Domestic Hot Water Production Efficiency: From Boiler to Heat Pumps

In this opinion piece, Olivier Boennec describes efficient methods of heating domestic hot water, from gas boilers to heat pumps.

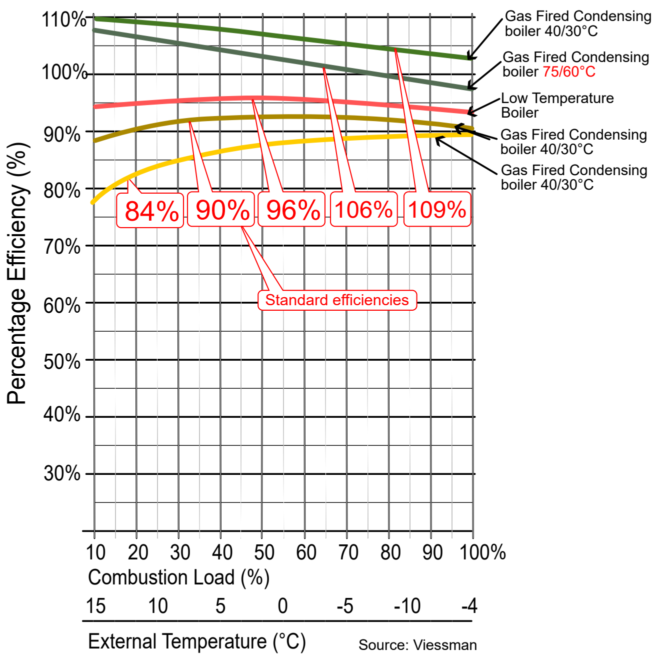
Domestic hot water production was traditionally performed with gas boilers. Before the 1970s boilers were non-condensing with active systems protecting the cast iron combustion heat exchangers from the corroding effect of water condensates resulting from the chemical reaction of combustion between the hydrogen in the gas and the oxygen from the fresh air comburant.

From the late 1970s onwards, stainless steel boilers became available, whereby condensing this chemically generated water was encouraged. However, so-called boiler back-end hydraulic protection continued to be provided. In 2012, CIBSE Application Manual AM14 was published, updating the guidance on how to optimise boilers to ensure that the condensation of the products of combustion is maximised (see graph 1).

The first method is to lower heating temperature and separate the hot water production via a dedicated higher temperature boiler as per figure (a).

To reduce installed cost or provide diversity between boilers, figure (b) provides the ability of a set of boilers to heat the storage vessel at high temperature for a few hours per day, then operate at lower temperature for heating-only operation in a change-over strategy. It is most common in domestic and Small commercial applications, including with combi-boilers and system boilers.

For larger systems CIBSE recommends adopting boilers equipped with two return connections, one to a passive heat recovery heat exchanger able to recover energy from the colder flu gases. It uses very low return temperature from the heating return header - see figure (c). Graph 1 quantifies how the variable temperature can benefit greater condensing efficiency.



Graph 1: Condensing Efficiency At Part Loads

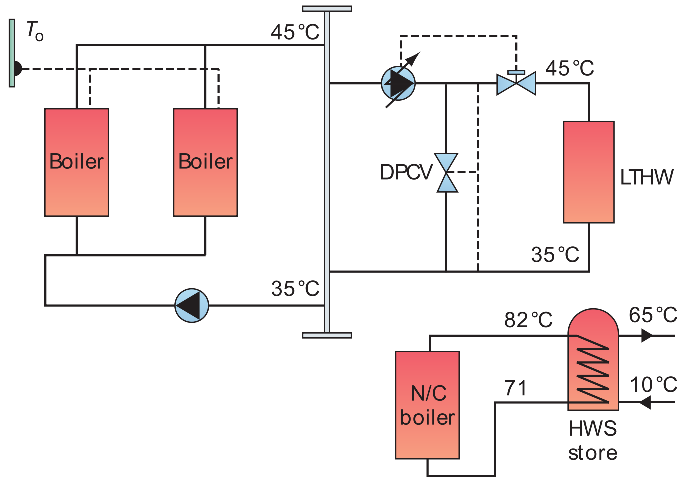
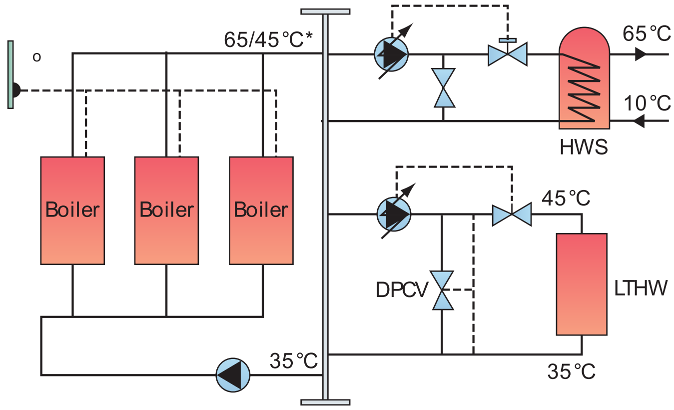


fig. (a) Separate boiler for hot water production



* 65°C if HWS needed; 45°C if LTHW only

Fig. (b) Boiler arrangement intermittent high/low set temperature

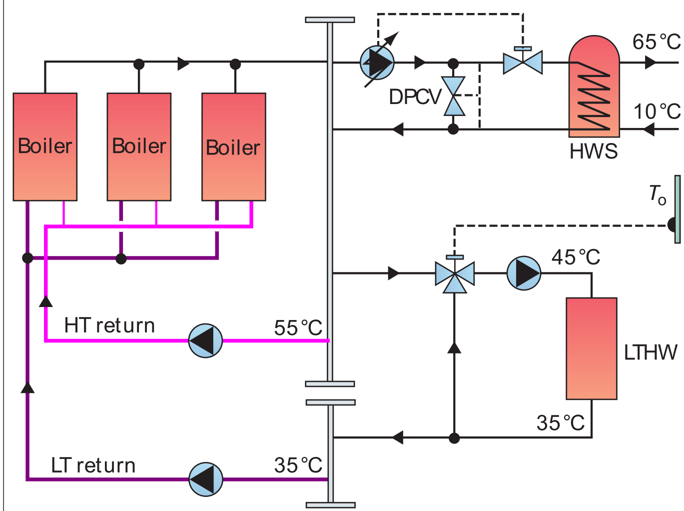


Fig. (c) Boiler arrangement with separate cold water return header

Diagrams above extracted from CIBSE AM14 Guide

From condensing boilers to heat pumps: how separating domestic hot water from heating can improve efficiencies.

Condensing boilers recover energy by condensing water in the products of combustion, which should flow into floor drains in the boiler plantroom, thereby recovering up to 12% of the fuel's dry heat combustion capacity.

From boilers to heat pumps: how domestic hot water production impacts the overall efficiency of heat pumps

Similarly, heat pumps contain gas that circulates in a closed circuit from condenser to evaporator, powered by a compressor. If the condenser (the hot part for the heat pump) is cold enough, the refrigeration cycle operates with greater efficiency. CO2 heat pumps can heat HWS with high delta T and operate at low return temperatures similarly to condensing boilers. However, when return temperatures are above 31.6°C, no condensation occurs and the "Condenser" operates as a gas cooler.

CO2 heat pumps can operate efficiently at high delta T with an operation envelop similar to that of boilers, so long as the cold water coming in to the heat pump is below 31.6°C. Otherwise CO2 heat pumps lose both efficiency and capacity. Whilst CO2 heat pumps operate at supercritical temperatures and the effect of condensation is less critical, other heat pump technologies (such as refrigerant R410A, R32 and R290 do require a suitable condensing temperature.

$$COP = \frac{Q_{hot}}{Q_{hot} - Q_{cold}} = \frac{T_{hot}}{T_{hot} - T_{cold}}$$

$$\mu_R = \frac{COP_{actual}}{COP_{carnot}}$$

$$COP = \mu_R \cdot \frac{T_{hot}}{T_{hot} - T_{cold}}$$

Where Q_{hot} = temperature of the hot sink

Q_{cold} = temperature of the environment (cold source)

$T_{hot} - T_{cold}$ are the corresponding temperatures

COP_{actual} is the electrical electricity used over the heating power delivered.

Figure (d) : Domestic Hot water in instantaneous heater with heating water thermal store (reduced flow temperature)(

Quantifying the improvement in the COP of heat pumps:

The efficiency of heat pumps is dictated by the ratio of the absolute temperature of the outlet versus the temperature lift performed by the heat pump from its source of heat to its delivered output temperature.

The equations in fig.d, derived from Carnot formula and the second law of thermodynamics reveal that the maximum efficiency of a heat pump has a theoretical limit. For example, a heat pump a compression cycle using air at 7°C outside to produce domestic hot water at 60°C, cannot have a COP greater than:
(60+73)/(60-7)=6.28. A COP of 6.28 would imply a 100% efficient heat engine. In a survey of various heat pumps, performed empirically from manufacturers' information, heat pumps typically achieve refrigeration efficiencies of 29% to 55%. It is to note that:

- These formulae help evaluate the relative refrigeration efficiency of heat pumps from different suppliers.
- The efficiency of a heat pump can be interpolated for different temperatures other than those quoted by suppliers.
- This enables better understanding of how COP change varying temperatures.
- Mapping the refrigeration efficiency of heat pumps helps optimise designs so that heat pumps operate at their 'sweet operation spot'.

> *"The local storage of domestic hot water can help elevate heat pump efficiency and reduce standing losses"*

The Impact of water heating in heat pump driven heat networks

For district heating systems, splitting heating demand from the domestic hot water demand as per fig. a. to c. can be challenging. Many systems operate with instantaneous hot water as per fig.e which results in the 24/7 operation of district heating systems.

HWS Keep-warm systems, present in many heat interface units (HIUs) guarantee the CIBSE CP1 criteria of achieving hot water at the tap within 45s but this constant operation can mean larger heat losses from distribution pipework, causing unwelcome heat gains to apartment blocks that are increasingly designed to near passivhaus standard.

Figure (e), (f), (g) and (h) illustrate the option of providing HWS local heat stores in apartments. CIBSE CP1 (page 75-76) describes how local storage gives the "*Opportunity to provide intermittent heat supply from the network to*

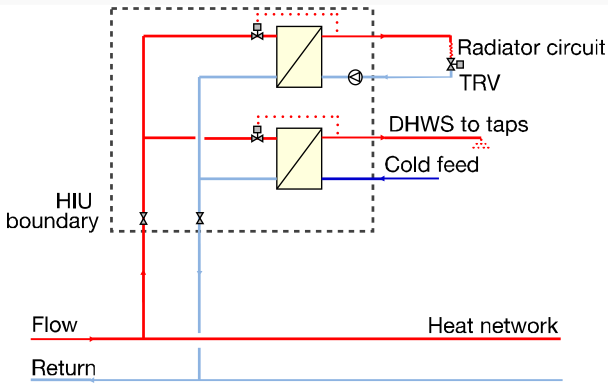


fig.e Indirect space heating and domestic hot water (CIBSE CP1 page 76 fig 24)

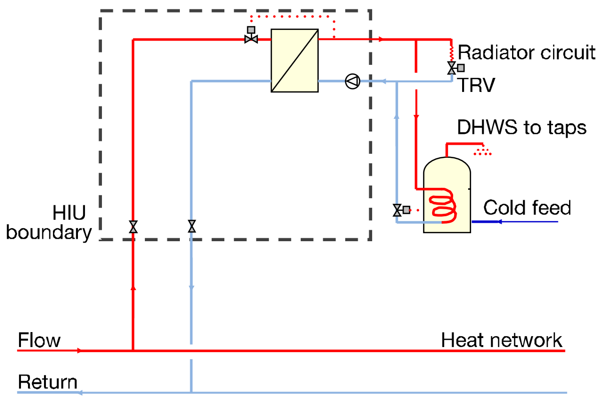


fig.f. Indirect space heating and hot water cylinder (CIBSE CP1 page 76 fig 25) *reduce heat losses from local branch pipework and there is no need for thermal bypasses."*

Figure (i) shows how a district heating system can be turned off during the warmer seasons. This can result in up to 20 fewer hours of daily heat network standing losses.
Fig. (h) shows a primary water storage tank and a secondary instantaneous domestic hot water heat exchanger that further reduce primary water temperature to 55°C where heat pumps can be implemented more effectively. This reflect the boiler strategies in fig. (b).

During heating periods, central district heating heat pumps can run more efficiently at 45°C flow temperature. Small additional immersion heaters can be added for the very occasional times of excess hot water demand or palliate system downtimes. The additional electricity consumption should be marginal if the hot water tank is sized to CIBSE guide G. Hot water vessels represent a small heat gain in apartments, but figure (j) shows that the gains are minimal compared with short length of district heating pipes. Hot water cylinders are normally located in cupboards with over 10 l/s of ventilation that reduce hot vessel heat gains to the apartments.
As part of the design of apartments, a review of the heat gain from both domestic hot water cylinders and associated distribution pipework within the dwelling should always be assessed and where necessary mitigated against to avoid unwanted heat gain.

Typical HIU with cylinder (Danfoss Thermix)

Using fig.(d) formulae reducing the district heating temperature from 60°C to 45°C during heating-only period can improve heat pump COPs by 33% (with Th=60°C dropping to 45°C with Tc=7°C).

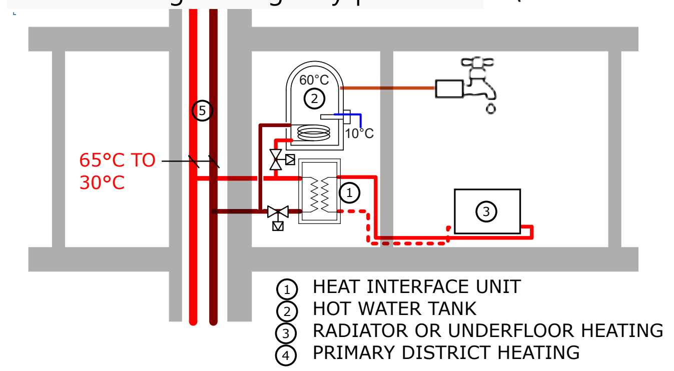


Figure (g) : Domestic Hot water calorifier (>60°C storage)

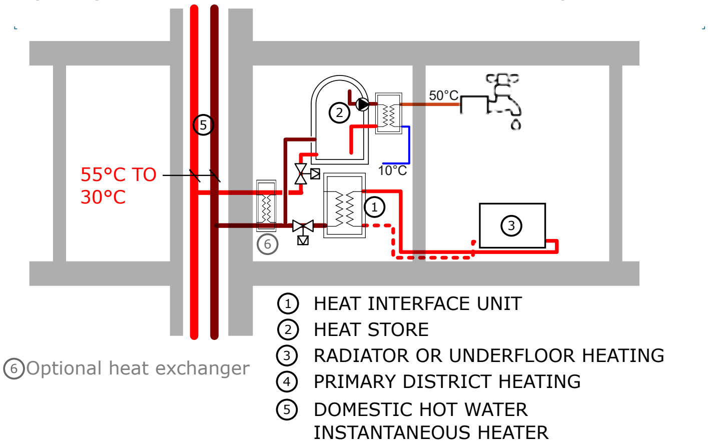


Figure (h) : Domestic Hot water in instantaneous heater with heating water thermal store (reduced flow temperature) as per CIBSE CP1 page 76 fig 27)

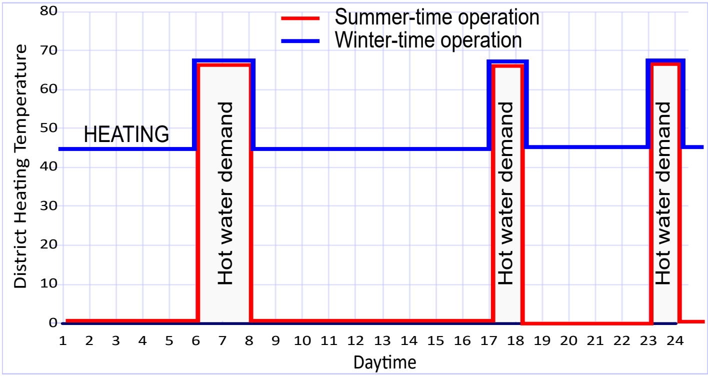
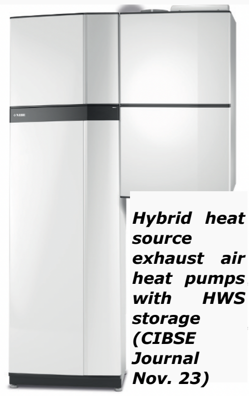


Figure (i) : Intermittent operation of district heating systems using HWS stores in apartment (Winter/Summer operation).

Local HWS storage can also help reduce primary flow rates: with CP1 simultaneous factor of 8.6%, 30 apartments demand 152 kW of heat vs. 30x3kW=90kW with storage.

Local storage of HWS is increasingly common in the UK and Europe notably in Exhaust Air Heat Pumps (CIBSE CPD module 225, Nov.23) and cascade or ambient loop heat pump (CIBSE Journal module 190, Jan. 2022) and illustrate in fig.(k).

The UK government promotes heat networks but new regulations announced in Feb 2025 impose new efficiency targets (See CIBSE Journal Feb. 2025). New technical solutions are emerging to help meet this challenge.



Hybrid heat source exhaust air heat pumps with HWS storage (CIBSE Journal Nov. 23)

Ambient Loop heat pump with HWS storage (CIBSE Journal Jan. 24)

Fig.k: examples of local DWHS storage

CYLINDER IN APARTMENT

Internal Diameter	0.55	m
Internal Radius	0.28	m
Insulation Thickness	0.08	m
External Radius	0.35	m
Length of Cylinder	1.5	m
Thermal Conductivity (Insulation)	0.02	W/m.K
Internal Temperature	60	°C
External Temperature	21	°C
Calculation		
Temp Difference	39	°C
Cylinder Wall Heat Loss	32.01	W
End Area	0.38	m^2
End Heat Loss	8	W
Total Heat Loss	**40.41**	**W**

PIPE IN CORRIDOR

Internal **Flow** Diameter	0.021	m
Internal **FLOW** Radius	0.0105	m
Insulation Thickness	0.05	m
External Radius	0.0605	m
Length of Pipe	**4**	**m**
Thermal Conductivity (Insulation)	0.04	W/m.K
Internal Temperature	60	°C
External Temperature	21	°C
Calculation		
Temp Difference	39	°C
FLOW Pipe Heat Loss	**22.39**	W
Internal return Diameter	0.021	m
Internal return Radius	0.0105	m
Insulation Thickness	0.05	m
External Radius	0.0605	m
Length of Pipe	10	m
Thermal Conductivity (Insulation)	0.04	W/m.K
Internal Temperature	35	°C
External Temperature	21	°C
Calculation		
Temp Difference	14	°C
return Pipe Heat Loss	20.092	W
Total Flow and Return	**42.48**	**W**

Figure (j): relative heat losses of apartment storage vs. pipework losses.

The vessel is equivalent to 4m of LTHW flow and return pipes assuming 75mm PIR insulation vs. 50mm Rockwool for pipes

"Newer heat pumps can operate with similar building envelops to boilers"

Although combining the process of domestic hot water heating with space heating can negatively affect the performance of heat pumps, newer heat pumps capable of operating at greater temperature differentials are becoming available using refrigerant other than CO2, driven by northern European countries keen to further decarbonise heating systems.
When high delta T is achieved on heat pumps, refrigeration efficiencies can exceed 50% and the COP of heat pumps can exceed 3.5 as discussed in a forthcoming white paper to be presented at the CIBSE Symposium in April 2025 (1).

Fig. l: R290 Heat pumps designed for 20K and 30~40K delta T

To achieve high delta T on heat pumps, three strategies are possible:
1) Choose high delta T heat pumps (CO2 or R290).
2) choose medium high delta T heat pumps in series.
3) opt for low delta T heat pumps but connect more of them in series.
4) provide heat pumps in cascade system.

Obtaining 30 K delta T (typical for a district heating system) is possible using heat pumps in series. Heat pumps in series are a solution still in development and few manufacturer's promote this solution but several installations have been successful around the UK such as installations illustrated in fig. m.
Obviously, installing six heat pumps in series to achieve 30K delta T is impractical and undesirable. Hence a desire for suppliers to offer heat pumps with the largest delta T practical and possible in order to obtain the same effect without the complexity of too many heat pumps in series.

As an alternative, heat pumps in cascade are sometimes proposed (fig. p): so-called ambient loops systems, designed to provide heating, cooling and hot water using terminal heat pumps in apartments offer in reality very limited simultaneous heating and cooling operation and function principally as 'cascade' heating system, reversing to be cascade cooling systems. The COPs of cascade system are relatively low because only the primary heat pump is able to harvest free energy from the ambient air as shown in the Sankey diagram (o).

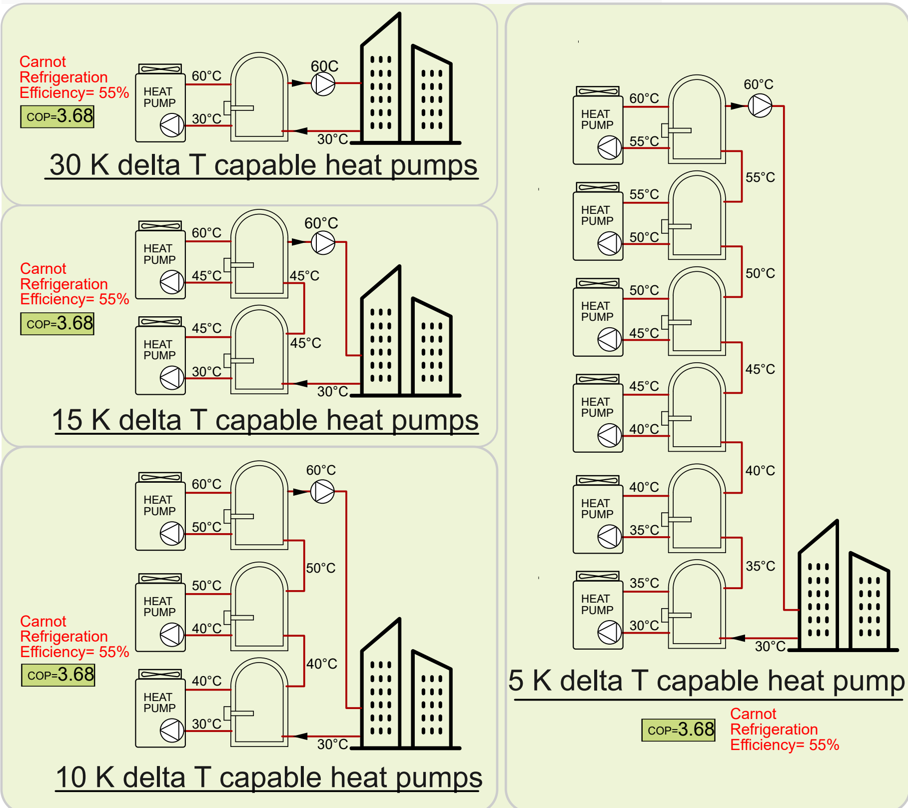


Fig. m: Heat pumps in series to achieve 30K delta T

$$\text{Total } CoP_t = \frac{Q_t}{E_a + E_w} = \frac{CoP_a \times CoP_w}{CoP_w + CoP_a - 1}$$

Fig. n: COP calculation of heat pumps in cascade

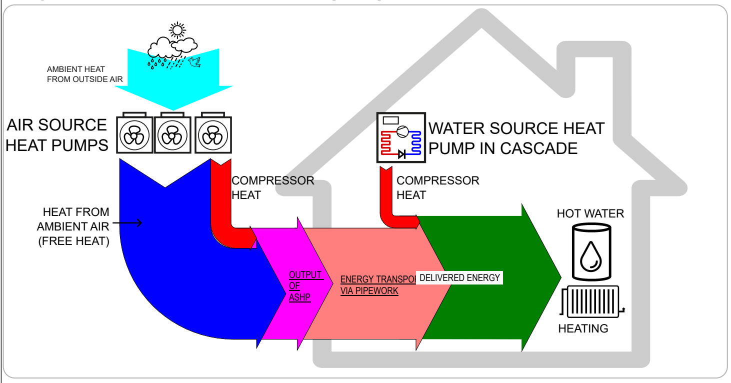


Fig. o: Sankey Diagram of heat pumps in cascade

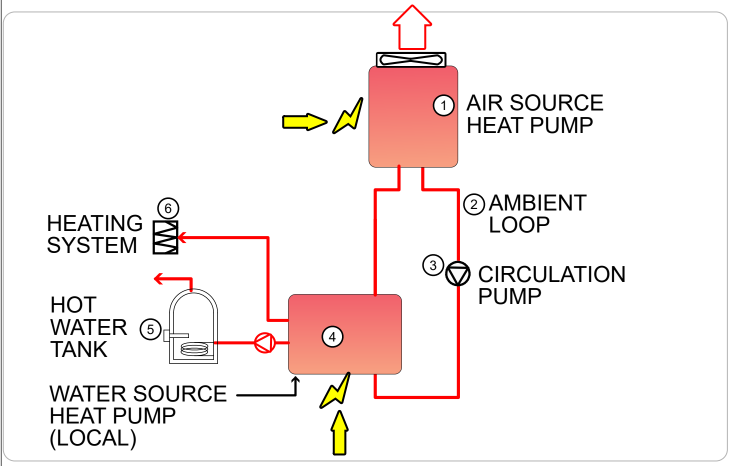


Fig. p: Diagram of heat pumps in cascade arrangement

Footnote:
Consider the use of smart energy meter with time of use electricity tariffs and smart water metering to help lower running costs and promote responsible water usage.

The equation (n) from CIBSE Application manual AM16 and AM17 shows that the combined COP of a cascade heating system typically achieves values well below the COP typically achieved by heat pumps design to high delta T and well below the COP of domestic heat pumps.

	Case 1	Case 2	Case 3	Case 4	Case 5
COP A (Air source heat pump)	3	4	4	4	5
COP W (water source heat pump)	5	6	7	9	9
Combined COP	2.14	2.67	2.80	3.00	3.46

Fig. q: Illustration of COPs obtained for various combinations of air source heat pumps and water source heat pumps in a cascade arrangement using fig.n equation.

Fig. q above illustrates how, in a cascade system, the COP of air and water source heat pumps result in a Combined COP. Cases 1 to 5 assume different COP values for each of the two stages. Even in the most optimistic case 5, the result is below that achieved by other alternatives. In addition to this, ambient loop systems or cascade systems have relatively high pumping energy costs that further handicap the total combined efficiency and involve a high capital cost.

Dedicated domestic hot water CO2 heat pumps offer relatively high COPs of 3.2 to 3.5 (fig. s) thanks to high delta T that are possible, but they may not be as high as some propane heat pumps designed for high delta T: this relatively low COP is attributable to the relatively low enthalpy of CO2 (refrigerant R744) (fig.r and t.).

CO2 heat pumps operate at very high pressures of over 100 bar in supercritical fluid. The passage from supercritical liquid to super critical gas takes place at 31.6°C with no latent heat of condensation. The condenser operates wholly or partly as gas cooler. Meanwhile the evaporator does not benefit from the full enthalpy range of latent evaporation as shown on fig. r. CO2 heat pumps require a guaranteed low return temperature. Otherwise, their capacity drops faster than for any other type of refrigerant. For this reason, they are not adapted to district heating systems where return temperature are subject to quality and maintenance issues.

In conclusion, the energy efficiency of producing, distributing and storing domestic hot water depends on achieving high delta T primary heat source and secondary distribution temperatures. Combining heating and domestic hot water delivery can have a negative impact on the total system's energy efficiency, but through better controls strategies, good hydraulic design and newer heat pump developments, improved energy efficiency can be compatible with greater design simplicity to meet the challenge of decarbonising both heating and hot water heating systems.

On the distribution side, multiple, localised energy storage units with the option of instantaneous hot water heating can also reduce heat losses and improve primary plant system efficiencies.

More information was presented at the CIBSE symposium on 24-25 April 2025. See inset (1)

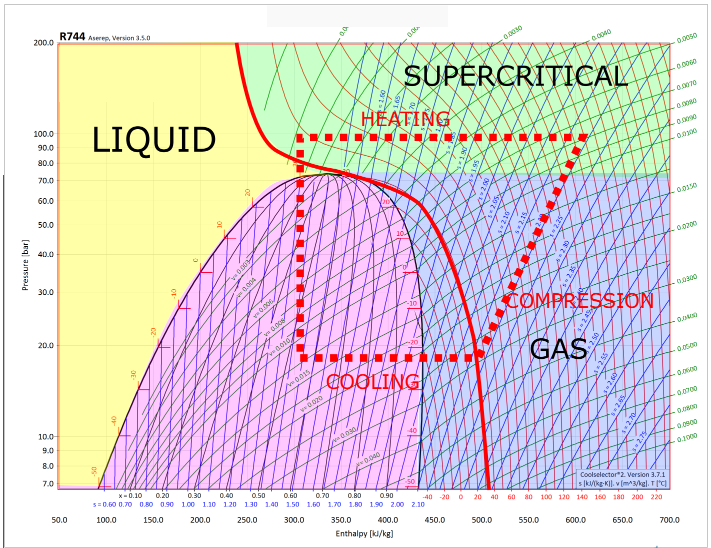
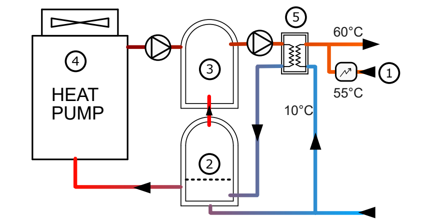


Fig. r: Enthalpy-pressure diagram of R744 (CO2)



① HWS RETURN WITH ELECTRIC REHEATER
② COLDER RETURN HEAT STORE
③ WARMER HEAT STORE
④ HIGH DELTA T HEAT PUMP (E.G. CO2)
⑤ INSTANTANEOUS HOT WATER HEAT EXCHANGER

Fig. s: Typical hydraulic arrangement of CO2 heat pump

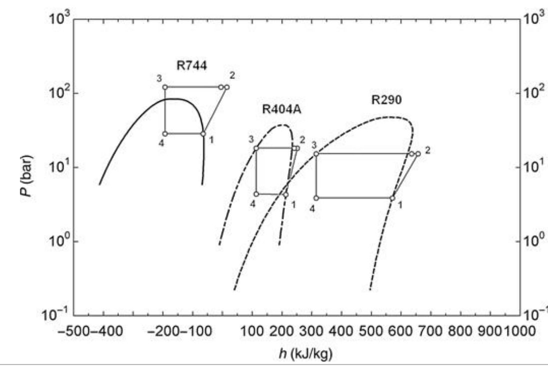


Fig. t: Comparative Energy and Exergy Analysis of R744, R404A and R290 Refrigeration cycles, J.A. Shilliday S.A. Tassou and N. Shilliday - School of Engineering and Design, Brunel University, Uxbridge

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Strategies to evaluate and improve the efficiency of heat pumps

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(1) Download the white paper of the CIBSE Symposium at https://www.cibse.org/knowledge-research/knowledge-resources/technical-symposium-papers/