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A low energy housing design in an area of high wind and rain
An innovative housing scheme at Stenness on the Orkney islands

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Abstract

Island and coastal areas in northern and western regions of Scotland are characterised by comparatively high levels of wind and rain — a combination that increases the wind-chill cooling of buildings and leads to higher energy consumption. This paper describes a low-energy housing demonstration project in the Orkney Islands, an island group located off the north coast of mainland Scotland. The background to the project is discussed, in particular, why there was a need for a more appropriate design, the features incorporated, and the main findings of the research.

Keywords: Housing; High wind; Rain

1. Introduction — housing appropriate to its surroundings

When considered alongside typical Northern Hemisphere 'neighbours,' it can often appear there are few countries so maladapted as the British to their own physical environment. Indeed, relative to our climatic conditions (especially in northern parts of Britain), we have probably one of the lowest standards of housing stock of any developed country in the world.

In many regards 'housing design appropriate to local circumstances' appears an issue largely neglected. In Orkney, the remarkably preserved Neolithic village of Skara Brae (circa 3100–2500 BC) offered a surprising level of comfort. The remains show several impressive features — separate dwellings with interconnecting passages, a drainage system, flagstone furniture, recessed beds, central hearth and a 'limpet (edible shellfish) box.' The houses would indeed have been remarkably warm with thick stone walls buttressed by mounds of midden (trash mixed with soil and plant matter) and overgrown with grass, providing an early example of a building technique to combat climatic effects. The foundations of the houses were found to include a layer of clay in the bottom course, which would have provided effective damp proofing.

In relative terms, and in comparison to other achievements, advances in housing standards in the intervening 5000 years, including the era of post-industrialisation, seem largely unimpressive. The industrial revolution produced 'housing for the masses' in industrial areas and a pressure (based on poverty) to produce market-goods in rural regions. This era produced a legacy of sub-standard housing in both urban and rural areas, which still exists and has only recently begun to be addressed.

In particular, the development of building practices seems particularly underplayed with regard to elements such as insulation measures, improving the microclimate, the use of solar gains, air-tightness, draught proofing, ventilation and sustainable approaches to key elements such as energy use and waste management. As well as the increasing standardisation of housing styles and building practices across the country, national building regulations, while obviously raising standards in housing, are uniformly applied across the country. The need for higher levels of insulation, airtightness and controlled ventilation in regions which have high wind–high rain climates is apparent. It is evident, however, that the link between climate and housing needs, although clearly understood, has never been adequately addressed.

2. Research aims

Orkney Housing Association Limited (OHAL) was set up in 1985 to provide low-cost rented housing for the

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elderly, single people and those with special needs. In the intervening years, it has widened its remit to include more general needs housing and has become increasingly concerned with energy efficiency. This is particularly important to persons in rented accommodation who are often on low incomes, while shared-ownership homes are overwhelmingly bought by individuals setting up home for the first time, the elderly and those with disabilities, all of whom have many other calls on their income.

The project aim was to design and construct one pair of semi-detached houses to an increased level of energy efficiency and at minimal additional cost. Particular attention would be given to reducing the effects of exposure to high-wind and rain conditions. The performance of the design would be assessed against a pair of standard houses built on adjoining sites (at the same time and by the same company) and against prevailing meteorological conditions. House performance and meteorological data were recorded simultaneously on site over two heating seasons.

3. The Orkney islands

3.1. General

Fig. 1 shows the Orkney Islands — an archipelago of some 70 islands lying 10 km off the northeast coast of Scotland, beyond Caithness and the Highlands. Eighteen islands are inhabited, with a total population of around 20,000, living mainly on the largest island known simply as "mainland." The overall population density is around 19.9 persons/km^2. The cornerstones of the economy are farming, fishing and tourism. There is little industrial presence; however, the islands continue to benefit from the oil terminal on the island of Flotta handling oil by pipeline from the North Sea, and more recently, by shuttle tanker from the new Atlantic frontier. Ironically, while the islands are heavily dependent on the import of petroleum products, none of the 13 million tonnes flowing into the terminal is useable locally.

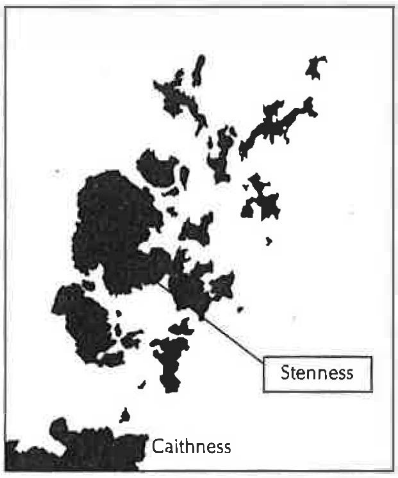

Fig. 1. Location of Stenness low energy house scheme on the Orkney mainland.

Table 1
Energy consumption by sector, Orkney [1]

Sector	Consumption (GWh)	
Domestic	179	33%
Transport	127	22%
Commercial/Industrial	164	30%
Agriculture/Fishing	80	15%

The most striking aspects of the Orkney landscape are its low-lying nature and the scarcity of trees. This means there is little natural shelter, but also that there exists a wealth of well-preserved historical stone-built constructions. The remarkable preservation of prehistoric monuments arises from the scarcity of wood and the abundance of flagstone. Famous examples include the prehistoric village of Skara Brae, and on Papa Westray, the Knap of Howar houses — 500 years older — are believed to be the oldest upstanding houses in western Europe. Other monuments include a wide dispersion of burial tombs and the great stone circles of Stenness and Brodgar. In contrast, the 12th century St. Magnus Cathedral in the capital, Kirkwall, was built from local red sandstone.

3.2. Factors affecting domestic energy use

3.2.1. Energy supply

An analysis of Orkney's energy consumption (Table 1) shows the dominant demand of the 'Domestic' sector.

The local cost of imported energy resources (oil, coal and bottled gas) is generally higher than on the Scottish mainland, although electricity is effectively subsidised in that island customers are charged the same tariffs as those elsewhere. Orkney is fortunate in being reasonably close to the Scottish mainland and connected by two 40-km submarine electricity cables.

3.2.2. Climate

The Orkney Islands have a latitude of 59.6°N, just south of that of Cape Farewell in Greenland. The climate may be described as hyper-oceanic, the most oceanic category in Scotland, which otherwise is applied to only the western and northern isles and peninsulas of the extreme west and north coasts of Scotland. Surrounded by sea, but directly in the path of the warm waters of the North Atlantic Drift, the more severe aspects of the islands latitude are ameliorated, providing the islands with a fairly equitable climate, with winter temperatures somewhat higher than expected. Long daylight hours enhance the summer months.

Lying in the track of Atlantic depressions, strong winds are frequent, with an average of 24 gales occurring per year, prevailing from a sector between west and southeast. Coupled with driving rain, such conditions often produce a substantial wind-chill factor.

3.2.3. Housing stock

Within the domestic sector the principal energy uses are in space and water heating. The space heating demand is seasonal and closely related to the climate and weather and often results in significant heating demands during the summer months. The situation is worsened in a large proportion of houses by ineffective heating systems, poor insulation and insufficient weatherproofing.

A significant proportion of the houses throughout Orkney and in particular the outlying islands are 'old' (many more than 150 years), often with additions built to modern times. The level of sub-tolerable housing was 16% in 1992[1]; significantly one of the highest figure in Scotland and greater than both the Western Isles and Shetland (both 10%) [2]. It is the policy of Orkney Islands Council (OIC) to eliminate below tolerable housing in Orkney by 2003. The distribution of such housing is random; however, concentrations are found in Orkney's northern isles. Many houses in these areas are pre-1930s one- and two-storey cottages, often with deficiencies in washing facilities and/or weatherproofing, although such occurrences are decreasing [3]. By providing improvement grants, the Council encourages the renovation of vacant properties and the upgrade of existing homes.

Building costs are also higher on the Scottish islands, principally due to transport requirements. On the Orkney mainland the overall costs of building a home are around 30% greater than on mainland Scotland, increasing to 50% on the outer islands.

4. Principle opportunities for improving energy efficiency

Early in the design process it was agreed to focus design efforts on six main areas where the most cost-effective investments were anticipated.

4.1. Thermal efficiency

Increasing insulation levels is regarded as the most cost-effective investment in energy efficiency. Over the past 20 years, the government, through the Building Regulations, has attempted to increase, incrementally, the thermal efficiency of new designs by limiting the maximum permitted thermal transmittance. Since 1976, when the thermal regulations were first introduced, maximum U-values for external walls and roofs have been reduced from 1.0 and 0.6 W/m^2 K, respectively, through 0.6 and 0.35 W/m^2 K in 1982, to the current 0.45 and 0.25 W/m^2 K introduced in 1990.

4.2. Wind chill

The main misconception about wind chill is the application of wind-chill equivalent temperatures to unheated inanimate objects. When the wind is blowing, any dry, unheated, inanimate object cannot cool below the ambient air temperature. However, an object with a wet surface (e.g. a wall of a building) can, of course, cool to somewhat below the ambient air temperature due to evaporative heat loss. A heated object, however, will lose heat more rapidly by convection when the wind is blowing. Once the source of heat is removed the object will quickly cool towards the ambient air temperature but will be unable to cool below this temperature. The rate of heat loss in housing terms is dictated particularly by the levels of insulation and the ingress of cool air (draughts) through gaps in the building envelope.

Meteorological data over the UK has previously been analysed to produce wind-chill indices and equivalent temperatures across the country [4]. If equivalent temperatures of 0°C or less are considered, then it has been shown that the proportion of the winter heating season with such values varies from about 25% in southern England to about 50% in lowland Scotland, to approximately 75% in the northern Scottish islands. The distributions indicate that the most frequent winter equivalent temperature is above 0°C in most parts of the UK, with the exception of these northern island regions where values as low as −4°C to −5°C are common.

4.3. Solar gain

In the Scottish islands, the long days of spring and late summer (during which space heating is often required) offer both the potential and demand for solar space heating. Indeed, at least one source [5] has suggested that Orkney lies close to the optimal latitude for cost-effective solar technology. Fuel savings due to the use of solar heating in buildings depend on the solar heat available (supply) and the heating load (demand).

In the likely absence of any effective method for long-term thermal storage, the effectiveness of solar heating will be governed by whichever factor is smaller. In the summer, for example, solar energy may be available in considerable quantities but the demand is likely to be low. This will minimise fuel savings. In winter, the demand will be high but the available solar energy will be minimal. It is clear that the best climate in terms of the effectiveness of solar heating for buildings is sunny in winter and cool in summer. The long cool summer days in Orkney are a close compromise.

4.4. Air leakage

Housing in the UK tends to be much less airtight than for example North American or Scandinavian dwellings — typically by an order of greater than 2.5 [6].

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[1] By 1998 the level of sub-tolerable housing had reduced to 11%.

It is believed that approximately 75% of the air leakage in normal housing could be occurring through background and hidden paths rather than identifiable gaps and cracks in the building envelope. Experience has shown that even though a building may be well insulated, draught-stripped and have tighter windows and doors, the building will still be leaky if the envelope has not been constructed to reduce air infiltration.

The problem is exacerbated in areas such as Orkney where the high winds and resultant pressure against the external housing fabric increase the air infiltration leading to excessive ventilation, energy waste, higher heating bills and greater discomfort.

4.5. Heating and ventilation

In a typical UK dwelling, heating accounts for around 60% of the overall energy usage. Where the occupier is concerned about heating bills, one perceived 'solution' is to heat rooms only as they are occupied (zonal heating). What is very obviously required is cheaper, more efficient and flexible whole house heating and ventilation systems, incorporated within higher standard housing.

Heat pump technology has been widely used on the European continent for some time, however until recently, it has been widely perceived as unreliable, noisy and both expensive to purchase and operate. These problems are now largely overcome and heat recovery/heat pump units offer energy-efficient heating, constant fresh air circulation and benefits to both the occupants' health and the increased preservation of the housing fabric. However, such units only provide a high level of efficiency when installed in well-sealed and highly insulated housing. In addition, such units are ideal in a climate such as Orkney where although the winter heating season is long, the temperature rarely reaches below freezing, and there is a small variance between indoor and outdoor temperatures throughout the year (between 40°F and 80°F).

In the past, houses in such climates were often ventilated more by accident than by design — in exposed conditions the infiltration of air through numerous gaps in the building envelope could be excessive and lead to discomfort. Building standards however now require that minimum standards of passive ventilation systems (external vents) are installed. In addition, it was often necessary to install some form of mechanical extract in areas of high humidity such as kitchens and bathrooms. In such conditions these active and passive systems can (understandably) be regarded as sources of draughts and heat loss and occupiers will often attempt to block the airflow. The result of such action can eventually lead to condensation, damp and mould affecting internal surfaces and the degradation of the housing structure.

As one of the main aims of the design project was to reduce air infiltration, the houses were expected to be much tighter than conventional build. In well-sealed low-energy houses air change rates below 0.2 have been noted. Under these circumstances, mechanical ventilation is an almost inevitable choice. The benefits include controllability (0.5 to 1.0 air changes per hour being the target) and the filtering of contaminants from air entering the house.

4.6. Draught proofing

Identifiable problem areas for draughts include windows and doors, permanent vents, hatches and service entries. Besides using high quality windows and doors, it was felt that several simple steps could be taken to reduce the air infiltration at such areas. Simple low-cost measures incorporated included a recessed front door, the elimination of trickle vents in window frames, positive catches on the loft entry hatch, sealing of conduits in the loft and a water-filled trap bend added to the cistern overflow.

5. The low energy design

Several features of the original OHAL 'standard build' house design would have positive energy benefits such as the following:

Building shape (2:1)
Concrete floors
300-mm overhang at eaves
High quality windows and doors
Centrally located immersion tank
Level of on-site supervision
Plasterboard incorporating vapour control membrane

5.1. Measures adopted

The additional measures adopted by the Technical Design Committee are summarised in Table 2. Following the design process, the houses were completed and house performance and climatic monitoring continued over two heating seasons. After a period of extensive data analyses and report writing the project was completed in 1999.

5.2. Measures rejected

Features that were rejected (for reasons of cost, aesthetics, practicality or site restrictions) included instantaneous water heaters, sun-space/conservatory, internal insulating shutters, solar panels, rain screen cladding and various site protection techniques (earth berming, trees or fences). Site protection methods were excluded from the initial design in order that the effects of the design could be more easily assessed. These methods would be encouraged once the

Table 2
Low energy features incorporated and additional costs (1993 prices)

Design elements	Increased specification of low energy house (In comparison to the OHAL standard design)	Increased cost of feature over the OHAL standard build (1993 prices) (£)
Orientation	Building line of 55° selected to offer both minimised wind-chill (orientation of the short end wall with the dominant wind sector) and a degree of solar gain to the main living space (angle of 'South minus 35°' being just outside the desirable solar range, south +/−25°).	None
Thermal efficiency	Insulation: in walls (glass-fibre) increased from 100 to 150 mm. Ceilings (glass-fibre) increased from 150 to 200 mm. Additional battens used to avoid compression damage to the thicker insulation and some access flooring laid. Floor insulation (polystyrene) remained at 50 mm and party (dividing) wall remained at 50 mm glass-fibre on both sides of partition.	125
Solar gain	Orientation and use of low emissivity double-glazing compared to double-glazing only in the standard houses. This glass incorporates a thin coating on the inside, which allows solar heat to enter but reflects back into the room. Living room located on south facing side.	527
Air leakage	Houses sealed to minimise air-infiltration. Achieved by treating the dry-lining (plasterboard) as the air-barrier, where all joints were sealed (including the floor slab-wall plate interface). Service penetrations also sealed as were joints between timber framing and window and door frames.	467
Heating and ventilation	Both services were provided by an air to air Heat Pump Ventilation Unit (HPVU). Stale air is extracted via ceiling ducts in the ceiling and passed to a heat exchanger. This heats the fresh incoming air, which is injected to all rooms in house. If there is a further heating demand then an additional heating element will operate. Controlled ventilation is supplied at typically 0.5–0.75 ach.	1000
Draught-proofing	The front entrance door was recessed by 1 m. Positive pressure catches added on loft hatch. Cistern overflow draught proofed by addition of water filled trap bend. Trickle vents and extractor vents in kitchen and bathroom eliminated by virtue of the active ventilation system.	50
Minor features	Low energy light fittings added in lounge, passage and external light.	50
TOTAL		2219

Cost of standard three apt. house — £30,908.
Cost of low-energy three apt. house — £33,127.
Increased building cost (over OHAL Standard) — £2219.

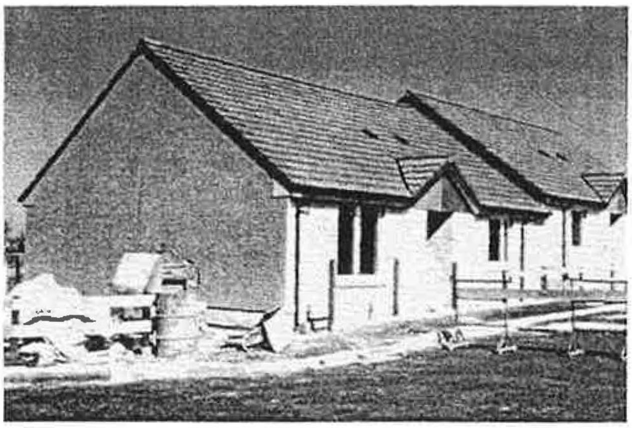

Fig. 2. Low energy houses nearing completion at Clouston's Corner, Stenness.

energy monitoring was completed. Fig. 2 shows the front elevation of the low energy houses nearing completion.

6. Main results

6.1. Building costs

The low energy house was built for an increase in costs of £2219 (around 7%) on the already high-standard OHAL standard build design. The major part of this cost was incurred by the heating/ventilation system (£1000), low emissivity windows (£527) and the external wall (£467) modifications of larger frame, increased insulation and the use of sealants at the dry lining.

6.2. Air-tightness

Air pressurisation tests carried out on completion of the houses showed that the techniques used had been extremely effective in eliminating unwanted leakage — the two low-energy houses proved to be the tightest which Building Research Establishment (BRE) had tested to date in the UK [7].

It is worth noting that the standard houses at Stenness also proved to be well above the average UK air-tightness levels, which indicates that the quality of the building contractor's work can have a significant effect during critical parts in the construction. In order to produce typical air-tightness levels in the standard houses, these apartments were progressed internally prior to the new air-tightness methods being demonstrated in the low-energy houses.

Following 2 years of occupancy, the Stenness houses were pressure tested again. The air-tightness in all four houses had decreased, however, they were still very much tighter than the typical UK dwelling. The techniques used in the low-energy houses were still working well and they were still more airtight than the standard.

Table 3
Comparison of Stenness houses' air-tightness with standards in other countries

House air-tightness results	ach at 50 Pa
Low-energy house	1.0
Standard house	2.5
Norway	4.9
Sweden	5.1
Canada	5.3
UK	13.6

These results indicate that air infiltration can be easily minimised providing the concepts are addressed at the design stage, the workforce is adequately briefed and there is a good level of site supervision.

The success of the air-tightness sealing operations is apparent when the values in Table 3 are compared with the results from 385 houses previously tested in the UK, shown in Fig. 3. The low energy houses were tighter than any house previously tested in the UK, while the standard houses were comparable to the previous best figures.

6.3. Heating and ventilation

Amongst the tenants, there was a high level of satisfaction with the quality of heat and ventilation provided by the Heat Pump Ventilation Unit (HPVU). In both houses there was an absence of condensation, which can be a particular problem in 'special needs' housing.

The trial with the heat pump/ventilation unit proved the concept of whole house heating by this method. If such systems are to be encouraged, then generating companies should consider providing incentives, either in the form of lower tariffs or an initial discount on the purchase cost.

With tight buildings, greater attention has to be paid to providing adequate controlled ventilation: the 'Build Tight — Ventilate Right' principle [8]. An experiment, conducted by the BRE, to assess the ventilation rates in both house types showed that the low energy (mechanically ventilated houses) have a greater air change per hour (ach), typically 0.6 to 0.77, than the naturally ventilated houses,

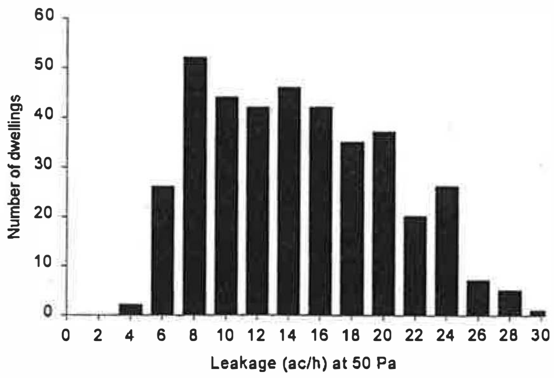

Fig. 3. Air-tightness tests carried out by BRE on 385 UK dwellings.

Table 4
Advantages of the low energy design over OHA standard

Performance indicator	Standard house	Low-energy house	Change
Building costs/apartment	£30,908	£33,127	+7.2%
Energy usage/year	9420 kWh	7389 kWh	−21.6%
Fuel bills/year	£470	£415	−11.7%
CO_2 emissions	2.8 tonnes/year	2.2 tonnes/year	−21.4%
Average 'U' value	0.4 W/m^2 K	0.29 W/m^2 K	−27.5%
National home energy rating (NHER)	6.8	7.8	+1 point

typically 0.28 to 0.42. BRE guidelines indicate that a whole building ventilation air change rate of about 0.5 ach is generally adequate to keep the relative humidity below levels at which condensation may occur [8]. Above 1.0 ach, however, further provision of ventilation is unlikely to help a dwelling with condensation problems. A further benefit of reducing humidity levels is the virtual elimination of the house dust mite, which is one of the major problems for asthma sufferers.

6.4. Energy consumption, fuel-bills and emissions

Various performance indicators are summarised in Table 4. While the fuel bill savings are not as high as expected at 11.7%, (due principally to the tariff rate applied to the new HPVU technology) they are still appreciable. It is however the energy consumption figures that are more significant. The low-energy house has a 22% lower overall energy requirement compared to the standard (7389 kWh compared with 9420 kWh annually).

7. Principle findings

All of the Stenness features were successfully trialed and are recommended as an integrated approach to low-cost, energy-efficient design in areas of high wind and rain exposure.

The low energy design resulted in increased building costs (per apartment) of £2220, amounting to a 7% rise in the cost of an OHAL standard design (1993 prices). The actual energy use confirmed earlier predictions, suggesting an energy savings of approximately 22% overall. The financial savings to the householder were less impressive (around £55 per annum; a 12% reduction in electricity bills), due principally to the 'experimental' tariff applied to the heat pump/heat recovery unit.

The sealing operations carried out to minimise air infiltration were extremely successful, with the low-energy houses being the tightest tested by BRE at the time in the UK (1994) and comparable with standards in Scandinavia and North America.

The project represented one of the first opportunities in the UK to install a heat recovery/heat pump unit to provide whole-house heating in a domestic situation. The trials were not without problems; however, the capability of the technology was largely proven — further research is required on the overall heat recovery market (trials are underway on ground source heat pumps) and on ensuring increased reliability. The electrical tariff applied to such systems does not (at present) provide sufficient financial motivation in the form of reduced fuel bills to reflect their reduced energy usage. This matter merits further discussion with electricity supply companies.

Wind chill did affect the rate of heat flow through the fabric of the dwellings and varied with orientation; however, the effects were less pronounced than expected. In terms of overall heat loss, wind chill within the well-insulated and airtight houses was a relatively small factor, affirming the need for high insulation and building standards within social or special needs housing in such climates.

The analysis of data does, however, suggest that the effect of tenant behaviour on the thermal performance is more significant than previously thought, and where neglected is undoubtedly greater than the effect of wind chill. There are very obvious implications for guidance to tenants (including low energy type dwellings) on obtaining the best performance from a house — this would include the elements of heating, ventilation and the avoidance of damp conditions and/or condensation.

Simple 'payback periods,' calculated as an indicator of investment return, indicated that it was more cost effective (almost twice) to improve the existing OHA Standard design to the Low Energy specification than it is to make the initial improvement from Minimum Building Standards to the existing OHA standard design.

These facts suggest that OHA: were correct in their original belief that despite an already high standard of housing, a modest increase in specification and costs could produce significant reductions in tenants/sharing owner's electricity bills. The added direct benefits for the association's housing stock include an increased protection of the housing fabric (and therefore reduced future maintenance costs) through the apparent elimination of condensation and related problems. Other 'hidden' benefits are increased comfort levels, a healthier living environment (e.g. reduction in asthma symptoms for sufferers and reduced risk of infants developing the condition), reduced CO_2 emissions and benefits to the local electricity supply.

By applying simple improvements in house construction techniques, increasing insulation standards, installing efficient heating systems and other low cost, low technology features, significant energy savings were made. Houses built today will be around for a long time — an increase in building standards particularly in areas where heating in the home is necessary on a year round basis, and where heat loss is significantly affected by the cycles of wind and rain — is a sound investment in the future housing stock.

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