed, replumbing of the radiator system may also be required. In this case, it may be advisable to take the opportunity to opt for the superior UFH solution.

Another criticism levelled against UFH by some is its high thermal inertia. This may result in an overshoot in temperature if, for example, solar gain from large windows requires a reduction in heat output from the emitter. However, in this case it may be that the sun shining directly on the floor quickly raises the surface temperature, automatically reducing heat output from the floor.

However, the existence of a high thermal inertia also confers benefits. As noted earlier, the ability to use this inertia to capture the benefits of demand response can make better use of time of use (ToU) electricity tariffs. This is a potential source of significant value .

However, somewhat perversely, the UK standard assessment procedure (SAP) which is used to determine compliance of new build housing with Building Regulations fails to recognise this benefit. Neither does it recognise the inherent synergies between high thermal inertia and optimising heat pump performance. Because SAP was developed in the context of conventional boilers, radiators and bimodal occupancy patterns, it does not recognise the benefits of heating systems which operate better when in continuous operation, most notably heat pumps. Given that we expect the majority of homes to be heated by heat pumps in the coming decades, it is a matter of some urgency that SAP be updated to better reflect the realities of low carbon heating solutions.

Additional advantages of UFH include:

- Avoidance of cold spots; the provision of a uniformly heated floor overcomes the common problem of cold corners, not to mention the equally common problem of choosing a suitable location for the radiator. Not only is this a comfort issue it can also lead to damp related issues.
- Avoidance of hot surfaces and sharp or hard edges; radiators (even “low temperature” radiators) represent a hazard to small children and the elderly. An evenly heated floor overcomes this problem and provides a safe playing surface for toddlers.
- Increased space availability; in many, particularly smaller modern homes, there is often no logical place for the larger radiators required for low temperature emitters. Even if a convenient wall can be found, this represents a significant loss of usable living space.
- Zone control in open plan spaces. It is widely accepted that zone control which allows occupants to heat different rooms to different temperatures depending on their respective functions, can deliver significant savings in energy bills. However, this is difficult to achieve in open plan (multi-use) spaces using radiators as the emitters. Not only does UFH remove the need to occupy wall space, it also permits zone control in such open plan living areas as kitchen, living, dining areas where different temperatures may be desirable in each activity area.
- Product life; although radiator systems tend to have a reasonable life expectancy, the use of non-corroding pipes protected from mechanical damage by the floor slab ensures an exceptional life for UFH.

Overall, not only does UFH provide a more efficient heating system with significant thermal comfort and other benefits, but it also represents a heat distribution solution particularly well suited to heat pump systems.

Appendices & acronyms

ASHP	Air source heat pumps
COP	Coefficient of performance
DH	District Heating
DSR	Demand side response
dT	Temperature Difference
GSHP	Ground Source Heat Pump
GCV	Gross Calorific Value
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
SAP	Standard Assessment Procedure
SPF	Seasonal Performance Factor
ToU	Time of Use
TRV	Thermostatic Radiator Valve
UFH	Under Floor Heating
WWHP	Water to Water Heat Pump

Appendix 1:

Potential savings from underfloor heating in Denmark

	Thermal comfort at reduced air temperature	Appliance efficiency at reduced flow temperature	Combined benefit	Comment
Gas boiler (80/60)	DKK 1,428.48 - DKK 2,856.96 -	DKK 714.24 - DKK 1,428.48	DKK 2,071.30 - DKK 3,999.74	
Heat pump	DKK 4,070.28 DKK 8,140.55	DKK 10,175.69	DKK 13,228.39 - DKK 16,281.10	
District heating	DKK 1,092.78 - DKK 2,185.56	DKK 0 DKK 2,731.95	DKK 1,092.78 - DKK 4,371.11	

Fig. 12: Potential annual household energy savings made by underfloor heating compared to radiator-based systems in Denmark, assuming a household annual space heating requirement of 12,000 kWh

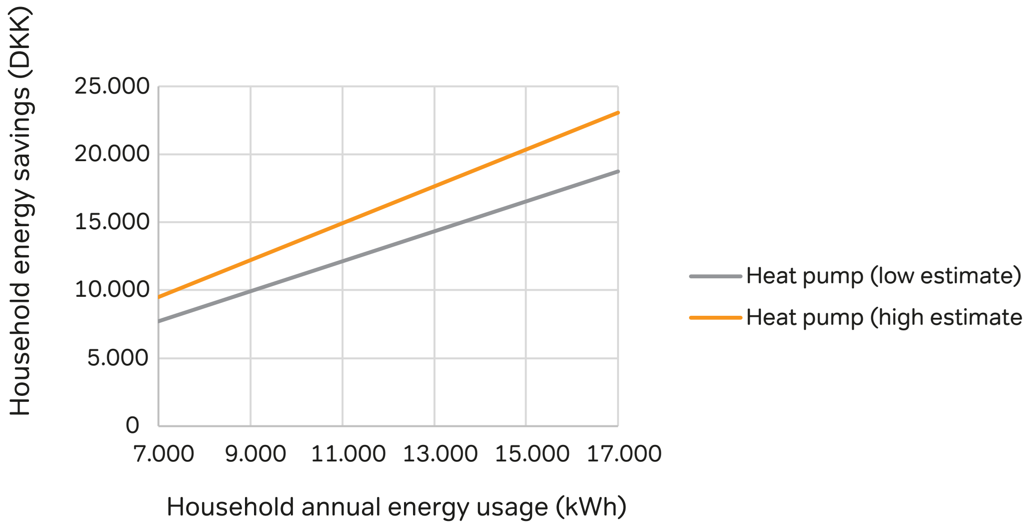


Fig. 13: Household annual energy savings compared to annual energy usage in Denmark.

Appendix 2:

Potential savings from underfloor heating in Germany

	Thermal comfort at reduced air temperature	Appliance efficiency at reduced flow temperature	Combined benefit	Comment
Gas boiler (80/60)	€96.72- €193.44	€48.36 - €96.72	€140.24 - €270.82	
Heat pump	€393.48 - €786.96	€983.70	€1,278.81 - €1,573.92	
District heating	€146.88 - €293.76	€0 - €367.20	€146.88 - €587.52	

Fig. 14: Potential annual household energy savings made by underfloor heating compared to radiator-based systems in Germany, assuming a household annual space heating requirement of 12,000 kWh.

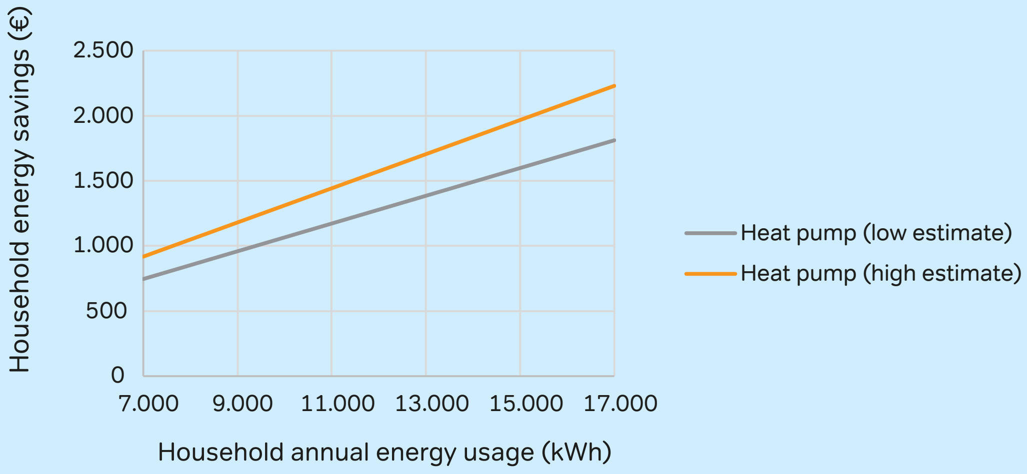


Fig. 15: Household annual energy savings compared to annual energy usage in Germany.

Appendix 3:

Potential savings from underfloor heating in Italyy

	Thermal comfort at reduced air temperature	Appliance efficiency at reduced flow temperature	Combined benefit	Comment
Gas boiler (80/60)	€118.32 - €236.64	€59.16 - €118.32	€171.56 - €331.30	
Heat pump	€373.80 - €747.60	€934.50	€1,214.85 - €1,495.20	
District heating	€47.52 - €95.04	€0 - €118.80	€47.52 - €190.08	

Fig. 16: Potential annual household energy savings made by underfloor heating compared to radiator-based systems in Italy, assuming a household annual space heating requirement of 12,000 kWh.

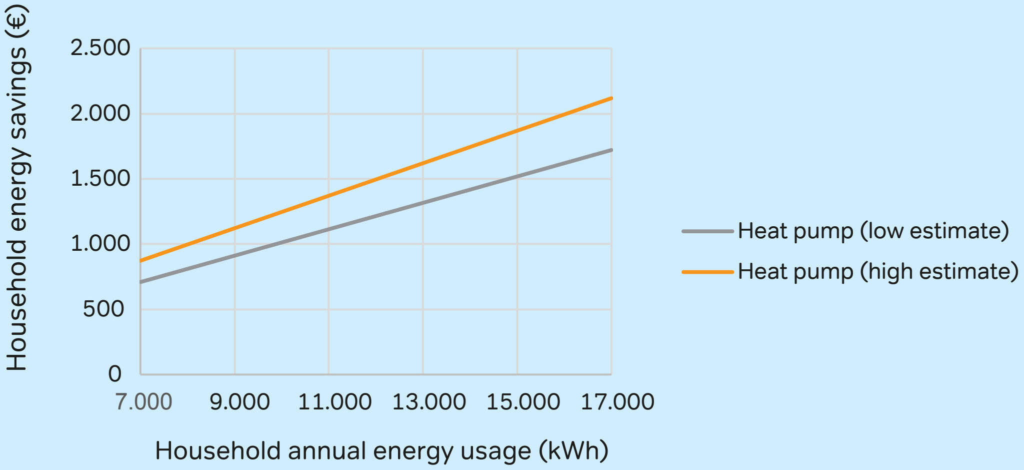


Fig. 17: Household annual energy savings compared to annual energy usage in Italy.

References & Notes

[1] ANSI/ASHRAE Standard 55

[2] Fanger's Comfort Equation was established by P.O Fanger in the 1970s

[3] VTT report showed that residents used a set point 2K lower for UFH than for radiator systems. (Guidebook to IEA ECBCS Annex 37 Low Exergy Systems for Heating and Cooling of Buildings Summary Report)

[4] UK Energy Saving Trust give rule of thumb that a 1K temperature reduction results in a 10% energy reduction. However, this varies in practice on design temperature and insulation level of home amongst other factors.

[5] Janne Hirvonen - Doctor of Science in Technology, Researcher at Tampere University

[6] Described in REHVA Journal 01/2018 - Radiators, convectors and energy efficiency

[7] Source: https://www.automaticheating.com.au/solutions/condensing-boilers-explained/

[8] High flow temperatures are needed to distribute the required heat through the available pipework, to provide a temperature suitable for DHW supply and to serve the existing high temperature radiators

[9] UCL 2017, Investigating variations in performance of heat pumps installed via the United Kingdom's RHPP scheme

[10] Danish Technological Institute; Pederson, S., and Emil Jacobsen. "Approval of Systems Entitled to Subsidies. Measurements Data Collection and Dissemination." (2011):

[11] Electrification of Heat Demonstration Project, Department of Energy Security and Net Zero, March 2023

[12] Additional values are given in the appendices for other countries (Germany, Netherlands, Denmark and France) based on their respective energy costs.

[13] Source: UK Gov https://www.gov.uk/government/publications/energy-bills-support/energy-bills-support-factsheet-8-september-2022

[14] European District Heating Price Series, Energiforsk, Sven Werner, 2016

[15] Demand Response (DR) is the shifting of (electrical) demand in response to (usually) cost signals which incentivize the reduction in demand when electricity prices are high and increasing demand by an equivalent amount to periods when it is available at lower prices

[16] A recent study (Flexible Heat, SIF funded study for Scottish Power Energy Networks, 2022) identified a value of up to £300 annually using thermal inertia of a home to avoid peak demand periods.

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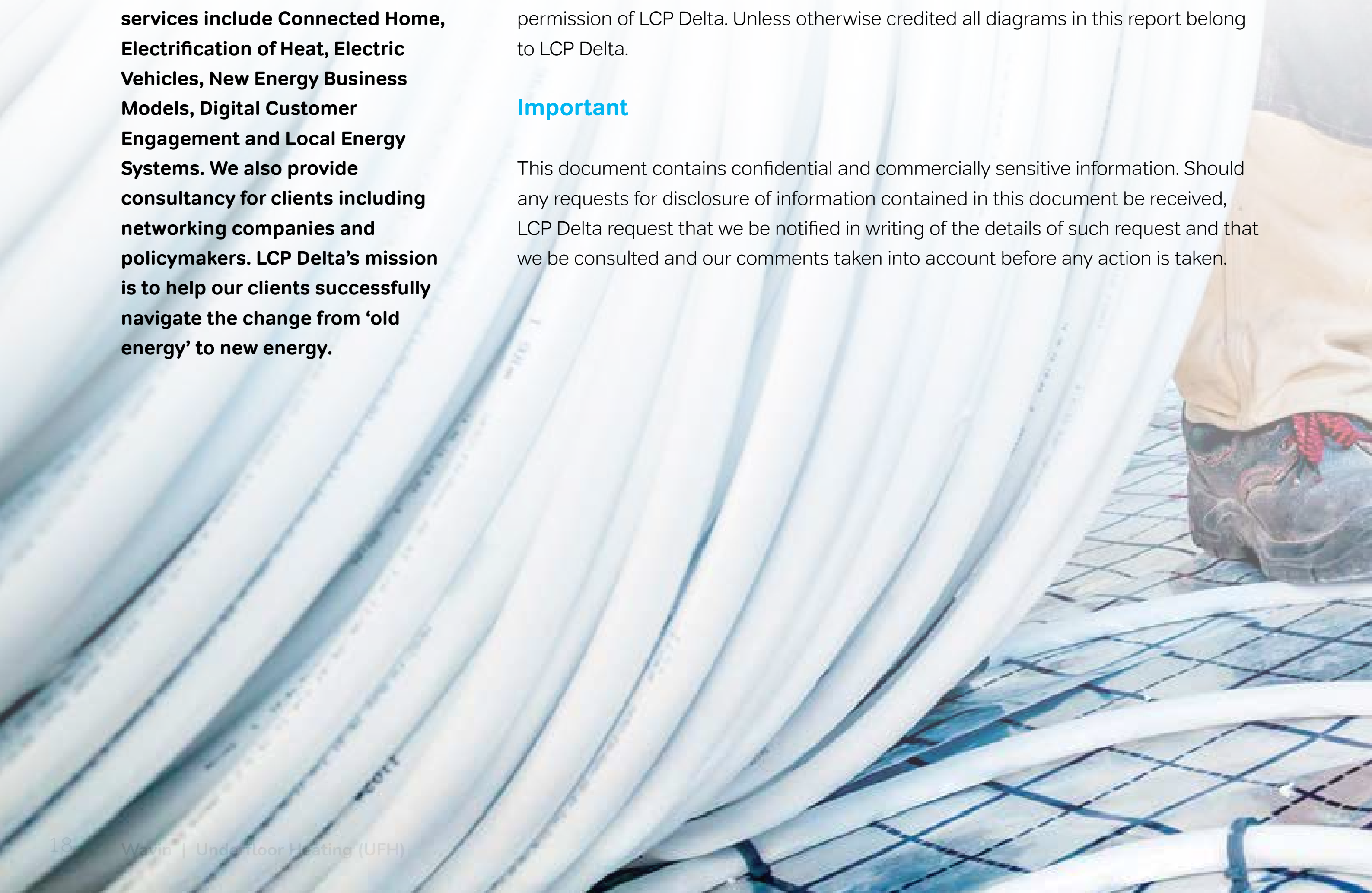

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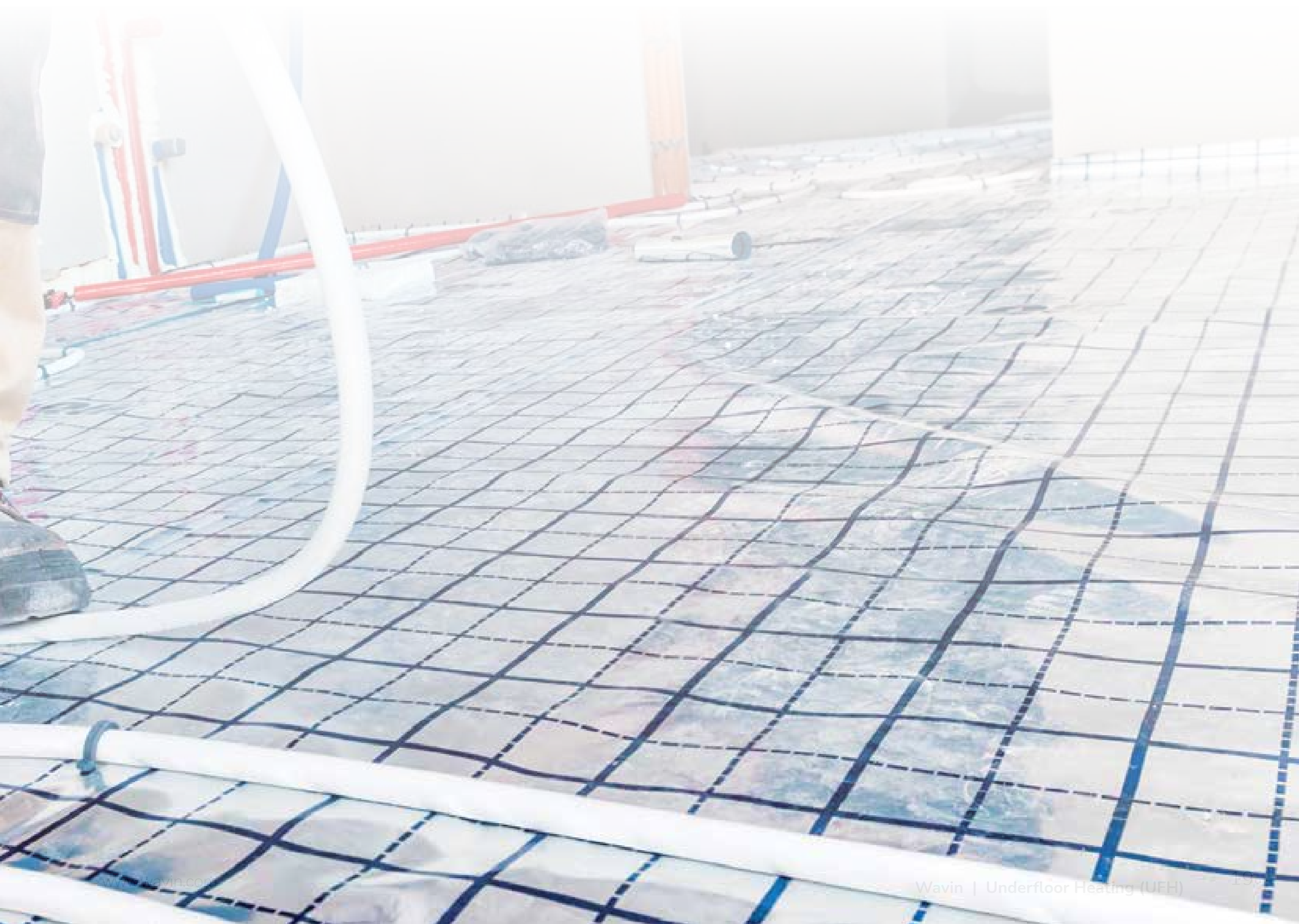

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