EFFICIENT COOLING AT THE HEART OF LOW CARBON ELECTRIFIED HEAT

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ABSTRACT

A decade of amalgamating the refrigeration, heating and the earth in food retail proves highly efficient and credible zero carbon pathway. 5th Generation Energy (heat) networks must apply the principles learnt – putting cooling at the heart of efficient heating, a focus on the optimisation of all connected energy sources and sinks across many buildings rather than capturing "waste". Air and the earth are key tools in an holistic balancing strategy.

This paper explores these principles to discuss:
- 10 years proven operation across multiple installations.
- Promoting added benefits of cooling to human comfort – without added cost.
- Improving cooling-system reliability
- Benefits of continuous energy monitoring, application of machine learning and AI.
- Intelligent use of electrical and thermal energy storage – time-shifting energy use and optimisation for electrical grids.
- Improved efficiency – 40%+ lower electrical energy on food retail refrigeration, 80%+ less heating energy
- Efficient cooling at the heart of low-carbon electrified heat

Keywords: Earth, Air, Thermal Energy, Intelligent, Efficient, Heating, Cooling, Network

1. INTRODUCTION

Nature and society are changing. The climate is changing from what society is used to, and natural gas is no longer compared to coal as the low carbon form of heat. There has been a reliance on gas due to its heavily subsidised cost and until recently its domestic availability. The last decade – thanks to heavily taxed electricity – the carbon intensity of electricity has reduced significantly as electricity production from wind and solar technology has become far more cost effective. The addition of cooling is to thermal energy decarbonisation a necessary evolution pathway to emulate that cost effectiveness of wind and solar.

The resurgence of "heat networks" – which were essentially a means to distribute more fossil fuels greater distances – now present an opportunity to place efficient cooling at the heart of low carbon electrified heat. Lower temperature "heat networks" sometimes known as 5th generation or ambient temperature networks are viewed as a natural progression. Traditionally, heat networks have operated to supply heating temperatures above 50°C, but this leads to "single vector" service delivery in the form of usable heating and usable cooling. The idea of 5th generation networks encourages the distribution of thermal energy that can be converted into usable heating and cooling at points of connection through the application of water-to-water heat pumps, chillers and refrigeration systems. 5th generation networks become a "multi-vector" means of sharing thermal energy – encouraging the collection and management of more energy. A 50°C 4th generation network would not be able to condense a refrigeration system at 40°C or collect energy from a sewerage station at 30°C and so on.

Far from being "just about heat" this paper explores evidence from the long-term operation of a system which aims to promote efficient cooling as a means to efficient decarbonised heating. Rather than replace gas with electricity to heat spaces in our built environment, by integrating cooling, heating the air and the earth, society can promote a reduce, reuse, and recycle philosophy which will use both thermal and electrical energy in truly a sustainable future-proof way.

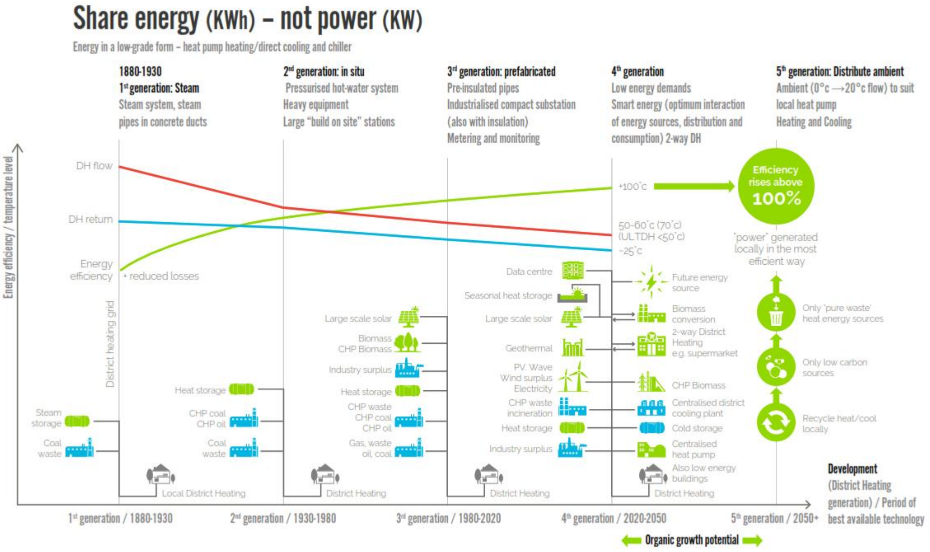


Figure 1 – based on Lund et al – Progression of District heating – 1st to 4th Generation[1]

2. CONTEXT

In 2012[2], the IOR reported the application of a closed-loop geothermal system that integrated both heating and cooling. That paper discussed integration of those systems through a shared low-grade temperature system – connected to the earth via steel cased coaxial borehole heat exchangers – which sought to optimise the benefits to both heating (heat pump) and cooling (refrigeration) performance. Novel at the time, the study looked at short term results (1 year) from the systems and clearly showed the potential for this arrangement. These systems have now been operational for many years and this follow-up paper highlights the enduring benefits and explores how this might be scaled to solve the decarbonisation of heat. The two systems are geographically opposite (site A in Scotland and site B in the South of England). Data sets from these sites are constantly reviewed by the system operator to identify potential for system performance improvement and to eliminate anomalies which would reduce efficiency. The heating and refrigeration demand are governed by the operation of the building services, the refrigeration plant, their geographical location plus the age and thermal characteristics of the building.

2.1. A decade of transition

Since the 2012 paper, numerous sites have applied this system – converting dated and inefficient cooling systems, fossil-based heating with forward thinking integrated systems, and this paper examines recorded performance from those sites to support the position that efficient cooling can sit at the heart of electrified heat. Each system comprises of 12no, steel cased, coaxial borehole heat exchangers, directionally installed at up to 15°. Boreholes act as a thermal energy battery to allowing heat rejection (during cooling) and heat extraction (during heating). Energy is extracted from the system via 3no water to water heat pump evaporators at a fluid ΔT between 1K and 3K. The system design allows for the fluid to float to -3°C meaning an evaporating design condition of up to -8°C so water/glycol mixture is used to prevent freezing. Two heat pumps provide space heating using R407C, semi hermetic reciprocating compressors and water to refrigerant plate heat exchangers.

Energy is actively managed between the air or the earth via interfaces with food retail CO_2 booster system. In previous iterations of the technology, it was quickly realised that the balance of total heat of rejection (THR) to heating energy required was far in favour of THR, and tools were needed to manage the energy balance. This was achieved in the form of discharge diversion units (DDU) to allow complete flexibility in the discharge of CO_2 – to reject energy to air, to earth or both in series (in either order).

The DDU interfaces comprise of 4no CO_2 to water plate heat exchangers and are located between the CO_2 booster packs and gas coolers. A pack to DDU fan speed control interface allows the geo-exchange system to reduce gas cooler fan speed as demand for THR (into the loop) increases. This is done on a staged control algorithm that increases THR from the pack (into the loop) depending on the temperature of the earth loop fluid. The systems analysed have been operating in the food retail sector for 7+ years over which time vast amounts of data points have been collected, stored, used to measure performance, and develop insights into how operation can be improved. Three key indicators were continually referred to, to measure the success of the systems – Consumption (energy), Carbon and Cost.

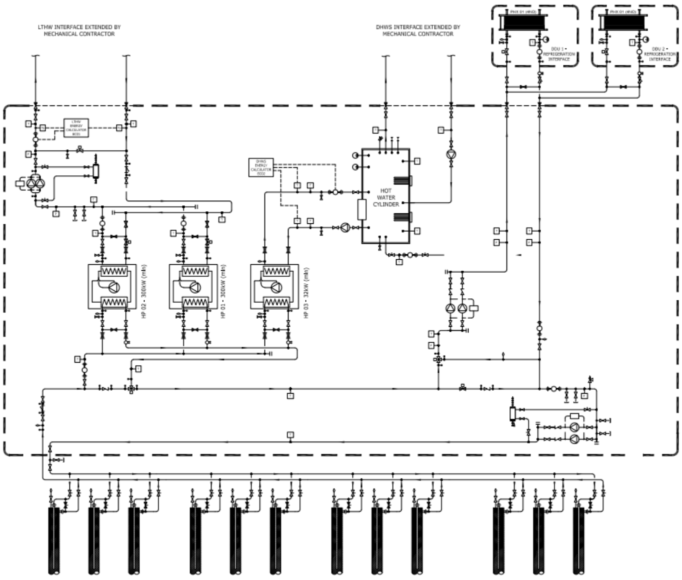


Figure 2 – Current system design schematic

Looking at a decade of building operation it is evident that reducing demand, upgrading building service systems, networking thermal energy, and using the air/earth as management tools, the energy and carbon transitions are a clear path to 2050 climate goals. See Figure 3. The removal of gas makes for a striking impact on the sites' total primary energy demand. It's also clear – despite a "Beast from the East" winter and a "Covid-summer" that performance continues to improve – that both cooling services and heating services get more efficient – despite a net increase in floor space at the time of transition. The chart displays total daily energy consumption for the site and reflects a 63% reduction in total site peak daily energy and a 47% reduction in total site annual energy consumption.

If Figure 3 demonstrates that a radical transformation of primary energy can be achieved with more efficient systems and services, then Figure 4 affirms the benefit of full electrification for on-site decarbonisation. Smart and efficient cooling (refrigeration) and heating served from a decarbonising electrical grid show a carbon-decline that would not have been possible if gas were still present and sets this site on a credible pathway to net zero operational carbon.

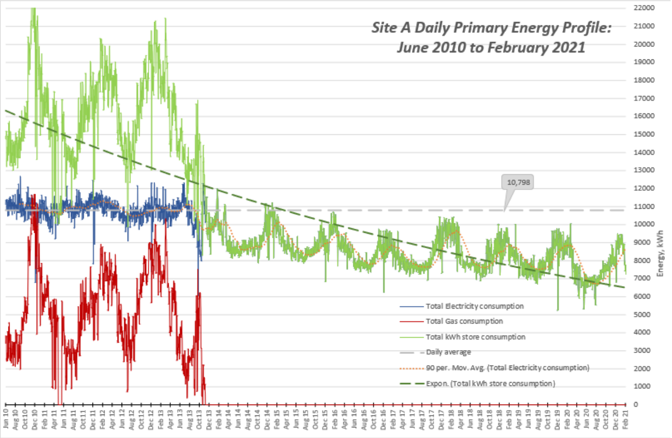


Figure 3 – A decade of energy transition post gas

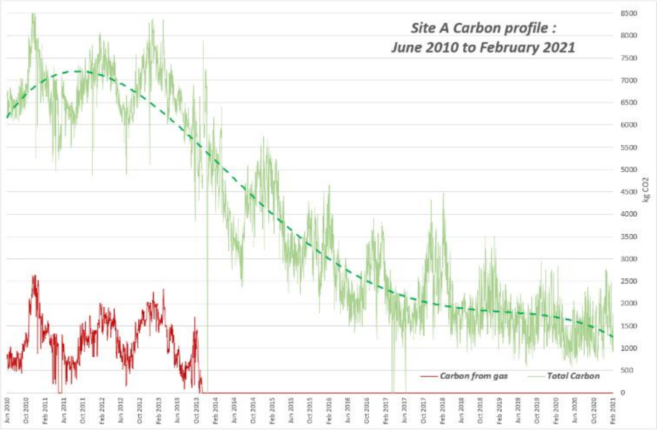


Figure 4 – A decade of carbon transition

While there has been 55% reduction in total store carbon, there should also be an understanding of the site in terms of heating and cooling only.

Table 1 – Typical energy reduction

Energy	2012	2020	Reduction
Heating	2,520,762	518,117	2,002,645 (79%)
Refrigeration	1,399,682	818,475	581,207 (41%)

Table 2 – Typical carbon reduction

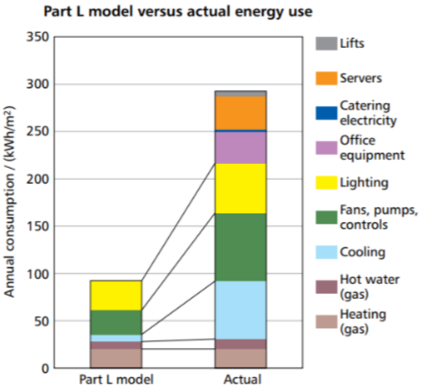
Carbon	2012	2020	Reduction
Heating	544,485	115,022	429,463 (79%)
Refrigeration	653,651	181,701	471,950 (72%)

3. EFFICIENT AND EFFECTIVE COOLING

UK society – perhaps unconsciously – is becoming more expectant of, and reliant on cooling – for comfort and commerce and industrial purposes. Maintaining the pressure to provide better means of refrigeration, more efficient refrigeration. Compressor and refrigerant developments are assisting in this, however elevated evaporating conditions and reduced condensing conditions will always provide the foundation to improved efficiency. As refrigeration pioneers the food retail sector continues to push the thermodynamic boundaries of evaporating conditions on cases and cold stores to enhance performance, but a reduction in condensing temperature is still a coveted area of improvement.

Space cooling energy demands are routinely underestimated, and this has been well documented in CIBSE TM54[3] – comparing the typical Part L modelling techniques against the "real-life" requirements. See Figure 5. The UK is unfortunately no stranger to cold-weather mortality, but as the climate changes, there were three separate periods in 2020 which met Public Health England's definition of a "heatwave". Since 2003 the UK has had a "heat wave plan", which PHE has reported summer mortality rates annually on since 2016[4].

Cooling will become more prevalent in the built environment. Traditional chilled water temperatures of 6/12°C offer effective cooling, but at a growing commercial and environmental penalty. With internal comfort conditions possible up to 26°C, chilled water temperatures could increase without loss of comfort.



With the integration of heating, cooling, the air and the earth, monitoring historical performance allows us to develop insights as to how "free" cooling can be optimised, and how the otherwise rejected energy from this process can benefit heating. Extending these principles to network a series of buildings together enhances a dual-vector approach to energy use. Combining empirical data from operating sites and the wider experience from TM54 for space cooling, there is a growing need to provide cooling and there is usually more thermal energy than expected in design. This supports the need to maximise cooling efficiency and the opportunity to place it at the heart of optimised heat pump operation.

Figure 5 – TM54 energy model vs actual showing higher rates of cooling

3.1. Monitoring and Artificial Intelligence

Generally, gas cooler design means CO_2 can only be lowered to around 3K above ambient using air alone. Monitoring this on actual site operation has highlighted the energy reduction benefits to food retail refrigeration systems. There is clear evidence that for most of the summer, the air and geo exchange combination allows operation at a lower condensing temperature than external ambient alone, and that the lower temperature CO_2 returning to the pack/ICMTS permits more efficient sub critical operation.

These proven savings in refrigeration cooling energy can be equally applied to space cooling. A typical earth loop profile (Figure 6) shows when efficient or even free cooling could be available for use in cooling systems, and when highly efficient heating would prevail. By reviewing operating data and understanding how this is affected by various parameters such as ambient air, time of day, changes to controls settings etc, we can assess how the energy system reacted to change, and we can assess what improvements could have been made leading up to the time of change. This allows the use of machine learning and AI applications to learn and automatically adapt system behaviour. For example, during 2020 benefits to the refrigeration systems were observable as warm weather arrived in late June. During geo exchange operation there was a benefit to heat rejection of up to 13K (Figure 7).

With a primary goal of keeping CO_2 sub critical, actions were developed to select the best method of heat rejection at the best conditions. Time and temperature-based switching of heat rejection modes between air only (mainly at night) and air + ground (traditional daytime operation) can be seen to optimise the capacity of each resource and produce the lowest operating cost. This is observed in Figure 8 – in late-summer when ambient air is high during the day. Refrigeration operates on air at the appropriate conditions, and then switched to the earth when the balance of conditions change.

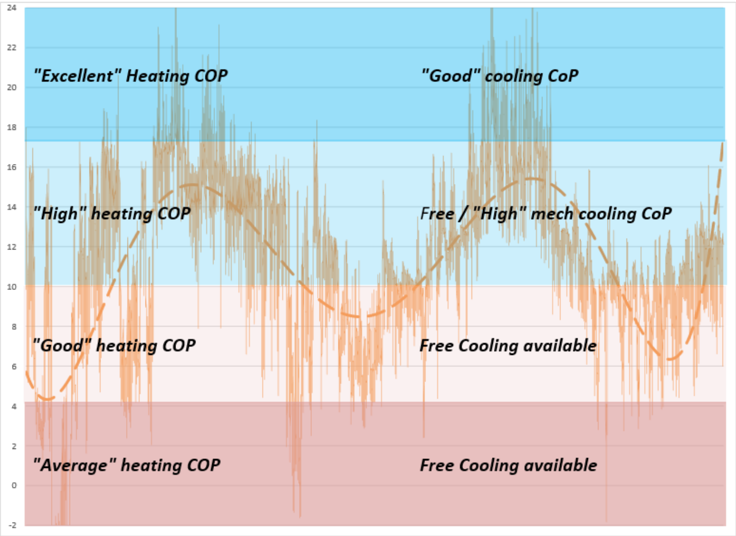


Figure 6 – Seasonal earth loop profile showing times of efficiency potential

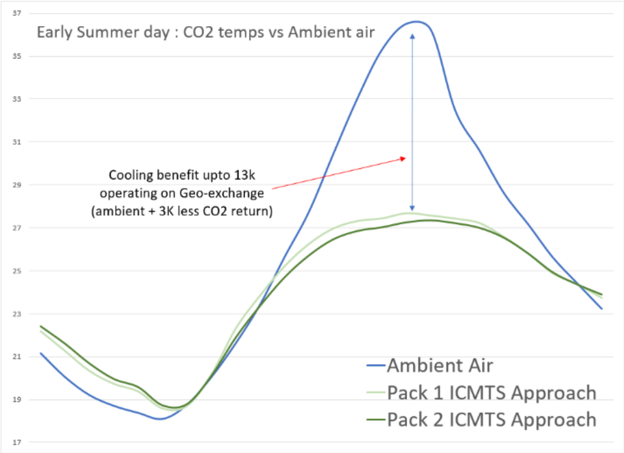


Figure 7 – Geo-exchange benefit to refrigeration

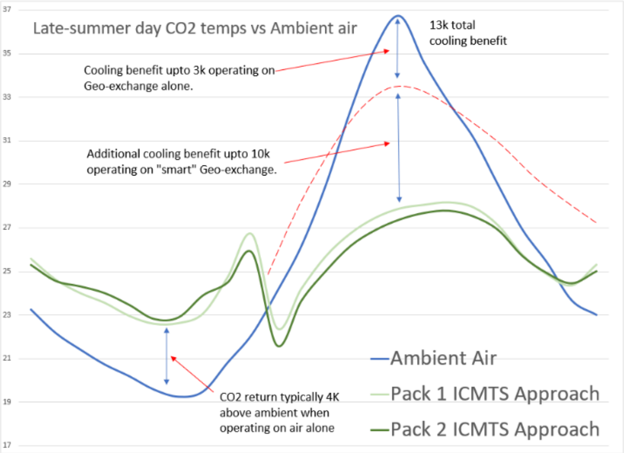


Figure 8 – Smarter hybrid air/earth operation

The earth responds and tends toward equilibrium, but as a negative effect, the CO_2 is slightly higher at this point. It can be seen when the pack changes to earth-based condensing the CO_2 immediately reduces in temperature due to the application of geo exchange. Cooling capacity stored in the earth supports sub critical operation during the day. Following this evidence, a target earth temperature below ambient can set and tracked to compare operation and consumption, and to allow a machine learning algorithm to automate these instructions. Figure 9 shows how the ambient vs earth vs electrical consumption is tracked and how the learnings from this are used to create new algorithms to ensure loop temperature does not exceed ambient air when it is needed most. As the External ambient became warmer, more and more thermal energy was rejected into the earth thereby warming the fluid temperature circulating through the boreholes – Figure 9. It can be observed that by reducing night-time thermal energy injection into the earth loop, the loop temperature is maintained at a similar temperature to ambient air over night but is able to maintain significantly lower levels during the warmest part of the following day and in doing so, maximising sub critical operation.

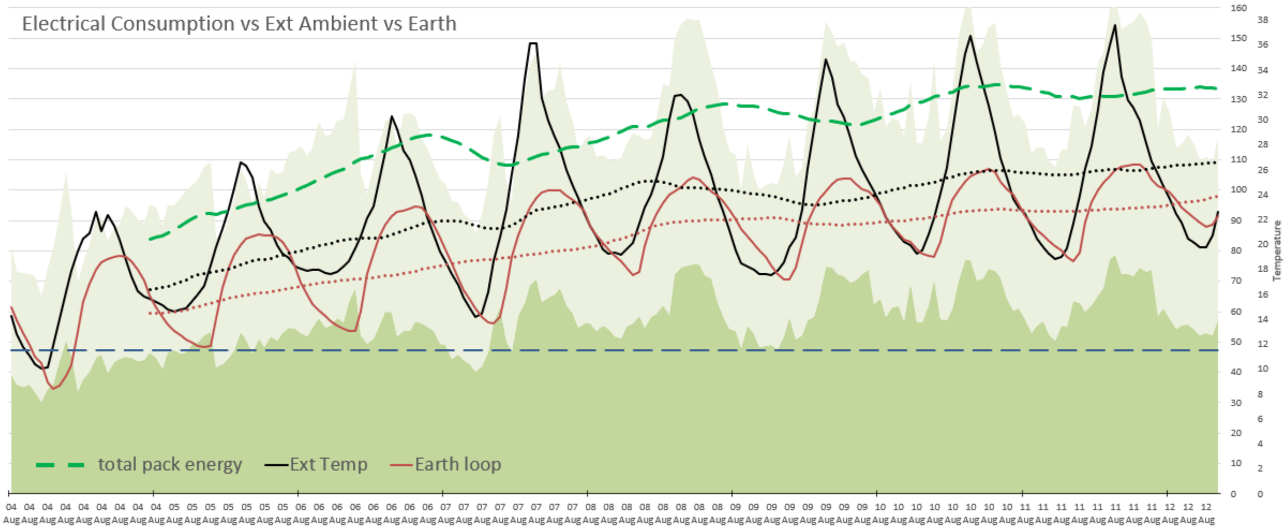


Figure 9 – Basis for algorithm maintaining sub critical CO_2 operation

3.2. Intelligence and Smart Operation

The nature of the UK energy system is rapidly evolving – decentralisation, democratisation and digitalisation are enabling new ways of cost-effective decarbonisation. Cooling can continue to play an integral part of the evolution. The physical integration of cooling, heating, the air, and the earth has enabled an efficiency and carbon step change to occur. Cooling – as part of an integrated energy system with the ability to store thermal energy – opens the potential for further use of digital strategies to enhance smart operation. Two such examples of this currently on trial on these systems are:

Prediction engines using weather forecasts user-patterns to determine future energy demands. More information, more accurate information, and the ability to obtain it digitally in "real-time" is changing the nature of how thermal energy is prepared. No longer just a "demand and supply" arrangement, intelligence actively prepares the supply side to serve demand most efficiently.

Time of use tariffs. On a grid dominated by intermittent energy sources (supply such as wind and solar) there are tangible benefits to the grid to influence demand profiles. The ability to vary the amount of energy used to provide cooling, and at what time, is currently being matched to variable electricity costs on a half hourly basis. Greater granularity of energy prices, greater predictability of volume (or energy) use matched with energy demand predictions the "supply" side can be manipulated to optimise for consumption, carbon and/or cost. Providing greater levels of thermal comfort need not come at an environmental or financial penalty. As 5th Generation networks enhance the scalability of decarbonised heating and cooling, intelligence and smart operation will ensure that all users connected to the network are getting the most cost-effective energy supply.

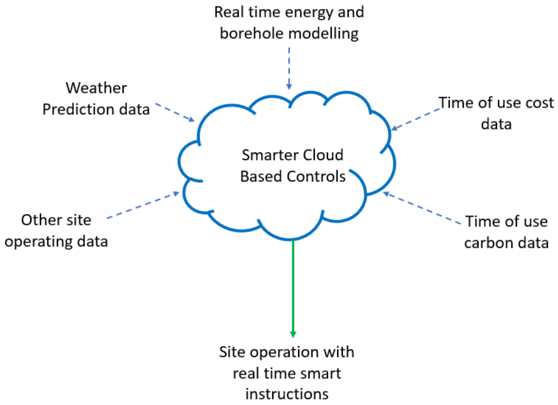


Figure 10 – Data-driven smart operation

3.3. Reliable cooling

Vapour compression refrigeration systems are generally very reliable provided they are regularly maintained and kept in good working order. Further gains in reliability can be made by lowering the head pressure of systems. The heat of rejection is also reduced meaning less full load running hours for compressors, less work on gas coolers and in the case of the built environment, potentially no chiller operation at all. Performance problems generally arise when energy cannot be introduced to the system (evaporators) or rejected from the system (condensers), compressors are subjected to stresses outside of manufacturers guidance, system impurities or control issues. Having dual-sink strategies for energy rejection increases the potential for reliable operation of the cooling services and reduces interruption in thermal comfort.

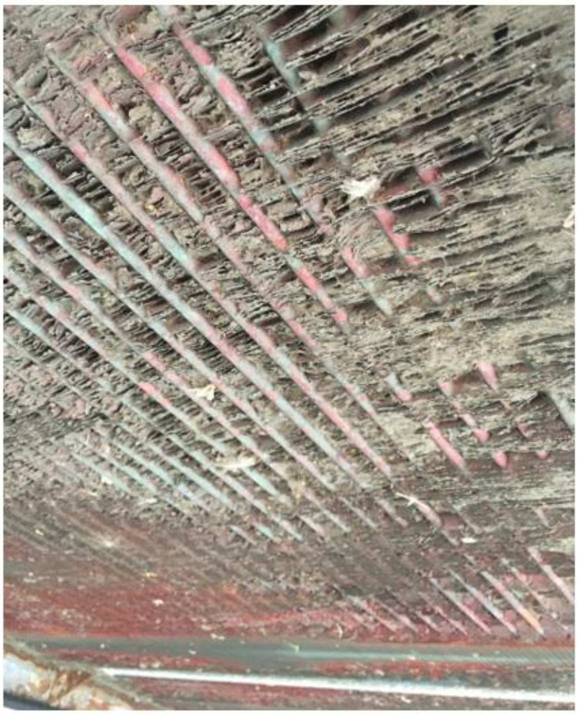


Figure 11 – Potential gas cooler conditions

Compressor manufacturers recommend start/stops within an hour are limited, and to overcome this in a variable-demand environment multiple or variable speed compressors are installed to eliminate undue stresses. Over 7 years of operation geo-exchange sites have delivered "up-time" run-hours in excess of 99% thanks to the application of dual-sinks.

When designing and operating electrified heating and cooling solutions (especially when integrated) there can be further reliability benefits in terms of compressor starts and running hours by a single machine achieving both operations. In some systems that operate heating and cooling, earth fluid temperatures have been kept below 10°C all year around by extracting thermal energy only thereby enhancing reliability due to less use.

4. CONCLUSIONS

The UK is, and will remain a heating-dominant nation, but as an affluent nation will come to expect greater levels of thermal comfort during summer. Through understanding how to place cooling efficiency at the heart of UK heating solutions, allowing both systems to be optimised to a point where it does not have a detrimental effect on the other, this can be achieved. These principles are extensively tried and tested in the hybrid air/earth system – where smart selection of energy sources and sinks can ensure overall system efficiency is maintained. The data gathered from these systems prove successful operation over many summer and winter seasons, and this efficiency-first approach should be applied to 5th generation networking to ensure thermal energy is managed well and low carbon heat is generated with a clear path to net zero.

While geo exchange is proven to reduce energy, carbon and cost specifically within the food retail sector, the path to further year-on-year improvements to system operation through smarter controls and algorithms can be realised. Continued trials in machine learning based on multiple cloud-based inputs are underway and future results will help demonstrate that efficient cooling can be safely and cost effectively placed at the heart of an electrified heat strategy for the wider built environment.

ACKNOWLEDGEMENTS

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NOMENCLATURE

p	pressure (kPa)	*CO2*	Carbon dioxide
T	temperature (K/°C)	*kWh*	Kilowatt Hour

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