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Paper 1 - UNDERSTANDING TOTAL EMISSIONS FROM COOLING SYSTEMS
IN URBAN BUILDINGS
by David Cowan CEng, Graeme Maidment FInstR, Issa Chaer FInstR

Paper 2 – EXPLORING THE OPPORTUNITIES AND LIMITATIONS OF LOW ENERGY
BUILDING DESIGN
by Prof Andy Ford CEng, Deng, FCIBSE and Aaron Gillich

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PAPER 1 - UNDERSTANDING TOTAL EMISSIONS FROM COOLING SYSTEMS IN URBAN BUILDINGS

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Abstract

Refrigeration, air conditioning and heat pump (RACHP) systems currently account for up to 19% of UK electricity use and over 7% of all UK greenhouse gas emissions. Under existing scenarios global warming and the trend towards urbanisation will result in increases in both cooling demand and the associated emissions. The UK commitment to reducing greenhouse gas (GHG) emissions by 80% by 2050 requires new and innovative approaches to the cooling of buildings: cooling loads must be reduced through optimisation of the building's design and operation and new low carbon methods of delivering cooling developed. This paper is based on a research study to characterise the energy demand and carbon footprint of cooling in buildings. A new dynamic energy balance model and a software tool have been developed for estimating the energy flows and carbon emissions from all sources. These can be used to predict the impact of alternative building design concepts, different types of RACHP system and alternative strategies for managing the building.

Introduction – cooling energy demand and carbon emissions

There is limited availability of real data on cooling energy used in buildings, since sub-metering for RACHP systems is rarely employed. Energy Performance Certificates (EPCs) and Display Energy Certificates (DECs) indicate only the total energy demand of a building and do not distinguish

between its heating, cooling and other energy use. It can therefore be difficult to identify the level of cooling emissions and the potential for reducing them. In practice, cooling emissions from a building cannot be considered in isolation from the other emissions, since changes to reduce the cooling load and emissions could also affect the building's heating energy demand and emissions. When planning changes to a building or its systems, the impact on total emissions must be assessed.
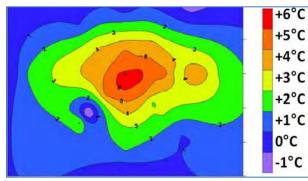
Estimates of the UK grid electricity used by RACHP systems and their energy related emissions can be made using market data reported by the industry for annual sales, equipment lifetimes and average power consumption. Total UK direct emissions from refrigerant leakage are identified (as F-Gas emissions by the RACHP sector) in DECC's annual reports of GHG emissions [1]. Estimates for 2010 are shown in Table 1. They suggest that the sector's carbon footprint is 42 million tonnes of CO_2 equivalent annually, or approximately 7% of total UK GHG emissions. Air conditioning systems are responsible for nearly 25% of this total.

Table 1. Estimated RACHP sector energy consumption and GHG emissions in 2010 [1], [2], [3]

Emissions Type	Emissions Source	Annual Grid Electricity Consumption TWh	Annual Grid Electricity as % of Total UK Consumption	Annual GHG Emissions MtCO₂e	GHG Emissions as % of Total UK GHG Emissions
Indirect	Commercial refrigeration	30.2	9.2%	15.0	2.54%
	Domestic refrigeration	14.1	4.3%	7.0	1.19%
	Air conditioning	18.3	5.6%	9.1	1.54%
Indirect	RACHP sector	62.6	19.1%	31.1	5.27%
Direct	RACHP sector (HFC refrigerant leakage)			10.9	1.85%
Direct + Indirect	Total UK RACHP sector emissions			42.0	7.11%

Day *et al* [4] reported a total cooling energy demand for all buildings in the UK of 14.8 TWh in 2007 (compared with the 2010 estimate of 18.3 TWh in Table 1). They estimated an annual cooling load for London of approximately 4.5 TWh (in base year 2004), corresponding to 1.6 TWh of primary (grid electricity) demand and 670 thousand tonnes of CO_2 emissions (approximately 11% of the UK total for cooling buildings). The methodology they employed was to estimate London's building stock (split by building type and floor area) and calculate cooling degree day energy demand using CIBSE guidelines TM41 [5]. Eight generic cooling system types were used in their analysis. They forecast that under a business as usual scenario the total cooling demand for London would increase to 8.5 TWh in the period 2004 to 2030, with corresponding increases in energy demand and associated emissions to 3.1TWh and 1.3million tonnes CO_2 respectively. Climate change could potentially add up to 350 thousand tonnes of CO_2 emissions each year, but this would be offset by the changing mix of system types, efficiency improvements and reduced carbon intensity for grid electricity.
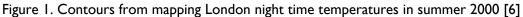
A study of the heat island effect in London [6] reported the measured increase in ambient temperature compared with rural areas for the summer of year 2000. Figure 1 shows the temperature contours from mapping the relative night time temperatures across a 36 x 25 mile area of London, indicating a temperature increase of 6°C in central London. Simulations performed for the same study predicted that with global warming the mean summer temperatures in London could increase by as much as 1°C by 2020, 3°C by 2050 and 6°C by 2080.

Measures that could mitigate some of the impact include:
- Greening, to increase shading and evaporative cooling and
- Increasing the albedo (reflectivity) of paved surfaces and buildings, to reduce the amount of solar energy absorbed

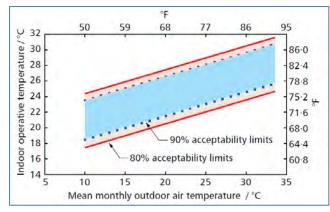However, the demand for cooling in buildings will continue to increase.

Figure 1. Contours from mapping London night time temperatures in summer 2000 [6]

Building design, comfort levels and low carbon cooling
Factors that influence the heating and cooling energy demand and emissions from buildings include:
- The building design, orientation and construction materials
- Glazing, solar gains and shading
- Density of occupation and occupancy profile
- Ventilation, heating, cooling and hot water systems and controls
- Internal heat gains (people, lighting, IT, small power, catering, machinery etc.)
- External environment (daily and seasonal weather), comfort levels and set points

There may be opportunities to make improvements over the life of the building, particularly during renovation or refurbishment, as well as to reduce carbon emissions through passive cooling methods and the inclusion of renewable energy technologies. However, the relative merits of different measures can only be assessed accurately through the use of building simulation and energy analysis software tools.

Opportunities may exist to reduce heating and cooling energy demand and emissions through adaptive control of temperature set points, according to the external environment. Figure 2 indicates that for any given outdoor air temperature there is a wide range of indoor temperatures that are considered acceptable by the majority of building users. Set points could therefore be adaptively moved near to these limits.

Figure 2. Acceptable operative temperature ranges for naturally conditioned spaces [7]

A Low Carbon Cooling Guide developed for the Greater London Authority [8] introduces the concept of a Greenhouse Gas Impact Factor (GGIF) and associated A-G rating for cooling systems. Figure 3 indicates the typical range of GGIF values for different cooling system types, including absorption, borehole and passive cooling systems as well as conventional vapour compression systems. This is a useful high level tool for comparing alternative cooling systems.
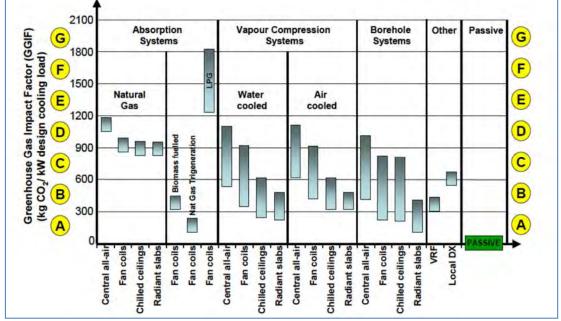

Figure 3. Greenhouse Gas Impact Factor and A-G ratings for typical modern cooling systems [8]

Benchmarks for estimating building heating and cooling energy demand
The recast of the EU Energy Performance of Buildings Directive or EPBD [9], which was implemented in the UK via an amendment to the Energy Performance of Buildings Regulations, encourages building owners and users to improve their energy efficiency. Part L of the Building Regulations [10] specifies the minimum requirements for many key building parameters, which can be used in simulations.

Various benchmark data have been published by building industry professional and trade associations such as CIBSE and BSRIA. CIBSE Guide F [11] provides guidance and a methodology for design and operation of buildings, together with benchmarks for energy use (generally expressed as kWh/m^2 per year) according to building type, component type and end use. CIBSE Guide TM46 [12] provides additional benchmarking data and adds factors that can be used to adjust the benchmarks for variable weather data (using degree days) and different occupancy profiles. The BSRIA benchmarking data [13] provides 'Rules of Thumb' for construction professionals.

Modelling energy demand and emissions in buildings
Several methods are available for estimating the energy performance of buildings, ranging from SBEM (Simplified Building Energy Model) to more complex Dynamic Simulation Models (DSMs) using CFD (Computational Fluid Dynamics) and 24 hour x 365 day weather data. However, many DSMs require lengthy computing times and generate large output data files that may require further post processing. Whilst they can be very effective for simulating the performance of buildings whose design has already been fixed, they may not be the most appropriate tools when multiple simulations are required in order to understand the relative contributions of specific design features and systems and for optimising the design. On the other hand, simpler models using techniques such as monthly heat balance, degree days and bin methods are unlikely to generate sufficiently detailed results.

A review of software tools for HVAC system design by Trcka and Hensen [14] concluded that "the initial modelling complexity should be the lowest possible complexity that satisfies the simulation objectives in terms of performance indicators". They identified 3 sources of error:
- Abstraction errors – due to an incomplete model of the physical system
- Input data errors – due to uncertainties in the parameters used in the simulation
- Numerical errors - associated with the discretization or step size used in the simulation

Increasing the complexity of the model should reduce abstraction errors, but this also requires more detailed data, which increases the input data errors. There is a trade off between simplicity and complexity, with a point at which the summed errors reach a minimum. Trcka and Hensen also concluded that to accelerate innovation in building technologies and to mitigate climate change there should be a focus on more flexible modelling environments.

A new dynamic energy balance modelling tool
A new model and Excel based software tool have been developed to address some of the perceived limitations of existing tools in relation to understanding and optimizing building energy demand and emissions. The key aims of developing the model were to provide a high level planning tool that:
- is simple and easy to use, with the data describing the building, occupancy and environment limited to only that which is necessary to achieve acceptable simulation results and accuracy (in accordance with the Trcka and Hensen approach)
- provides easy to interpret output data and graphing, with rapid visualization of the impact of changes
- can simulate passive and low carbon cooling measures
- calculates the direct emissions from RACHP equipment as well as the energy related carbon emissions of the building
- will assist users to establish optimal high level solutions for building design and operation
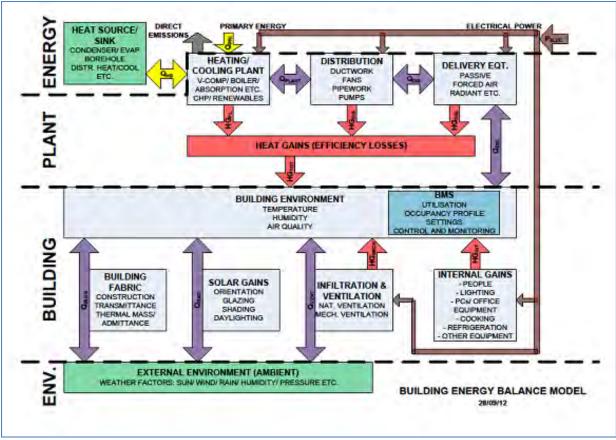
Figure 4. Dynamic energy balance model

The new dynamic energy balance model (Figure 4) uses simple algorithms and a reduced weather data set to generate rapid results, allowing the user to view the effects of making changes in near real time. It can therefore be used to quickly establish the potential impact of changes to key building design and operating parameters on comfort, energy efficiency and carbon emissions.

At hourly intervals the heat gains and losses associated with the building fabric, solar gains, ventilation and internal gains are summed in order to calculate the energy required from the heating or cooling plant to balance the energy flows and sustain the required environment inside the building. The default external temperature profile is the mean hourly air temperature from CIBSE Guide A, Table 2.34 [15] and the 97.5 percentile irradiance data (Table 2.30) is used to estimate the solar gain of the building. Building design parameters and operational data are input by the user, using CIBSE and other benchmarks. The user can specify the occupancy profile, ventilation rate, heating and cooling temperature set points and pre-heat and cooling periods. The heating and cooling plant type and efficiency, together with distribution and delivery losses, can be modelled to estimate primary energy demand and the associated carbon emissions, plus any direct emissions from the cooling plant.

The algorithm calculates the rate of change of temperature of the building for each one hour period and the temperature error (from the set points) is used to determine the required output from the heating and cooling plant to achieve balance over the next one hour period. The simulation is run over 72 hours, which also allows the thermal profile to be simulated when the system is recovering from an out of balance condition (for example when the building has been unoccupied and the heating and cooling plant switched off for long periods).

In order to simplify the analysis, the constraints and assumptions include:
- Restricted alignment of the building's main axis (N-S or E-W only) for solar gain calculations
- Limited options for zoning (a single zone for the building is assumed as default)
- An empirically derived cloud factor is used in the solar gain calculation

- Only sensible heat is considered
- Hot water used within the building does not contribute to the internal heat gains
- Heat flows are assumed to be constant during each one hour calculation period

New model validation

Due to the difficulty in accessing real data for buildings the Excel tool was validated against an industry standard software package, IES_VE (IES, 2014) [16]. The building used for validation was a 6 storey office building 60m x 30m in plan, located in London suburbs and constructed to the 2006 UK Building Regulations [10], with the major axis aligned East-West. The windows on all sides are 40% of the wall area and the low emissivity double glazing has a transmittance of 0.54 and a U value of 2.2 W/m^2K. An occupation density of $12m^2/$ person was assumed and a ventilation rate of 12.5 l/sec per person. The building was assumed to be occupied between the hours of 7 a.m. and 6 p.m. Monday to Friday and the heating and cooling set points were 19°C and 21°C respectively. It was assumed that the building was heated using a 1 MW gas boiler with 90% efficiency and cooled using an 800 kW air-cooled vapour compression chiller with R410A refrigerant and a system EER (Energy Efficiency Ratio) of 2.25. Both were capable of being modulated in 20% increments of their peak output power and the pre-heating and pre-cooling periods could be varied. The building is described in the Excel model by its dimensions, whereas in IES-VE it is represented by a 3D sketch (Figure 5).
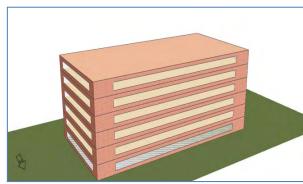

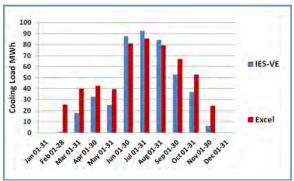Figure 5. 3D representation of office building   Figure 6. IES and Excel cooling load results

The results that were compared for the validation exercise included the heating and cooling loads, building temperature profiles, solar gain, ventilation gain, building fabric heat gain and internal heat gains. The example shown in Figures 6 (building cooling load) is indicative of the correlation between the two sets of results.

Results for office building cooling energy and emissions

Figure 7 indicates how key results from the Excel software tool are displayed in a 'dashboard' window that updates almost instantly when a parameter is changed. The dashboard approach is very flexible and allows any charted result from the simulation to be copied and pasted to the dashboard window, according to the optimization criteria specified by the user. This dashboard shows a breakdown of the 24 hour heat gains and losses on day 3 of the simulation, for each calendar month, together with the temperature profile over the 72 hour simulation period. The temperature plots indicate that, following a cold start, the building stabilizes by day 2. During the daytime occupancy period the temperature remains within the range 19-23°C.
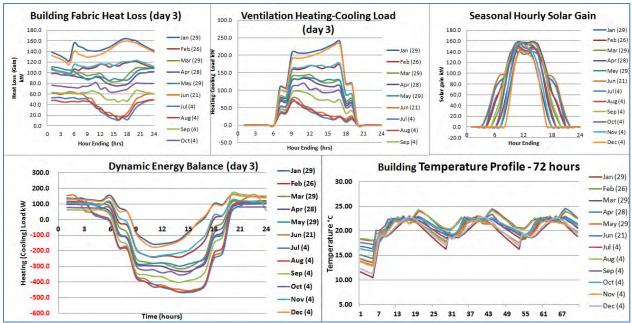
Figure 7. Excel software tool reconfigurable results dashboard

The dynamic energy balance chart for day 3 indicates whether the building requires heating or cooling energy in order to maintain balance. It shows that for most of the time that the building is occupied (07:00-19:00 hrs) the heat gains are higher than the thermal losses, even in mid-winter, so the building normally requires cooling. This suggests that for modern buildings of this type, the focus on energy conservation and emissions reduction should shift from heating to cooling, especially when taking future global warming into account.
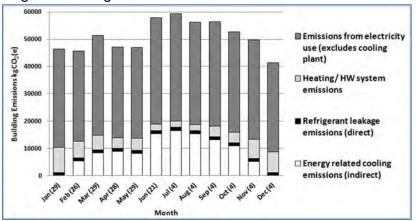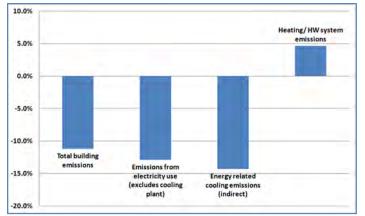

Figure 8. Monthly breakdown of building emissions

Analysis of the monthly emissions from the building (Figure 8) confirms that the total emissions associated with cooling are significantly higher than emissions from the heating system. However, the chart also demonstrates that the highest emissions are due to the other electrical loads in the building (lighting, equipment and ancillaries such as pumps and fans) and the peak monthly emissions associated with cooling energy are less than 30% of the total. Direct emissions from refrigerant leakage are less than 2% of total emissions. For this particular building, reducing the electricity use (for example through the use of more efficient lighting and IT systems) could be the most effective way to reduce emissions, since it would at the same time reduce the internal heat gains and consequent cooling load and emissions. There might also be opportunities to reduce emissions still further using a more efficient cooling system.

Using the tool to investigate building emissions
The following examples show how Excel tool might be used to investigate cooling and other emissions from buildings. In the first example the impact of reducing the lighting heat gain from 12

W/m² to 8 W/m² (corresponding to replacing the fluorescent lights with LEDs) has been assessed. Figure 9 demonstrates a reduction of more than 11% for the total building emissions. The energy related cooling emissions reduce by over 14% as a result of the reduced cooling load, although in absolute terms the emissions reduction for non-cooling elect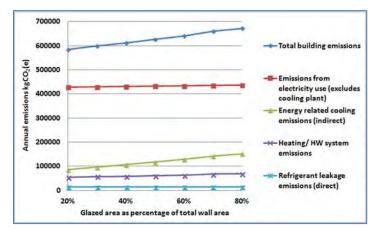ricity use is more significant (55,000 kgCO$_2$(e) vs 15,300 kgCO$_2$(e) for cooling emissions). The small increase in heating emissions is due to the reduced contribution from the lighting system to heating the building in winter.

The sensitivity of the building's solar gain and emissions to the glazing design can be assessed by characterizing the emissions for different glazed surface areas.

Figure 9. Percentage change in emissions due to replacing fluorescent lighting with LEDs

Figure 10 indicates how the emissions would vary as the glazed area is varied between 20% and 80% of the total wall surface area. It shows that if the glazed area is reduced from 40% to 20%, the cooling energy related emissions reduce by almost 20% and the building's total emissions by almost 5%. Reducing the solar transmittance factor (by appropriate selection of glazing materials) could achieve a similar improvement. On the other hand, if the glazed area were increased from 40% to 80% (as in many modern buildings) the energy related cooling emissions increase by over 40%.

The impact of increasing the cooling temperature set point can also be demonstrated. Figure 11 shows that an increase from 21°C to 23°C reduces the cooling emissions by 25% and the overall building emissions by nearly 6%. A similar reduction could be achieved by improving the EER of the cooling plant from 2.25 to 3.5.
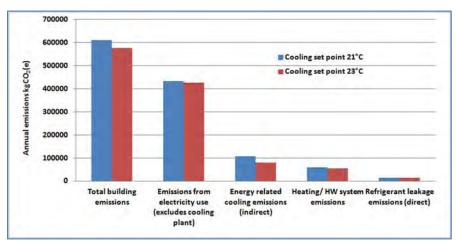
Figure 10. Sensitivity of building emissions to glazed surface area

Figure 11. Impact of increasing the cooling temperature set point on cooling emissions

Conclusions

This paper has described one approach to understanding cooling energy demand and emissions in buildings. A building's cooling and heating energy demands and emissions are both influenced by many of the same factors, so heating and cooling cannot be considered in isolation if the aim is to reduce the total building energy use and emissions. Assessing and optimising alternative building design concepts, RACHP system, passive cooling techniques and strategies for managing the building requires simulation tools that allow the user to evaluate and view the building's dynamic response, energy use and emissions in near real time.

The dynamic balance model described in this paper has been validated against industry standard IES_VE software for a typical large office building. The results demonstrate that cooling systems in such buildings may be responsible for a significantly higher level of emissions than their heating systems. However, for this example the highest level of emissions is associated with electricity use for lighting and equipment.

The model can be used to explore options for reducing cooling demand and for estimating the emissions from the selected cooling system, as well as to predict the impact of climate change using future weather data; some examples have been presented. Further work to refine the model and develop a cooling hierarchy for buildings is continuing.

Acknowledgement and Disclaimer

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PAPER 2 – A REVIEW OF EXPERIENCES OF LOW ENERGY BUILDINGS: EXPLORING THE OPPORTUNITIES AND LIMITATIONS OF LOW ENERGY BUILDING DESIGN

by Prof Andy Ford CEng, DEng, FCIBSE and Aaron Gillich

Abstract

Understanding how to design sustainable Low Energy Buildings is a topic with high relevance in a world facing the challenge of decarbonisation. This paper describes a time line through the thinking over a twenty year period. It draws on the author's personal experience of designing and constructing low energy buildings. It will consider the key elements for success, how thinking evolved through a chain of designs and suggest how the ideas might be taken forward. The paper begins with a series of buildings designed in the late 1980's at the University of East Anglia which made significant steps forward in delivering long term low energy buildings. It then explores how the ideas evolved with particular consideration of the role of thermal storage and cooling both at an individual building scale concluding with community level solutions delivered in the first decade of 2000.

Introduction

This paper is a short summary of work carried out over a 20 year period exploring the possibilities and challenges of low energy buildings, how policy has gradually shifted in this direction and where the current challenges lie. It draws on a few particular examples to explain what has and what has not worked.

Fulcrum was established by two Mechanical Engineers, an Architectural Engineer and a Biologist. With the idea of innovation at its heart utilizing lessons learned from one project to inform the next and drive forward understanding. This process was referred to in house as 'Continuous Controlled Innovation'. Using CCI we were able to operate as a research development practice in a commercial setting delivering significant contributions to knowledge. As a consultancy our commitment was to our clients but CCI allowed our clients to benefit from each other. Key to this was the concept of 'informed consent'. Each client was informed of our current understanding and on any single project only small steps were taken and only with our clients' consent. Within the company however these projects were all viewed as part of an ongoing research project.

In 1986 I visited the Centre for Alternative Technology in Machynlleth Wales. A house had been built on the CAT site using a concept known at the time as 'super insulation', which is essentially insulating a building so well that its structural heat loss is reduced to a trivial level.   The building still exists and is known as the 'Wates' house it was insulated with 450mm of fiberglass insulation in the walls and roof and had small quadruple glazed windows.

Figure 1: Wates House [1]

The opportunity to experiment with this in a real project occurred shortly after when we were appointed to advise on the construction of 800 student rooms at the University of East Anglia with Rick Mather Architects. Our client was interested in long life and low running costs. The architect was a modernist whom we had previously worked with on a number of innovative smaller projects but nothing at

this scale. The site was at the far end of the UEA campus almost half a mile from the MTHW central boiler room.

Working closely with the QS a full comparative cost analysis was carried out looking at a 20-year life cycle to consider the minimum constructional changes necessary to incorporate sufficient fabric and building services improvements to justify non connection to the existing inefficient district heating. The 'Wates' house concentrated on super insulation but there is significant heat loss due to air leakage, with air leakage rates of 1-2 AC/hr considered quite normal design conditions at the time (though Building Regulations Part L now require much better levels of air tightness such that new buildings are typically 0.25-0.50 ac/h). Working with David Olivier EAA [2] in a review of European low energy housing sponsored by Fulcrum had suggested that this could be significantly improved through careful detailing and care in construction, but controlled mechanical ventilation with heat recovery to deliver the energy reduction.

We needed to make sufficient savings to justify omitting a district heating system connection which would have involved a new long run of underground pre insulated pipework, replaced with 200-watt electric panel heaters and provide electric supply air tempering and heat recovery as well as bathroom extracts. A challenge carried out in very close liaison with the QS. In the event the running costs compared to typical medium cost university residential buildings showed a saving of £5.30 per sq metre at 1992 energy costs.
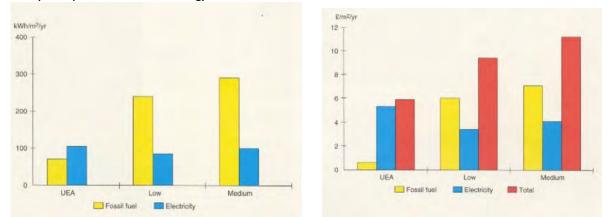

Figure 2: Annual fuel use (above) and energy costs (below) for Constable Terrace at UEA compared with the DOE's 'low' and 'medium' yardsticks for university residential buildings. [3]

Electricity use

Four typical houses were used for monitoring the electricity use, and end uses. This was achieved by sub-metering the power supplies for the MVHR systems, the backup water heaters, the panel heaters and for lighting and small power, in each house.

The total electricity used in the four monitored houses averaged approximately 98 kWh/m2/yr, of which approximately 34 kWh/m2/yr was for the MVHR units. The average percentage breakdown of total electricity use by end uses was as shown in figure 6. The designers of Constable Terrace did not intend electricity to be used for water heating (except for trace have.

heating of pipework). The individual electric immersion heaters were specified only as backup for the central gas-fired system. However, premature disintegration of sacrificial anodes caused a build up of sludge in the hot water storage tanks, effectively insulated the heating coils, and restricted the supply of hot water. Consequently, the electric immersion heaters were switched on during parts of the monitoring period, in order to increase the quantity and temperature of hot water. In the four monitored houses this procedure appears to increased the use of electricity slightly and reduced the demand for gas by a thermally equivalent amount.

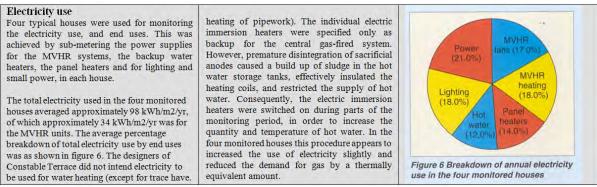Figure 6 Breakdown of annual electricity use in the four monitored houses

Figure 3: Electricity use summary for Constable Terrace. [3]

To achieve the radically reduced air leakage, additional specialist detailing help for the architects was required and following design team discussions this was provided by Halcrow Gilbert. With the confidence of this assistance in place, the contract was tendered with a requirement to achieve air tightness of 1A/C at 50pa, the first time we believe such a requirement was part of a construction contract together with a clause requiring that it should be proven post construction. Interestingly no contractor raised this as an issue during tender.

In the end the final pressure test achieved 2A/C at 50pa and this was accepted (at normal pressures this would be approximately 0.1 ach). In order for the systems to be confidently sized it is essential to know the construction is well done. In this case the client had an experienced clerk of works who took on board the low energy construction requirements and monitored the construction closely.

A large part of the heating is in effect provided by occupation i.e. heated by students as one article highlighted the project. This brings with it issues such as, what happens when they are not all there and the occupation loads are reduced? What happens in summer? How far can you go before cooling is required?

The performance of the building was independently monitored for the Energy Efficiency Office DOE during 1993-94. During the first year low occupancy during the winter caused some discomfort for the few occupants who remained over the holiday season. This problem was identified as being due to running the heat recovery ventilation system at 17°C, which was the normal set point. During low occupancy a raised tempered supply air of 21°C was instituted and the problem resolved.

Experiments were run by the facilities manager during the summer to see if energy could be saved by running with extract only but because of the buildings high air tightness it was soon shown that this caused stuffiness and the supply air has since always been run continuously with heat recovery bypassed during summer. Although such issues were easily dealt with by the occupants opening the window and energy use was indeed slightly lower during the experiment comfort was clearly more important. This however highlights the percentage of energy use attributable to the MHVR was 17% and demonstrates the need for careful low pressure drop system design and the importance of efficient and reliable fans (MVHR manufacturers are now generally using low energy EC/DC fans).

Summer conditions were also monitored and were typically in the range 24-30°C in south facing rooms and 24-26°C in the north facing which highlighted the impact of solar gain on buildings which have such low heat losses raising the question of how best to deal with summer design should some form of cooling be introduced or the building simply be designed to avoid solar gain?

In 1993 we were, in parallel to the testing being carried out at UEA, designing with the same architects a residence building at the University of Oxford (Arco Building). We held a number of design workshops to consider the findings and the following changes were implemented which show how feedback can be very useful if it is timely and can be used by the team immediately.

In the Arco building the construction was as in UEA but the AHU were centralized to improve efficiency and reduce maintenance time. The corridors were utilised as the supply air route which reduced pressure drop in the system. Pressurising the corridors was part of the fire strategy. Significant Brise-Soliel was added on the southern face. The building thermal mass was deliberately exposed in the rooms requiring a shift to full distribution of services in the floor and concealed lighting. Finally as the significant new step part of CCI floor insulation in the lower ground floor rooms the was redesigned to run out from the building as an underground umbrella causing the mass beneath the ground floor lecture theatres to become thermally part of the building and stabilise temperature across seasons. This was the first step towards utilising seasonal heat transfer a technique pioneered at the Rocky Mountain Institute.

Overall the results were more reportedly comfortable and energy use similar but in this case there was no independent monitoring so this cannot be verified.

Thermal Mass

Whilst the buildings described so far are exploiting the value of insulation and airtightness to separate the internal environment from the external it became evident that the control of the internal conditions by largely passive approaches would also yield benefits.

The buildings discussed have utilised thermal mass by exposing the concrete soffits the next will discuss the active control of the temperature of the fabric as an approach to achieving comfort in a simple manner.

Typically altering the air temperature is the primary approach to controlling the temperature of a building; however our comfort is affected by the 'environmental temperature'. Where there is no significant air movement, this can be expressed as:

$$(T_a + T_r)/2$$
Where: T_a – Air Temperature, T_r – Radiant temperature.

Our exploration of this begins with the Elizabeth Fry Building at the UEA. The logic being that heat is largely stored in the fabric of a building and the temperature of this fabric can be adjusted over time using external conditions that occur naturally but not at the same time as the occupancy. This is not possible with air temperature but can be viewed as an extension of the concept of 'free cooling'.

Active control of the fabric temperature is not new, Roman hypocausts, underfloor heating and embedded wall heating coils are all examples. They have one thing in common, which is that a fluid is passed though the fabric to adjust its temperature. But the best surface for radiant heat exchange is the largest and most exposed i.e. the ceiling. The simple choice of fluid is between water, with the ability to transmit a large amount of heat but a nuisance if it escapes; and air, which can carry less but can be discharged into an occupied space with positive benefits.

We needed to both heat and cool the building since it was a teaching building with high internal loads. One key driver to find a solution was the statement by the client that there was 'no way air-conditioning was going to be provided for the students', since it was considered a luxury. However all of our calculations indicated that we needed cooling to avoid overheating in a highly insulated building. So we searched for examples of air being used to directly control the temperature of the mass of the slabs and identified a patented Swedish fabric thermal storage called TermoDeck.

The system utilises precast hollow core extruded concrete slabs as typically found on display in car parks in the UK. These were capped at the ends and then diamond drilled on site to create a labyrinth in each slab through which the full fresh air primary supply air is routed. Great care is taken to minimise pressure drop in the system, and circulation spaces are used for the return air path with low resistance high efficiency flip-flop heat recovery stacks in the AHU.
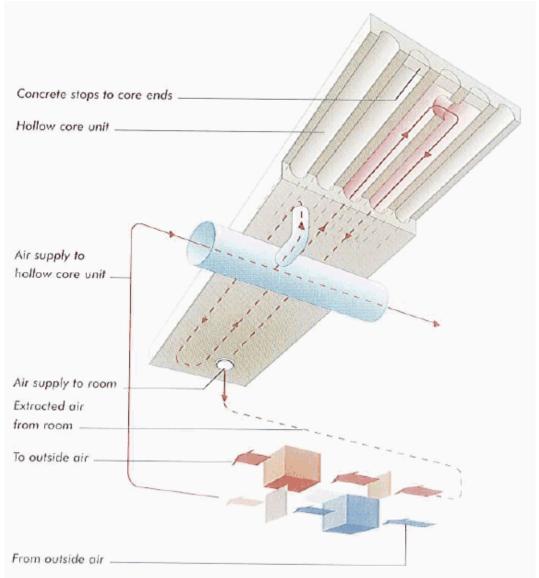
Figure 4: Diagram of TermoDeck fabric thermal storage system [4].

The building is designed and constructed with rigorous attention to detail with Fulcrum responsible for providing the full package of advice on building services and fabric thermal detailing. This combination, it was already becoming clear, was required to mitigate our risk as building services consultants designing services with low output.

With high levels of insulation and airtightness achieved, the building required less than 10 W/m² of heating, and this permitted the surface temperature of the slab (heat emitter) to be less than $23C^0$ peak. This is a great advantage meaning we could utilize low grade heat sources which in this case are early domestic condensing boilers but could also be renewable heat sources. All other distributed heating was omitted from the design. This low heating emitter surface temperature also introduced a very useful and initially not fully anticipated, benefit of simple control of temperature for a building with highly fluctuating occupancy. Effectively when large numbers of people enter a room the heat emitter ceases to emit and becomes an absorber. The control system was initially set up in 1995 and controlled based on the air temperature. However, this was reconfigured in 1996 to control based on the slab temperature with no loss of comfort and significant reduction in energy demand.
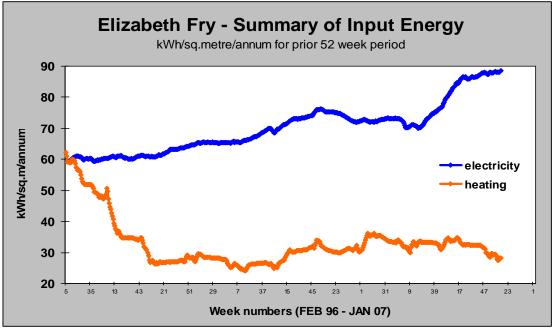
Figure 5: Energy record UEA, Elizabeth Fry building. [5]

The active control of radiant temperatures utilising a system with significant thermal storage and a long time lapse enables highly effective use of free night cooling. The facilities managers' report great flexibility in maintenance of the system since the temperature is maintained by the fabric and the windows can provide ventilation whilst they maintain plant. The Elizabeth Fry Building was studied as part of the PROBE studies [5] into building performance and revisited in 2012 to understand changes and sustainability of solutions over time CIBSE Journal March 2012 Bill Bordass and Adrian Leaman.

Fulcrum have since utilised TermoDeck in many buildings and most significantly in the PFI procured Brighton Jubilee library in 2000. Here the established approach of radiant temperature control and full building ventilation were taken to another level. Mechanical ventilation is provided to the three stories of office and ancillary areas with the high air volume per person required by the TermoDeck system discharged into the 5000sqm main library space. This effectively conditions it without any additional plant using the height and massive structure to moderate temperature swings with wind assisted extract.
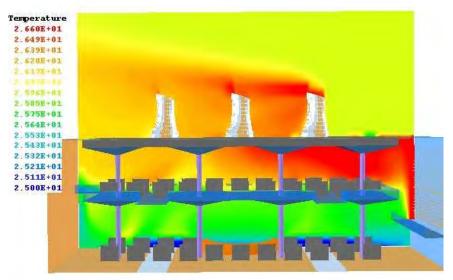

Figure 6: CFD simulation of airflow in Brighton Jubilee Library by Fulcrum Consulting
(now Mott MacDonald). [6]

Experiments with seasonal storage

The success of our buildings with integrated active fabric thermal storage encouraged the further investigation of seasonal thermal storage first explored in the Arco Building at Keble College. This time the research question was: can we find a way to easily make use of seasonal fluctuations to provide an 'on demand' source of heat or cold for buildings we were designing with short term fabric thermal storage embedded? Two further buildings had been built which used the passive annual heat storage approach explored in Keble, the Ecology Pavilion in Mile End Park East London and the Archaeollink Visitor Centre, Oyne, Aberdeenshire. While these examples to work as designed, they were effectively underground buildings, which meant that their broader application was limited.

Work with ICAX Ltd. [7] explored the modelling of the flow of heat through the ground and storing solar heat collected from tarmac surfaces for deicing applications. This eventually led to a full size demonstration with the Transport Research laboratory in 2005 validated our CFD modeling techniques for underground heat flow TRLPPR302 Performance of an Interseasonal Heat Transfer facility and established the feasibility of Interseasonal Heat Transfer as a predictable solution. Meanwhile we had established links with a Dutch

Figure 7: Interior Brighton Jubilee Library showing exposed concrete soffit (Bennetts Associates Architects). [6]

company exploring similar opportunities but using aquifers for the heat exchange. The key advantage being that by utilizing Ground Source Heat Pumps for heating in combination with recharge through cooling creates lower temperature cold heat storage enables direct cooling without the use of mechanical refrigeration and increases the efficiency of the heat pumps in heating mode.
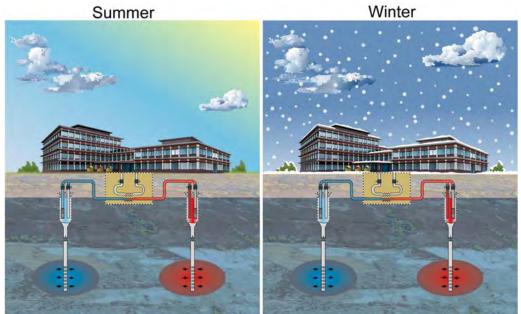

Figure 8: Interseasonal recirculation system in summer and winter. [8]

Both solutions were taken forward for use in buildings. The first UK Aquifer Thermal Energy Storage building was a social housing scheme Westway Beacons [9]. This is possibly the only cooled social housing scheme built in the UK. But the reason was the location on the major arterial road out of London with a requirement to seal the windows to control noise and air pollution which had caused the site to remain undeveloped for decades. We utilized all of the lessons learned in the buildings listed above and the scheme is highly insulated, airtight, with MVHR, and exposed mass. There are large south facing communal atria/wintergarden, which is cooled, providing solar heat to raise the temperature of the ATES store. The scheme functioned successfully but suffered from disconnects in the contractual chain which caused difficulties in the resolution of system control issues. A similar scheme but this time for a new sustainable primary school in Hertfordshire Howe Dell Sustainable School brought together all the concepts of lowering heating demand, fabric thermal short term storage with UTS for longer term allowing the cooling of the building in summer to collect heat and added the use of a tarmac connected surface in the form of the playground as a thermal collector/rejecter to balance loads over a year. [10][11]

The ideas initiated in early work at the UEA have since become carefully codified in the 'Passivhaus' approach to construction developed by a German physicist, Dr. Wolfgang Feist through a major Passivhaus research project called Cost-Efficient Passive Houses as European Standards (CEPHEUS), from 1997 to 2002. This project reviewed several hundred super-insulated projects from around the world and came up with a simple definition now called a Passivhaus. The building ('house' since initially this was a residential standard), should have an infiltration rate no greater than 0.60 AC/H @ 50 Pascals pressure difference, a maximum annual heating energy use of 15 kWh per square meter, a maximum annual cooling energy use of 15 kWh per square meter and maximum source energy use for all purposes of 120 kWh per square meter. It recommended a maximum design heating load of 10 Watts per square meter and windows with a maximum U-value of 1.4 W/m^{2}K.
Since this project, the idea has taken off exponentially providing a clear target and a detailed approach to the thermal design and implementation which appeals to the industry arguably more than the rather wider sustainability targets as personified by Code for Sustainable Home and BREEAM.

An understanding of the penetration of the standard can be gained from the fact that there are now 4000 plus certified Passivhaus designers around the world in 30 countries [12]. This from a point when the initial idea of certification was not at first considered necessary and growth has been significantly organic in nature.

Several interesting examples of the extent of buildings now being constructed to these standards in the UK are housing by Camden council in London [13], the Interserve office building at Watermead Business Park [14], and London Borough Tower Hamlets refurbishment of Stebon Primary School [15]. The variety of building types effectively demonstrates that the approach pioneered in the 1990s is neither just for housing, nor only for new build. These buildings largely eliminate the need for central heating but often could benefit from cooling even in a country where suitable cold temperatures are typically naturally available for much of the year - at least at night.

Summary

This paper has drawn together a particular chain of building designs which have explored the limits low energy solutions for the heating and cooling of buildings in practice through the work of one practice. Key lessons learned are that within any engineering or architectural practice the concept of CCI is applicable and with good client engagement and a long view by the management of such a practice considerable progress can be achieved. The most important steps occur when detailed monitoring takes place. Not all buildings need be part of the long term project but those that are so deemed with the clients informed consent should be monitored post occupation and ideally by independent parties with the involvement of the design and construction team (e.g. Soft Landings).

Detailed guidance is required for architects, engineers and builders to teach truly effective thermal fabric design such as now offered through the German inspired Passivhaus [16] approach this can then be combined with thermal storage both short term building fabric based and long term such as UTS cooling approaches that make use of our fluctuating climate.

Significantly heating and cooling must not be viewed as independent if maximum efficiency is to be achieved.

Buildings, their surroundings, the ground they stand upon, and adjacent buildings within a reasonable distance should all be considered as a holistic set to minimize need for energy. The future limitations are legal - who owns stored heat?; practical - how to most cheaply and efficiently move heat which is for use both in cooling and heating between buildings, collectors and stores; and social - around the sharing both of heat and information to enable long term thinking.

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