Heat pumps and their role in the decarbonising of heat

CIBSE North-east region technical meeting, January 2018

Chris Underwood
(Professor of Energy Modelling for the Built Environment, Faculty of Engineering & Environment, University of Northumbria at Newcastle)

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Outline

- First, how can we use them why should we get interested in heat pumps
- Next, a technology review
- The potential of heat pumps to reduce carbon emissions will be demonstrated
- Current technology however is not living up to this promise – reasons will be explored
- A look at some of the research and engineering practice questions that might be posed to address performance shortcomings
- A look at some examples of how the technology might be exploited in future

A future for heat pumps?

- There is a growing need to reconsider the means by which we deliver domestic space and hot water heating in the UK in order to…
  - Reduce carbon emissions
  - Diversify from an over-dependence on gas
  - Arrest the alarming rise in fuel poverty
- The government likes to call this its *energy trilemma*
- It will be shown that heat pumps have the potential to address all of the above
- They are expected to play an increasing role in the search for alternatives to conventional gas boiler-based heating

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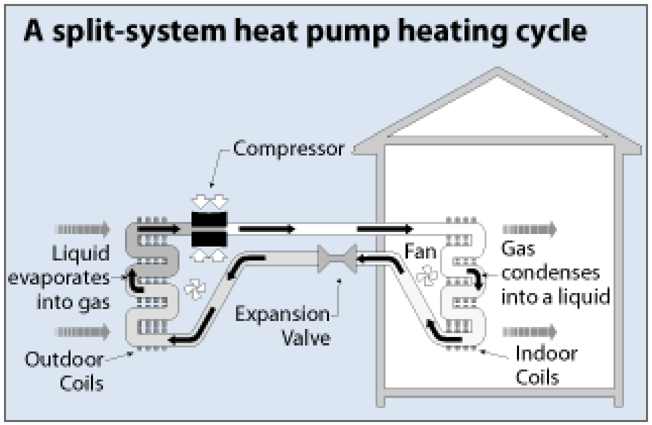
Vapour compression cycle – accounts for >90% of heat pumps worldwide

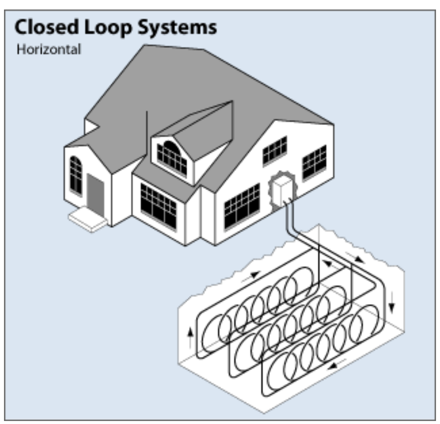


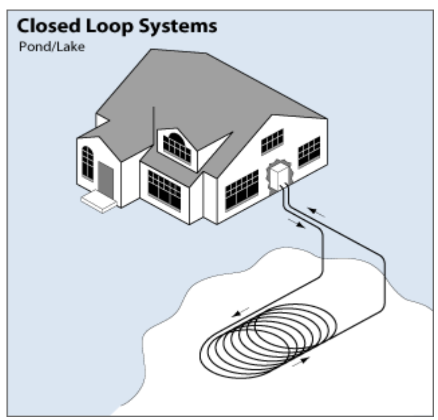
According to the First Law: $Q_c = Q_e + W_c$

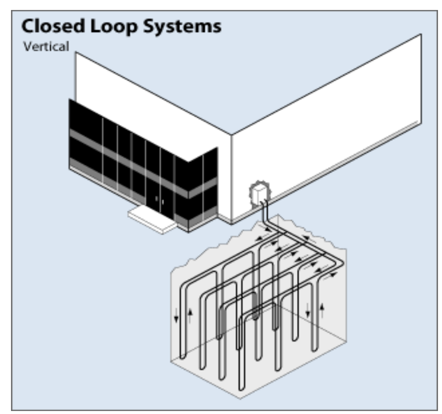
Practical cycle, for a heat pump: $CoP = Q_c / W_c = Q_c / (Q_c - Q_e)$

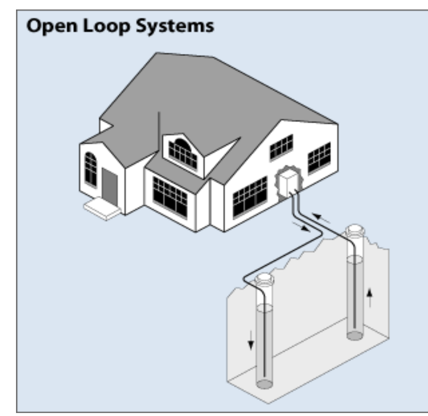
$$CoP_{\text{Refrigerator}} = Q_e / W_c = (Q_c - W_c) / W_c = (Q_c / W_c) - 1 = CoP_{\text{HeatPump}} - 1$$

That is: $CoP_{\text{HeatPump}} = CoP_{\text{Refrigerator}} + 1$









(Figures reproduced courtesy of the US DOE Office of Energy Efficiency and Renewable Energy)

So what?

- In the UK alone 300,000 domestic gas boilers are replaced every year.
- At best, each operates at a seasonal mean efficiency of 0.92 (*).
- Each will discharge 0.184/0.92 = 0.2kg of CO_2 to the atmosphere per unit of energy delivered to the connected heating system (**).
- Today in the UK, a heat pump, operating with a *CoP* of 3, will discharge 0.352/3 = 0.117kg of CO_2 – nearly 42% less than the best gas boiler.
- In 2015, the same heat pump would have discharged 0.15kg of CO_2 – 25% less than the gas boiler
- The reduction in CO_2 emission since 2015 is the result of the electricity grid decarbonising in the meantime

* Recent surveys suggest that as many as 90% of UK domestic gas boilers rarely condense which means that their seasonal efficiencies are more likely to be around 0.85.

** https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2017 (accessed 7th August 2017)

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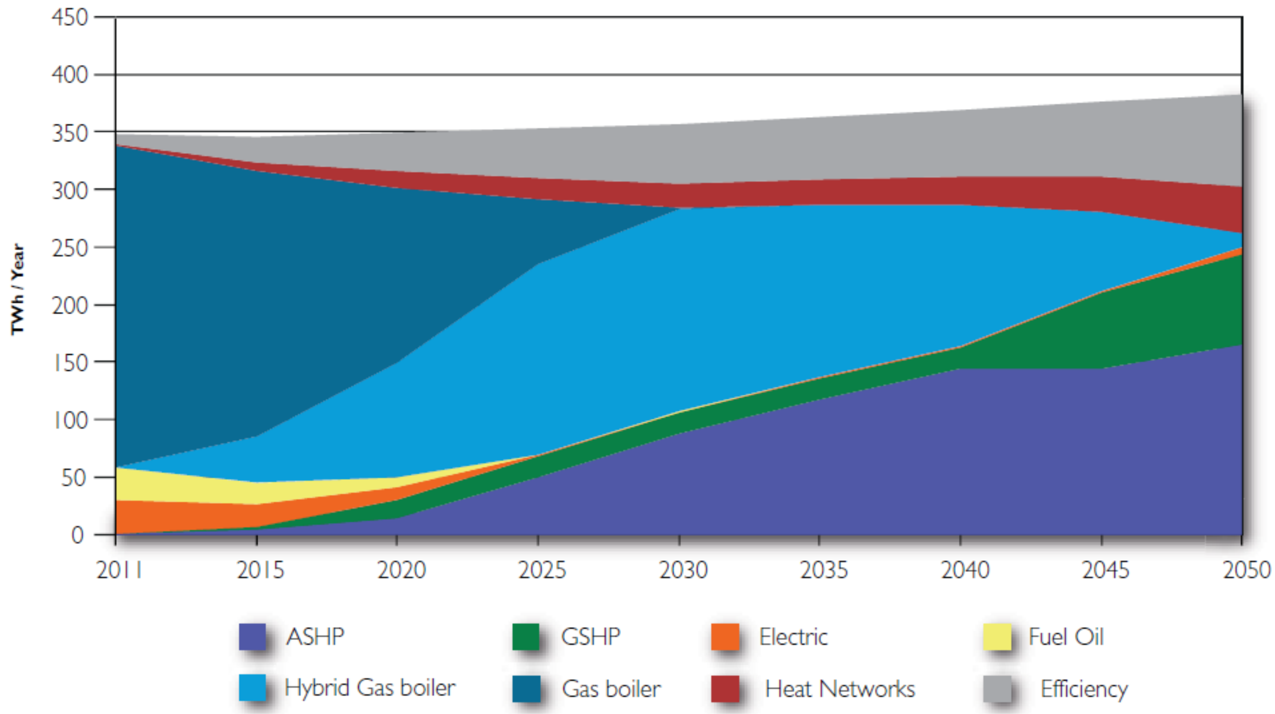
UK domestic space and hot water energy by technology to 2050



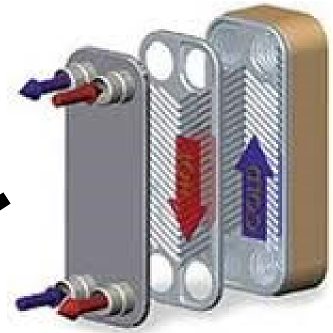
(Notwithstanding fracking, the pressure is on to diversify away from gas for those countries without indigenous reserves)

Source: *The future of heating: Meeting the challenge*. London: Department of Energy and Climate Change. [Online] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/190149/16_04-DECC-The_Future_of_Heating_Accessible-10.pdf (accessed November 2014)

Heat pumps – a review of the technology

Well established 1st and 2nd generation technologies…

Brazed plate condenser
(typical ‘pinch’ 2-3K)

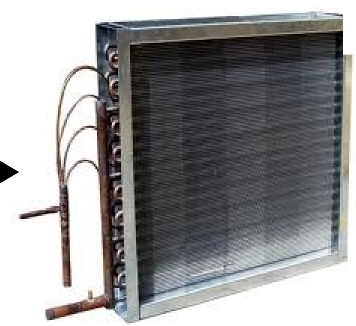


Mechanical thermostatic
expansion valve

Working fluids – R134a or
zeotropic blends R407C, R410A

Water source - brazed
plate evaporator
(typical ‘pinch’ 2-3K)

OR



Air source – fin-and-coil
Evaporator (typical ‘pinch’
3-5K)

Scroll
compressor

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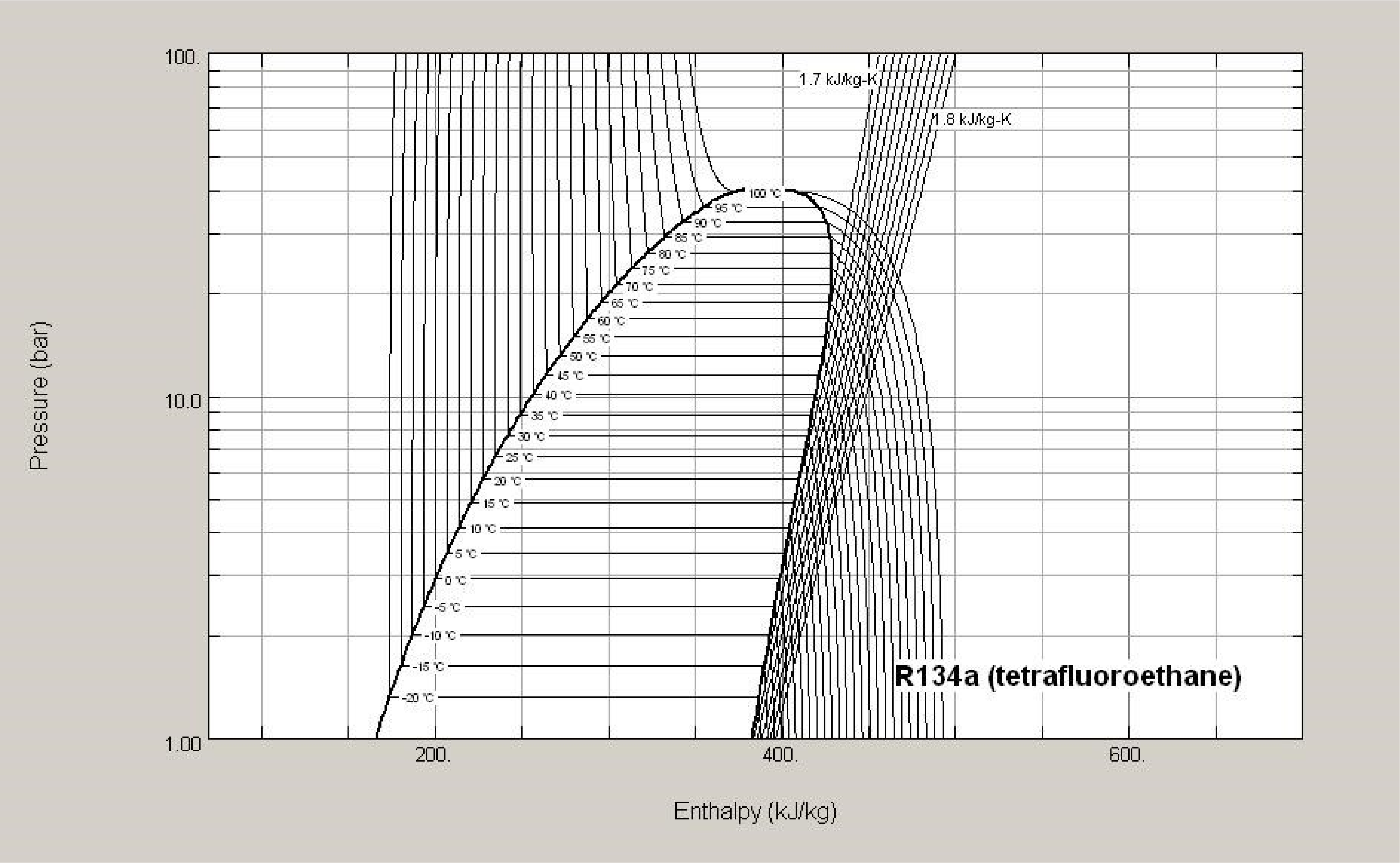
Working fluids – pure fluid R134a



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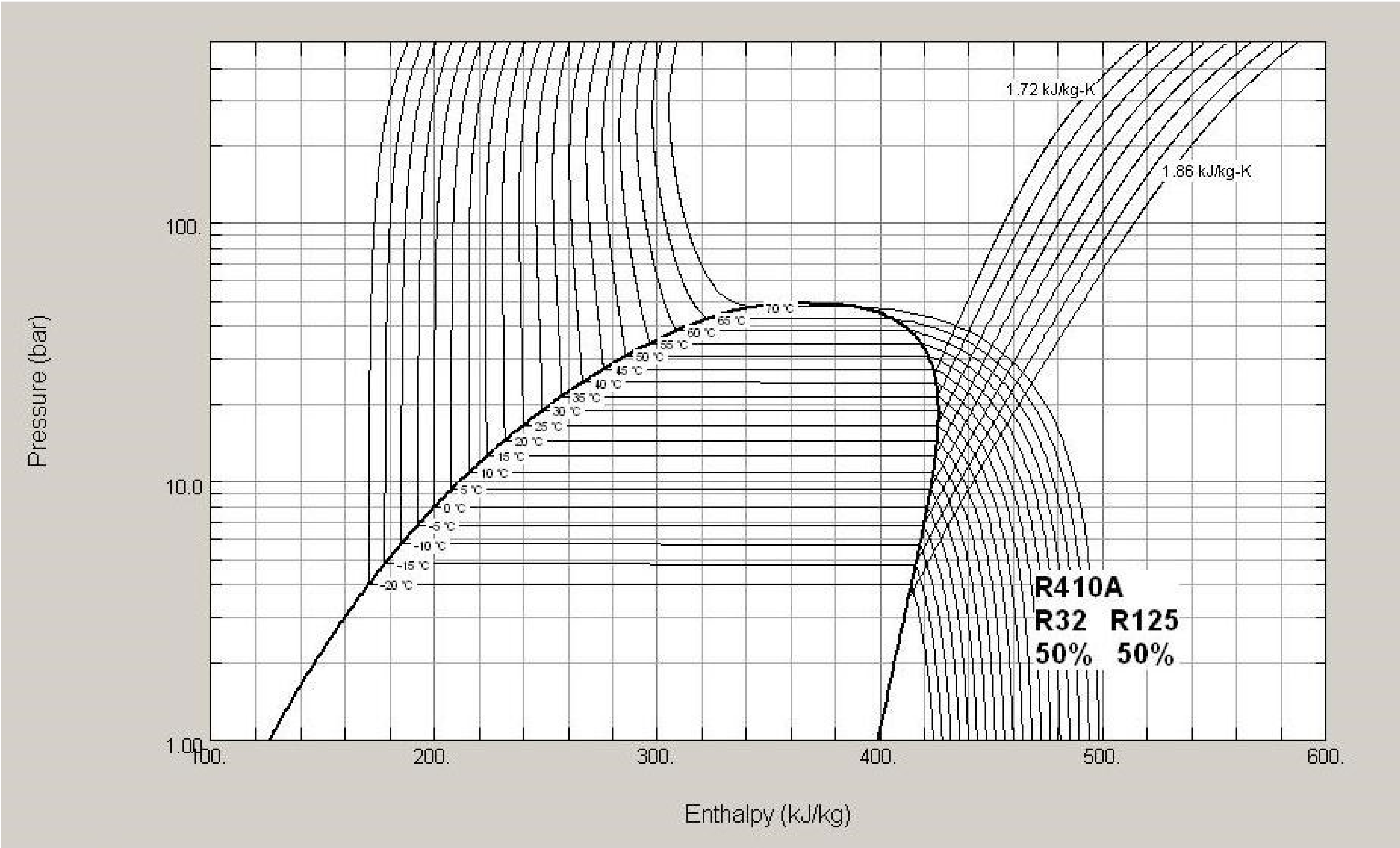
Working fluids – binary near-azeotrope blend R410A



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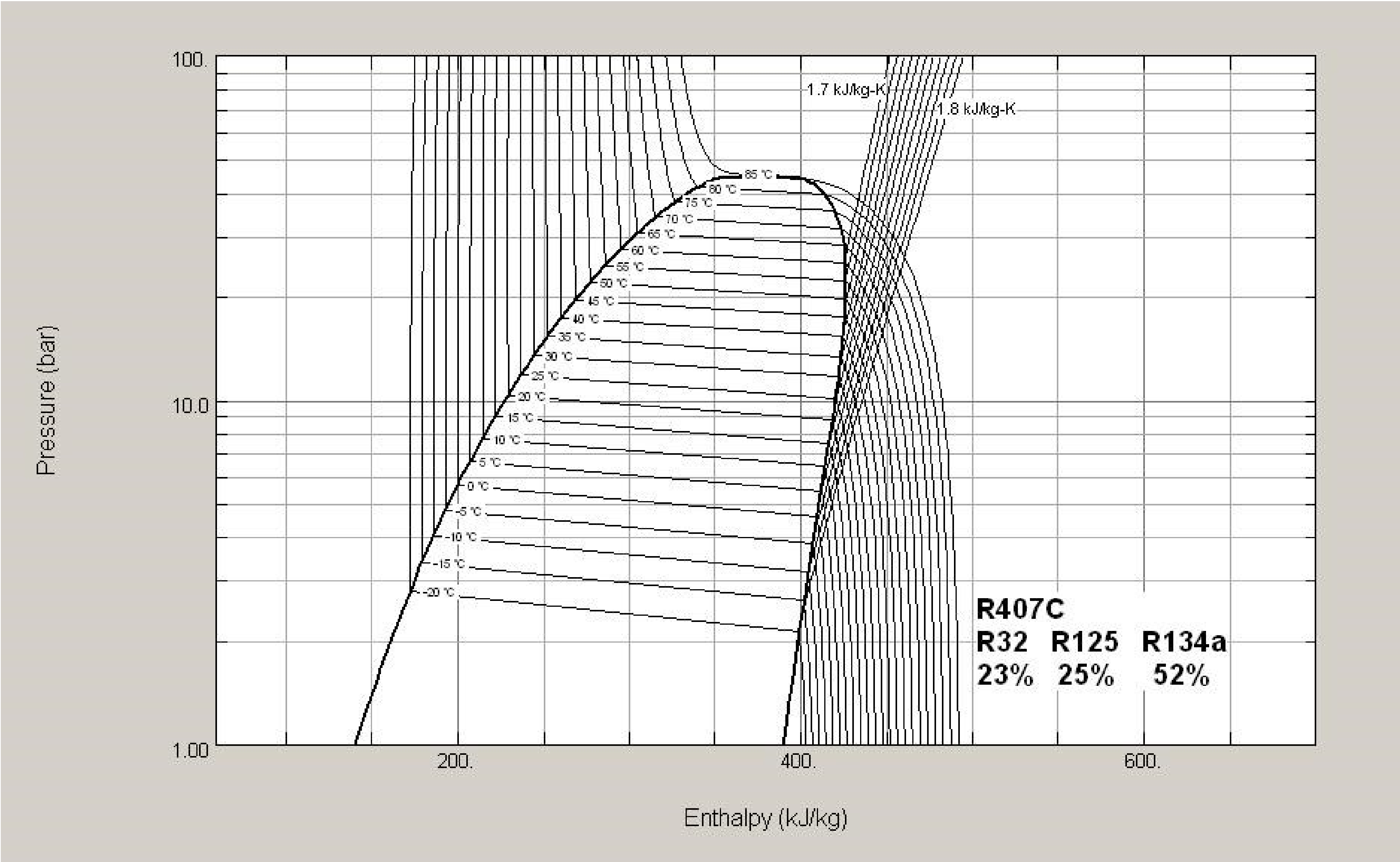
Working fluids – ternary zeotropic blend R407C



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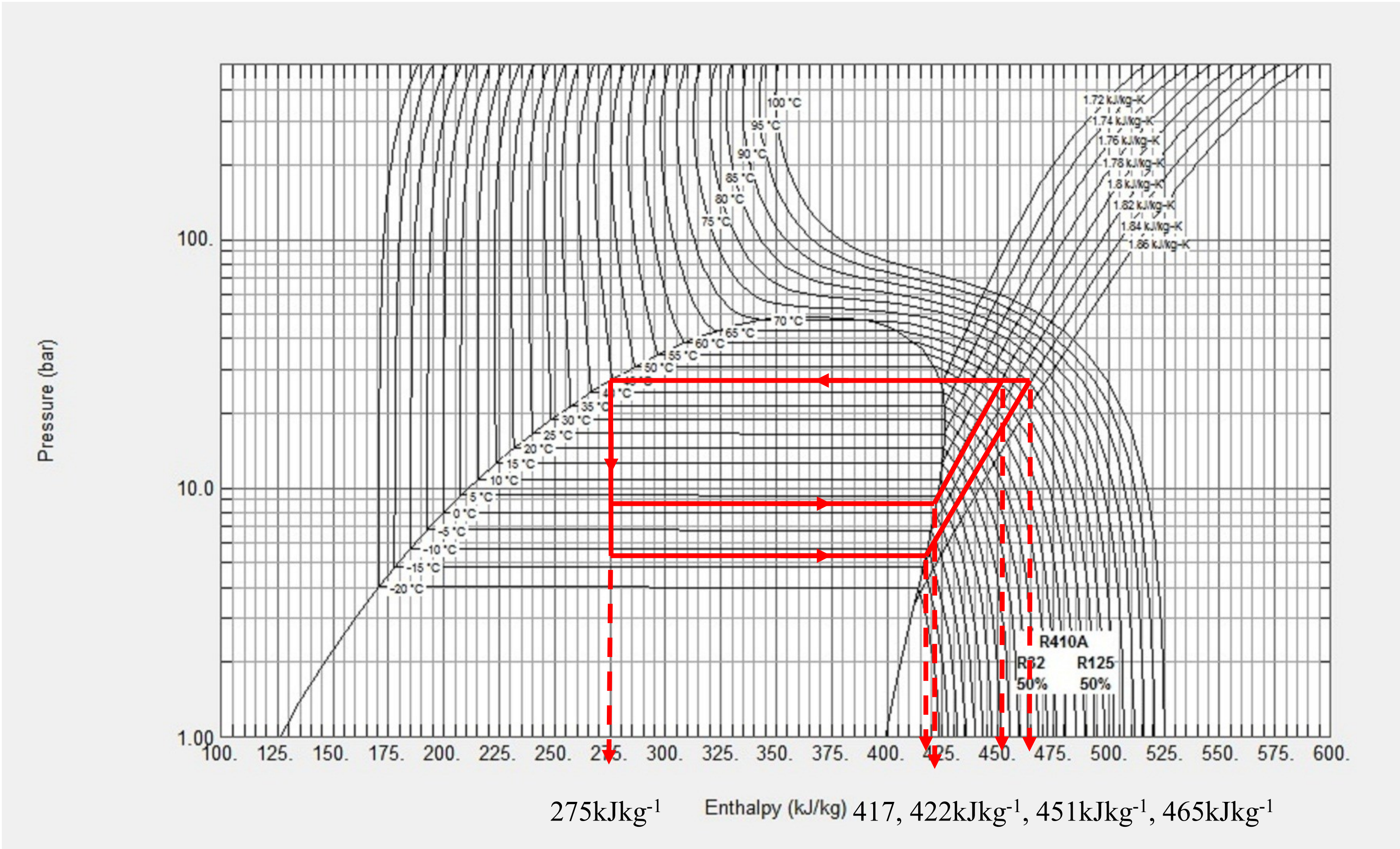
Common working fluids compared

FLUID	TYPE	GWP (*)	COMMENT
R134a	Organic HFC	1430	Mainly commercial
R407C	Organic HFC blend	1774	Domestic/commercial
R410A	Organic HFC blend	2088	Domestic/commercial
R32	Organic HFC	675	Not yet widespread; flammability
R290	Organic HC	3.3	Mainly process; flammability
R717 (ammonia)	Inorganic	?	Toxicity
R744 (CO_2)	Inorganic	1	Low critical temperature

*Global warming potential – the global warming effect with reference to CO_2

Theoretical performance

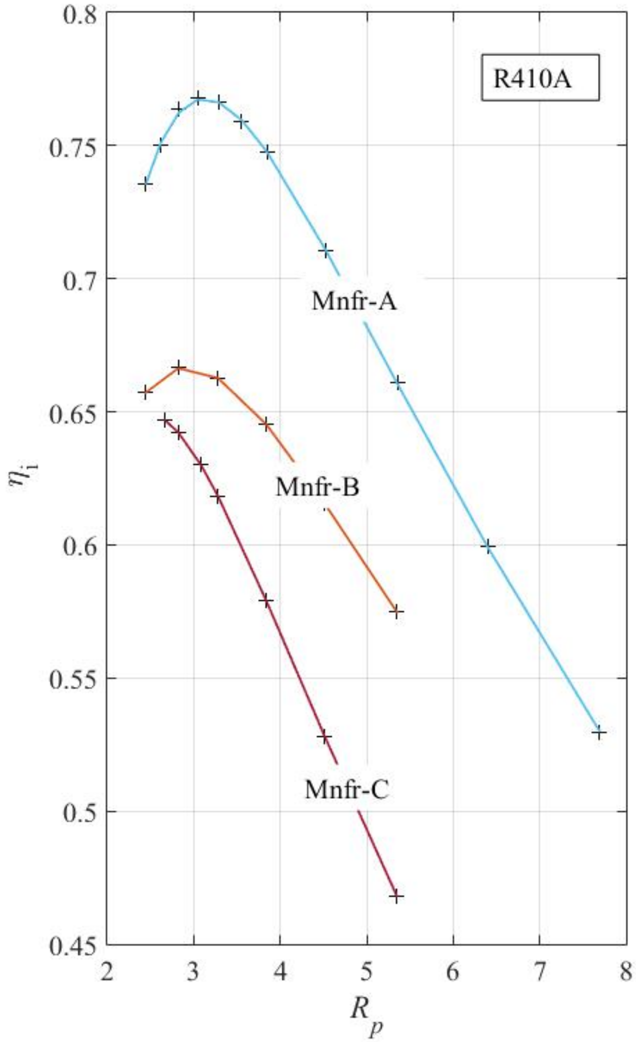


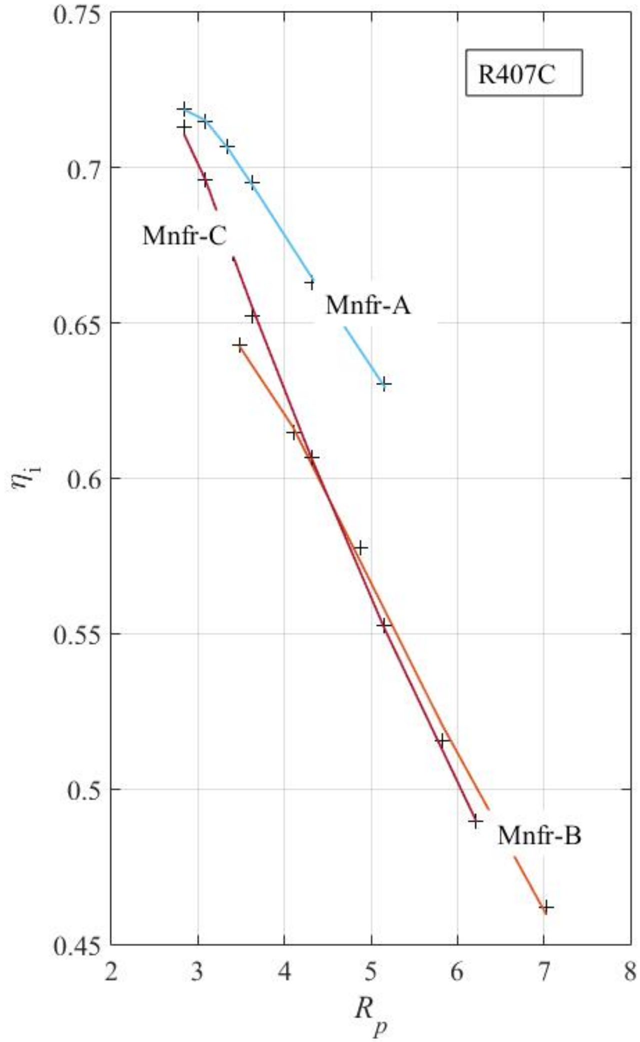
For an overall compressor isentropic efficiency of 0.65...

Ground source: $CoP = 0.65 \times \dfrac{451-275}{451-422} = 3.9$ Air source: $CoP = 0.65 \times \dfrac{465-275}{465-417}$ =2.6

(Typically, the source pump will reduce CoP_{GS} by up to 5% and the source fan CoP_{AS} by up 10%)

Typical compressor efficiencies are key





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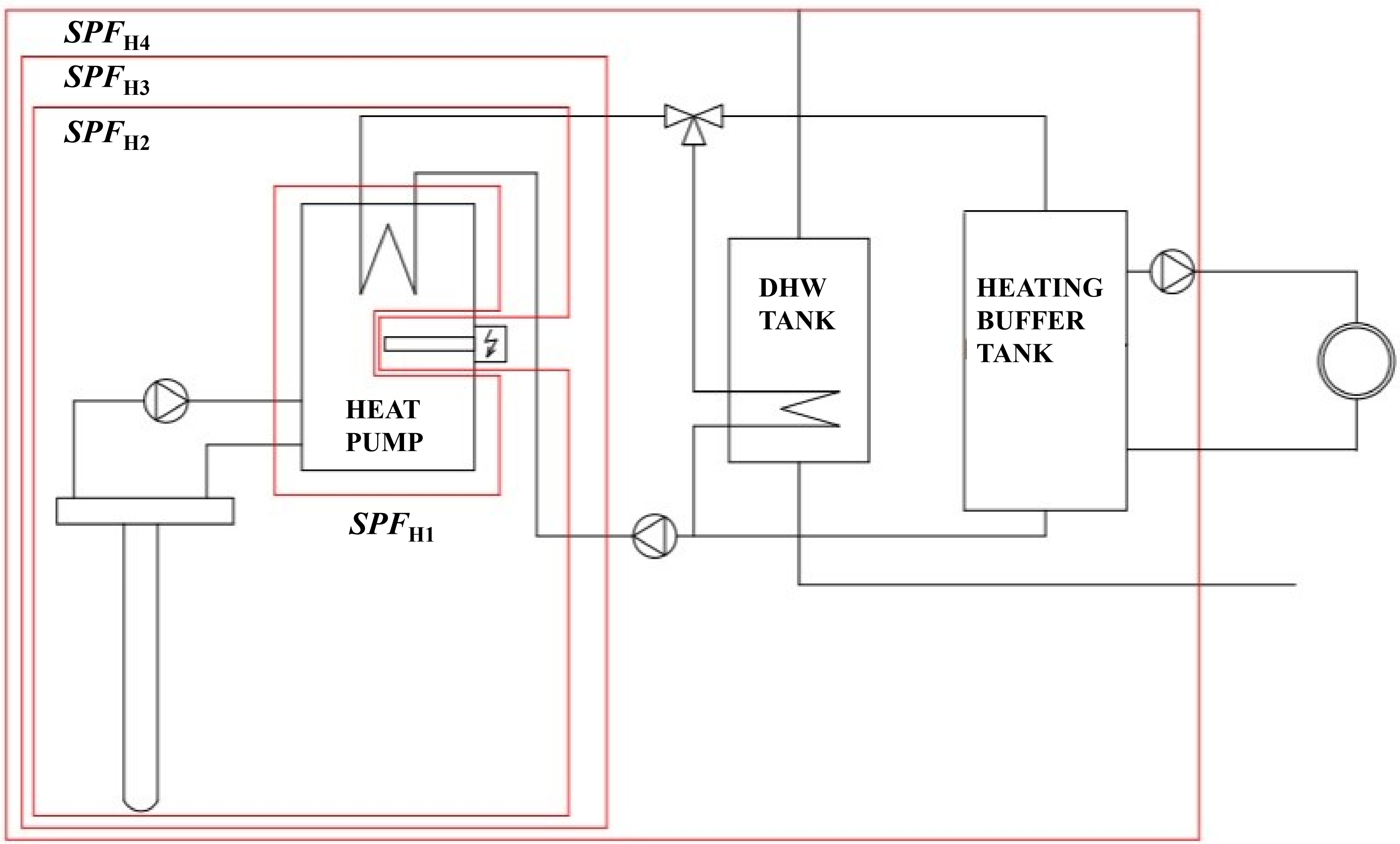
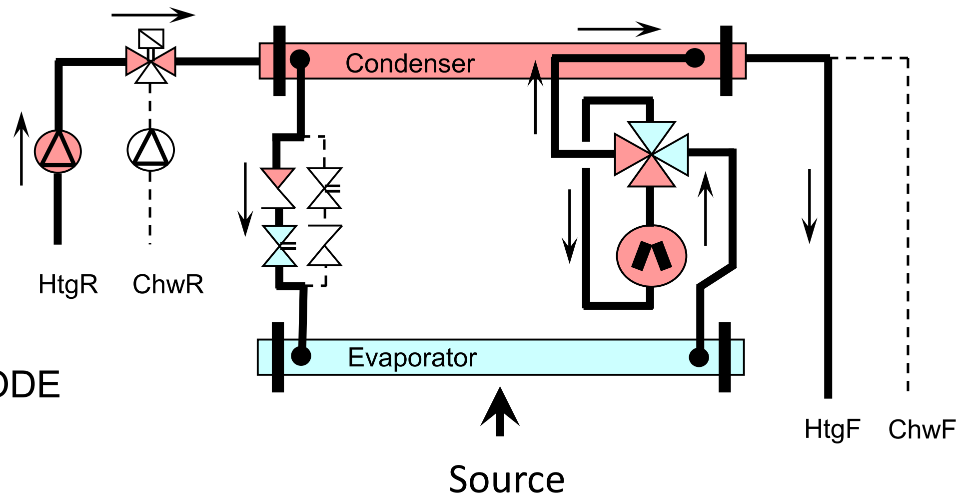
Seasonal performance factor, *SPF* vs. *CoP*



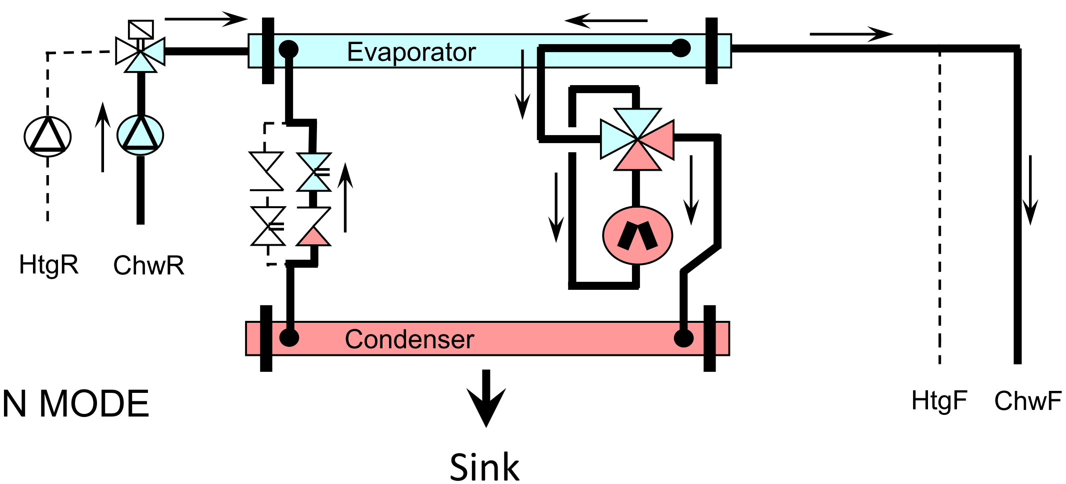
e.g. $SPF_{H3} = (Q_c + E_{cassette}) / (W_{HP} + W_{src\ pump} + E_{cassette})$

Reverse cycling for air conditioning and defrosting



HEAT PUMP MODE

These refinements permit the same plant to operate as a heat pump in winter and an air-conditioner in summer.



REFRIGERATION MODE

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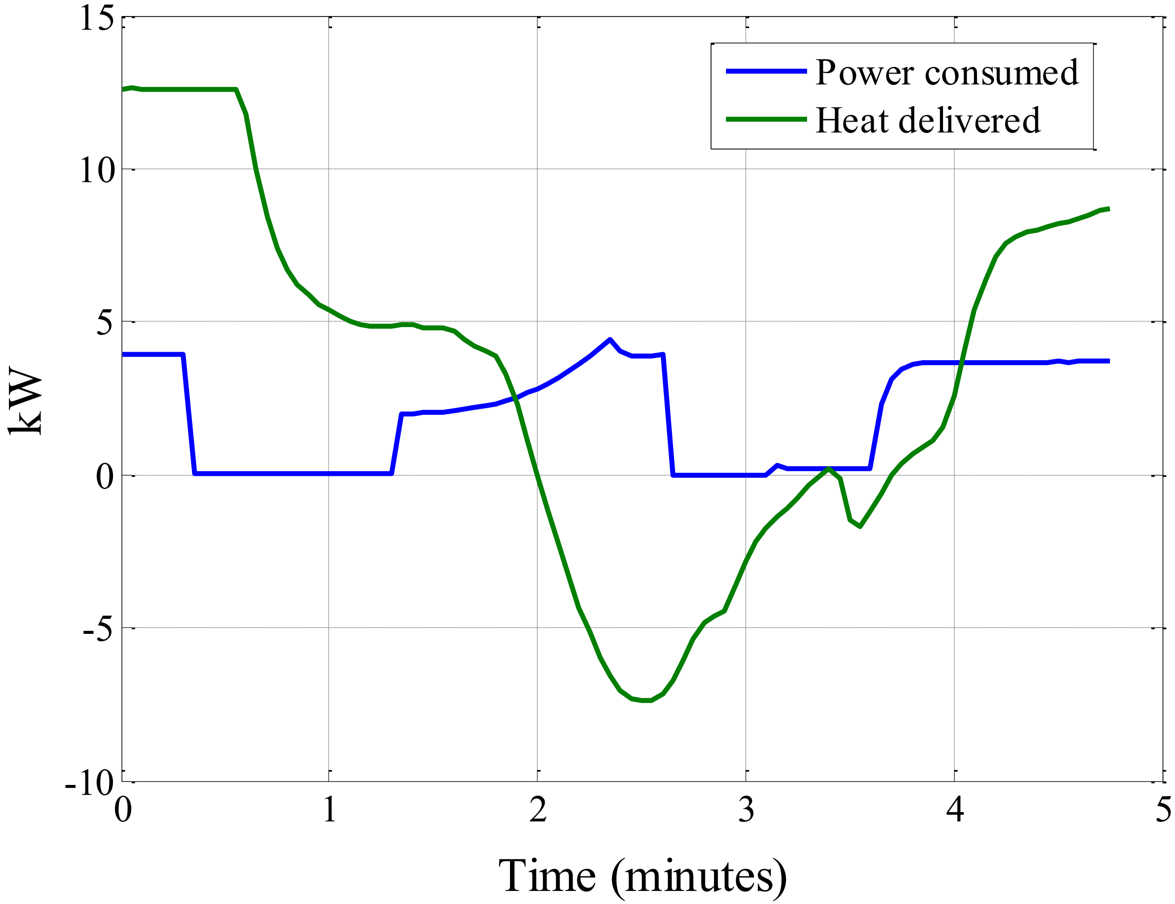
Defrosting in air-source heat pumps

DEFROST EVENT DYNAMICS - POWER AND HEAT



(Typical domestic heat pump example)

Periodic defrosting is needed in air-source heat pumps. In UK conditions this will typically arise at external air temperatures < 7 °C.

At these lower external temperatures, the refrigerant in the evaporator drops to below 0 °C. Thus, water condensing in the air being cooled across the evaporator subsequently turns to ice as it settles on the evaporator surface. Typically in UK conditions, defrosting will add a 8-10% ‘overhead’ on annual power consumption.

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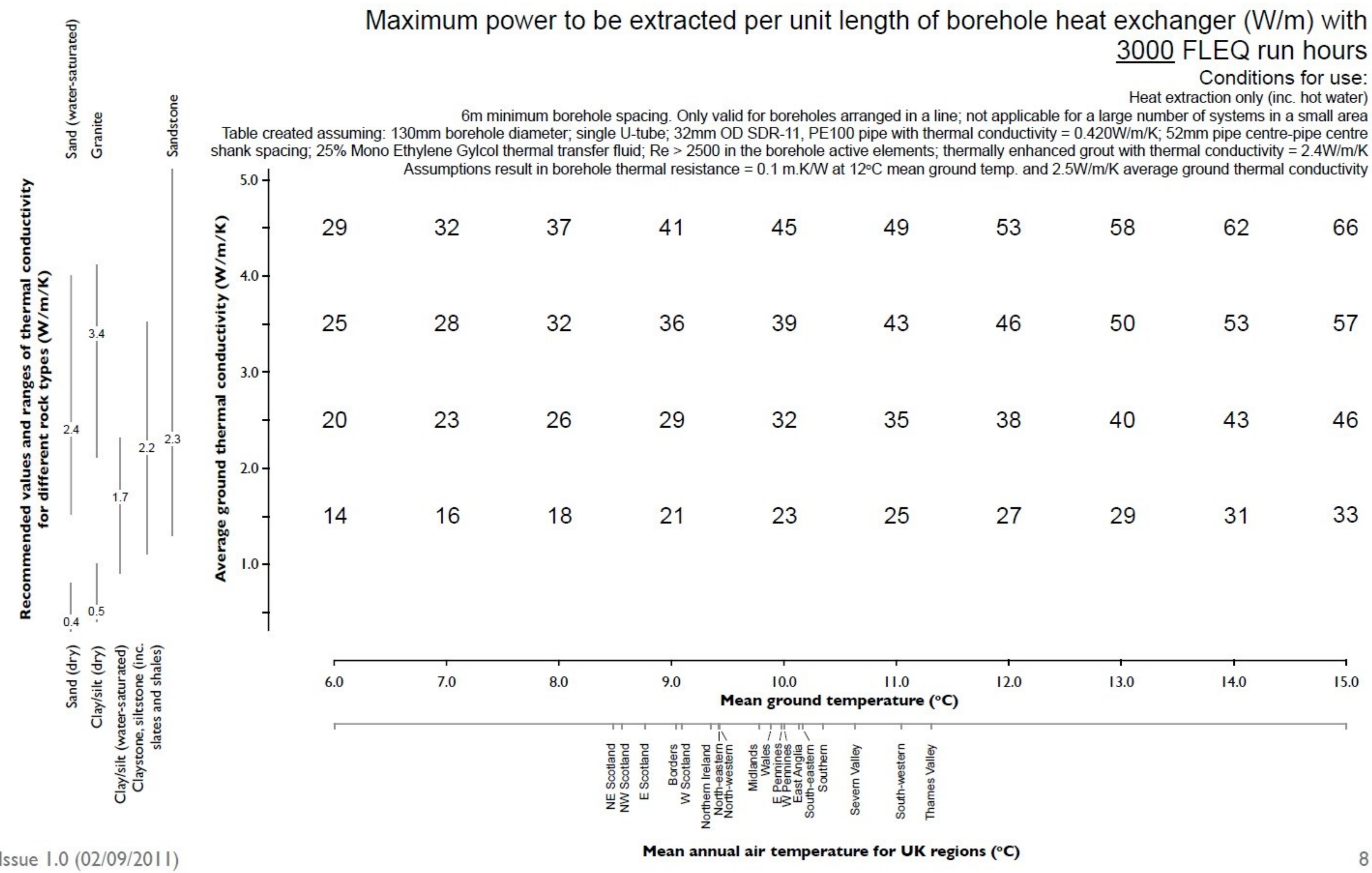
Ground sourcing alternative – typical array capacities



6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
29	32	37	41	45	49	53	58	62	66
25	28	32	36	39	43	46	50	53	57
20	23	26	29	32	35	38	40	43	46
14	16	18	21	23	25	27	29	31	33

Issue 1.0 (02/09/2011) 8

Source: Microgeneration Certification Scheme – MCS 022 Ground Heat Exchanger Look-up Tables, 2008. Available at: http://www.microgenerationcertification.org/mcs-standards/installer-standards (accessed April 2014)

Performances in practice

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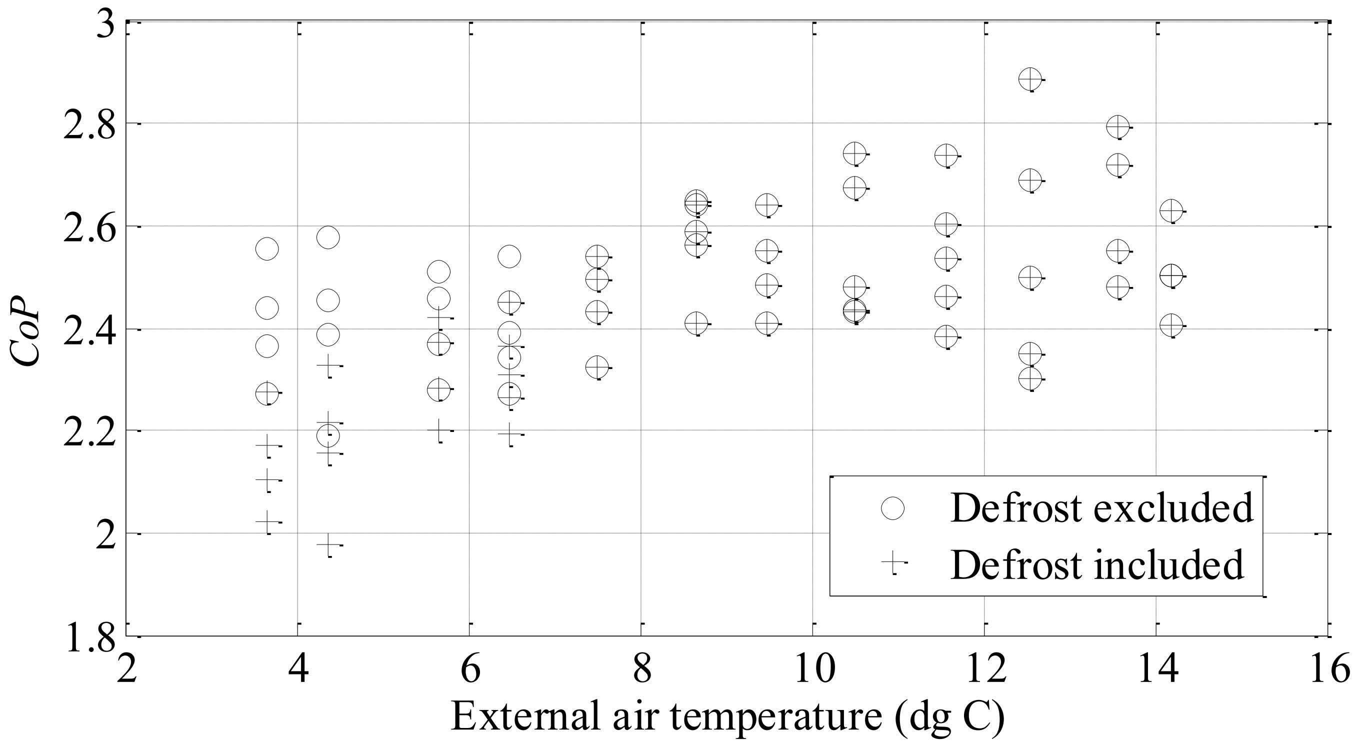
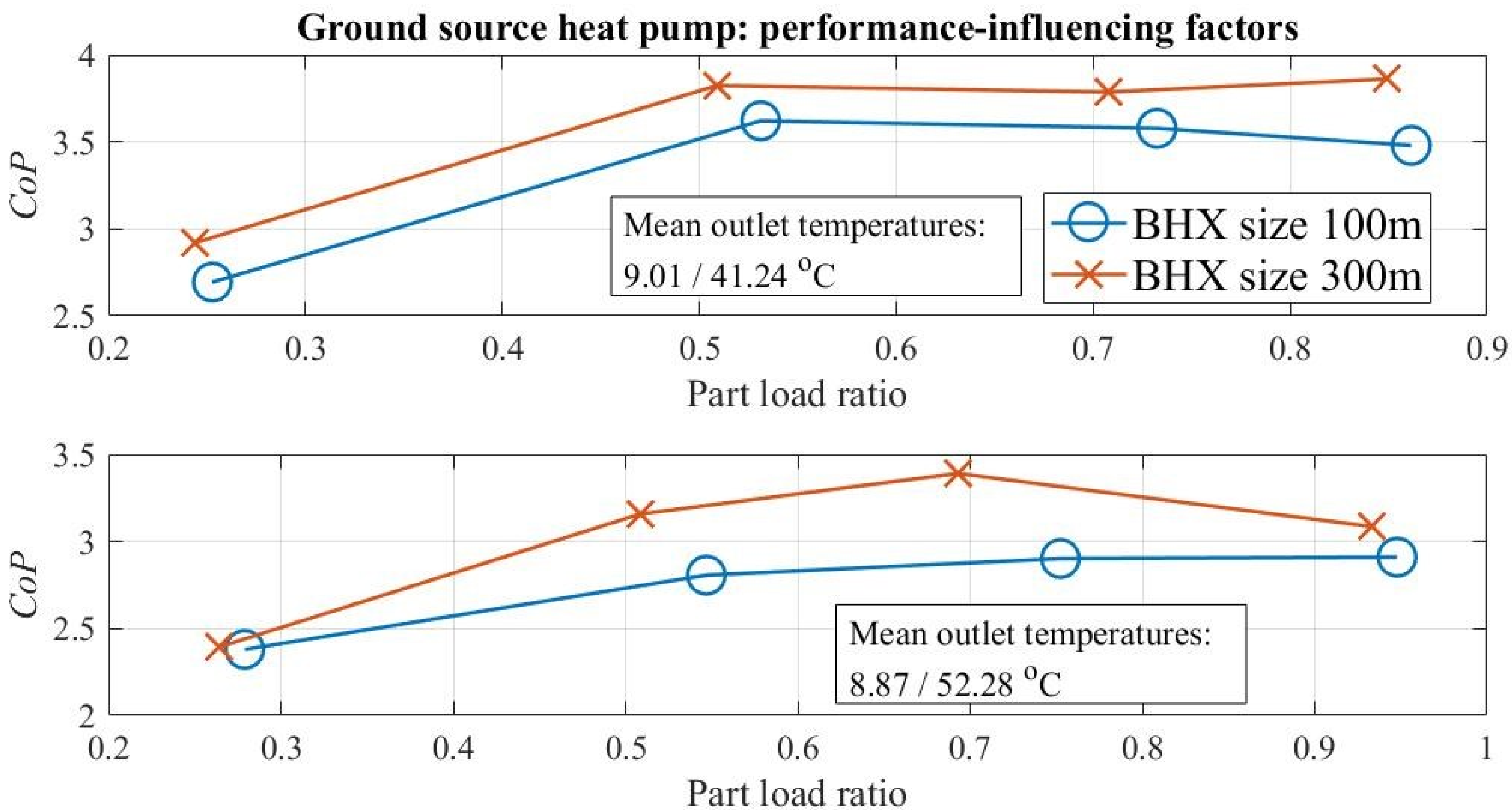
Practical performances – air-source

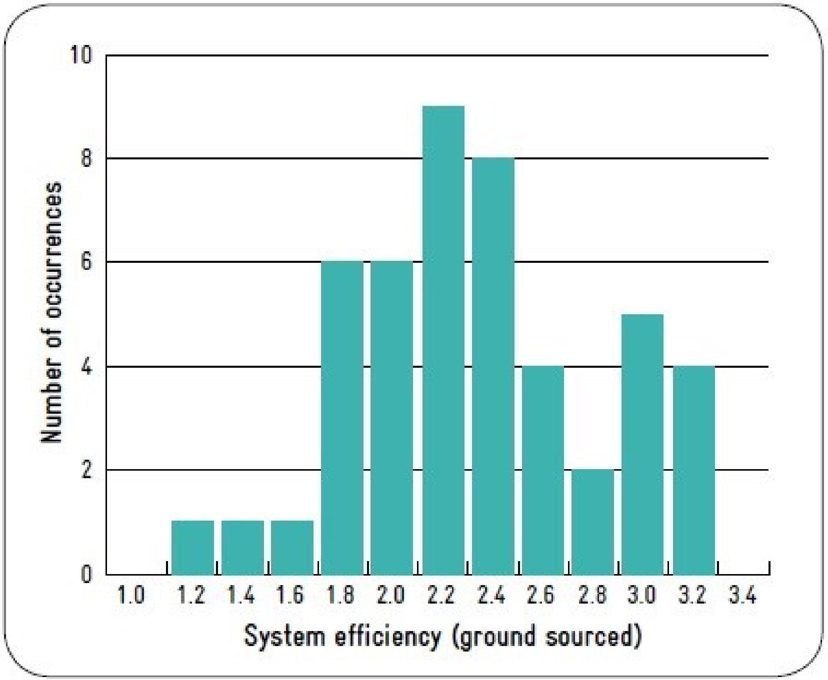


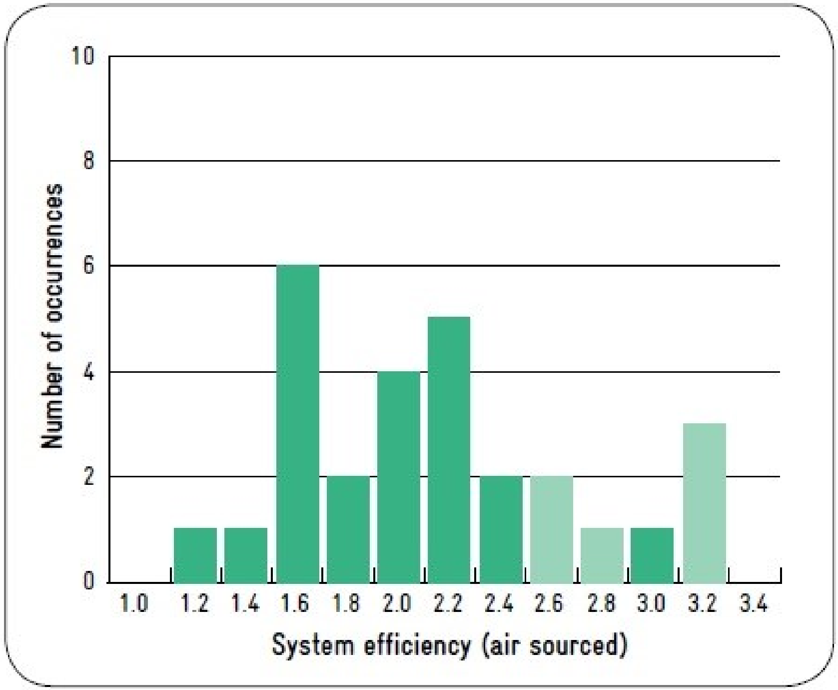
Practical performances – ground-source



Field-trialled UK performances

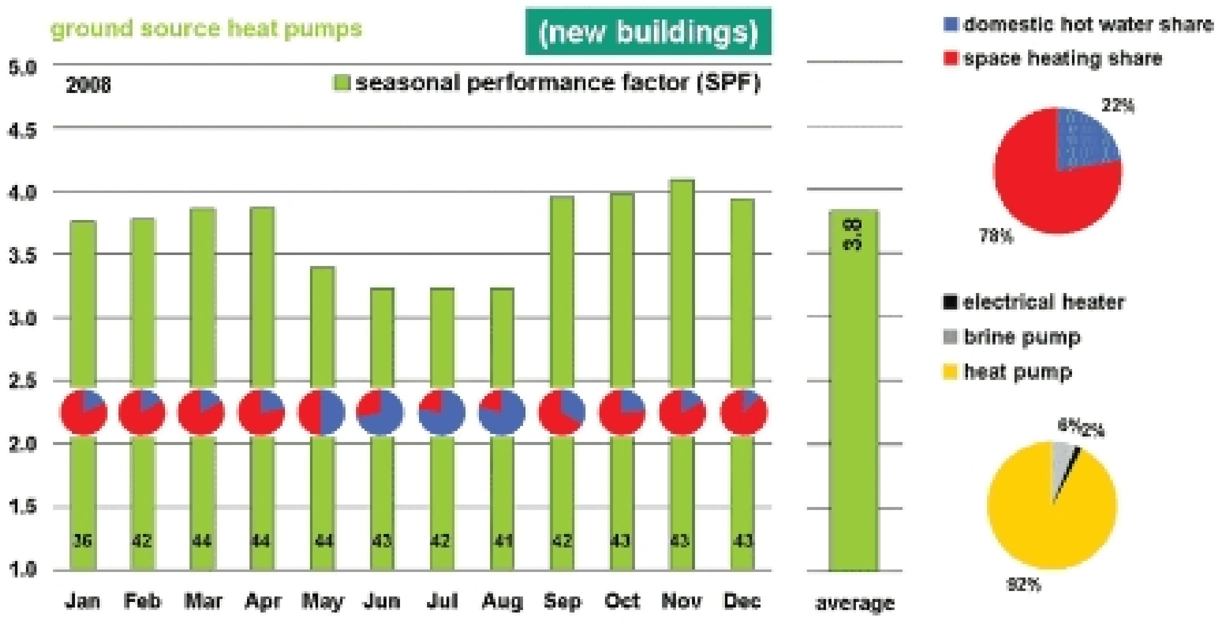
First year (2009/10) results of UK field trials conducted at 82 domestic sites of ground- and air-source heat pumps…





Source: *Getting warmer: a field trial of heat pumps*. London: The Energy Saving Trust. [Online] Available at: http://www.heatpumps.org.uk/PdfFiles/TheEnergySavingTrust-GettingWarmerAFieldTrialOfHeatPumps.pdf (accessed December 2013)

Compared with Germany…



This shows results obtained by the Fraunhofer Inst. from 68 German ground source heat pumps in new low energy houses, the majority (93%) of which used underfloor heating. The annual mean *SPF* is 3.8. For air source heat pumps the annual *SPF* was 2.9 (new houses) and 2.6 (existing); the main differences being the lower insulation standard and the predominant use of radiator heating in the existing houses.

Source: Miara, M. (2009). *Heat Pumps in Action*. RenewableEnergyWorld.com. [Online] Available at: http://www.renewableenergyworld.com/rea/news/article/2009/10/heat-pumps-in-action (accessed November 2014)

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SPFs compared

COUNTRY	SOURCE	SITES	MEAN
Sweden	Ground	6	3.26
Germany - existing	Ground	36	3.30
Germany - new build	Ground	56	3.88
UK phase 1 trials	Ground	49	2.31
UK phase 2 trials	Ground	21	2.82
BEIS/UCL RHPPP trials	Ground	223	2.75
Germany - existing	Air	34	2.60
Germany - new build	Air	18	2.89
UK phase 1 trials	Air	22	1.83
UK phase 2 trials	Air	15	2.45
BEIS/UCL RHPPP trials	Air	76	2.30

Gleeson, C.P., & Lowe, R. (2013) Meta-analysis of European heat pump field trial efficiencies. *Energy and Buildings 66*, 637-47.

Getting Warmer – a Field Trial of UK Domestic Heat Pumps. Energy Saving Trust, UK. [Online] available at: *http://www.heatpumps.org.uk/PdfFiles/TheEnergySavingTrust-GettingWarmerAFieldTrialOfHeatPumps.pdf*

The heat is on: Heat pump field trials phase 2. UK: Energy Saving Trust, UK. [Online] available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/225825/analysis_data_second_phase_est_heat_pump_field_trials.pdf

DECC, Detailed analysis of data from heat pumps installed via the Renewable Heat Premium Payments Scheme, 2017, [On
https://www.gov.uk/government/publications/detailed-analysis-of-data-from-heat-pumps-via-the-renewable-heat-premium-
(Accessed 18 August 2016)

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So why do UK systems perform so badly?

- Sizing of the heat pump itself – risk-averse design the main culprit.
- Sizing of the array (ground-source).
- Control factors – defrosting (air-source); inappropriate (or lack of) use of weather-compensating control.
- Choice of heating – underfloor versus radiators (especially problematical in retrofit applications).
- Thermostatic controls (especially with inappropriate buffering)
- Domestic hot water storage temperatures and tank pasteurisation.

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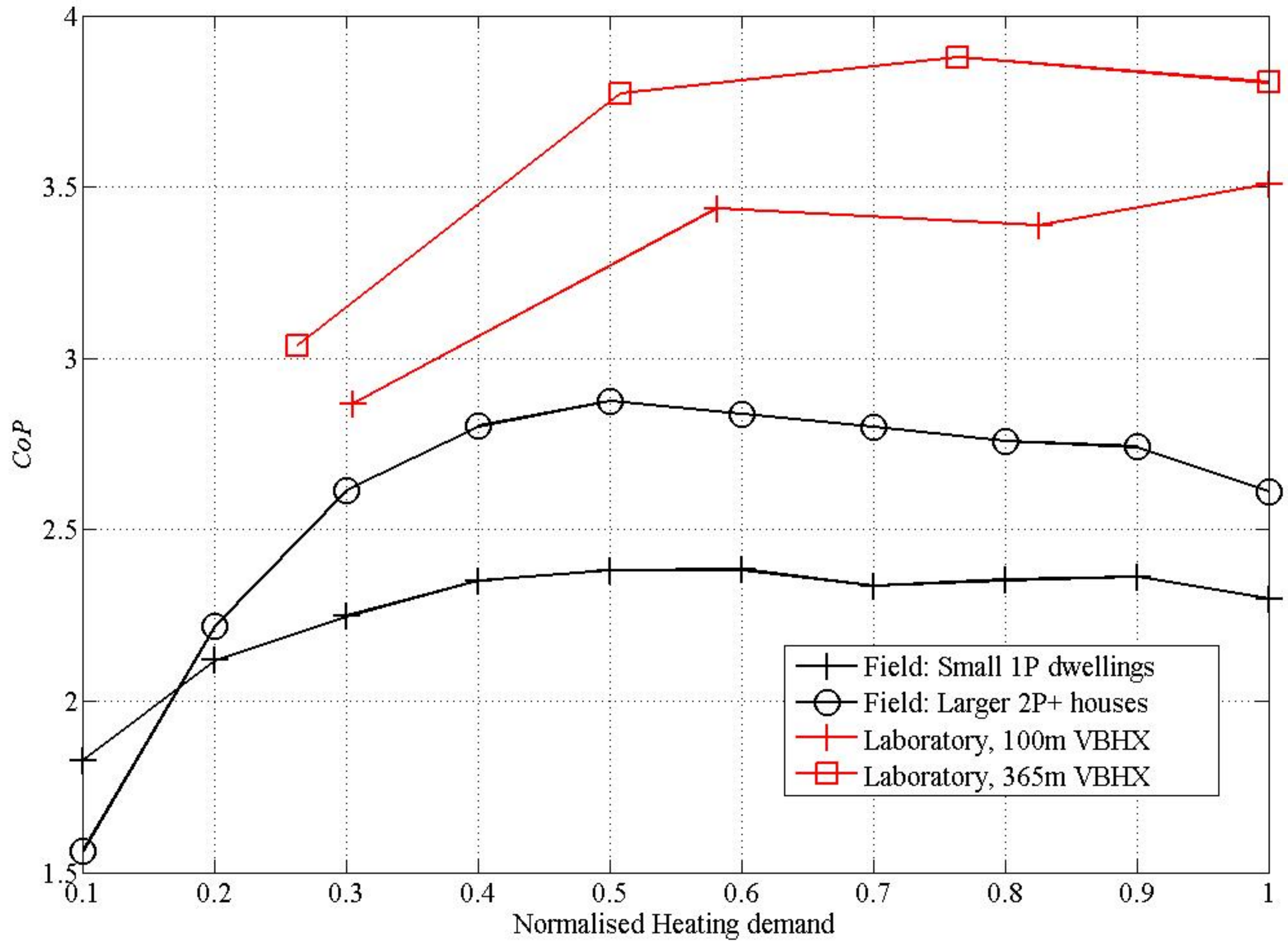
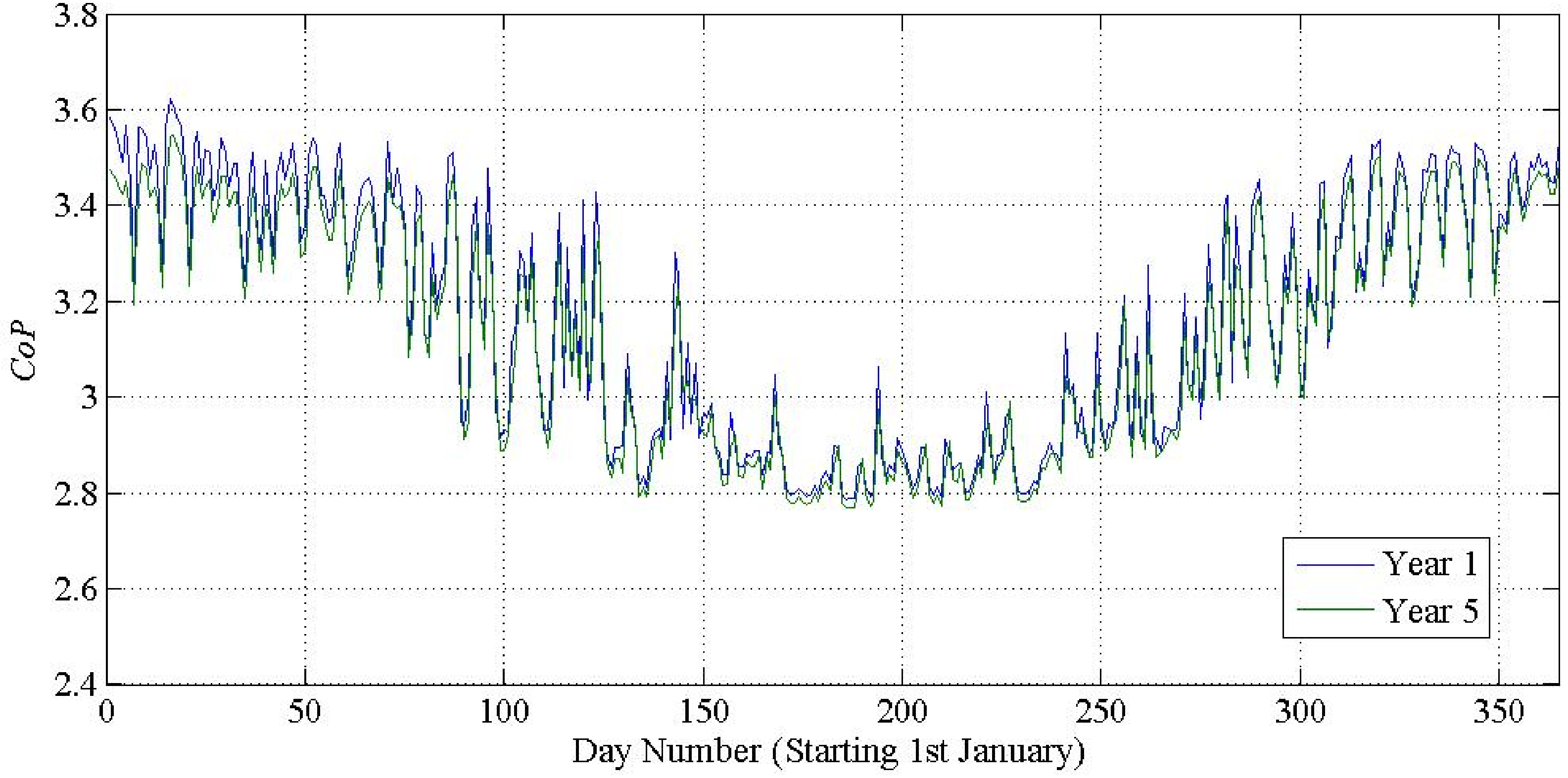
Part-load performances



Part load problems also evident during summer months even with good heat pump sizing…



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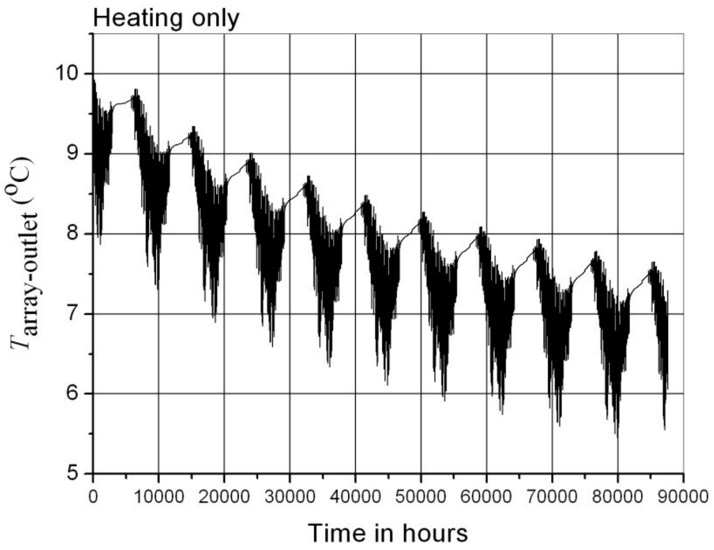
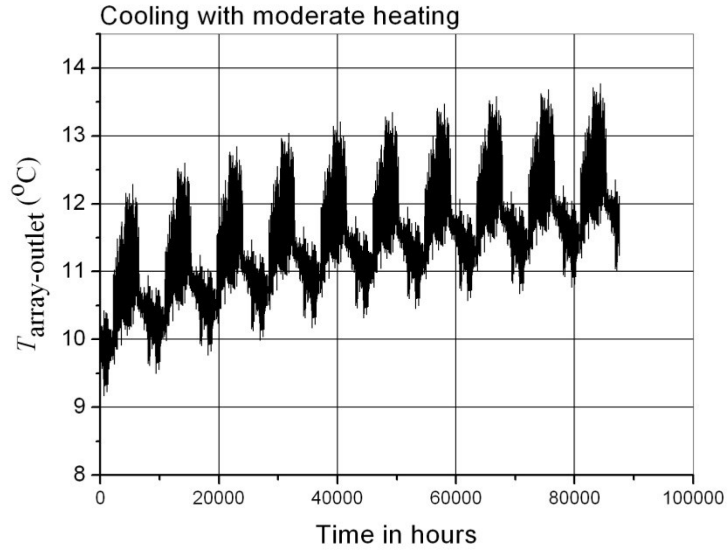
Impact of poorly-sized sized array (ground-source)





Social factors*

- The highest 10% of gas users consume four times as much as the lowest 10% but are unaware of this.
- About 40% of this variation can be explained by physical factors (property type, age, size, insulation standard).
- A major part of the remaining 60% is due to social factors – how the occupants behave (comfort temperature choice; time spent at home; use of windows, etc).
- Even the lowest 10% have the potential to reduce energy use without affecting comfort.

* Fell, D. & King, G. (2012). *Domestic energy use study: To understand why comparable households use different amounts of energy.* London: DECC.

Some challenges for the future

Where now? (Suggestions for further R & D)

- The *potential* for ground source heat pumps to reduce household energy bills and deliver carbon savings has been shown to be excellent and the market size is substantial.
- Existing performances in the field are not good enough – earlier slides have shown that seasonal *CoPs* must be at least 3 to be viable.
- Between 1995 and 2003, domestic heat pump efficiencies improved by 20% due to continuous product improvement during those years (Gleeson & Lowe – slide 24).
- Though there are numerous reasons for poor performances in the field, the following issues are repeatedly mentioned…
  - Heat pump sizing – in particular the avoidance of over-sizing (consider the use of dynamic thermal modelling to size the heat pump rather than current practice which uses a steady-state energy balance with 'worst case' boundary conditions).
  - Heat pump technology – a rapid move to 3rd generation technology using variable speed compressor drives and electronic expansion devices is needed.
  - Heat pump integration – increased buffering through the use of phase change materials.
  - System controls – life beyond the thermostat can be found using AI methods the most promising of which for this type of problem is fuzzy set theory.
  - Ground array design – simulation tools are maturing and becoming robust and reliable but most have impracticable computational demands; simplified but reliable design-sizing tools such as '*g*-functions' need to become more widely available for practitioners.

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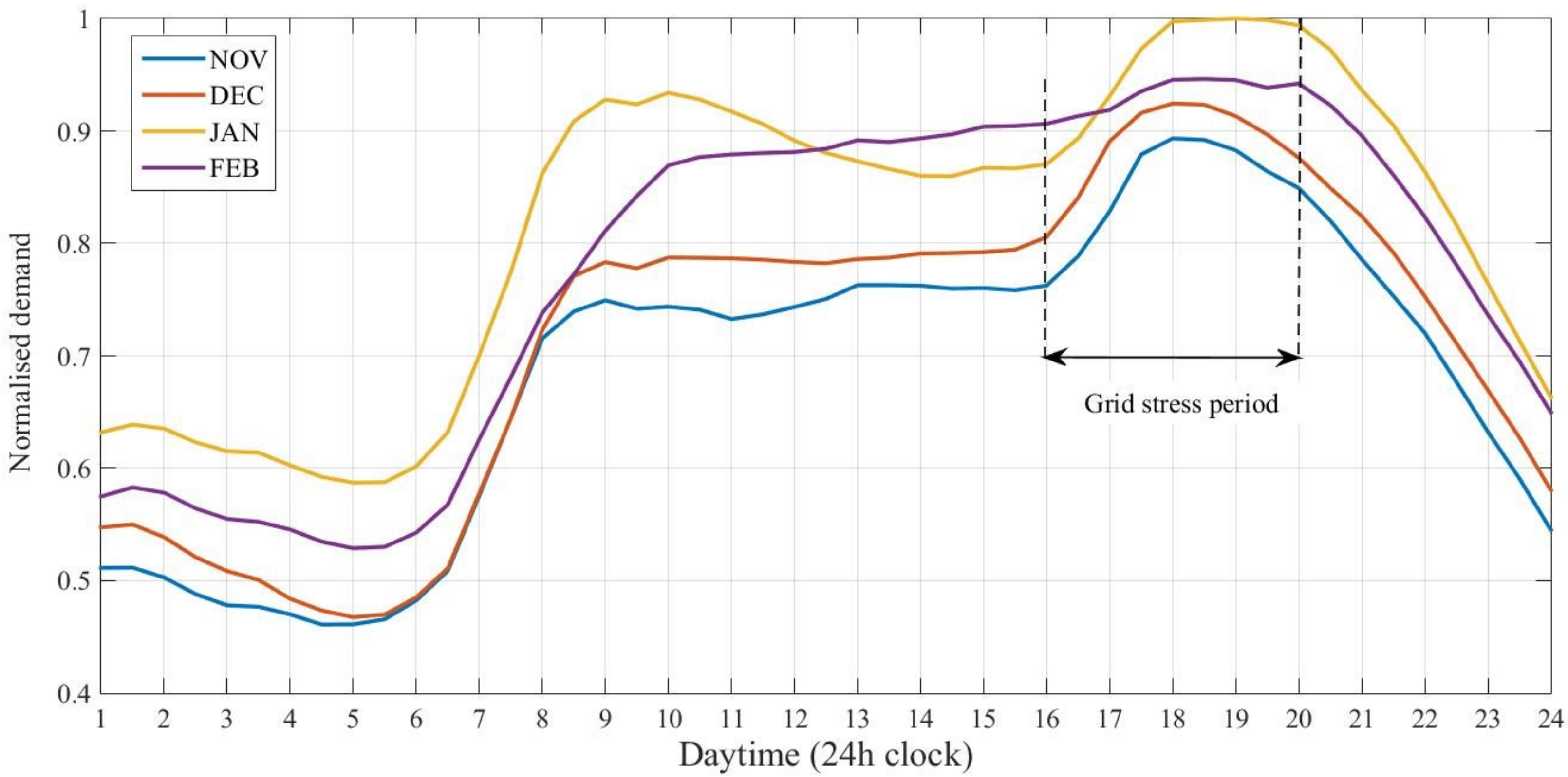
The challenge of grid stress – grid reinforcement or storage?



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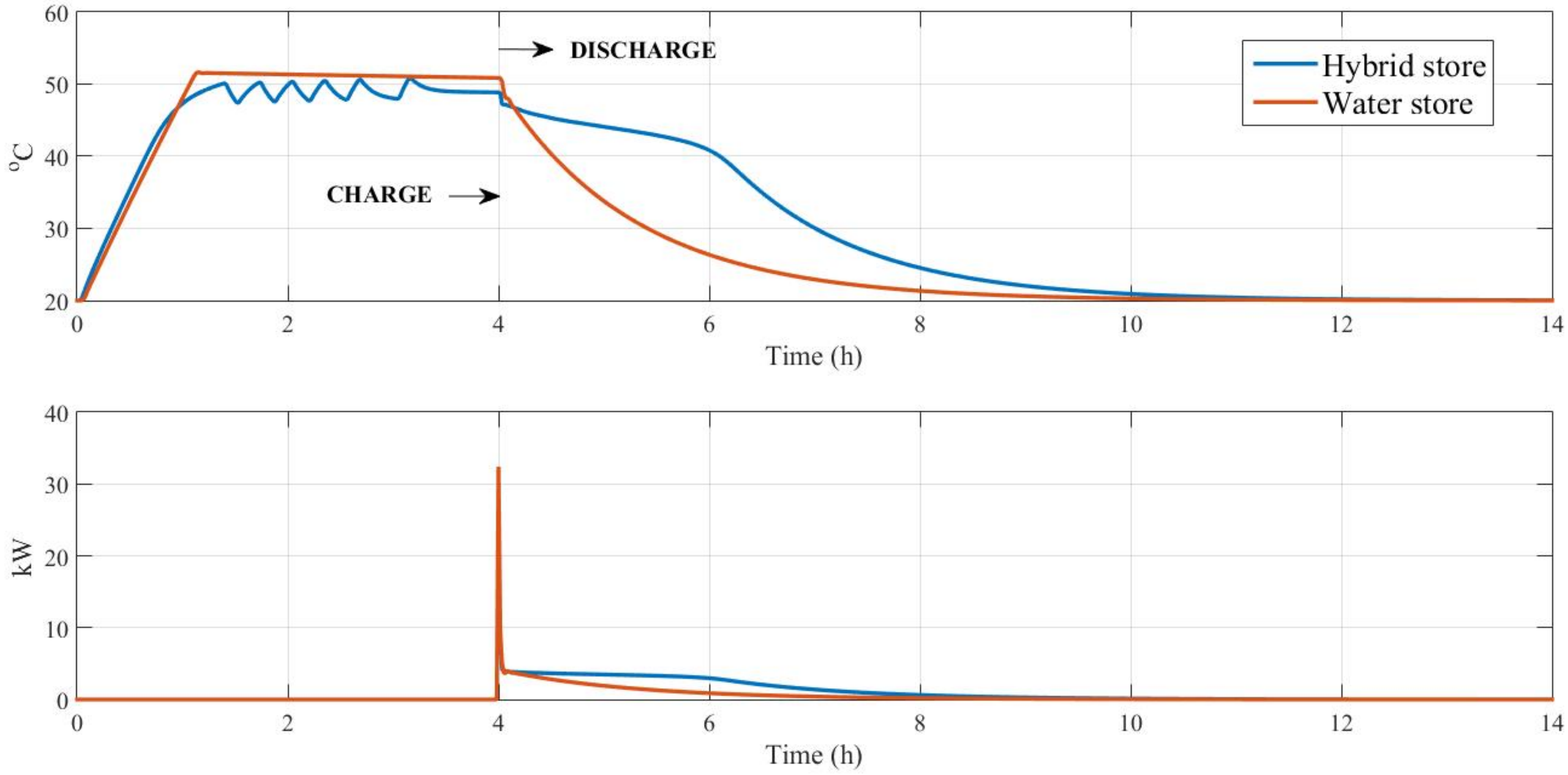
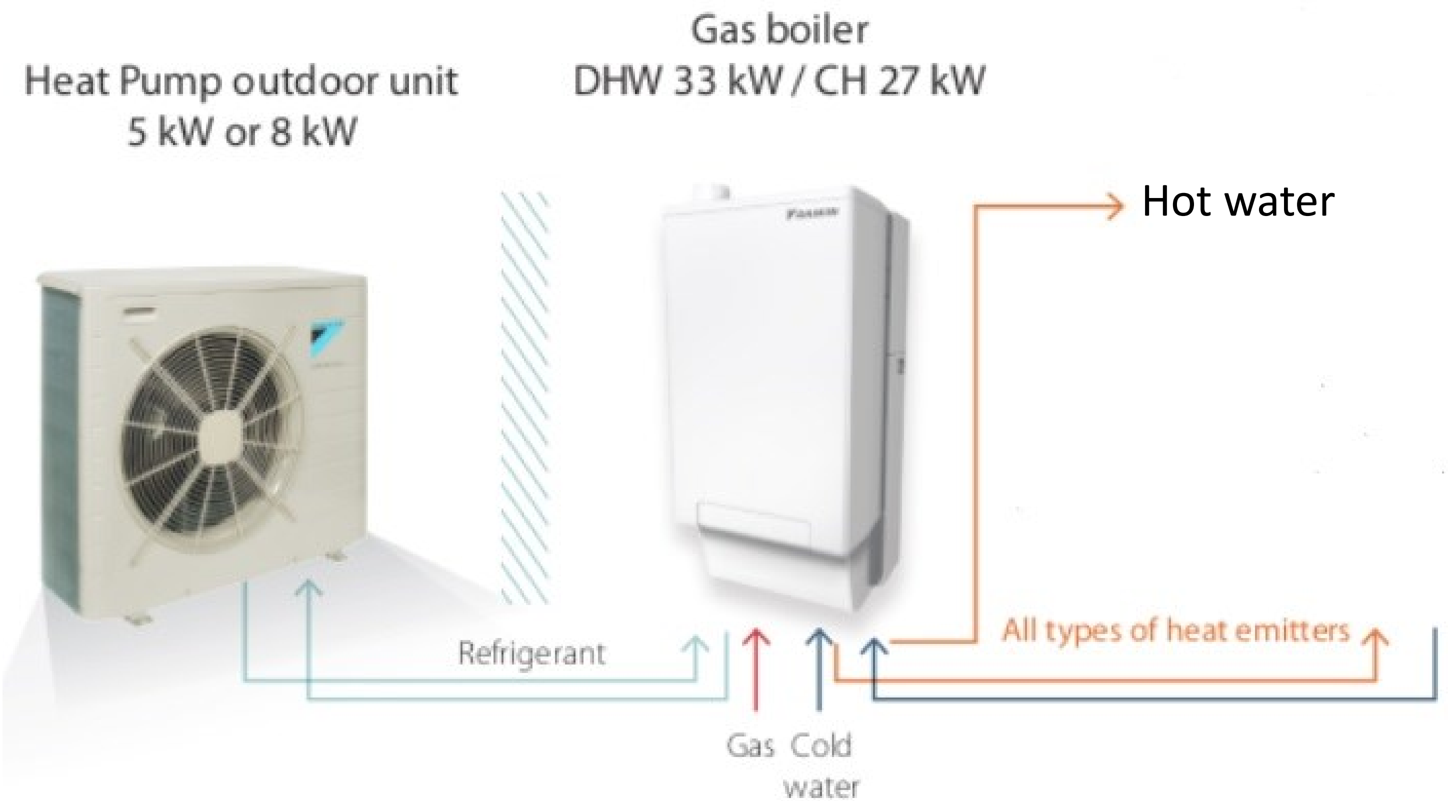
Smart thermal storage to alleviate grid stress



Hybridisation of phase change material in a water storage tank

Northumbria University Newcastle

Hybridisation – an interim way forward?



Large scale applications – district sourcing by mine dewatering

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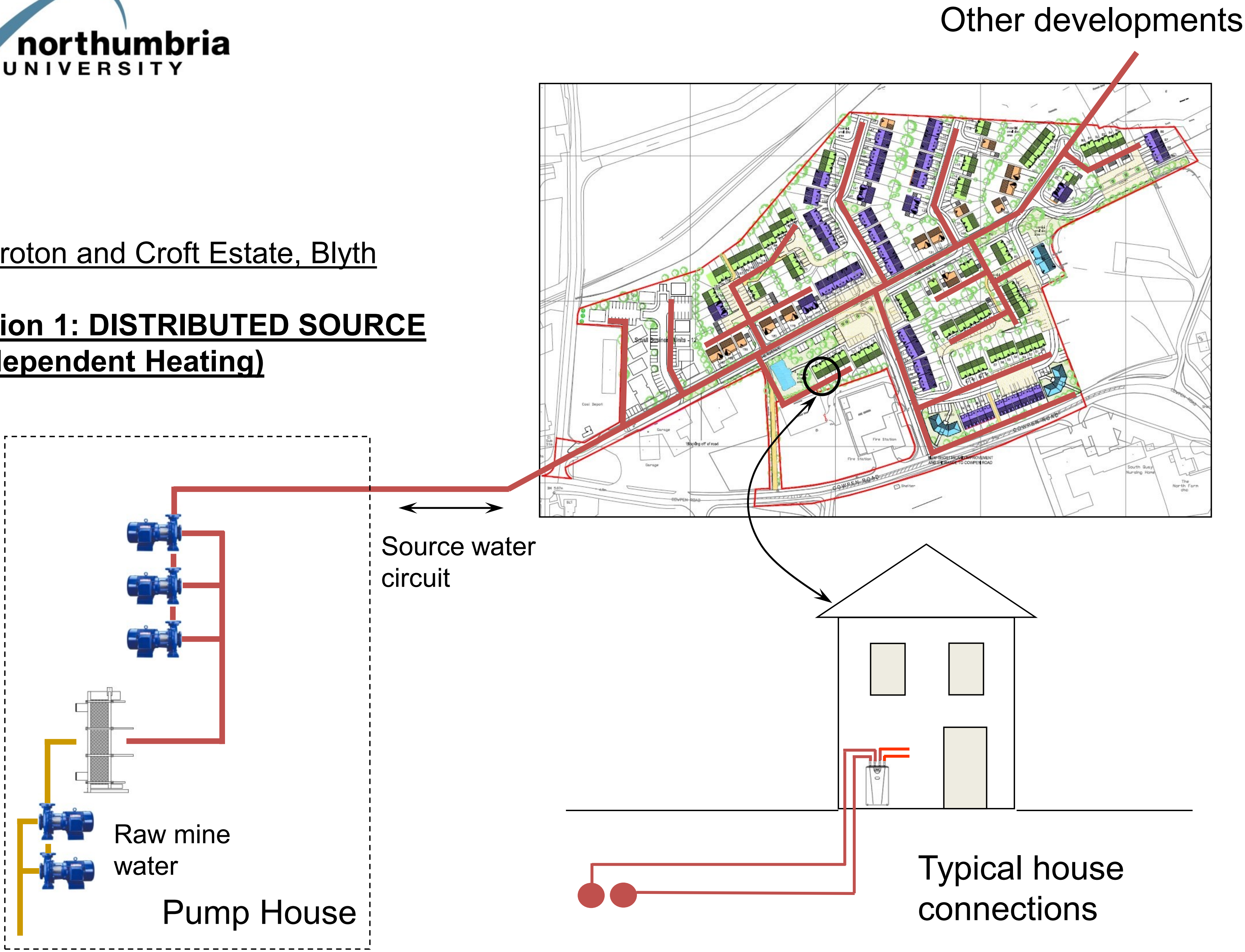
Thoroton and Croft Estate, Blyth

Option 1: DISTRIBUTED SOURCE (Independent Heating)



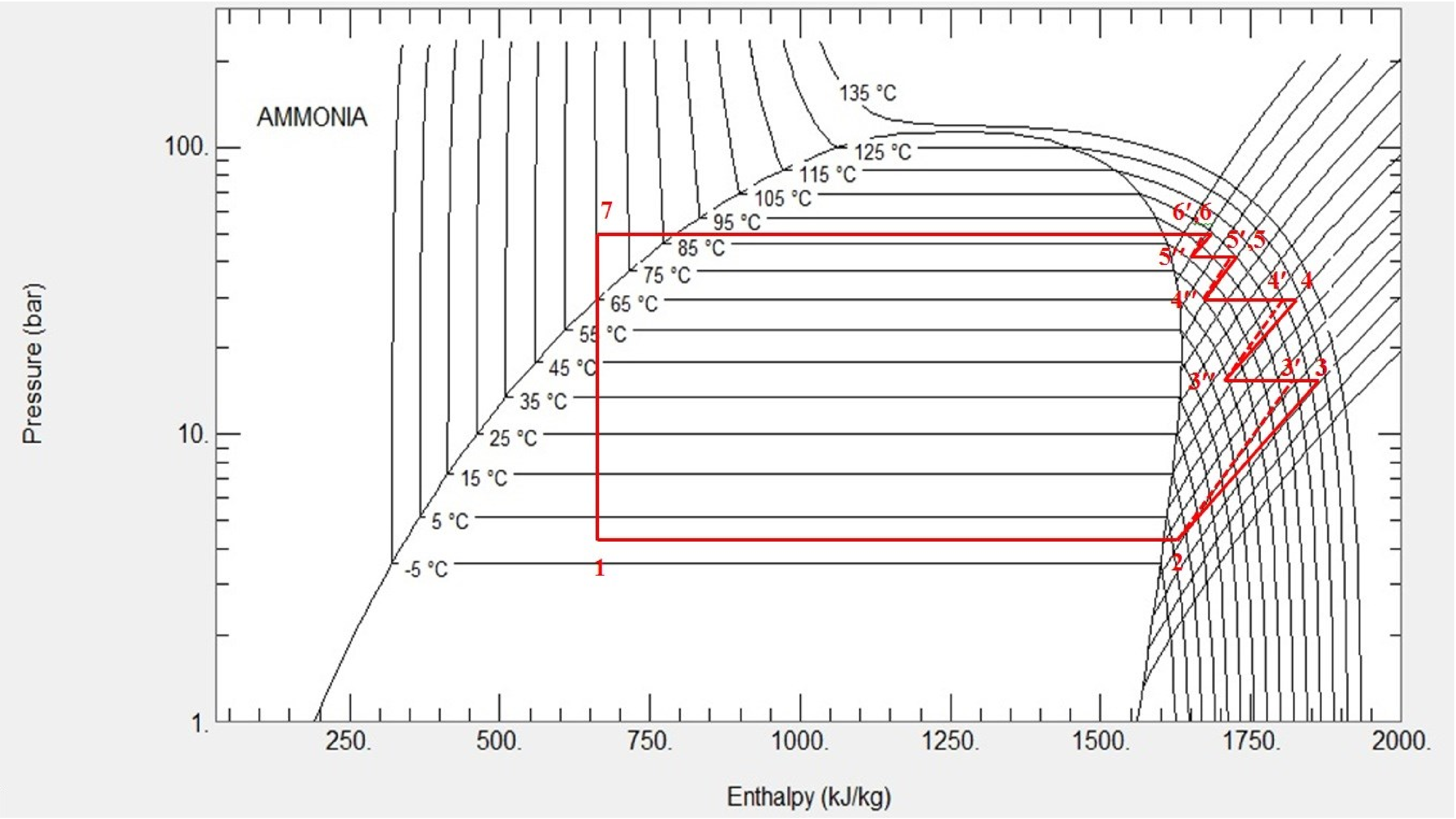
Heat networks – the Drammen fjernvarme heat pump…

- The Drammen fjernvarme district heating plant in Norway hosts the world's largest seawater source heat pump plant
- Total capacity 14MW based on 3 multistage single-screw compressor ammonia heat pumps generating hot water at 90^{o}C (peak) flow, 60^{o}C return generating 67GWh of heat per year
- Single-screw compressors used with a maximum discharge temperature of 135^{o}C; the cycle for this high lift application is managed through a series of compression stages each followed by a desuperheat (and oil cooling) process
- Single screw compressors used because they are expected to enjoy longer bearing life than their more efficient twin-screw counterparts
- Source: north sea water from the Oslo fjord, drawn 18m below the seawater surface at constant year-round temperatures of 8-9^{o}C (4^{o}C evaporator outlet temperature)
- Operating pressures 4.4bar (evaporating – superheated to 6^{o}C); 26bar (intermediate) and 50bar (condensing – sub-cooled to 65^{o}C) – the three heat pumps are connected in series hence these conditions are nominal

Further reading…

http://www.ammonia21.com/web/assets/link/Hoffman7thApril2011London%20colour.pdf (accessed November 2015)

‘High lift’ heat pump cycle for use with heat networks



And, finally, economics: The UK's Renewable Heat Incentive – a financial 'leg up' for heat pumps and other thermal technologies…

- Launched in 2011 (non-domestic) and 2014 (domestic)
- Tariff support for a range of renewable heat emitter systems to incentivise take-up of these new technologies
- From 1st July 2017 in the non-domestic RHI, ground- and water-source heat pumps receive a tariff payment of 9.09p/kWh (for the first 15% of full load equivalent hours 'FLEH') and 2.71p/kWh (for the remainder) applicable to the renewable (source) heat only and payable for 20 years
- The tariff for air-to-water heat pumps is 2.71p/kWh and strictly for heat pumps (i.e. reverse cycle heat pumps with summer cooling are ineligible)
- The tariff payments in the domestic RHI are 7.63p/kWh (air-source) and 19.64p/kWh (ground-source) but are payable for just 7 years
- To be eligible, the heat pump must have a minimum *seasonal performance factor (SPF)* of 2.5 (the *SPF* is defined in the same way as the *CoP* but represents a value averaged over the entire heating season)
- Note that the above is subject to change

Further details:

http://www.ofgem.gov.uk/environmental-programmes