Before

After

Lessons from a Whole House Low Energy Retrofit

Caroline Mason
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Preamble

This paper records key points from my meticulous refurbishment of an Edwardian semi-detached urban house in Oxford to combine comfort and ultra-low energy use. It may be helpful to an architect, an interior designer, a builder, a homeowner, a developer or a policy-maker, and encourage those contemplating major refurbishments to capitalise on the opportunity for super-comfortable houses with minimal energy use.

There are design and technology decisions for healthy homes and minimal energy use that are deeply embedded in the fabric of a house. These need to be considered at the very outset, even before layout and finished appearances. At the heart of these is ventilation strategy.

An overview of our refurbishment, our dilemmas and decisions, and the implementation are described here. Further details of our choices and of the refurbishment process itself, including a photographic record, are on my blog: www.myretrofit.blogspot.com.




Background

I come to this as a homeowner, who is persuaded of the need for action to cut our energy use in the face of looming global climate chaos. We have undertaken energy improvements to our own house over the years, but in a very piecemeal way, and felt challenged to see what could be done in a whole house, whilst providing a comfortable, convenient and healthy home.

A scientist by original training, but not specifically in the energy field nor architecture, I have been learning as I've gone along.

My conviction is that minimising the total energy demand for a house is paramount. The UK simply cannot supply an ever-increasing energy demand. I was looking to minimise the carbon footprint, too, in the long run, so decided that fossil fuel use (and so gas) had to be eliminated. I therefore opted for all electric, even though much of our grid electricity is still generated from fossil fuels. The hope is that the grid will be decarbonised as more and more electricity is generated from renewable and other non-fossil fuel sources in the future. In addition, as many solar pv panels as possible were fitted on the roof to supplement the electricity supply.

I decided to buy a house in need of full modernisation. My thinking about what specifically to do developed as I looked at houses on the market and thought about the possibilities in each. I wanted to be actively involved in all the decision making.

The main objectives of the project were initially set out as:

- to create a light, airy and comfortable home well suited to contemporary living
- to provide practical living and utility space
- to respect the character of the original house
- to ensure that the house has the lowest possible energy consumption
- to provide the energy from low or zero carbon technologies
- to make the house easy to operate and maintain
- to test the financial implications of these decisions, including the rental market's readiness to pay for such investment.

I spent time at Ecobuild (at ExCeL in London's docklands in March each year), at which companies were showcasing so many technologies and ideas for "sustainable design, construction and the built environment". It was quite bewildering, but opened up the sorts of questions I needed to ask myself. I set to researching issues of types of insulation, heating options, window specifications and so on. I quickly established that there is no single "right" answer, and it is a question of making a suite of integrated choices. Issues of moisture management and airtightness were difficult to fathom, as there are many different opinions on what is crucial.

I also came across the government's "Retrofit for the future" competition which, back in 2009, invited companies/landlords to propose projects to retrofit social housing, focussing on ambitious, cost-effective carbon and energy reductions with potential widespread applicability in low-rise, whole house solutions. 50 demonstrator projects were selected and funded, including one in Nelson Street, Oxford. Their performance is being monitored for two years and the results are due to be published in 2013, I think.

Having contacted a number of local architects, I felt most confidence in the architects of the Nelson Street project, Ridge and Partners LLP, and worked with them on conceptual design. They suggested that we should aim for energy performance levels similar to the ones they targeted for Nelson Street (specifying how little heat energy should be transferred through the walls, floors and roofs, and how much air leakage is acceptable). I hadn't realised at this stage just how demanding these targets were (though I was well aware that we were going significantly beyond current building regulations). Ridge then recommended another architect, Guy Roberts, they sometimes work with on really small projects such as mine, and he took over to do the detailed design and to oversee the implementation. He didn't have experience of these ultra-low energy demands, but was more than willing to get to grips with it.

Preparation of the tender documents was very laborious as he and I both tried to pin down all the details that we wanted from the builder. None of the builders who tendered had experience of the extremes of airtightness or insulation that we were expecting either, and we emphasised during the tendering process the need to allow extra time and costs. We chose R&J Construction, a small local business. We ended up with a really positive team of me, architect and builder, but all of us were tackling this ultra-low energy brief for the first time.

Some technicalities

It may be helpful to touch on some of the concepts used in thinking about low energy buildings.

Primary versus delivered energy. A distinction needs to be made between primary and delivered energy. What we actually use in a house is delivered energy, measured on our meters in kWh, which may be from gas or grid electricity or the sun. Primary energy is the energy from nature, so it also takes into account how much energy has gone into providing the delivered energy. It is most significant in the case of electricity. When coal or gas is burned to create steam to drive turbines which generate electricity which is then delivered to our homes, the primary energy is the original energy in the coal or gas. It is more than the delivered energy as there is inevitably energy lost in the conversion process and in distribution. Based on the mix of coal, gas, nuclear, hydro, wind and other renewables that are used to generate electricity in the UK, 2.58 kWh of primary energy is used to deliver each 1 kWh of electricity to our homes. (2.580 is the primary energy factor in SAP 2012 based on a three year projection for 2013-2015.) Similarly for gas, the primary energy factor is 1.112 – most of the energy reaches our homes, though some is used in getting it there.

Energy and carbon dioxide. Reducing energy demand is about living within the limits of what can actually be supplied, and also about finding sources that don't burn fossil fuels (coal, oil, and gas). Burning fossil fuels releases into the atmosphere carbon dioxide, methane, etc that have been trapped in the ground since the plants from which they were formed died some three to four hundred million years ago. This carbon dioxide and other greenhouse gases are causing climate change which is stressing our planet unbelievably at a rate it cannot accommodate without dramatic consequences. So we need to be able to calculate the carbon dioxide associated with our energy use. In the case of gas, there is 0.184 kg of carbon dioxide equivalent (CO_2e) released for every kWh of gas burned. Grid electricity production on aggregate releases 0.525 kg of CO_2e per kWh of delivered electricity. Data from SAP 2012 three year average projections (2013-2015).

Heat loss and insulation. The bulk of our household energy demand is used to heat our homes, and most of this is wasted as it escapes from the building. Buildings lose heat through the walls, windows, doors, floors and roofs, so we insulate to reduce this. Ideally, we are aiming for a continuous layer of insulation around the whole house.

U values. How well or badly a building element (such as a wall or window) allows heat to pass through it depends on the effectiveness of the insulation and is often expressed by a U value. This measures the rate of heat transfer through a given area of a composite building element under standardised conditions (in watts per metre squared per degree of temperature difference, W/m^2K). Temperature here is measured in degrees Kelvin (K). A degree Kelvin is the same size as a degree Celcius (^oC), but the scale starts at a different zero such that 0^oC is the same as 273K, and 100^oC is 373K.

The lower the U value the better (lower heat loss). A well-insulated wall has a low U value (0.15 W/m^2K is very good). A 215mm solid brick wall (such as in our 1903 house) has a U value of 2.3 W/m^2K. An excellent triple glazed window (for the whole unit including the frame) might have a U value of 0.7 W/m^2K, where an old single glazed window with a wooden frame might have 4.8 W/m^2K. Comparing these figures, a good window loses about four times as much heat as a good wall. A poor window loses about seven times as much as a triple glazed window.

Thermal bridges. There shouldn't be any corridors through the insulating layer to allow heat to cross from the warm inside to the cold outside: such escape routes are often referred to as thermal bridges, and may exist, for example, where a joist is sitting directly into a wall and thus punctures the insulating layer.

Airtightness. Also very significant is the loss of heat with escaping warm air – sometimes there are obvious draughts but also there are less perceptible leaks in the fabric of the building. Water can leak out through any tiny gap in a container – and so can air. We need to stop air leaking out, in other words improve the airtightness. It is measured by pressurising (and depressurising) the building to 50 pascals above (or below) atmospheric pressure and seeing how much air escapes (or enters). There are two common ways of expressing airtightness. One considers the number of air changes per hour (ach) that occur in such a test; this depends on the internal volume of the building. The other considers the volume of air (in m^3) that escapes per hour for each m^2 of surface area of the building (in $m^3/h/m^2$), the permeability. I think that air changes per hour is easier to visualise:

effectively the entire volume of air in the house under pressure is replaced this many times in an hour. A normal house with single glazing may, I think, have 15-20 air changes per hour in a pressure test, whereas a Passivhaus has 0.6 ach or less.

Thermal mass. The amount of heat that a building holds in its fabric is a function of its thermal mass. A house with thick stone walls will have a much higher thermal mass than something flimsy like a wooden shed: it takes much longer to heat up because there is so much stone to heat and conversely cools down more slowly. The effective thermal mass is significantly reduced if the stone is insulated on the inside of the walls: in this case, the walls will remain cold even when the inside of the house is warm. If the stone is insulated on the outside, then the building continues to have a high thermal mass. This is an important distinction when considering how quickly or slowly you want a house to respond to heating.

Passivhaus. The Passivhaus philosophy emanates from Germany and seeks to create buildings that are very comfortable, affordable and highly energy efficient. At its purest, it seeks to eliminate the need for active heating within the building by using the sun, internal heat sources and heat recovery (hence its name "passive house"). The Passivhaus Institute defines performance criteria rather than specifying how things need to be built, so there is plenty of architectural freedom. The standards stipulate airtightness (at less than 0.6ach) and annual energy demand per m^2 of floor area for space heating (less than 15 kWh/m^2) and for total primary energy including appliances (less than 120 kWh/m^2). There are slightly modified standards for retrofits called EnerPHit, as it is more challenging to eliminate thermal bridges, etc. The key element of the design requires heat recovery combined with a ventilation system to achieve the very low energy use – hence the emphasis on airtightness.

The standards (for both new buildings and refurbishments) are very demanding, but are clearly spelt out and this is gaining support in the UK. The certification process is rigorous and is therefore well-respected and meaningful.

The key strategic decision

Message: the choice is either traditional ventilation or mechanical ventilation with heat recovery

I have given much thought to this low energy project and have come to the conclusion that ventilation decisions are at its heart. A healthy home must have fresh air. There are broadly two options: rely on traditional ventilation or include mechanical ventilation.

Traditional ventilation includes draughts and smaller air leaks, poorly sealed windows, extractor fans in bathrooms and kitchens, and opening windows to introduce fresh air into the house. This is typically on a room by room basis, but can provide reasonable air quality. However, it inevitably lets warm air escape from the house and wastes energy.

The traditional option is the normal pattern in this country (for both new build and refurbishments). We can achieve significant energy savings with lots of insulation, good double glazed windows, and efficient heating systems (I hear figures of potential savings of up to about 60% on fuel bills compared to old houses with no insulation, etc). It can be undertaken piecemeal, even whilst the house is occupied. Ventilation is still important, and so such devices as trickle vents are added to the windows. This may be adequate from a ventilation point of view, I'm not sure, and it is the way we have lived up until now. However, it will never deliver the additional energy savings associated with preventing warm air escaping. This is more of an issue than it has ever been before because we have started to reduce draughts for example with double glazing, we tend to keep our houses warmer, often heating the whole house rather than just one room (traditionally with an open fire), and we have the heating on more of the time as it is so easy with a system on a timer (it doesn't wait for us to get home and light the fire).

Alternatively, mechanical ventilation for the whole house circulates fresh air everywhere through ducting with appropriate filters, and gives excellent air quality all the time. Critically from an energy point of view, it can be coupled with a heat recovery system. In this, the outgoing stale air and the incoming fresh air both pass over a series of metal plates in a heat exchanger, though the two air flows never mix. Heat passes through the metal plates from the warm stale air to the cool fresh air. This allows for more significant energy savings. It does rely on a pretty airtight building (probably less than about 5 ach at pressure) to be most effective.

I am persuaded that the heat recovery option is the only way to reach <u>very</u> low energy demand (we may be talking about savings of around 90%). It has to be coupled with masses of insulation, triple glazed windows, complete sealing of the house to make it close to airtight and the installation of ducting for air circulation. The figures are very compelling. It is claimed that an efficient heat exchanger can recover as much as 95% of the heat from the stale outgoing air and transfer it to the fresh incoming air. This reuse of heat reduces the need for the addition of extra heat. And the heat will be circulated time and time again: this repeated reuse of heat has a multiplier effect – equivalent to a multiplier of 4 if we assume only 75% efficiency for the heat recovery. Furthermore, the heat exchange will be most effective in cold weather when the temperature difference between the incoming and outgoing air is greatest, so exactly when it is most valuable.

Luckily, we were set off down this route by the architects before I had appreciated the full implications.

Decision-making process: the trio of insulation-airtightness-ventilation

Message: the choices for insulation, airtightness and ventilation go hand in hand. There is no single right choice, but the choices of technologies/products must complement each other.

Our refurbishment design considered the house as an entire energy system: having decided on going airtight, there were lot of choices to make about how to achieve this goal: what insulation? how do we make it airtight? what ventilation and heat recovery? and what about heating systems? There are no single right answers, but the choices interact and must work together to give a self-consistent system. Each house has its own priorities and constraints. All the companies that are selling technologies to help with these elements are focussed on promoting their products: what I found difficult was picking the right mix!

Our decision-making process had a number of stages (many happening in parallel) which are summarised here and examined below:

- we started with the physical constraints of the house: its construction, its character, its setting, its orientation
- we identified the modernisation options (extension, reorganisation of rooms, dormer, etc) that we would like to include
- we took into consideration the orientation of the house and the opportunities for solar gain and conversely losses from north-facing windows
- we considered the practicalities of external insulation (the preferred option) versus internal insulation: we had to opt for internal
- we researched the choices for internal insulation (breathable versus non-breathable, thicknesses required, etc)
- we identified methods for creating airtightness (which go hand in hand with the insulation choices)
- we investigated ventilation options, including heat recovery
- we looked at the residual space heating requirements and ways of delivering this
- we also considered options for heating water
- as we went along, the interactions of various options emerged, and guided us to suites of choices: so we had to keep revisiting the different options to reassess in the light of our preferences.

Our starting point had to be the nature of the house itself: it has a 215mm solid double-brick wall construction. It is not in a conservation area, but in a road of attractive Edwardian period properties. The front faces south.

I considered external insulation: this is preferable thermally as it encompasses the whole house in a blanket, and poses less risk of thermal bridges. But the house has brick below and render above on all faces, so external insulation would change/spoil its appearance. Also, it is semi-detached, so the junction with the next-door house would be awkward with external cladding. Plus there are complications at the eaves where there is insufficient overhang to comfortably accommodate the thickness of the insulation.

Therefore, my conclusion was that we must go for internal insulation.

This was complicated by the fact that the house was originally constructed as a breathable structure, with air flows around and within the fabric preventing moisture build-up and the potential for rotting timbers. There are conflicting views on how to maintain the fabric of the house with internal insulation: some think there should be ventilated air gaps between the brick and the insulation, others say leave a gap but it doesn't need to be ventilated, others say definitely no gap. I spent a lot of time trying to work out the facts, but I don't think I ever fully convinced myself whether we got the right answer. We went for a gap between the bricks and insulation (as recommended by Kingspan), but it is not ventilated.

With internal insulation, all the brickwork is outside the thermal envelope and therefore the house will have a low thermal mass. This means that it will heat up quite quickly, but won't retain a lot of heat in the fabric.

I looked at airtightness. The exact position of the airtight layer depends on the type of insulation chosen. More on this later.

Having made a decision to go for ambitious airtightness, ventilation is required to maintain a healthy atmosphere in the house and eliminate a moisture build-up from general living (breathing, showering/bathing, cooking, etc), and thus prevent condensation.

Ventilation of the internal air in the house requires ducting to extract stale, moist air and replace it with fresh air. This then provides the opportunity to recover the heat from the out-going warm air and transfer it to the fresh incoming air in a heat recovery unit.

It is easy to use the same ducting to circulate additional heat as required around the house. There is no need for an additional wet system with radiators and/or underfloor heating. Hot water heating can be done separately.

This now gave us the overall energy system design.

Our targets for insulation and airtightness

The architect set us targets, which I now understand are broadly based on EnerPHit performance standards (the Passivhaus standards for residential retrofits – they are more complex than new-build Passivhaus standards because they recognise the additional challenges with existing buildings). However, we only had a sub-set as guidance, and they don't quite square with EnerPHit:

- airtightness 1.0 $m^3/h/m^2$ at 50 Pa (equivalent to approximately 1 air change per hour as the numerical surface area of the house envelope at 444 m^2 is coincidentally very similar to the volume of 426 m^3)
- insulation on external walls, ground floor, roofs to give U=0.15 W/m^2K
- all new windows, external doors to have U=0.8 W/m^2K for entire units

We didn't specify annual energy consumption targets (EnerPHit has an upper limit of 25 kWh/m^2 per annum for space heating): perhaps with hindsight we should have done.

We aimed to reduce energy demand for heating:

- by stopping heat escaping as far as possible (by excellent insulation of walls, floors and roofs; good triple glazed windows; positioning, size and structure of external doors; and making the house as airtight as possible). All these elements are deeply embedded in the house, and mostly invisible once the refurbishment is completed.
- by reusing heat rather than wasting it (by use of heat exchangers rather than simple extraction fans)
- by having a good control system for the heating so that the house is cosy as required.

Scope of the work

We undertook a full modernisation of a fairly typical 1903 semi-detached house. This entailed:

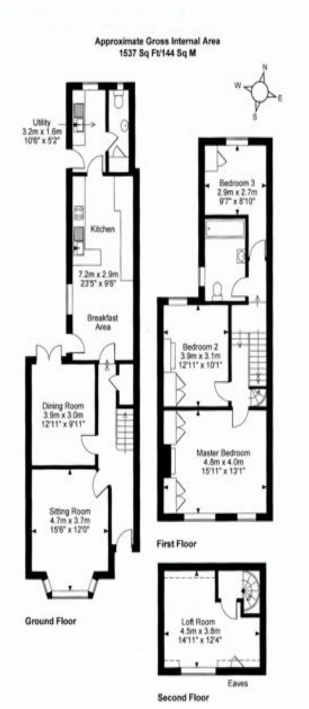
- adding a single storey extension at the back of the house to create one large family living space for the kitchen, a dining area and a sitting room, opening straight onto the garden at the back

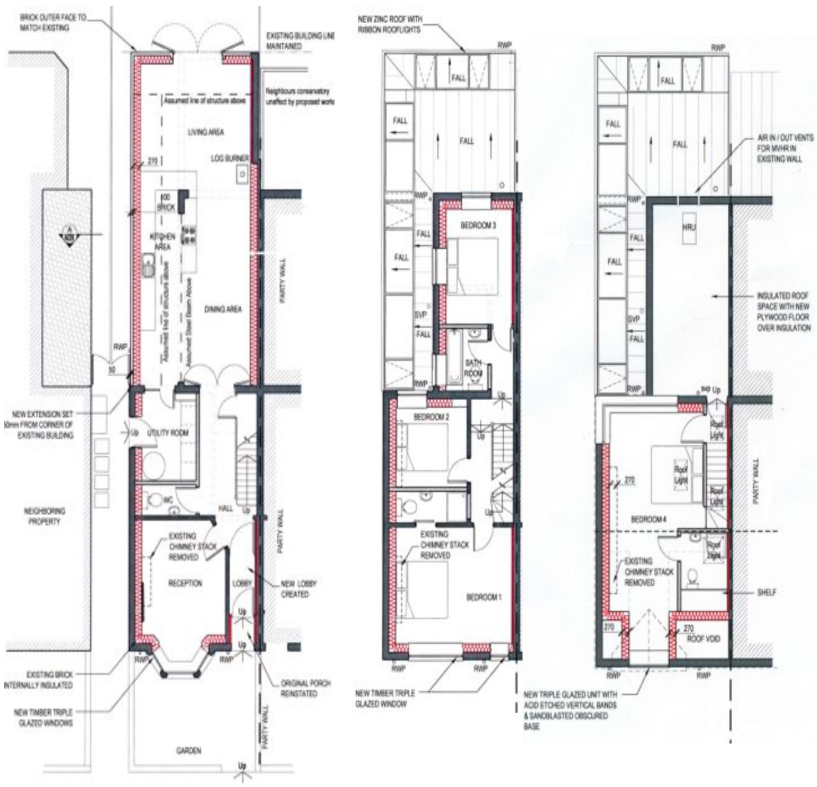
- removing a grotty dormer on the front face of the house and adding a new dormer roof at the back to upgrade the attic room to a bedroom with ensuite
- reorganising the internal space, including widening of the hallway and creation of a utility room and downstairs loo in dark middle of the house, creating an ensuite to the master bedroom and resizing the existing bathroom to make a larger bedroom
- all new wiring and data cabling
- all new plumbing
- new bathrooms and new kitchen.

In addition, the energy efficiency measures for the whole building included:

- extensive insulation of all walls, ground floors and roofs
- creating a continuous airtight layer around whole building
- installing a new mechanical ventilation and heat recovery system, with an integral air-source heat pump that takes the residual heat out of the extracted air
- adding new hot water tank with its own dedicated air source heat pump, plus heat recovery from waste bath and shower water
- replacing all the windows and external doors with triple glazing.

The end product is a lovely four bedroom family house. These are the before and after floor plans.





Choice of insulation materials

Message: there is a choice between natural materials (such as wool, wood fibre) and foams. Breathability for the old building fabric needs to be considered. The space available to achieve our target U value drove our decision in the end.

I have already described our decision to opt for internal insulation. Next is the choice of the insulation material itself. There are two main issues: heat loss and breathability. It proved really thorny trying to decide what the real issues for us were, and what was our best option. We went round and round in circles, before we made a decision.

My initial instinct was to opt for a sheep's wool system, as it is a natural product and this appeals hugely. The wool would be packed in between wooden battens. However, we rejected sheep's wool on the grounds of the thickness required (around 200mm plus a 60mm layer of say wood fibre board to give a basis for the final wall finish) to achieve the U value of 0.15 that we were aiming for, and some lingering doubts on longevity (will it slump with time, for example). We also considered a wood fibre option, which I liked very much (especially for its ease of installation), but we were too limited on the U value we could achieve on our old walls (only about 0.34) with the recommended maximum thickness of 100mm of wood fibre board.

This led us to a rigid foam system: there seem to be polyisocyanurate foams, polystyrene, polyurethane and phenolic foams. The phenolic foams have the best thermal properties for any given thickness (we needed 120mm for the total wall U value of 0.15), so this is our choice. They are based on petrochemicals, which is perhaps less desirable. In terms of minimising heat loss with minimum loss of internal space, these are the best.

However, this question of breathability for old buildings kept nagging at us. The existing property was a breathable structure and had stood the test of time. Would changing it to a non-breathable design affect the fabric of the building?

A natural system (like sheep's wool or wood fibre) is a breathable system. Foams are non-breathable. It took me a long while to work out the fundamental differences between these and their pros and cons.

Breathability in the context of a house is about moisture (both water vapour and liquid condensation), and not air (as I had originally assumed). The existing house with its 215mm thick solid brick walls was a breathable structure. Water vapour indoors (from people breathing, and creating steam with showers, baths, laundry and cooking) has to be able to escape to avoid lots of condensation leading to mould and rot. This happens by air (and its water vapour) escaping through gaps (draughts) principally around doors and windows, or by diffusion of the water vapour into the walls. Rising damp (there is no damp proof course in the walls) is minimised by having a suspended timber floor and by moisture rising up the walls being drawn up and out by capillary action of the bricks.

With natural insulation that allows for the diffusion of water vapour, this breathability is maintained.

However, foam insulation is impermeable, so there is no diffusion of water vapour into the walls. Furthermore, if the building is also made airtight, there are no gaps through which air can escape (no draughts). Water vapour indoors will build up and condense on cooler surfaces - but we have a mechanical ventilation system which will remove water vapour with the air changes, thus avoiding excessively high humidities (40-60% indoors is comfortable).

In addition, and rather more difficult to assess, is the risk of water vapour getting into the walls anywhere (for example where the seal is imperfect, or from the outside) and condensing in the fabric of the walls. In this connection, the dew point is all important. This is the temperature at which water vapour condenses for any given humidity level. For any particular wall make-up, there is a temperature profile through the wall from the inside temperature to the outside temperature. The profile will have varying gradients according to what each layer of wall is made of and how well it insulates: a steeper gradient in insulating materials and a flatter one in poorer insulators (like bricks). Similarly, there is another profile that shows the dew point temperature through the wall from the inside humidity level to the outside humidity level. If at any point, the temperature gradient crosses the dew point temperature gradient, then there is a risk of condensation. If the insulation layer is impermeable, then it is not possible for the condensation to be wicked inwards by capillary action, and it can just sit where it forms and cause long-term damage, especially if there happen to be any wooden joists into the wall at this point.

We had these calculations performed by Kingspan for our walls with the proposed phenolic foam insulation. There are many profiles, for varying inside and outside temperatures and humidities. Taking a fairly worst case scenario (of internal temperature of 20^{o}C and relative humidity of 61%, and an external temperature of 1.5^{o}C and relative humidity of 90%) the temperature gradient across our proposed wall make-up never crosses the dew point temperature gradient. So we went ahead on the strength of this.

I have some disappointment that we did not go for a wholly natural option, but with the insulation level we are seeking and the space available, foam seemed best. We have opted for Kingspan's phenolic range: Kooltherm.

In order to avoid any moisture build up at the base of the external walls, we decided to keep the suspended wooden floor on the ground floor of the old house, rather than replacing it with a concrete slab, even though the latter would probably be better from an insulation point of view. However, some air flow around the base of the walls is remaining just in case of any hints of rising damp there. We insulated around the floor joists as much as possible.

Installation of insulation

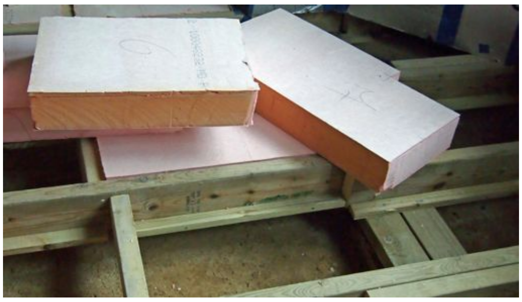
Message: this is a fairly slow and meticulous process that requires conscientious workmanship and careful supervision.

The objective was to create a continuous layer of insulation like a box around the house (though in our case on the inside of the external walls, ground floor and roofs). Note that internal partition walls don't need to be insulated as they are inside the warm box. We decided to remove all chimney breasts – these are just a route for air to escape – and this created more space. All the external walls were stripped back to the brick on the inside.

We selected the Kingspan Kooltherm range of phenolic foams, as described above. We used several different styles of the foam:

- for all external walls, we used **K12 framing board**, 60mm thick with foil backing on both sides of the rigid foam (sheets seen here stacked and ready to use). We needed 120mm thickness of foam to reach our target U value of 0.15 for the walls overall. This was built up from two sheets of the 60mm thick K12, one over the other. First the walls were battened with 85mm deep battens, their centres 400mm apart. This allowed for a 25mm air gap against the bricks and then 60mm of insulation between each stud, so the insulation was flush with the front of the battens. A second layer of K12 was then added over the first and in landscape rather than portrait format to ensure that, as far as possible, the joins did not coincide. The insulation was made continuous down the whole height of the house including the space between the ceilings and the floors above.

- for the party wall (which is neither external nor internal really) we used **K18 insulated plasterboard** straight onto the bricks, as we didn't have the space available for more insulation. You could argue for no insulation on the party wall, but the attached house in our case is often empty and is completely uninsulated, so it is probably not a very warm space on the neighbour's side most of the time. The part of the party wall beside the staircases had no space available for insulation, so these were given a proper 13mm wet plaster finish only. These walls then provide some thermal mass to help regulate the temperature of the house in the summer.
- for the roofs, we used **K7 foil faced foam boards**, 60mm between the rafters and a further 60mm over the rafters.
- under the suspended floor, we use **K3 tissue faced board**, 120mm thick between the floor joists (seen here cut to shape and ready to be put in place). We had to fit small retaining batten at the bottom of the joists to stop the foam dropping down into the air gap below the floor. The foam went right across to the brick of the walls and so under the vertical foam board insulating the walls to give a good overlap.



- over the new concrete slab in the extension, we used more **K3 tissue faced board**. There were two layers giving a total of 120mm of insulation above the concrete slab and below the screed. We didn't have to dig down much to accommodate this extra thickness, as the floor level in the back part of the house was originally lower than the front area, so we just raised it all to the same level.

There was lots of attention to detail, for example at the window reveals, to ensure continuity of insulation.

It was not possible to eliminate thermal bridges, for example where the floor joists sit into the external walls. We insulated along the joists for a short distance from the wall towards the inside of the house to minimise the transfer of heat to some extent.

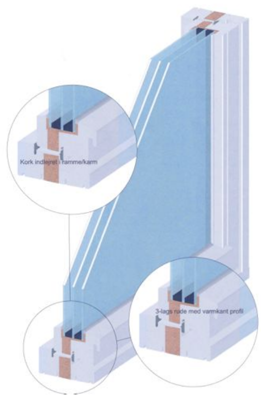
In an old house, there are inevitably lots of nooks and crannies that are awkward to insulate, but we did our best. We used expanding foam extensively, squirted into the awkward spaces.

Windows and doors

Message: only triple glazing meets the U value specified, so it is not possible to replicate exactly the originals. Good alternatives are available.

The house had a mixture of sash and casement windows. Along the rest of the road, there is a mixture of original styles and various types of replacements (wooden and uPVC).

Our specification of whole window U values was for 0.8 W/m^2K or better. The bottom line with the thermal performance of windows is that we couldn't achieve such a low U value by trying to replicate the old traditional styles. Glazing bars compromise performance – large single panes are much better. Triple glazing is essential and therefore too heavy for sliding sashes. This specification tends to result in a continental style of design. Emotionally, this didn't grab me, but rationally it is what we needed to select.

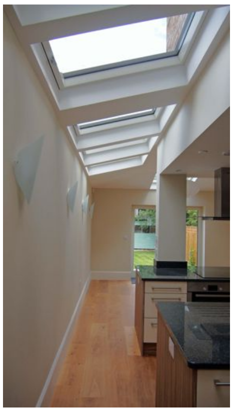


I investigated a number of suppliers of windows and doors: then I was delighted to discover some Danish windows by Scandia that more than met our thermal spec (typically around 0.7 W/m^2K) and look good, and were available from a local supplier. The frames are a wood/cork/wood composite (see illustration right). There was an option to have some added cosmetic glazing bars that don't seem to look "stuck on", but retain the high thermal performance of the single panes of glass. So, we opted to have horizontal glazing bars in the middle of each window in the bay at the front of the house to hint at the sash widows, and in the room above, a pattern of glazing bars to reflect the existing pattern of smaller opening lights. This goes some way to retaining the original character of the façade without actually replicating it.

The same company also supply high performance external doors, including some quite Edwardian-looking front door designs. So we used these for the front door, the alleyway door and the large glazed double doors onto the garden at the back.

Then there was the question of ceiling glazing for the single storey part of the back extension. The original plans had most of the side and end of the room with a glass roof. This was designed to flood this back part of the house with light. It was a compromise, as glazing is never going to give such good thermal insulation as a solid roof, but we thought it was worth it. However, the initial quotes we had for masses of glass were huge, although very elegant with essentially an entire structural glass roof. We wanted a more cost effective solution. It seemed to be triple glazing at a sensible price that was the challenge, and with a good enough U-value overall. We were trying to achieve a U-value around 0.8 for the glazed system. I was rather reluctant to have "Velux" style roof lights on aesthetic grounds, but in the end this is the route we took.

However, I was very pleased to find Fakro rooflights from Poland. They are the second biggest supplier after Velux, but are much less well-known. They have some excellent "thermal" triple glazed units (FTT U6), with purpose designed thermal insulating flashing kits. The system U-value with these kits is 0.72 W/m^{2}K. (Fakro also do a quadruple glazed unit U8, but we decided against these as they seem very bulky.) They cannot be opened with motors as they are too heavy, but I don’t think they will be opened much in reality. The end result is great!



For all the windows and doors, the installation details are critical to ensure the continuity of insulation and airtightness at all the junctions. This required careful thought and supervision.

Airtightness – challenges and pitfalls

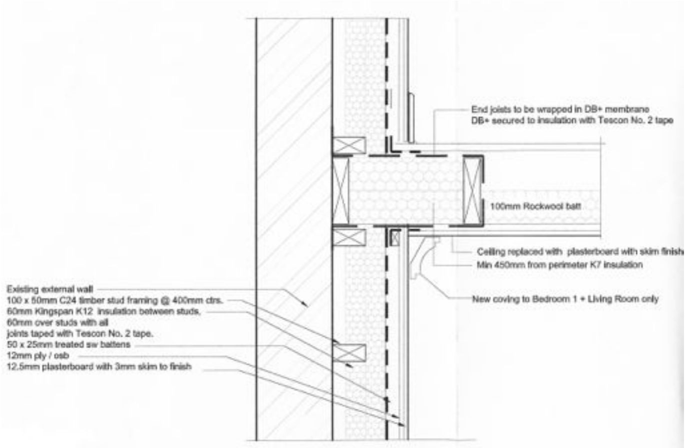
Message: airtightness (around 1 air change per hour) is very difficult to achieve in an old building. Taping and sealing must be planned and executed meticulously. Testing for remaining leaks needs to done before finishes are applied over the airtight layer, whilst it is still possible to rectify any problems. This challenges normal building sequencing and requires close supervision.

A key aspect of this house's energy efficiency relates to its airtightness. The objective was to seal every join, corner and detail to create an airtight envelope around the whole house. We decided to make the airtight layer the inside of the inner layer of insulation: so there had to be one continuous surface at this layer.

The foil surface of each Kooltherm foam board is itself airtight. We then put airtight tape across every join. We used Pro Clima Tescon 1 airtight tape, with a peel-off backing. This was a massive job and a vey slow, painstaking process. The foil on the boards needed to be dusted before the tape was applied to ensure a good seal. Care was needed to ensure there were no air bubbles under the tape. Then there needed to be tape from the insulation around every joist, around all the windows, at the eaves, where the walls meet the ground floor. There were even small pieces of tape stuck over each of the fixing screw heads. Where there were some awkward gaps, we squirted in expanding foam.

We put so much effort into creating an airtight envelope right around the house that we then wanted to make sure that it would not be inadvertently punctured by the electricians or plumbers as they wired and plumbed the house, nor would it be damaged in the future if pictures are hung on the walls, for example, and the fixings penetrate the airtight layer.

Therefore, we put battens over the second layer of insulation to create a void in which cables and pipes can run. Over the top of this, we fixed OSB (oriented strand board) to give a firm layer for fixing things to and also to avoid the hollow sounding rooms that can result if plasterboard is fixed immediately over the void. It was finished with plasterboard and a skim coat. The wall section is illustrated in this diagram.



05. TYPICAL SECTION THROUGH EXISTING EXTERNAL WALL
U value 0.15

Where services (including the main electricity cable, mains water supply pipe, waste pipes, media cable, and ducts for the heat recovery and ventilation system and the air source heat pump) enter or leave the house, they inevitably cross the airtight layer: we have used suitably-sized gaskets taped to the insulation layer to seal them.

There is an outstanding issue of the longevity of the sealing. There have been lots of tests and manufacturers of tapes claim decades, so it is hopeful.

Rather quirkily, there is no letterbox in the front door as it would not be airtight: quite sad really.

The moment of truth came when we tested the airtightness. We had hoped to make measurements at various stages during the refurbishment process, but we failed to reach a stage where we thought we were airtight until we were pretty much all finished - too late in the day to be able to make major improvements.

The testing involved sealing up all the ceiling terminals for the ventilation system. All the external doors and windows were closed, except one of the double doors. A frame was covered with a

tarpaulin cover and fitted into the doorway to give a tight fit. A fan was installed into the tarpaulin, as shown in this picture. The fan was covered and the static pressure was measured. The fan was then run to give a pressure difference between indoors and out of 50 Pascals. The rate of air loss was recorded by the instrumentation to allow the permeability and the air changes per hour to be calculated.

The calculated surface area of the external box that comprises the house was 444 m^2. The calculated volume of the house was 426 m^3. It is rather surprising that these are numerically so similar, but apparently not unusual for a house like this.

The result from the first pressure test was 4.61 air changes per hour (equivalent to a permeability of 4.43 $m^3/h/m^2$). The permeability and air changes per hour figures are very similar because the surface area and volume figures for the house are very similar.

THIS WAS HUGELY DISAPPOINTING! After all our efforts.

It was extraordinary to walk around the house whilst the fan was running and feel the draughts where air was leaking. There were gales blowing in through all the sockets, also around the soil pipes at the back of the toilets, by the stair string, where all the ducting dives into the service void from the plant room to the utility room two floors below - strange as this is all internal space, and so on. The plant room had been sealed off for the purposes of the test (as it is not habitable space and would not normally be included for a final reading). However, I am not sure about this as we had considered it as within our airtight box. The reading including the plant room was 6.17 ach (compared to 4.61 without it). So clearly the plant room with all the awkward corners at the eaves and the remnants of a chimney and all the pipe accesses is a leaky room.

Another campaign was waged to improve these obvious gaps - with more expanding foam and yet more tape. The pressure test was repeated, yielding a much improved result of 3.02 ach.

This is the best we are going to manage. Still disappointing as far as I am concerned, but apparently an excellent result for a house of this age and size.

So another time, we need to sequence building works to allow testing at a much earlier stage when it is still possible to rectify problem areas before they are all covered up. This doesn't fit with the normal way builders proceed in refurbishment: they ripple through the property with one trade following another in different parts of the house. Instead it would be better to get all rooms to the airtight point before plasterboarding and finishes, and stop for testing before anything else is done.

Next time, we won't underestimate the ability of air to exploit any tiny gap and run along internal pathways, maybe to emerge well away from the initial leakage point!

Ventilation, heat recovery and heating choices

Message: the need for ventilation is critical to a healthy house, but creates the opportunity for heat recovery, the ultimate in energy saving measures. The heating system uses the same ducting that is used to circulate the air, without the need for a wet system of radiators or underfloor pipes.

All houses need good ventilation to maintain healthy air quality. In draughty, single-glazed old houses, there is always plenty of air circulating. As soon as the leakages are reduced, for example by insulation and double glazing, alternative ventilation is needed: common practice is to add trickle vents above the new windows and to open windows. This is very wasteful in energy terms – it just lets warm air escape. The alternative is mechanical ventilation with heat recovery. It seems that once you have as few as 5 ach per hour, such a system becomes very effective. I think in general that ventilation issues are not being given sufficient thought, and heat recovery is essential to achieving really low energy demand for heating.

A mechanical ventilation system ensures that there is always fresh air coming in and stale air being expelled, essential to maintain low carbon dioxide levels, prevent damp build-up (especially in bathrooms, the kitchen and utility room) and generally to create a healthy and pleasant environment. Stale air is extracted from the bathrooms, the kitchen and utility room, and fresh air introduced into all the living areas and bedrooms. This requires quite a lot of ducting all around the house: one set of insulated ducts supplying warm fresh air (see example in picture on the right), and a second set of uninsulated ducts returning the stale air to outside.

We used metal ducts, mostly circular in cross section and mostly running in the void under the first floor and above the ceiling below. In some places, rectangular vertical sections were hidden in stud walls (see picture left). The extract and input vents are all ceiling mounted.

A heat exchanger can be added in conjunction with the ventilation so that warm stale out-going air gives up most of its heat to the fresh incoming air (sometimes referred to as MVHR, mechanical ventilation with heat recovery, or as HRV, heat recovery ventilation). This involves a set of metal plates, and the fresh and stale air pass over these plates but on different sides so they are not mixed. Heat is transferred through the plates from the warm stale air to the fresh cool air. It is more energy efficient that simple extractor fans in kitchens and bathrooms that just discharge all the heat and the steam to the outside. Recycling this heat will significantly reduce the amount of space heating required.

A big advantage of the heat recovery system is that all the heat generated in the house is recirculated and contributes to keeping everywhere warm. This includes heat from people and the sun, as well as cooking, laundry, the cooling fins on the back of the fridge, showering and bathing, the wood-burning stove, and the electrically-heated towel rails. And all of these are subject to the multiplier factor (on a conservative estimate of heat recovery efficiency of 75% - our heat exchanger claims up to 95% - the multiplier is 4) as discussed previously, because the heat is reused over and over again.

A small amount of additional space heating is still likely to be needed for our climate. We have decided to go all electric, so a heat pump is ideal. We don't have enough space in the garden for a ground source heat pump, so we opted for an air source heat pump to provide the heat.

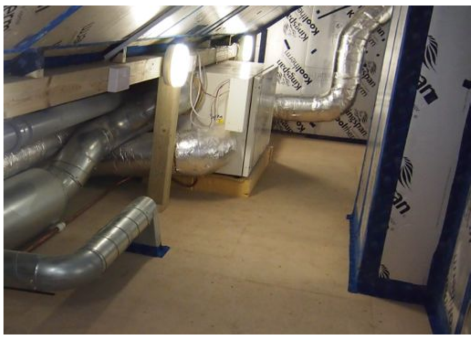
Both the air and the ground are low grade heat sources used by heat pumps: heat from the air or ground is absorbed at low temperature into a fluid, the fluid is compressed thereby increasing its temperature and the higher temperature heat is transferred to provide space heating and/or hot water. Ground source heat pumps require lots of heat collection pipe to be laid about 1 metre below the ground surface, where the temperature is fairly constant year round. Our garden space is not large enough for this. An alternative is a borehole into the ground, but the cost and practicalities of installing this in our confined space preclude it – we couldn't get the equipment through the house.

Air source heat pumps have to deal with a much wider range of input air temperatures during the course of a year, and are least efficient in very cold weather when heating is most needed. However, they are very much easier to install, and proved a good alternative for us given that our heating requirements have been minimised. They use electricity for the compression cycles, and generate around 3 to 4 units of heat for each unit of electricity used (a coefficient of performance COP of around 3-4). Quoted COPs are under test conditions. It is hard to assess the amount of electricity one will actually use in a year for a given heating scenario: it depends on the specific heat pump, the source air temperature throughout any particular year, the output temperature required (heat pumps are less efficient for heating hot water than for lower temperature space heating outputs), correct system sizing and installation, the control system and the way people use it.

We could have used a wet system of underfloor heating, which is consistent with a heat pump as it only requires water heated to about 30-40^{o}C. It would require of lots of pipes laid under the floors (quite easy on the ground floor where we are putting in a new floor, but more difficult upstairs with all the joists to dodge). Underfloor heating gives a very even and comfortable room temperature, but has a very slow response time: it takes a long while to heat the house and a long time to cool down if the house overheats (for example if it suddenly turns sunny and there is high solar gain).

An alternative was a hot air system, using a heat pump to heat the air directly and then circulate it round the house. This requires a lot of ducting, but has a rapid response time, especially in a house with a low thermal mass (which ours has as a result of the internal insulation). And we had already planned to have ducting for the MVHR system: so the ducting can serve both the hot air heating and the ventilation system. This seems to make a lot of sense.

I should say that there is a school of thought that favours keeping the ventilation and heating systems quite separate – so for example have a conventional boiler with a wet system of underfloor heating or even traditional radiators. I have not opted for this.



I spent quite a lot of time at EcoBuild where I came across the Genvex system from Denmark (supplied by Total Home Environment), which combines a heat exchange ventilation system with an air source heat pump. It uses residual heat in the stale air once it has been through the counter-flow heat exchanger as the input to the heat pump. This makes is more efficient than heat pumps that use the outside air as the exhaust air will generally be warmer. All these functions are contained in one unit (the white metal box in this photograph). There is also an air filter within the unit (that needs changing maybe annually), so it has further advantages for air quality (pollen, etc): a big advantage for hay fever sufferers, for example. In fact, this is already proving a major benefit for the house occupants, where one person's non-specific allergies with hay-fever-like symptoms have simply gone away.

A further advantage to this ducted-air system is that there are no radiators: this creates a great feeling of extra space in the rooms, and there is no restriction on where furniture can be put. This compensates for the loss of room space to insulation on the external walls.

Hot water

Message: hot water has very different demand characteristics to space heating and can be heated separately.

We decided to heat the hot water completely separately from the space heating. An air source heat pump (ideally coupled with solar pv) is an alternative to solar thermal tubes.

The hot water cylinder is sited in the utility room. It has a dedicated air source heat pump that vents directly through the external wall. We have set the heat pump to heat the water to 52°C. In addition, there is an immersion heater inside the cylinder: this is programmed to ensure that the water is heated to 60°C once a week as a disinfection cycle (to protect against legionnaire's disease). It is also available if there is a sudden run on hot water over and above what the heat pump can supply. The hot water unit is a Vanvex, supplied by Total Home Environment. The hot water cylinder holds 285 litres of water.

The air-source heat pump uses low grade heat from the ambient air outside to heat the hot water. It runs continuously until the tank reaches the set temperature. The heat pump can heat approximately 100 litres of water an hour.

We decided not to install solar thermal tubes to supplement the heating of the hot water, as we have dedicated the limited roof space to solar pv. Therefore on a day with lots of solar available, our own solar-generated electricity is being used to fuel the heat pump that is using the sun-warmed air to heat the hot water. This has the advantage that no solar is wasted, as would be the case with thermal tubes that are only effective until the water has reached the set temperature - but the pv goes on generating.

We are supplementing the hot water heating using a "heat squirrel". It is designed to preheat the water supply to the hot water tank using hot waste water that normally goes down the plug hole from showers and baths. The heat squirrel has a coil inside through which the cold water supply to the hot water tank runs. There is a jacket around this coil through which the waste water from the showers and baths passes: this allows the residual heat in the waste bath and shower water to preheat the cold water supply. This is another energy saving measure to minimise the additional energy needed by the house. This unit has been problematic to install, as it did not come with any installation instructions, and was more involved than we had anticipated. It is now properly connected up, and in operation, and hopefully making a meaningful contribution to water heating. It isn't easy to gauge just how much difference is makes without some flow meter measurements, which we haven't put in. Suffice it to say that its contribution will be most significant when there is a large demand on water for showers – exactly when it is most helpful to supplement the heat pump.

Lighting design

Message: a sun path survey showed how best to use natural daylight. It drives me mad when every light fitting in the house takes a different type of lamp - so I decided to keep everything as simple as possible and limit the number of different lamps in use, but with the objective of everything being LEDs (light emitting diodes).

In designing lighting for the house, the aim overall has been to create a lovely bright house with a comfortable ambience, but without squandering energy.

The front of the house faces south and during daytime is wonderfully bright with big windows. The back of the house where we extended therefore faces north. At the design stage, we undertook a computer simulation to track the path of the sun falling on the house through each day throughout the year. This clearly showed that roof lights in the extension gave the best natural lighting that we could have given the orientation of the house. The utility room is in the darkest middle of the house.

For artificial lighting, we decided that the future is all LEDs, and CFLs have had their day. We have opted for LED lights as far as possible. Lamps of 5-8W can give as much light as 50-60W incandescents or halogens: a very significant energy saving is possible. Development of LEDs is coming on in leaps and bounds: the various types of white that are now available give a great light, though they do vary considerably from make to make. The colour is often described by a temperature in degrees Kelvin, for example warm white is typically 3000K, very warm white 2700K. Natural white is a bit hotter, around 3500K. Cool white is hotter still, at around 4000-4500K. (For comparison, halogen lamps are around 2800K). Also, the range of fittings available has improved: they can be dedicated units, or straight replacements for mains voltage GU10 spotlights (or the 12 volt MR16 spotlights), for E27 fittings, and even for G9 halogen capsules.

Light output (measured in lumens) is now a more helpful indicator of brightness for lamps rather than watts. So for comparison, a halogen 50W GU10 lamp gives out about 300 lumens. A replacement LED in the same situation needs to be matching this.

We decided to have recessed downlights in as many places as possible, so everywhere that there is space in the ceiling void. We have used dedicated LED recessed lights, dotted into the ceiling much like halogen spotlights. We have chosen H2s from Halers in warm white (3000K) with white bezels.

Full details are on the Halers website. These give an excellent light and use 7.9W, or 8.5W in the dimmable version (in place of normal 50W halogen spotlights) and give 330 lumens of light. It has been very difficult to assess just how many lights we need in each room, so we have erred on the side of too many rather than too few to be sure it doesn't end up dingy. We have included dimmable circuits in quite a few rooms to give flexibility both for ambience and to reduce the light level if we have gone over the top. LEDs use less electricity when they are dimmed.

These units are also fire-rated, so don't need separate fire hoods in the ceiling, and they are IP65 rated, so can be used in bathrooms and even directly over showers.

I was originally introduced to these by Efficient Light. Prices vary at different sellers but are currently around £40 (including VAT) each. They have a 7 year guarantee - so a big plus is that there is no need to keep changing the light bulbs. Typically, a domestic light is assumed to be on for an average of 1,000 hours per annum, so just under 3 hours every day. On this basis, a normal 50W halogen would use 50kWh of electricity in a year, and the H2 non-dimmable would use 7.9kWh, thus each lamp saves £6.30 a year (at today's electricity prices of about 15p/kWh).

Special dimmer switches are needed to cope with the very low power consumption of these circuits, and must be compatible with electronic transformers. Ordinary dimmer switches tend to buzz as the LEDs are below their minimum load. It was difficult to pin down exactly what we needed: in the end, we talked with Halers themselves and they recommended Richmond Zano Grid 500 leading edge dimmers, which they have bench tested with the H2s and found to perform well.

There are places where recessed lights are unsuitable. In the attic, the insulation and airtight layer in the ceiling means that all lighting has to be surface mounted. In the shower room and cupboard, we have surface mounted spot lights – with GU10 fittings, and LEDs. There are plenty of these on the market, and I used warm white (3000K) lamps.

In the attic bedroom and on the staircase we needed wall lights. I decided that all non-spot lights must be E27 (Edison screw fittings) as these are widespread and then all the lamps will be the same. It wasn't easy to find luminaires that I liked with E27 fittings - but in the end I found some on www.inspiredbylight.co.uk - however I discover that this company has since been liquidated!

Similarly, in the kitchen, wall lights are required where there are the glazed roof windows, as there is no ceiling for mounting. These are again E27 screw fittings and LED lamps.

The outside luminaires also take E27 lamps, and I have used LEDs.

We also needed some under-cabinet lighting over the work surface at the side of the kitchen. This is provided by LED tape, with the transformer hidden out of the way on the top of the wall cabinets.

Energy supply

Message: all electric is the only way of eliminating a carbon footprint in the long run, although generation in the UK isn't yet decarbonised (I know this is a contentious issue). We chose to encourage supply from renewable generators and supplemented this with local generation.

I have already explained that we have focused on creating a house with the lowest possible demand for delivered energy.

As we were also aiming for as close to a zero carbon footprint as possible, this ruled out fossil fuels, eliminating mains gas. I know it has very high conversion efficiencies compared to generating electricity, but it will always release carbon dioxide.

Our energy is all coming from electricity, supplied by Good Energy, a company that is very proactive in establishing renewable generation in this country. I like their attitude and customer service, and their electricity is 100% from renewable sources (although they still sell their surplus renewables above their government obligation, so this dilutes their mix in reality). Nevertheless, I feel that I am voting with my feet for more renewable supply.

In addition, we wanted to generate as much solar electricity as possible with our available roof space - and the front of the house faces almost due south so is ideal. The photovoltaic panels just keep generating with every bit of daylight - they need no human intervention and it doesn't matter whether you are at home or not. The mains electricity grid will act as a buffer, taking excess electricity from the house when the panels are generating more than the house is using, and supplying electricity when the house demands are not being met from the self-generation.

We considered using the sun to help with heating hot water, but decided this was a lower priority for roof space. It is most effective in the summer, can make a small contribution during the shoulder seasons of spring and autumn, but adds pretty much no heat at all in the winter. Therefore, it has to be used in combination with another energy source. Although it makes good use of the sun, it is only used up to the point that the water in the tank is hot enough. So on very sunny days, a lot of the available solar energy is not used. Also, it requires the tank to be cold at the start of sunny days: it will not transfer solar energy if the alternative energy source has already heated the water - so a clever control system or manual intervention is required to take advantage of the sun. Overall, I think the conversion efficiency of total available solar energy to heat is not as high as one might think. Our combination of pv generation and an air source heat pump for water heating may be better, especially when electricity has been decarbonised.

We have installed Romag solar panels to take advantage to the south facing, unshaded front of the house. The panels are made in the UK from polycrystalline silicon solar cells and claim to be highly efficient. Each unit can generate 235W at best. We could fit 7 panels on the front roof, and 6 on the back, giving a total potential peak generation capability of 3.055kW. Typically in central England, that should correspond to annual generation of about 2,625kWh.

Different makes of solar panels have different dimensions, so one consideration in choosing a particular make is which size fits best on the shape of a particular roof. These Romag ones are pretty good for our roof, having to fit around the front gable and the Velux (although this window was positioned specifically to accommodate the solar array).

In addition, we have a second array on the flat roof of the dormer extension, supported on frames to tilt them up to a 15^{o} angle to the horizontal. We had originally planned to have a slope on the dormer roof itself to accommodate this, but the planners would only allow a dormer construction within permitted development constraints with a flat roof, so this was not possible.

I have said all our energy is coming from electricity, but this is not quite true: we also have a wood burning stove as supplementary heat for cold and really extreme weather. The heat recovery and ventilation system means that the heat from the stove is circulated around the whole house (with the multiplier effect, estimated to be 4 times as described previously, because it is reused over and over again): this at a time when the air source heat pump will be operating at its least efficient because the air is at its coldest. A stove also gives a very homely and calm feel to the house.

Energy Performance Certificate (EPC)

Message: the current rating system can't recognise some of the ultra-low energy options (such as heat recovery ventilation) and so gives distorted ratings. EPCs will only gain credibility when they reflect reality.

I AM VERY DISAPPOINTED THAT THIS HOUSE HAS BEEN GIVEN A "C" RATING.

The house has been assessed for its Energy Performance Certificate (EPC), using the standard methodology. The aim of such certificates is to allow the comparison of the energy efficiency of different properties, and to highlight potential energy saving measures by which their performance could be improved. The ratings range from A (very energy efficient and thus lower running costs) through to G (not energy efficient and higher running costs).

But 73 Lonsdale Road has been rated C. This is clearly nonsense given all the insulation, the air-tightness, the high specification of the heat recovery and heating system, and all the LED lighting. It is also extremely disappointing that the EPC system designed to highlight and extol energy efficiency doesn't accurately reflect reality.

New EPC guidelines were introduced in April 2012 and now allow the actual U values of the walls, floors, roof and windows to be input. This is an improvement. The EPC assessor undertook a survey of the property filling in boxes on a pro-forma sheet. We had to supply a letter from our architect confirming all the insulation values that we had installed for walls, floors, ceilings and windows, as they are not visible in the finished house.

However, the assessment form does not recognise in any way a heat recovery system, which is providing fresh air whilst still recovering most of the heat from the stale air. Nor does it take into account airtightness, which further reduces heat loss. These two elements are significant in this refurbishment.

We scored well for low energy lighting, but actually we have done better than that with all LEDs rather than CFLs. This is not recognised.

We are all electrically powered (including the heating and hot water), and this counts against us in the EPC as the unit costs of electricity are higher than for gas. However, we have no gas so that we have removed all fossil fuels from the building, which seems to be the way forward. Our solar electricity generation also allows the house to move closer to carbon neutrality by contributing to the supply.

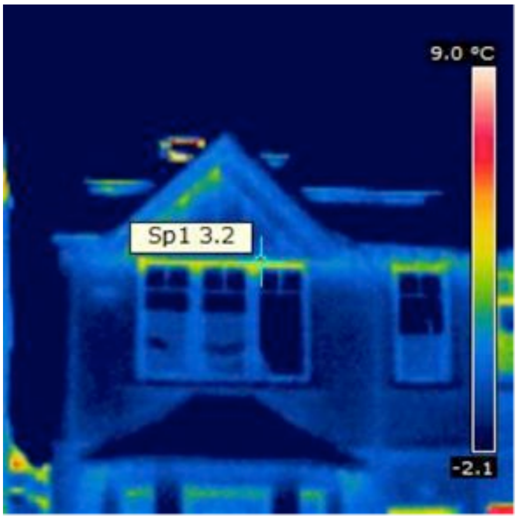
We opted for an air source heat pump for heating the hot water. This takes heat from the ambient air and is most efficient on hot days – effectively this is using the sun's energy. However, the EPC recommends installing solar water heating: a dubious advantage given our set-up.

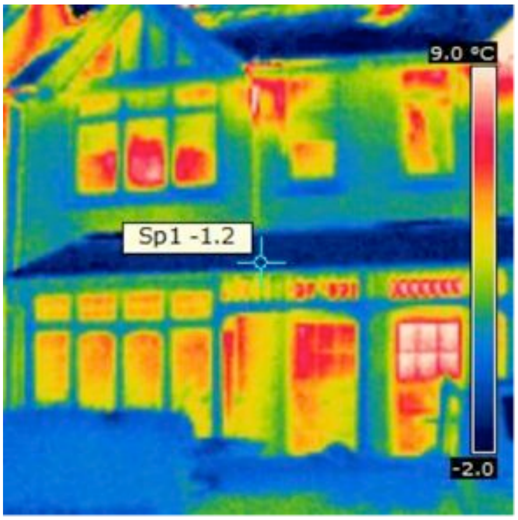
The only potential improvement suggested (namely solar water heating) moves the overall EPC score up marginally but it still remains within the C band.

The EPC system needs to be urgently overhauled to reflect the technologies that are now being used, and the blends of them within the property. It could be a powerful tool, but it is not meaningful as it currently stands for super energy-efficient homes.

Thermal imaging

A very visual demonstration of the completeness of the insulation is given by thermal imaging, where photographs taken using an infra-red camera show where heat is escaping from the building. We waited for a perfect day, cold (about 1°C), dry and still, and took the pictures before the sun was on the buildings. The house was heated internally to about 20°C.





The colours in these images indicate temperature – so blue is colder than orange/red. The scale is from about -2°C (blue) to 9°C (red). The pictures revealed a bit of thermal bridging above the front first floor windows (see image on left) and around the front door. Otherwise, it was pretty good. The image on the right is of a neighbouring property on the same scale. The temperature registered on the glass of our triple glazed windows was 0.5°C, and on the single glazed sashes of neighbouring properties was about 8-9°C (we don't know how warm this house was indoors). This is a significant difference in heat loss between the two.

The challenges to monitoring energy performance

Message: individual circuit monitoring capability has to be designed into the wiring of the electric circuits. Current measurements alone cannot tell you how much real power an appliance is using. All of the readily available real time monitoring and display systems seem rely on measuring only current and therefore misallocate energy consumed between different appliances.

The question is how is this house performing after all our efforts to make it as economical as possible with energy whilst still being comfortable?

Electricity consumption needs to be monitored to see how it performs against expectations, and also to allow the occupants to see their pattern of use in real time and thus modify it where possible. I decided that the whole house consumption is too crude a measurement on its own and needs to be split to monitor different activities as follows:

- the heat recovery and ventilation unit and its integral air source heat pump, which provides all the heating to the house
- the air source heat pump which is dedicated to heating hot water and the immersion heater in the hot water tank (a boost to provide additional hot water if required) - these two are wired on the same circuit so can't be separated easily
- two ovens
- induction hob, grease/odour extractor fan
- fridge and freezer
- dishwasher
- laundry (washing machine and tumble dryer)
- other sockets around the house
- three electric towel rails in the main bathroom and two ensuites
- lights
- car charger point
- solar electricity generation.

The house has been wired with this in mind, so these circuits are all separately identifiable. I hadn’t realised when we started out that energy use by circuit would be difficult to measure, but this it has proved to be.

In addition, the monitoring data will be used for academic research by the University of Oxford Energy and Power Engineering Group. They need high sampling rates, accurate time stamping of the data, and power factor information.

The problem with current only measurements: power factor and why it matters

Electricity meters measure the energy that a household consumes. This requires them to measure three things - the voltage, the current and something called the "power factor". Power factor is a measure of how "out of step" the current and the voltage are. Our electricity is supplied with a voltage and current that are alternating, following a pattern of peaks and troughs. Normally, current and voltage move in step (with peaks and troughs coinciding) - but many electrical loads, such as motors in fridges or washing machines, cause them to move out of step. Current that is out of step with the voltage does less work - or may even return energy to the grid - so to understand the real power consumed by a device we need to account for the "out of step" element, namely the power factor.

Our electricity meters measure real power correctly, using the overall power factor for the whole house (and therefore accurately reflect the total amount of energy we use and pay for). However, if you want to sub-divide this and you measure the current on each circuit, the circuit power factor is also needed to calculate the real power used by each circuit. The reason is as follows.

Imagine two appliances on separate circuits consuming the same real power. One has a power factor of 1 - all the current contributes to useful work, so real power and apparent power are the same. The second has a lower power factor - say 0.5. There will be twice as much current flowing as in the first circuit, but only half of it will be doing useful work. The house electricity meter will measure two units of power - as we would expect - but there are three units of current, one going to the first appliance and two to the second appliance. If you allocate the real power to each appliance on the basis of the current flowing, it will seem 1/3rd should go to the first appliance, and 2/3rds to the second. In reality, there is the same real power consumed by each appliance. It is essential to include the power factor to ensure an accurate allocation of real power between appliances.

Here are some indicative power factors based on informal measurements made with a plug-in energy monitor:

	Real power	Power factor
Kettle	2,300W	1.0
Iron	2,300W	1.0
Flat screen TV switched on	25W	0.56
CFL lamp	18W	0.5

Monitoring systems

We looked at monitoring systems on the market - they nearly all consider the whole house only. They have a single clip (current clamp) that goes around the main cable from the electricity meter.

This measures only the current flowing and estimates the real power for the whole house without measuring the voltage. Because it doesn't measure the voltage, the device has to guess the extent to which the current and voltage are out of step (power factor) and therefore this approach will be inaccurate. The inaccuracy is made worse where there are loads whose power factor changes significantly over time (for example laptop power supplies and televisions).

Also, if there is solar electricity generation, the total house use will be understated by the amount of own-generated electricity that is used: what the current clamp measures is the net import from the grid.

A few monitoring systems allow measurements by circuit, but we discovered that they also seem to make assumptions about power factor rather than measuring it. Such assumptions can be very inaccurate: power factors for fridges, for example, can vary significantly from one fridge to another. More significantly, as we have seen, it would be impossible to see where real power is actually being consumed.

(As an aside, it is interesting that the plug-in meters that go into an individual socket are good: they measure real power.)

Finding a system to measure the power factor (the phase relationship between voltage and current) on each circuit was difficult. But we now have such a system! It is a National Instruments Compact Rio (CRIO) system, with sixteen 50A current clamps that have high sampling rates, one clamp for each circuit (or group of circuits) to be monitored. The algorithms to identify the circuits and label the data have been specially written for us. A single voltage is recorded for the whole house, and the phase relationship of the current in each circuit is related back to the voltage. These readings can be amalgamated into larger time slots and the reduced data uploaded to COSM, for real time cloud access. This we can then use for further analysis, and user-friendly display. We are having some teething problems with getting the data to stream to the web, but we are working on these.

Currently, we are collecting data but haven't yet created a meaningful real-time display. Also, we haven't been collecting data for long enough to have a feel for the overall performance of the house.

Is the house performing?

Message: actual energy consumption, disaggregated by use, will show degree of success. A year of data is needed before this can be assessed fully.

How do we know the house is as good as it claims? This question can't be answered straight away. We really need a year's worth of data on electricity use before we can assess its success from an energy point of view.

We didn't initially specify a target space heating demand nor target total primary energy demand. Let's take the Passivhaus criteria as a benchmark, namely a maximum space heating demand of 25 kWh/m^2 per annum of delivered energy, and total demand of no more than 120 kWh/m^2 per annum of primary energy.

We looked at the actual energy used in the house over a year before refurbishment (occupied by an individual, not a family):

- Gas supplied was 30,790 kWh and electricity 2,256 kWh of delivered energy. The floor area of the house was 144 m^2.
- Therefore the delivered energy from gas was 214 kWh/m^2 and from electricity 16 kWh/m^2, giving a total of 230 kWh/m^2 .
- Gas was used for cooking, and space and hot water heating via a gas boiler. If we estimate cooking used 5% of this, hot water 15%, then space heating demand was the remaining 80%, roughly 170 kWh/m^2.
- The primary energy (ie energy from nature – see earlier explanation in Technicalities) for the gas was 214 x 1.11 = 238 kWh/m^2 and for the electricity is 16 x 2.58 = 41 kWh/m^2 (taking the average mix of electricity in the UK, this reflects the energy used in the generation and transmission process). So total primary demand was 279 kWh/m^2.

Thinking in terms of a carbon footprint, natural gas has a greenhouse gas content of 0.184 kg of carbon dioxide equivalent per kWh of gas burned. UK grid electricity has an overall greenhouse gas content of around 0.525 kg of carbon dioxide equivalent per kWh of electricity delivered. So in the year before refurbishment, the gas used in the house created 30,790 x 0.184 = 5,665 kg of carbon dioxide and the electricity 2,256 x 0.525 = 1,184 kg of carbon dioxide, giving a total house carbon footprint of 6,849 kg (or 6.9 tonnes) of carbon dioxide equivalent in a year.

We are still collecting data post-refurbishment, so can't yet see what impact we have made. Early indications, based on the first six months of electricity (July to Jan), give an estimated annual use of 10,094 kWh (net of any generated solar). The floor area after the refurbishment is 158m^2, giving 64 kWh/m^2 of delivered electricity, equivalent to 64 x 2.58 = 165 kWh/m^2 of primary energy in total (about 60% of the previous 279 kWh/m^2). We hope to have a meaningful breakdown of this in due course.

The suppliers projected annual energy consumption for the Genvex unit to be 745 kWh for the ventilation, and 1,675 kWh for the heat pump, giving a total of 2,420 kWh. This works out as 15 kWh/m^2 per annum for space heating, comfortably inside the Passivhaus maximum of 25 kWh/m^2 per annum for a refurbished property.

Costs

Message: the additional cost of going to near Passivhaus level compared to stopping at building regulations was about 18% of the total project costs.

This whole refurbishment was to a very high specification. The total cost of the project was £310,000 (plus VAT, some at 5% on energy efficiency, most at 20%). This can be broken down into the costs of the modernisation itself to meet building regulations, and then the additional costs of extreme energy efficiency.

Separating out the costs is not quite as straightforward as it sounds, because what we did for ultra-low energy use is not just what the building regs require plus a bit more, it was actually a different design. Nevertheless, it is worth making some estimates to give a rough idea of where the additional costs lie.

The modernisation elements include all the structural works (demolitions, groundworks, drainage, steels, brickwork, floor slab, guttering), the roofs, all the internal works (carpentry, joinery, plastering, wiring, plumbing, data cabling, decorating, floor finishes, all sanitaryware, kitchen and all appliances, lighting, blinds), landscaping, and professional fees. The decisions we made for these elements would have been broadly the same whatever the final energy performance targets.

To comply with current building regulations (Part L), the new ground floor extension and the attic upgrading would have had to be insulated with required U values of 0.28 for the walls, 0.22 for under the ground floor, 0.18 for the roofs, 1.8 for the windows and the external doors (double glazing would be sufficient for this), and 1.6 for the rooflights. These are all much less demanding than the ones we set ourselves. We would have needed a new boiler and hot water system, as the existing combi boiler had reached the end of its life. We would probably have put underfloor heating in the new extension, and radiators in the attic rooms. We would not have been required to thermally improve the old house at all.

We estimate that this would have given a total project cost of £255,000 plus VAT.

Our extra costs were a further £55,000 (plus VAT, a good proportion at 5%). This additional cost is about 18% of the total project cost (pre VAT), and breaks down approximately as follows:

- £12,600 for full insulation of the old house (including under the suspended floor), taping to minimise air leakage, and service void for cabling (materials and labour)
- an extra £7,000 for building the extension and attic to the same high specification rather than just building regs
- £12,000 for new triple glazed windows and external doors in the old house, including fitting
- £2,500 for triple (rather than double) glazed windows, doors and rooflights in the extension and attic

- £9,800 for the full ventilation, heat recovery and exhaust-air heat pump system, including installation (over and above the cost of a gas boiler, underfloor heating in the extension, additional radiators in the attic, and retaining the rest of the old radiators and pipework)
- £2,400 for the new hot water cylinder with its air-source heat pump, and the heat squirrel (over and above the cost of just a hot water cylinder to run in conjunction with the gas boiler)
- £5,700 for the wood-burning stove, flue, hearth and fitting (although you might have decided to include this anyway, and not have treated it as an extra)
- £2,100 for all LED lighting (rather than CFLs)
- £900 for airtightness testing.

If we were to do exactly the same again, it would be interesting whether we could reduce these in the light of our experience. It is difficult to speculate, though there may be some streamlining possible on the insulation.

VAT is a bit complicated. Normal VAT is 20%. A lower rate of VAT (5%) applies to the installation of heating controls, insulation on walls, floors and ceilings, solar panels, and heat pumps, and a few other renewables not applicable to us in this case. The lower rate applies on the installation and associated work as well as the actual materials. New windows, energy efficient boilers and energy efficient fridges and freezers pay the normal 20%. Ironically, had this been new build, there would have been no VAT payable on the works!

On a house that is probably now worth in the order of £1 million, the additional costs of making it something approaching Passivhaus standards were around 5.5% of the value of the property overall.

Separately, we added an array of solar pv panels which cost £9,000 plus 5% VAT. I have not added these into the other project costs, partly because we are being paid for the electricity they generate through the feed-in tariff.

Feedback from occupants

Message: tenants are finding that the house design works well – overall, energy is not an issue.

The house has been rented out to a family with three school-age sons. They were keen to rent the house because everything was new, it had plenty of bathrooms, a high spec kitchen and a good location. Energy was not a particular concern. They moved in mid-summer. I provided a handbook with guidance on how to "operate" the house for optimum performance, for example living with the windows closed in the winter and using the wood burner in very cold weather. I have kept in touch subsequently.

The initial feedback after the first three/four months was very positive. The overall design of the house works really well, for living and entertaining.

A major bonus has been the filtered air: one of the boys is susceptible to non-specific hay-fever-like allergies, but has not been affected when living in the house. This is a benefit that is not to be underestimated.

They have observed that the absence of radiators makes placing furniture easier.

Having an drying rails hanging from the ceiling in the laundry room is a welcome and effective alternative to the tumble dryer. The ventilation should certainly help to remove the damp air associated with drying washing.

Their visitors have commented on the warmth of the house.

On returning from a week away in warmer climes and arriving back in a cold snap, the house felt chilly (although it was still at about 17/18^{o}C). At that time, they had not appreciated how quickly lighting the stove would rectify this.

Over all, non-energy factors have been more important. Energy is effectively a hygiene factor (ie not an issue provided it works easily and is comfortable).

Rental market

Message: rental agents and potential tenants not really geared up to appreciate the comfort benefits or reduced fuel costs.

I kept in touch with several of the local estate agents throughout the refurbishment process. There is a lot of general interest around energy issues, and they were keen to visit and see work in progress (plus any excuse to see local properties). There is still a huge pre-occupation with "original features", such as draughty old sash windows and fireplaces with open chimneys that suck the warm air out of the house and away. Very little store is placed in EPCs – they are required for all sales and rentals, but they are not highly regarded as far as I have seen.

Our house actually rented so quickly that there was no need for any hard sell of its energy advantages. Running costs didn't seem even to be discussed.

The rent is at the top of the market in the area, though I think this only reflects the high spec finish of the whole place. We really need a year of electricity bills to prove the case for a higher rental price to compensate us for our capital investment in energy efficiency versus the lower running costs enjoyed by the tenants. We will review the rent at the end of the first year.

Some concluding thoughts

Message: airtightness coupled with mechanical ventilation and heat recovery is a demanding but desirable goal for a healthy environment and maximum energy savings.

Such a full energy upgrade is easiest in the context of a whole house refurbishment. We made it more difficult for ourselves by opting for internal insulation – with external insulation, then maybe the disruption inside the house would be less, but there is still the question of where the airtight layer goes; I haven't fully thought through this option.

I have a sense (from having undertaken the work to go airtight) that it would be more difficult to go down this route if there had already been wall insulation and double glazed windows in place. There is a cost disincentive, for example, to changing reasonable double glazed windows to triple glazed. There are practical difficulties in creating airtightness without access to everywhere – for example sealing the windows to the walls, the detail between the ceiling and the floor above, at the junction between the ground floor and walls, and so on, not to mention the overall disruption. So I feel that going some of the way towards energy efficiency ("natural" ventilation option) acts as a disincentive to going the whole way (mechanical ventilation and heat recovery) subsequently.

This begs the question as to whether airtightness is a realistic goal. It is a measurable property of the house, so is an objective test of performance. It is certainly the case that good and conscientious design and workmanship are critical. All the insulation (whatever option you take) is invisible in the finished house, so we need a way of proving what is in place and how well it was installed. Photographic records during installation help, but don't guarantee quality. Thermal imaging is very revealing and a good guide to the effectiveness of insulation. The advantage of having an airtightness test is that it does reveal how well sealed the house is and this to an extent goes hand in hand with continuity of insulation. The pressure test can be repeated at any time during the subsequent life of the house, so it adds objectivity. And there does need to be space heating energy use data to back up claims.

The further question is whether airtightness is a desirable goal. On purely health and comfort grounds, I think I am now more persuaded than I was before we started. The Passivhaus philosophy makes sense, is very challenging in practice, but has the advantage at the end of the day of a certification process that stays with the house.

The learning process for me, my architect and builder has been significant and, I think it is fair to say, overall positive for all of us. We are much better placed now to undertake another project, and are all keen to do so.

The additional cost is significant – £55,000 is saving maybe 22,000 kWh per annum of delivered energy for space heating (an estimate in advance of actual use figures) equivalent to £2.50/kWh saved. Because of the switch from gas (currently 4p/kWh) to electricity (currently 15p/kWh), this may be saving around £620 a year in bills. So it is going to take decades to recoup the cost – but the ever-increasing utility prices will significantly reduce this. And there is hopefully a benefit in an increased property value in the longer run as people realise the desirability of the comfort levels it affords.

I look forward to having details of the actual energy performance in due course for a proper assessment.

Contact details:

Ridge and Partners LLP, Property and Construction Consultants www.ridge.co.uk

Guy Roberts, Architect www.guyr.co.uk

R&J Construction, Building Company www.rjconstructionoxford.com