Low Energy Building Design

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Summary

Low energy building design is important if ambient energy sources and free heat from people and processes are to be effectively used and thus reduce the demand for fossil fuels. Thermal insulation alone is not the answer. A combination of passive and active environmental control methods are necessary if energy collection and distribution are to be efficiently arranged in space and time and provide a comfortable environment for people. A low energy house is proposed which uses a heat pump to distribute solar and free energy via a thermal storage wall to the space; a heat pump may not be necessary in other climates for other built forms.

Sommaire

Il est important d'établir les plans de bâtiments qui requièrent peu d'énergie, si l'on doit utiliser à bon escient les sources d'énergie ambiante et la chaleur produite par les gens et leurs activités, et ainsi réduire la consommation de combustibles fossiles. L'isolation thermique en elle-même n'est pas suffisante. Il faut combiner des méthodes de contrôle du milieu, qui soient à la fois passives et actives, si l'on veut distribuer efficacement le captage et la répartition d'énergie par rapport à l'espace et au temps, et offrir aux gens un environnement confortable. On propose une maison à énergie réduite quit utilise une thermopompe pour distribuer dans l'atmosphère l'énergie solaire et produite par l'activité humaine, au moyen d'un mur d'emmagasinage thermique; il se peut qu'une thermopompe ne soit pas nécessaire sous d'autres climats ou pour différents types de constructions.

Buildings as Energy Systems

The world has a finite supply of fuels, as more become used the economic laws of supply and demand raise prices and limit availability. Ideally zero energy buildings are required, leaving the fuels available for industrial, chemical and transportation purposes and for a fairer distribution of them around all the countries of the world. It is sometimes argued that highly insulated buildings carry high energy costs in the manufacture of suitable materials, Herman (1975) (1) but this has to be balanced against the life cycle costs for operating the building and the fact that fuel costs are rising at a faster rate than insulation costs - but insulation alone is not the only important aspect of energy conservation. Natural ventilation energy losses are high, these may be reduced by employing tighter forms of building construction although this demand comes at a time when the standard of workmanship is not generally high.

The average annual net energy consumption of a UK house is 22500 kWh (81 GJ) per year (see BRE Current Paper 56/75). These figures can vary widely depending on the climate, the way in which people use the house and the heating system. Work by Ellis and Gaskell (1978) (2) has shown that there is a considerable spread of energy usage in houses having the same fabric heat loss. In well-insulated houses the 10% highest energy users may consume 2.5 times more energy than the lowest energy users, but in poorly insulated houses this variation may be nearly three times higher.

Buildings soak up heat from or emit it to the surroundings and the efficiency for this process can be likened to that of a heat pump. They may be designed to be isolated from the external climate and reflect incident energy back to the surroundings or to collect ambient energy and use it. At the time of collection the energy may not be required and controllable time delays have to be placed in the system.

Available Sources of Energy

Piped Energy

Coal, electricity, gas, oil and wood must be compared on a basis of useful heat output per unit cost. That is to say effective fuel costs depend not only on source but also on conversion efficiency. Electricity may be cheaper to use than natural gas if a heat pump with a COP of 3 is achieved. The choice of heating system, however, depends on capital and running costs besides other factors such as thermal response, flexibility in layout and control, reliability and maintenance.

Solar Heat

This comprises gains to the building via direct radiation through the glazing. Also it encompasses the heat gains from solar energy transmission through the building fabric, together with gains from active and passive solar collectors if used.

At a latitude of 53.3°N the daily mean solar irradiation on a south facing sloping roof varies from 0.5 kWh/m^2 (December) to 4.5 kWh/m^2 (June), Siviour (1978)(3). In low energy buildings this is worth collecting. Air solar collectors allow both the heat collecting and building construction to be easily integrated. There are no freezing problems as there are with water; air collectors have a fast response but need more space for the circulation ductwork system.

Free Heat

The free heat is contributed by the occupants, lighting, cooking, domestic hot water, electrical appliances and processes within the space. In a highly insulated building these sources are significant and can partly offset the heat losses. Energy from people (about

3-5 kWh per day for a normal family), lighting, cooking, appliances (about 10-15 kWh/day) and hot water (5 kWh/day in use losses and waste heat recovery) contribute nearly 5000 kWh per year of free heat. A detailed survey of data concerning free heat sources has been made, Siviour (1978) (3).

Waste Hot Water

An average household consumes domestic hot water at a rate of 120 litres per day at 55°C. In energy terms this amounts to about 2500 kWh (9 GJ) per year at the tap; some families will use three times as much hot water as this. It is reasonable to assume that at least half of this heat is lost down the drain; 1250 kWh per year is worth recovering when the net space heating requirements of the house are 4000 kWh per year and perhaps even on hot water heat requirements alone. Work at the Building Research Establishment has used a heat collecting tank containing the evaporation coil of a heat pump, the condenser and the compressor of which are mounted in the conventional hot water cylinder. Initial trials at BRE give heat pump coefficients of performance ranging from 3 to 4.2 for temperature differences between cylinder and collector or 36 to 12°C respectively Warren (1979) (4).

Heat Pumps

These make effective use of heat in the air or the water in the vicinity; their use to supply heat to buildings could save about 7% of the UK primary energy consumption (BRE Digest 191, 1976). When the heating requirements of a building are very low, heat pumps become most effective because the yearly variation in COP will be less; preheated air will decrease this even further.

Low Energy Buildings

The effective use of alternative energy sources depends on the energy consumption of a building being significantly reduced. The performance of three houses are shown on Table (I) and further analysed in Figure (1).

It can be seen from Figure (1) that as the degree of insulation increases:

a) the slope of the heating load bands decrease, showing that well insulated buildings are less influenced by climatic temperatures;

b) the heating season contracts because the heating load bands cross the thermal balance line further to the right (i.e. deeper into the winter);

c) the range of the heating load bands, for any given number of degree days, decreases. This indicates that the thermal behaviour of this type of building becomes more predictable as its energy consumption is reduced.

Table (I) Net Space Heating Demands (33 week heating season)

Construction and air changers/hour	Building Element	'U' Value ($W/m^2 {}^{o}C$)	Net Space Heating (kWh/year)
Standard House	Window	5.7	16500
(2.0 a.c.h)	Wall	1.0	
	Roof	0.6	
	Floor	0.6	
Insulated House	Window	5.7	12000
(1.5 a.c.h)	Wall	0.5	
	Roof	0.6	
	Floor	0.6	
Well Insulated House	Window	2.8	4100
(0.75 a.c.h)	Wall	0.3	
	Roof	0.3	
	Floor	0.3	

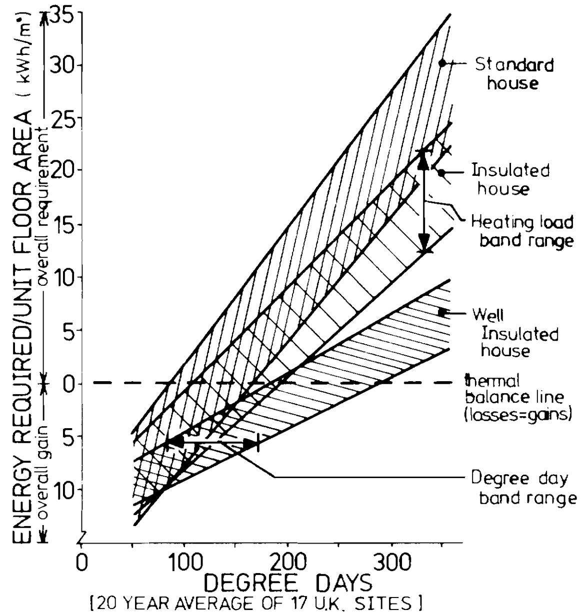


Figure 1
Heating Load Bands for 3 house constructions (detailed in Table I)

Energy Balance Equation

Ideally the energy balance for a building should be:

Fabric loss + ventilation loss $\leq$ ambient energy + free heat (1)

This equation shows that for a given temperature criterion the choice of materials, the air tightness of the building, the regional climate and the use of the building all interplay to dictate the amount of extra energy that has to be provided ultimately by fossil fuels.

During the night there are little free heat gains and no solar gains. This emphasises the importance of designing the structure to combat the effect of cold nights, or collection of cold dark days, by introducing time lags into the building fabric and including internal surfaces of sufficient thermal capacity to give a "flywheel effect". To utilise the output of solar collectors during these periods one requires an easily accessible storage system combined with output regulation control.

The equation is also important because it shows that when there is an energy balance the choice of fuel can be made in a more flexible manner because the differences between fuels become less important when the building is less dependent on them.

For effective low energy buildings, the distribution and storage of energy is an important as its collection. Using passive systems, the building envelope has an important role to play in controlling these funtions.

The energy balance equation can be expressed as:

$$\Delta\theta \left[(\Sigma(A \mathrm{x} U) \mathrm{~x~} 10^{-3}) + (V \mathrm{x} 0.33 \mathrm{x} n) \right] \leqslant \frac{F + S}{24} \qquad (2)$$

where:

$\Delta\theta$ = design mean temperature difference ($^{\circ}$C),

A = area of external building fabric (m^2)

U = 'U'value of external building fabric (W/m^2 $^{\circ}$C)

V = internal volume of the building less 10% dead space (m^3),

0.33 = kWh required to raise 1 m^3 of air through 1°C (kWh/m^3 $^{\circ}$C)

n = number of air changes per hour (hours $^{-1}$)

F = average free heat per day from miscellaneous gains during heating season (kWh/day)

S = average abmient energy gains per day from direct solar radiation into space, glazing and the building fabric, together with input from active and passive solar collection systems (kWh/day)

Passive Environmental Control

Over the ages man has used his ingenuity to make his habitat safe, warm and weather protected. Troglodytic architecture sculptured out of the hillside landscapes of Morocco; the igloo of the Eskimoes; African courtyard houses; the Malaysian tree dwellings and even the English thatched cottage all have features which aim to orientate, to shape buildings and to contruct them from materials so that the inhabitants are comfortable during the hot or cold rigours of the regional climate. These features are the essential ingredients of passive environmental control where the building rather than the equipment primarily controls the internal environment. Whereas active systems have the disadvantages of heavy duty plant and complex networks to distribute hot and cold fluids; produce noise and require both maintenance and plant space.

The Trombe wall allows winter sun to warm the airsteams circulating around the room whilst in summer the airstreams carry room heat away and the wall acts as a solar barrier. Heavy floors or walls permit energy to be stored and may even have channels for night air to pass through them and cool the building down, whilst the mass not only attenuates but retards the maximum summer heat so that it does not occur when the people are working.

Buildings can collect, store and distribute ambient energy using simple princples such as gravity forces to circulate air, mass to delay and alternate heat flow, built form to protect from the sun but to encourage breezes to pass through the interior.

The building time constant T, for a given material thickness is defined as:

$$T = \frac{\text{material properties (product of mass and specific heat)}}{\text{heat flow/degree temperature difference}} \qquad (3)$$

For passive control, buildings should have a value of T which not only exceeds the occupancy period for the building, T_{O}, but is also longer than the likely minimum time period for the lowest and highest temperature changes (T_{W}, min) so that $T_{\mathrm{O}} < T > T_{\mathrm{W}}$, min. This inequality expresses the important balance between selecting building materials whilst taking into account building use and the regional weather pattern. Some current and future trends in passive environmental control are now described which reduce the energy requirements and also the heating and the cooling plant by allowing the building structure to act as a dynamic environmental control.

Hollow Block Ventilated Floor

Outside air is passed down a hollow block floor so that the external daily temperature curve is attenuated by the mass of the floor to give a comfortable supply temperature; background heat may need to be supplied in winter. In summer night air can be used to give cooling. No ducts or suspended ceilings are necessary for heating and cooling services. Noise and air movement characteristics are good. Economic studies have indicated that a 2-3% reduction in total building cost is possible and the refrigeration load will be reduced by about 70% Isfält(1979) (5). Figure (2) shows the principle of the hollow block ventilated floor system.

Recent studies by Södergren (1979) (6) on an office block (Sollentuna Local Authority near Stockholm) have shown that the temperature in a space is strongly affected by the floor temperature. By using airways in concrete floors and the airspace in double glazing for distributing warm air or cool air heat gains can be used effectively, heat losses can be reduced, and the concrete floor can also be used to delay the transfer of heat to or from the room.

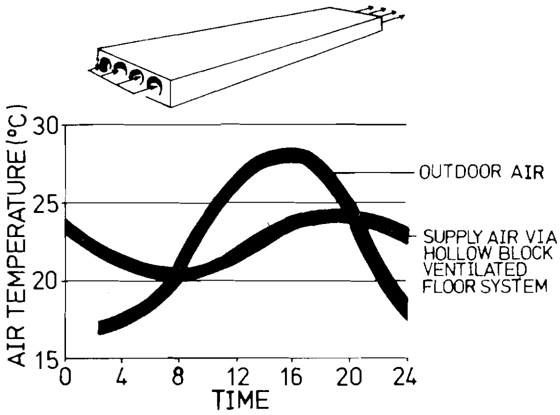


Figure 2
The Principle of the Hollow Block Ventilated Floor System

The basic principle is designing the building so that the winter heat losses throughout the occupied and unoccupied periods are balanced by the heat gains; in summer night air circulates through the floor slabs to cool the building down and so balance the daily heat gains collected and stored in the slab.

If the floor slab is assumed to be affected only by air passing through the airways (whereas in reality disturbances at the floor-ceiling surfaces are superimposed) it is possible to determine the temperature variation of the outgoing air assuming a sinusoidal input temperature function.

The damping factor (Z) and the time lag (ϕ) of the output temperature function have been found by Isfält (1979) (5) to depend on the two dimensionless numbers: -

$$\frac{hA}{Gc_p} \quad \text{and} \quad \frac{Gc_p}{\omega mc} \qquad (4)$$

where h = the film coefficient ($W/m^2\,^oC$)
A = are of the hole surfaces (m^2)
G = air mass flow per time unit (kg/s)
C_p = specific heat capacity of air ($kJ/kg\,^oC$)
m = mass of the slab (kg)
c = specific heat capacity of the slab material ($kJ/kg\,^oC$)
ω = angular velocity of temperature variation (radians/s).

Figure (3) shows curves for constant damping factor (Z) and time lag (ϕ) (for 24 hour variations 360^o = 24 hrs) as functions of these dimensionless numbers.

In order to obtain an effective system the parameter combinations have to be chosen with care. For an angle lag less than 60^o (corresponding to a time lag of 4 hrs for a 24 hour variation) the lines of constant damping factors fall rapidly and so to be effective the combination of parameters in a system should fall to the right of the curve $\phi = 60^o$. Isfält regards a damping factor Z = 3 as a lower limit for an effective system. Combinations below the curve Z = 10 correspond to extremely heavy structures with low airflow rates (e.g. a Cathedral) and are not of interest here. A zone of effective parameter combinations can be seen on Figure (3) outlined by a heavy line.

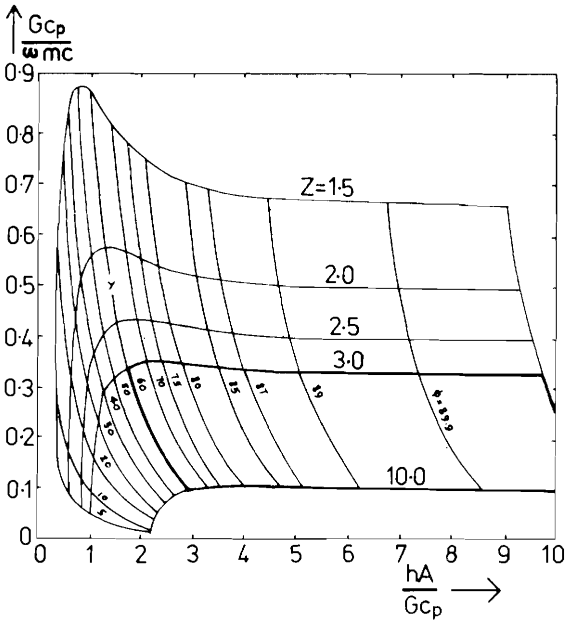


Figure 3. Damping Factor Z and Angular Lag ϕ in dimensionless representation for Hollow Block Floors (Isfält 1979) (5).

Airvent Window

Heating and cooling loads are reduced by letting an airstream (10-20 l/s per m width) pass between two glass panes. The 'U' value will be in order of 1-2 $W/m^2\,^oC$ depending on the airflow rate. Warm extract air is removed via the window and discharged or recirculated remembering that ventilation rates up to about 4 air changes per hour have a very significant effect on reducing heat gains. In winter the glass surface temperatures are increased; in summer heat in the space is removed whilst air movement is provided. The total heat flux through the structure is reduced and significant decreases in environmental services plant will result. Figure (4) illustrates the window and shows the expected thermal performance Södergren (1973) (7).

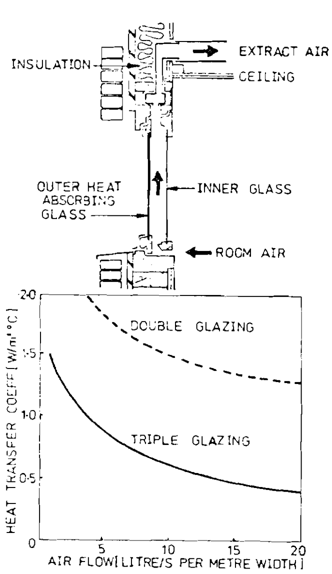


Figure 4. Airvent Window. Heat Transfer as a function of extract air flow, from full scale model tests. (Södergren 1973) (7).

Thermic Controls

Structures can be designed to behave like thermic diode valves. By sandwiching a thick storage layer between two layers of high thermal resistance, and using water to separate the layers, heat can be conducted from one outer layer to the other outer one or alternatively can be stored in the sandwich. This heat flow can be controlled by a thermic oil pressure valve linking the water layers each side of the storage layer (Buckley (1978) (8) and Fig. (5)). Room heat or external heat gains are utilised and by incorporating some air ducts, independant control of the radiant and convective components can be achieved. Domestic hot water distribution can be incorporated into the system.

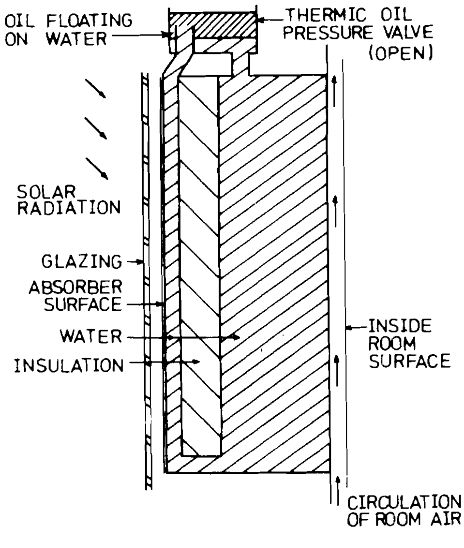
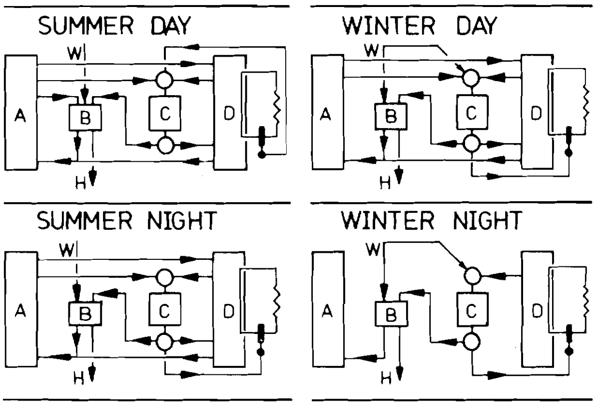


Figure 5. Thermic Oil Pressure Valve in Thermic Storage Wall (Buckley 1978) (8)

These systems offer the possibility of directly transmitting, or delaying, the heat flow to and from a space through opaque or transparent building structures besides using natural radiant (solar) or convective (air) heat sourses, and decreasing considerably the traditional plant, piping and ducting networks.

In the experimental low energy house design, shown in Figure (6), passive environmental control is achieved by roof and wall solar collectors plus an internal mass wall (or floor) for distributing and storing heat.



KEY:

A	Ambient energy collection
B	dhw/heat pump pre-heat cylinder
C	Heat pump(s)
D	Mass storage wall/floor
H	Feed to dhw cylinder
W	Energy input from waste hot water
○	Heat pump input/output selector
→	Direction of energy flow
≀	Warm air space heating/cooling
▮	Heating/cooling coil in room supply air

Figure 6. Environmental Control System for an Experimental Low Energy House.

Microprocessor technology is to be applied to control the system, which until recently would have proved prohibitively expensive.

Ranking Energy Conservation Strategies

Heap (1979) (9) describes a simple ranking procedure using an energy return factor, R, defined as: -

$$R = \frac{E}{M + \frac{C}{L}} \qquad (5)$$

where R = energy return factor (kWh/£)
E = annual energy saving (kWh)
M = annual maintenance cost (£)
C = purchase cost (£)
L = lifetime (years)

The reciprocal of R may be compared directly with present or expected fuel costs. If R^{-1} exceeds the fuel cost considered then the energy conservation measure will not be cost effective.

Low Energy House Design

Objectives

Conservation of energy by reducing amount of energy required and using ambient energy and free heat sources wherever possible.

Emphasise passive environmental control so that the external climate is modulated through the structure, form and building envelope.

Satisfactory environmental conditions - low total cost by reducing equipment and distribution costs, decreasing fuel consumption and plant maintenance.

Solution

- Emphasise passive environmental control; minimise the use of active systems; use the energy balance equation to evaluate the balance of materials needed for climate and building type.
- Utilise as much of the building for collecting, distributing and storing energy as is practically possible.
- Select building materials and constructions with insulation and thermal response as important factors; distribute high mass storage walls, floors and internal walls appropriately.
- Link active system design with passive control system; consider heat pumps and combined heat power schemes where possible; evaluate response of convective and radiant methods of heating spaces.
- Orientate buildings between SE and SW; loss in solar efficiency is within 8% of south facing building Lakmaker (1979) (10).
- Optimise angles for solar collectors inclined to the horizontal Lakmaker (1979) (10).
- Use landscaping to provide wind relief around buildings; wind tunnel tests will be required.
- Space buildings to avoid overshadowing Ó Catháin (1979) (11).
- Housing is more energy efficient in terraced rather than detached or semi-detached forms Nelson (1979) (12).
- Facade design can help to give solar and wind protection.
- Maximise glazing on SE to SW faces
- Use maximum overall thermal transmittance of U = 0.3 W/m^2 °C for roofs, walls and floors; provide insulating shutters for windows where applicable.
- Reduce infiltration to a minimum by draughtstripping of all opening lights and external doors, but provide small on-off fans to give ventilation where necessary for vitiation and condensation control.

These measures determined the form of the experimental house described below, which could be constructed using present building methods and technology:

Experimental Low Energy House

Two storey semi-detached 5 P dwelling with internal floor dimensions of 6 m x 7 m:

Construction

- External wall, 'U' value = 0.3 W/m^2 °C

Construction to give a wall with a time lag of over 8 hours and an internal leaf of high thermal capacity. Some parts may incorporate air solar collectors.

- Windows, 'U' value = 2.8 W/m^2 °C

Standard double glazing with insulation filled frames incorporating a thermal break, frames having adjustable ventilation slots.

- Floor, 'U' value = 0.3 W/m^2 °C
- Roof, 'U' value = 0.3 W/m^2 °C

Incorporating air solar collectors.

- Weatherstripped external doors and openings.
- Internal storage walls 300-400 mm dense concrete with prefabricated air circulation channels; insulated externally with 50 mm insulating material plus surface finish.

General Concept

The integrated energy system for the dwelling consists of a passive-active environmental control system illustrated in Figure (6). An array of roof mounted air solar collector panels are incorporated in a closed system which circulates air via a small fan through the internal storage wall. In winter, warm air will be circulated using free heat and "back-up" heat supplies, together with a waste-water heat recovery system. In summer, cool night air will be circulated to cool the store and hence balance the daytime heat gains.

A second small fan supplies fresh air to a diverting box. This directs the air through insulated or uninsulated airways in the internal storage wall, depending on the extent of the heating or cooling effect desired. The air is then supplied to the spaces at high or low level via a small "back-up" heating coil for use in extreme conditions.

The introduction of 0.04 m^3/sec (0.75 ach) fresh air is adequate for vitiation and condensation control, but local extract is required in moisture producing areas, e.g. the kitchen. The pressurisation of this well-sealed building will lessen the extent of natural infiltration and the required "leakage" from each space can be fine-tuned by adjustable air slots in the window frames.

Energy Balance for the Heating Season

Using a mean temperature difference of 10^{o}C and a heating season of 26 weeks, as suggested by Figure (1) the energy balance is as follows: -

Fabric Loss	- 4491 kWh
Ventilation loss	- 2043 kWh
Domestic Hot Water	- 2500 kWh
Free heat + solar gains (25 kWh/day x 70% ultilisation factor)	+ 3185 kWh
Solar heat from solar collectors and heat store	+ 2200 kWh
Balance:	- 3469 kWh

Solar heat is calculated for 40 m^2 of roof mounted solar collectors, orientated SE/SW with 40% efficiency and 70% utilisation factor. Average solar radiation per month taken as 120 MJ/m^2. (1MJ = 0.278 kWh). Solar heat = solar radiation x area of collectors x collector efficiency x utilisation factor, (kWh) = (kWh/m^2) x (m^2).

The balance of "back-up" energy required is 3649 kWh/ year. This can easily be provided by one air source heat pump using off-peak electricity. One water-air heat pump may be used for heat recovery from waste hot water. When the heating demands have been satisfied then the excess heat collected can be used for preheating domestic hot water.

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