Admissible evidence

We are all understandably enthusiastic about the superior nature of our own building designs, particularly their potential to provide comfortable living conditions at incredibly low energy inputs. Such claims are often only based on the calculation of 'U' values alone which more often than not take no account of thermal bridging and actual ventilation losses.

During the last thirty years **David Finney** has been frustrated to read about the unsubstantiated virtues of 'eco homes' so here he presents the results of thirty years of monitoring of his last three homes.

In the hope of starting an open debate and exchange of data about thermal gains and losses in homes lived in by real people, I present below a description of the three properties I have occupied since 1976 and a discussion of the lessons I believe I learnt by monitoring their performance.

I designed and built the first house in Pembrokeshire and lived in it from 1976 until 1983. It is of masonry construction with 100mm external and 125mm internal Thermalite skins with polystyrene beads in the 60mm cavities. The external finish consisted of 'Alpine' render, or interlocking PVC planks or native cedar fixed on 19mm battens over Sisalkraft building paper, both faces of which had reflective aluminium. Internal walls were constructed of plastered dense concrete blocks or exposed brickwork. The concrete ground floor slab contained no horizontal insulation. Instead, scrap polystyrene packaging was collected from outside TV shops and used as external edge insulation with an average thickness of 50mm and depth of about 750mm. Further edge insulation was provided by the 300mm wide insulating 'trench blocks' used below DPC and the below-ground part of the wall constructed from insulating blocks with polystyrene beads in the cavity. The sarking was insulated with 25mm of mineral wool and 150mm of mineral wool was placed between the ceiling joists. A further 100mm of mineral wool was packed between the rafters over the large NW facing living room and reflective building paper was placed on the underside of the remaining rafters. Windows were of a twin-framed aluminium construction, with the frames separated by thermal barriers. Whilst something of a compromise with respect to insulation properties and embedded energy, their design had the advantage of enabling the insertion of 25mm polystyrene panels between the panes during winter evenings. The window on the SW wall of the NW living room was an aluminium curtain wall 4194mm tall by 1830mm

Wenlock

Port Lion

Solaria
(Photo courtesy of Self Build and Design)

wide, included as a source of passive solar gain to the two storied entrance hall and second living room. This room and entrance hall were intended as 'luxuries' to be closed off during the few cold days of the Pembrokeshire winter when the solar gains were insufficient to make an impact.

The initial heating system was an off peak electrical hot air system. This was chosen because of its simplicity and ease of installation and also because I was interested in gaining experience of a ducted distribution. I reasoned that, given the level of insulation and likely solar gains, off-peak electricity would not prove prohibitively expensive and consumption and associated carbon dioxide pollution would be well below a less well insulated property built at that time. This was, in practice, true but after two years use and further reflection on green issues, we decided to install a wood burning stove. Quite fortuitously, the house design had included a cast concrete spiral staircase situated almost dead centre of the main living block. Beneath it there was room to locate the wood burner and connect its boiler to one of the two super insulted hot water cylinders. This change reduced our heating costs, and part of our hot water costs, to £20 per year plus the cost of a few gallons of petrol for my chain saw. This was achieved by purchasing a 'Sticking Licence' from the Forestry Commission which entitled us to collect as much of the forest waste as we could remove from a Larch forest a quarter of a mile from our front door.

No particular attention was paid to the purchase of low energy electrical equipment but additional polystyrene insulation was fitted around the fridge, chest freezer and electric oven. Fluorescent tube lighting was installed in most of the rooms with the intention of reducing lighting energy consumption below the norm.

The bedrooms, on the ground floor, had the minimum window area but the first floor living accommodation benefited from large windows. All the curtains had insulated linings.

The second house was a speculative build purchased in Much Wenlock in 1983 and lived in until 1998. It was of conventional brick cavity construction with internal timber stud partition walls. I increased loft and hot water cylinder insulation and installed cavity insulation.

The third property, located in Diddlebury in Shropshire, was commenced 1991 and has been lived in and monitored since we moved in 1998. It is of timber frame construction with a minimum of 140mm of insulation in the walls and 200mm in the roof. A 19mm deep service channel was constructed between the internal vapour barrier and the dry lined plasterboard. A heat recovery system was installed and a chimney was avoided by fitting an LPG fired combination boiler with a balanced fanned flue. There is 50mm of polystyrene laid over the slab and 200mm of rock wool beneath the floor boards of the guest bedroom and bathroom located over the garage.

The wall windows were of the highest specification I could locate in 1991. The glass is double glazed of optimum gap width, heat reflecting Kappa glass in the internal pane and argon filled. The manufacturer claimed a U value of 1.35 W/sq m K. The three south facing and five north facing Velux windows have only conventional double glazing but 50mm polystyrene shutters are wedged in place during winter nights. Attention was given to the ratio of glazing to floor area and the ratio of south facing to north facing glazing. For aesthetic and day lighting reasons, I compromised on 2:13 and 55:45 respectively. The ratio of south facing glazing to floor area of south facing rooms is 1:5. Very much aware of the risk of summer overheating, I inserted two Velux windows above the staircase spanning three floors to act as a manually controlled solar chimney.

Table 1. Calculated average 'U' values for each property

House	Solaria	Wenlock	Port Lion
Area sq m	193	129	208
Average U Values (W/sqmK)			
Walls	0.30	0.50	0.35
Roof	0.23	0.41	0.18
Floor	0.34	0.70	0.35
Glazing	1.41	2.05	2.00
Air changes per hour	0.5	1.5	0.5
Specific heat loss W/K	244	364	321
Sp ht loss W/K/sq m	1.26	2.82	1.54

The site is near ideal, being well sheltered from the winter weather on the north side by very tall ash trees and orientated about 23 degrees west of south on the living rooms side.

With just two adults in residence, a combi boiler was fitted in preference to a system boiler and solar hot water heater to reduce initial costs, to minimise plumbing and to completely eliminate standing losses.

The calculated average U-values for all three properties are shown in table 1.

U-values are usually calculated on the assumption that theory closely models reality but my reading of the literature has led me to the conclusion that how close usually depends on your political position! U-values are particularly suspect when quoted for properties where builders generally take no consideration of the importance of avoiding thermal bridging and the intention is to promote the property's superior virtues. I would like to think that I took particular care over my calculations and avoided over optimistic assumptions. For example, the U value calculated for walls of Solaria, takes account of the cold bridging caused by the timber studs, laboriously calculated for each sub-frame. This increased the U value from 0.21 to 0.30 W/K sq m! By taking account of the thermal bridging caused by the timber rafters the roof U value increased from 0.18 to 0.23 W/K sq m. However, no matter how careful one's calculations might be, given the vagaries of the practical building process, it has to be admitted that all such calculations are approximations. The figures for the air change rates are taken from the literature as typical of tightly built properties in the cases of the two properties I built and of typical spec built properties with a chimney and retrospective draught proofing for the Wenlock property.

Predictions of the energy consumption for heating of each property have been calculated using the Index Method described in 'Solar Energy & Housing Design'[1] and compared with the actual consumption. These are shown in table 2.

With a window to floor ratio of only 13.6% the calculated solar gains at Solaria are, not surprisingly, considerably less than at Port Lion. This was a necessary design feature because of the low thermal inertia of the timber frame and the need to guard against overheating. It was also partly a consequence of a glazing to floor ratio of only 5.7% in the largest bedroom situated over the garage. If this bedroom is ignored the ratio for the main living area is 15.6%. In practice it has been found that Solaria can be prevented from overheating by judicious use of blinds, cross ventilation and roof windows. The 'solar chimney' has been found to be a less effective cooling device than cross ventilation but it has provided a nice architectural feature! Despite the enormous thermal inertia in the Port Lion house there was a tendency to overheat during the afternoon when the solar gains through the SW windows were very large. In this situation cross ventilation and the insulated curtains had to be used as solar controls except in the front sitting room where the large mass of floor tiles and exposed brick walls combined with the large air volume to limit temperatures rises to a comfortable level. However, I could see inhabitants lacking my awareness of the precautions needed to guard against over heating suffering in either property, particularly during August and September when the sun follows a lower trajectory. Our Wenlock home, with its window to floor ratio of 18.2%, suffered severe overheating problems. Although the external walls were of brick and block the internal walls were all constructed of timber, as was the first floor. The two south facing bedrooms were often unbearable and closure of the insulated curtains and cross ventilation failed to control the overheating.

The enormous consumption of energy for water heating in the Wenlock home (Table 3) illustrates well the importance of installing controls and low thermal inertia boilers. The hot water was heated by an over large cast iron boiler via a semi gravity system. Although I always turned down the boiler thermostat during the summer and installed additional insulation around the cylinder, the standing and transmission losses were clearly enormous, not to mention the inefficiencies caused by running a high inertia boiler so far below its rated loading. These losses exacerbated the serious summer overheating of the two south facing bedrooms.

Some semi gravity systems and in fact all systems with hot water storage can suffer inefficiencies during the summer. In the references section I highlight a research document[2] that for anyone not aware of the multiple sources of loss in such systems makes alarming reading!

The Port Lion water heating system provides an interesting contrast. It consisted of two super insulated copper cylinders heated on off-peak electricity with about 711 kWh p.a. contributed from the wood burner. So effective was the insulation that our hot water supply remained tepid even after a week away when the off-peak immersion heaters had been switched off.

Table 2. Energy consumption predictions compared with measured consumption

House	Solaria		Wenlock		Port Lion	
	Energy kWh/pa	Energy kWh/sqm/pa	Energy kWh/pa	Energy kWh/sqm/pa	Energy kWh/pa	Energy kWh/sqm/pa
Calculated annual space heating loss	18,197	94	23,912	185	24,466	118
Contribution from casual gains	3,000	16	6,900	53	4,500	22
Contribution from solar gains	6,635	34	5,952	46	9,750	47
Predicted heating shortfall (net)	7,564	39	9,573	73	7,720	37
Actual heating net	7,293	37	9,419	73	8,021	39
Actual heating gross	9,116	47	12,559	97	14,583	76
Window to floor ratio	13.6%		18.2%		21.6%	
CO_2 emissions kg pa.	1,914		2,386		3,650 to Oct 78, zero thereafter	
CO_2 kg pa./ sq m	9.92		18.5		17.54 to Oct 78, zero thereafter	
Boiler efficiency	80%		75%		87% to Oct 78, 55% thereafter	
Fuel	propane		mains gas		Off peak elect 76-78; Wood & off peak elect 78-83	

The relatively poor performance of the Solaria hot water system is in part illusory because an un-measured proportion of propane gas is used for cooking on the gas hob. From the literature available a reasonable estimate of the amount of energy used in this way is 560 kWh so I have shown the net estimate in brackets in the table. This latter figure is more reasonable and, I believe, supports my decision to avoid standing losses by opting for a combi boiler. Having said this, as the Port Lion house demonstrates, storage of hot water can be done economically if cylinders and pipe work are super insulated.

Both the Port Lion and Wenlock properties had an electric hob and oven whereas Solaria has an electric oven and a gas hob. Solaria and Wenlock have two microwave ovens and Solaria has

two electric showers. In all other respects the number of appliances have remained much the same but the fridge and freezer in Solaria are low energy models and a low energy washing machine was installed in July 2003. The higher electricity consumption at Port Lion has at least four obvious components. The first is that low energy compact fluorescent lamps were not available in 1976 and three 150W spot lamps were fitted in the large NW sitting room. It is a salutary thought to reflect that the wattage of the lighting in this room exceeds that for all of the compact fluorescent lights fitted in Solaria. The second is that way back in the 70's we used to indulge in Sunday roasts. Since then we have realised that meat eating is grossly energy inefficient so the Sunday roasts had to go! The third is that, even after the woodburner had been installed, 1973 kWh of off peak electricity continued to contribute to the heating of hot water and is included as a component of the figure shown for Port Lion in table 3 as well as table 4. Finally, having two teenagers at home who shared a propensity to entertain their friends in the large NW sitting room cost me dearly! My suggestion that this room should not be used during the coldest winter evenings was ignored and they simply switched on an electric fan heater as they felt necessary!

The CO_2 emissions arising from electricity use at Solaria are correctly shown as zero because our supplier sources all electricity from 100% renewable energy sources.

Table 4 shows the electricity consumption for Solaria up to the year ending 12th November 2002. This date is significant because we took advantage of a 50% government grant and had photovoltaic panels installed on our roof on 13th November 2002. The system has a rated peak DC output of 3.36 kW and produced 2704 kWh during its first year in operation.

The PV option is not cost effective in conventional terms. The system will produce more than 15 kWh during a sunny day in spring or autumn but perhaps less than 1 kWh during a dull day in winter. As we were already so economical in our use of electricity our average electricity consumption, drawn from the mains, has only been reduced from 6.4 kWh to 5.2 kWh per day. Any unused balance of our PV output is exported to the Grid. Our supplier has agreed to pay us 4p for every unit our system produces. Even so, the sum total of the savings from mains electricity displaced and the payments for exported electricity will not even cover the loss of interest on our £9,000 contribution towards the installation costs. One consolation is that, instead of choosing to lose £6,000 in immediate depreciation on a purchase of a new 4 x 4 vehicle, I now have the option of purchasing an electric car which does not add 0.43 kg of CO_2 to the atmosphere for each mile I drive it and will reduce the payback on the PV investment from more than 75 to about 14 years. We can also claim that, by off-setting the carbon dioxide avoided by exporting our surplus electricity against our carbon dioxide produced from burning propane for central heating our net production is about halved.

So, what conclusions do I draw from my 27 years of observations? The first is that homes insulated and sealed against leaks to

Front elevation of Solaria showing the pv array and large south facing windows

(Photo courtesy of Self Build and Design)

Table 3. The energy consumed in producing hot water

House	Solaria		Wenlock		Port Lion	
	Energy kWh/pa	Energy kWh/sqm/pa	Energy kWh/pa	Energy kWh/sqm/pa	Energy kWh/pa	Energy kWh/sqm/pa
Energy for hot water	2,639 (2079)	14 (11)	9,782	76	2,674	13
CO_2 emissions kg pa.	554 (437)		1,859		1.197 to Oct 78, 829 thereafter	
CO_2 kg pa./ sq m	2.9 (2.3)		14.4		6.20 to Oct 78, 3.99 thereafter	
Fuel mix	propane		mains gas		Off peak elect 76-78; Wood & off peak elect 78-83	

the levels shown are a delight to live in. The air is still and draught free and the surfaces tend to be warm enough to reflect back body radiation, thereby removing the 'chill' factor associated with less well insulated homes. The quality windows in Solaria make a significant contribution by not causing cold down draughts and preventing serious condensation. However, the trickle vents need to be closed most of the time from October to the end of March if they are not to be allowed to cause alarming heat losses. During this period it may sometimes be necessary to open trickle vents in rooms where more than four people are present to avoid body odours but not to prevent condensation. Small amounts of condensation appear along the bottom of windows only when the external temperature falls overnight to below about minus one degree Celsius.

Because condensation is so insignificant the heat recovery ventilation system installed in Solaria is generally only switched on to remove excess vapour from the kitchen and bathrooms between the start of November and the end of February. During the rest of the year water vapour is quickly removed via trickle vents or opened windows without significant loss of energy. Odours are removed from the two additional WC's throughout the year by means of the heat recovery system activated via the light switches. Although its fan only consumes 0.09 kW, used in the way described I remain unconvinced that it saves a significant amount of energy. A more modern system, driven by DC motors, might use less energy but I doubt if it would save significantly more because it is needed so infrequently. We have learnt from experience that a large volume dwelling (Solaria 498 cu m, Port Lion 542 cu m) with around four occupants or less is not going to suffer from condensation problems which can't be solved by opening trickle vents and/or windows most of the year and switching on small timed extractor fans in appropriate locations at other times. So, the verdict has to be that a better investment in both energy and financial terms would have been a solar water heater linked directly to a super insulated storage cylinder and driven by a PV pump! However, heat recovery systems driven by heat pumps are another story...

The solar chimney in Solaria proved to be less effective as a cooling device than simple cross ventilation

(Photo courtesy of Self Build and Design)

I certainly missed some tricks when I planned the insulation levels of each property. In particular, I paid too little attention to the extent and severity of cold bridging, which continues to be ignored in most of the literature and by many who advertise the virtues of their 'eco homes'. As I made the decision to clad most of the exterior of the Port Lion property I should have used 100mm instead of 19mm battens and installed 100mm of insulation under the cladding instead of the reflective foil insulation, equivalent to only 25mm of rockwool insulation. At Solaria I should have filled the cavity completely with 50mm thick insulation batts as parts of it already had to be obstructed by fire stops consisting of strips of insulation in polythene tubes. This would have reduced the cold bridging of the mortar at Port Lion and the timber wall studs at Solaria to an insignificant level. The internal service cavity in Solaria could also have been increased to 50mm and fully insulated. I should also have placed 100mm of insulation underneath and around the internal edges of the concrete slab. The cost of these additional measures in Solaria would have been covered by the savings achieved by omitting the central heating system. However, thermal bridging around apertures remains, in my opinion, a problem still without a satisfactory solution. In the Port Lion property cavities were closed at apertures with Thermalite blocks and at Solaria with timber battens, both an improvement on conventional brick or dense block closures. Even the plywood box sub-frames employed by the Vales in their 'New Autonomous House'[3] and at BedZed[4] provide a degree of thermal bridging and cannot prevent thermal bridging across the window and door frames.

Finally, how has living in the low thermal mass at Solaria compared with living in the very high thermal mass of Port Lion? With regard to energy use during its lifetime, computer simulation has suggested that, overall, a high inertia house will use at least 10% more energy, dependant on the level of insulation[5,7,8]. Further, a reasonably well insulated house requires a reduced heating period and there are few days when solar gain exceeds the demand for heat throughout all rooms. Adding mass may therefore increase demand by requiring morning heating before the sun can have any effect. This demand hides some problems[6]:

a) Low temperatures in high mass elements prevailing during warm-up create low radiant temperatures and discomfort, calling for higher than normal air temperatures in compensation, thereby increasing the annual heating demand.

b) The peak demand is increased. If this is met by installing a larger boiler it will operate at less than optimum efficiency during other periods.

Problems a) and b) were partially side stepped at Port Lion by installing a wood burning stove which was thermally very closely coupled to the enormous mass of the cast concrete spiral staircase which, under most Pembrokeshire winter conditions, radiated heat noticeably until the stove was lit again the following evening. None the less, more fuel was clearly required to 'charge up' and keep the high thermal capacity of the spiral staircase and dense concrete internal walls 'filled' if they were not to act as cold sinks. The thermal admittance of the Thermalite external walls was much lower than that for the dense concrete internal walls so they would not be expected to act as cold sinks, as appeared to be the case. Our experience was that, apart from the NW facing second sitting room which was designed as an add-on indulgence to be heated passively, the main living areas were always maintained at comfortable temperatures. The over heating of the Port Lion house is probably explained by its NW-SE orientation, over sized SW facing windows and too large a window to floor ratio. By way of compensation, the NW sitting room, despite it SW facing curtain wall, generally attained and maintained comfortable temperatures from springtime until early winter without the need for any heating. My experience of the thermal response of the remaining first floor living rooms in Port Lion supports the view that there is a limit to the rate at which heat can be conducted in and out of surfaces even when the surface is exposed brick. It also supports the evidence that only the first 10-20 mm of concrete wall depth is effective in diurnal variations of temperature[6] so Port Lion would have been less inclined to overheat without severe loss of passive solar gains with a smaller window to floor ratio and reduced area of SW facing glazing.

The low thermal capacity of Solaria is taken full advantage of by setting the central heating clock for 3 hours from 7 am, a 1 hour mid day boost and a final run from 5 pm until 10.30 pm during most of the winter. The room thermostat has to be set at 17 degrees Celsius and the boiler thermostat is set back to avoid overheating during most of the winter. Response to short lived solar inputs is rapid in the two south facing living rooms. Solar inputs seem to be retained long enough to suggest that a significant amount of solar energy is absorbed by the structure. The quick response is probably in part due to the presence of insulation in all partition walls and ceilings, a clear energy saving arrangement which enables TRV's to be set on the frost thermostat position in rooms not in use. Such rooms can quickly be brought into use by opening doors to encourage convection but the continuous slow conduction from the heated rooms ensures that air and surface temperatures never fall anywhere near critical levels.

With regard to the energy embedded in the building materials and their environmental impact there is no competition – the timber frame wins hands down! So you see, I am on the side of the angels after all!

Table 4. Electricity consumption for the three properties

House	Solaria		Wenlock		Port Lion	
	Energy kWh/pa	Energy kWh/sqm/pa	Energy kWh/pa	Energy kWh/sqm/pa	Energy kWh/pa	Energy kWh/sqm/pa
Electricity Consumed	2,348	12	2,704	21	5,867	28
CO_2 emissions kg pa.	0		1,136		2,464	
CO_2 kg pa./ sq m	0		8.8		11.8	

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References:

1. 'Solar Energy and Housing Design Vol 1'. Architectural Association. Simos Yannas ISBN 1-870890-45-0.

2. 'The Efficiency of Domestic Hot Water Production out of the Heating Season' Building Research Establishment GE Whittle & PR Warren CP 44/78 July 1978.

3. The New Autonomous House Brenda & Robert Vale ISBN 0-500-34176-1.

4. 'From A to ZED: Realising Zero (Fossil) Energy Developments.' Bill Dunster Architects ISBN 0-9545059-0-5 mail@zedfactory.com

5. Table 6.1 in Thermal Energy Conservation: Building and Services Design J W Weller & A Youle. ISBN 0-85334-938-X.

6 . 'Role of Thermal Mass in UK Housing' J Littler & P Ruyssevelt in 'The Efficient use of Energy in Buildings', Conference Proceedings C46, UK-ISES.

7. A Burberry (1974). 'The Choices for Designers'. Architects Journal, 160 (37), 615-28.

8. E R Hitchin (1980). 'The Sizing of Heating Systems for Well Heated Houses'. Studies in Energy Efficiency in Buildings No.2. British Gas, Watson House Research Station.