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Energy and Buildings 32 (2000) 267–280

ENERGY AND BUILDINGS

www.elsevier.com/locate/enbuild

Energy efficient modernisation of housing: a UK case study

Malcolm Bell *, Robert Lowe

Faculty of Health and Environment, Leeds Metropolitan University, Calverley Street, Leeds, LS1 3HE, UK

Received 24 November 1999; accepted 21 March 2000

Abstract

This paper sets out the results of the York Energy Demonstration Project and discusses its implications for the modernisation of low rise housing in the UK. The project consisted of three schemes, which were carried out in the early to mid 1990s and monitored over a 2-year period. Results indicate that modernisation schemes have a very important part to play in reducing CO_2 emissions and that improvements in the region of 50% can be achieved at modest cost using well proven (early 1980s) technology. The possibility of additional improvements are also identified which could see emissions fall by a further 30–40%. In addition, the project identifies difficulties posed by, often small, variations in dwelling construction, which can have a disproportionate impact on costs, and by the design and use of mixed heating systems which can reduce overall heating efficiencies. The paper also discusses the impact of the demonstration project on the dissemination of good energy efficient practice within the Local Authority and highlights the lessons learned for implementation in future modernisation schemes. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Existing housing; Energy efficiency; Retrofit; York

1. Introduction

In the last 10–15 years, the majority of governments around the world have come to accept the importance of reducing greenhouse gases and since the Kyoto protocol, signed in December 1997, have intensified their search for ways of making large reductions in emissions. At the heart of many policies is the quest for more efficient use of energy in all economic sectors. In most countries, housing is a major consumer of energy and is responsible for a large fraction of national carbon dioxide (CO_2) emissions. Figures for 1996 show that, in the UK, housing accounted for 28% of national CO_2 emissions and was the largest single contributor, followed by industry at 27% and transport at 25% [1]. Although the majority of research into energy efficiency improvements in housing has been conducted in the context of new dwellings, it is clear that improvements in the design of the new stock will only have marginal effect in the short to medium term. In the UK, demolition rates are low with new construction adding to, rather than replacing, the dwelling stock. Figures for Great Britain indicate a net gain of almost 200,000 dwellings per annum and a simple linear projection of this trend suggests that by the year 2050, the dwelling stock may have risen by over 9.5 million dwellings of which the post 2000 stock would constitute only 30% [2]. Although it is likely that replacement rates may increase, the improvement of the energy efficiency of existing housing provides an important opportunity to achieve significant reductions in CO_2 emissions over a much shorter time scale than can be achieved by the construction of new dwellings. In addition, if such improvements are carried out at the same time as more general modernisation and repair works, there are important cost advantages to be gained.

In the early to mid 1990s, the UK government funded a series of demonstration projects in local authority housing designed to implement a wide range of energy saving measures which could be incorporated into modernisation programmes. This programme (the Greenhouse Programme) ran from 1991 to 1994 and funded some 183 schemes (over 50,000 dwellings) of which the York project was one [3,4].

In common with many energy demonstration projects over the last 10 years, the York Project had two main aims. The first was to confirm that the application of readily available technology could deliver significant energy benefits within the context of a routine local authority

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* Corresponding author. Tel.: +44-1-113-283-1704; fax: +44-113-283-3190.

E-mail address: m.bell@lmu.ac.uk (M. Bell).

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PII: S0378-7788(00)00053-0

housing modernisation programme. The second was to extract lessons for the operation of future energy conscious modernisation schemes. This paper sets out to report the results of the project both in terms of the measured energy and CO_2 reductions and the lessons which were learned, together with their impact on future modernisation policy.

2. Project description

Housing in the City of York is predominantly low-rise (two and three storey) single family houses of terraced, semi-detached, or detached types and is typical of a large proportion of housing in the UK. The York area has about 75,000 dwellings, the vast majority of which (73%) are owner occupied. Some 9500 are owned by the Local Authority (15%) and the remainder rented either from private landlords or from a housing association. The demonstration project involved around 230 local authority dwellings, which were in need of modernisation. The construction of the houses was typical of about 75% of the local authority stock and about 60% of the stock in York as a whole. Fig. 1 shows a house which is representative of those used in the project. The general form of construction is summarised in Table 1.

The project was made up of three related schemes with different standards of energy efficiency and monitoring arrangements. All houses were taken from the Authority's modernisation programme, which included an internal refit of kitchens and bathrooms together with internal repairs as necessary. All external fabric was in good condition and no external replacement works were necessary. The energy efficiency works and monitoring arrangements for each scheme are summarised in Table 2.

The 4-house scheme was designed to modernise a small number of properties to as high a standard as possible within a number of practical and financial constraints and to contrast the use of four different heating arrangements; two based on gas and two on electricity. Although it was recognised at the time that the inclusion of electricity would result in higher CO_2 emissions in the electric houses, the Authority were keen to explore the steps which could be taken to minimise emissions where tenants wished to have electric systems installed. The small number of houses enabled a more detailed monitoring regime to be adopted than was possible in the other schemes. The fabric insulation standard achieved was some 25% higher than the Building Regulations for England and Wales 1990 (the standard in force at the time) and overall energy performance was similar to the regulations currently in force (Building Regulations for England and Wales 1995 [5]).

Fig. 1. Typical house type.

The 30-house scheme sought to improve the energy efficiency of 30 houses as part of a larger modernisation scheme in an attempt to demonstrate the impact of energy efficiency works when compared with "normal" modernisation work. In order to make the comparison, monitoring was carried out in both the energy efficient (experimental) group and a control group of houses from the rest of the scheme. The principal difference in overall energy standard between this scheme and the 4-house scheme was that windows were not replaced and therefore glazing U-values were not improved. This resulted in an envelope standard some 25–30 % below that achieved in the 4-house scheme. Condensing gas boilers were installed in all dwellings together with a gas fire in the main living room. This arrangement resulted in an overall heating efficiency, which was potentially lower (depending on gas fire usage) than that in the condensing boiler house in the 4-house scheme (see discussion in Section 4.3 below).

The 200-house scheme was carried out some 12 months after the other two schemes and sought to apply the 4-house standard to a full modernisation scheme. This scheme was monitored using a sample of 10 houses over a 12-month period.

Monitoring data for the 4-house scheme was recorded (with the exception of electricity consumption in the two gas houses which was read manually) using data loggers with data downloaded at monthly intervals. Sub-meters enabled energy inputs to be disaggregated and in Gas House A, the heat output form the condensing boiler was metered to enable its efficiency to be established. Internal temperatures in all schemes were logged at three points (living room, kitchen, and main bedroom) using 2 kΩ thermistors in conventional room thermostat housings. Monitoring in the 30- and 200-house schemes was done using four channel temperature loggers and energy utility meters (read manually at approximately monthly intervals). Energy consumption was also cross-referenced with energy utility billing data. Further details are contained in Ref. [9].

Part of the function of a demonstration project is to look at the processes involved in implementation as well as the technology. A decision was taken very early in the project to seek to employ as much of the Authority's existing modernisation contracting procedures as possible. This was

Table 1
General construction of dwellings

Characteristic	Description
House type	Three and two bedroom, semidetached and terraced houses the majority constructed in the 1930s or 1950s.
Construction	Load-bearing cavity brickwork with a pitched tile roof. Ground floor constructions — a mixture of solid and suspended timber. Floor area range; 75–95 m^2.
Condition	Sound structural condition and good general repair; internal fixtures, fittings and heating systems in need of replacement; electric wiring in good condition; roof renewals previously carried out in the 4-house and 200-house schemes (see Table 2 for scheme descriptions).
Existing insulation	Existing thickness of loft insulation varied from 25 to 100 mm fitted in the early 1970s. No other added insulation.
Heating and hot water	Most houses were heated by a gas fire in the main living room and hot water provided by an immersion heater fitted to a lagged cylinder. A small number of houses had electric storage heaters (installed in the 1970s) and an electric fire in the main living room. Hot water was provided from an insulated storage cylinder and heated by an immersion heater designed to operate on an off-peak electricity tariff.

done partly for pragmatic reasons and partly to assess their effectiveness in delivering energy efficient improvements. In York, these procedures involved small contractors working closely with the authority and the tenant in order to provide a considerable element of choice over such things as bathroom and kitchen fittings and a secondary room heater (usually a gas fire in the main living room). The houses chosen for the 4-house scheme were vacant at the time of modernisation and all fixtures, fittings and heating systems were specified by the project team with no tenant involvement. In the 30-house scheme, all tenants were required to accept a condensing boiler but had a free choice as to a secondary gas fire. The 200-house scheme provided a wider choice of heating system, and although a majority of tenants chose to have a condensing boiler, this was not always the case and particularly where tenants requested a gas fire with an integral heating boiler (for which condensing versions where not available), a non condensing boiler with optimiser was fitted. As in the 30-house scheme, a free choice of secondary heating was available to all tenants. The results from each scheme are presented below.

3. The 4-house scheme

The results from the short term monitoring on this scheme demonstrated considerable improvement in air-

Table 2
Energy efficiency works and monitoring arrangements

Scheme	Energy efficiency works	Monitoring
4-House scheme	Fabric improvements. 200 mm loft insulation, cavity wall insulation[a], 20 mm low emissivity double glazing — new timber window and door frames with draught proofing. Heating systems. 4 systems: Gas systems — condensing boiler central system and gas unit heater system. Electric systems — off-peak electric boiler system and air–air heat pump with resistance heating back-up. Ventilation systems. Gas schemes; intermittent mechanical extract (fan in kitchen and bathroom) with trickle vents in new window frames. Electric schemes. Balanced MVHR which, in Electric House B, was integrated with the heat pump and resistance duct heaters to provide whole housing heating.	Short term. Co-heating[b] and pressurisation tests before and after improvements. Long term. Internal temperatures and energy consumption — May 1992–May 1993. Energy flows disaggregated. Measured values compared with estimates of "before" consumption.[c]
30-House scheme	200 mm loft insulation, blown fibre cavity wall insulation[d], draught-proofing to existing windows and doors. Central heating system with gas condensing boiler and a gas fire (tenant choice) as a secondary heat source. Ventilation, as 4-House scheme — gas houses.	Internal temperatures and gross energy consumption for the period Nov. 1992–March 1994.
200-House scheme	Fabric improvements as the 4-house scheme; most houses were fitted with gas boilers (a mixture of condensing and non-condensing boilers) and a gas fire (tenant choice). Some houses had one non-cavity wall which was not insulated. Ventilation, as 4-House scheme — gas houses.	Internal temperatures and gross energy consumption were monitored in a sample of 10 houses — April 1993–March 1995.

[a] Blown fibre in gas houses, polyurethane foam in electric houses.

[b] Co-heating tests give an estimate of the heat loss coefficient of a dwelling — see Refs. [6,7].

[c] Energy modeling calculations throughout the project were done using a computer programme (NHER evaluator) which incorporates the UK Building Research Establishment's Domestic Energy Model [8].

[d] Dwellings in this scheme had a complex mix of cavity, solid and timber frame walls, each requiring different treatment.

Table 3
Air-tightness before and after improvements

Dwelling tested	Air leakage rates from blower door tests (ac/h at 50 Pa)		Percentage reduction (%)
	Before	After	
Gas House B	19.3 ± 1	7.5 ± 0.4	61
Electric House A	16.9 ± 1	4.9 ± 0.3	71
Electric House B	–	6.8 ± 0.3	–

Table 4
Heat-loss coefficients before and after improvements

Dwelling tested	Heat loss coefficients from co-heating tests (W/K)		Percentage reduction (%)
	Before	After	
Gas House B			
Measured	218 ± 3	133 ± 1	39
Calculated	266	146	45
Electric House A			
Measured	229 ± 4	121 ± 4	47
Calculated	300	125	58

tightness and overall thermal performance of the house envelope. Tables 3 and 4 set out the before and after measurements of air-tightness and overall heat loss.[1]

In the case of air-tightness, there was a 2.5–3-fold improvement which was achieved by improved performance of windows and doors, sealing of suspended timber ground floors where necessary and the repair of defects in the plaster work around window frames. Fig. 2 compares the air-tightness results with a data base of 385 UK dwellings. The leakage rates before modernisation were higher than the UK average of about 12–14 ac/h at 50 Pa, but after the works, the houses were among the most airtight in the UK. Observations at the time of the tests (such as gaps round the edge of the floor sealing) suggested that air-tightness could have been improved even further with modest additional effort, offering the prospect of air-tightness of 3 ac/h at 50 Pa or better, a level which approaches current Swedish standards for new housing (about 2.4 ac/h in these houses) [10].

We have argued elsewhere [11] that savings in ventilation-related heating requirements of around 30% could be achieved if an airtightness target of 10 ac/h at 50 Pa could be enforced in new UK dwellings.[2] The evidence from the study reported here clearly indicates that significant sectors of the existing stock have the potential for rates well below this level.[3] It has also been estimated [13] that at leakage rates of 2–3 ac/h at 50 Pa, coupled with continuous mechanical extract ventilation, a further 30–40% reduction could be achieved compared with dwellings with a leakage of 10 ac/h at 50 Pa.

Co-heating tests (see notes to Table 2) were carried out on two of the houses (one gas and one electric). The overall heat loss coefficients clearly demonstrate the impact of the improvements made to the house envelope with measured reductions of 47% (electric house) and 39% (gas house) being observed. These reductions were broadly in line with the difference, which was predicted before works were carried out (a calculated improvement of 58% in the electric house and 45% in the gas house). However, the agreement between measured and calculated values was significantly better in the after case (differences of 9% in Gas House B and 3% in Electric House A) than in the before case (differences of 18% and 24%).

Table 5[4] sets out a breakdown of the heat loss coefficient for the two co-heating test dwellings. These data illustrate the importance of both fabric and airtightness measures in efficiency improvements with each being reduced by about the same proportion (37% fabric, 32% ventilation).

Following occupation, the houses were monitored in use for a further 12 months. Energy consumption and heating season internal temperatures (October–April) are set out in Table 6. Since the dwellings were vacant immediately before and during the works, it was not possible to obtain measured data in the 12 months prior to modernisation and therefore, the measured consumption after modernisation was compared with an estimate of consumption prior to works. The houses performed broadly as predicted with total delivered energy consumption falling by 49% in

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[1] The error ranges shown in Tables 3 and 4 show the error relating to the regression line through the raw data (goodness of fit). They do not include measurement error in the raw data itself. The errors quoted therefore underestimate the true value.

[2] At this level of air-tightness, a continuous mechanical ventilation system would not be necessary.

[3] This is, of course, dependent on initial construction and renovation techniques. The majority of the existing UK housing stock has wet plastered walls (as in the case of the York houses) which are intrinsically airtight [12], however the practice of replacing defective plaster in renovation works with a plasterboard-on-dabs dry-lining system is likely to reduce airtightness and make subsequent sealing works very difficult indeed [13].

[4] Figures in Table 5 are the mean of the two houses (Gas House B and Electric House A). The fabric coefficient was determined by subtracting a ventilation term (estimated from the pressurisation measurements in Table 3) from the results of the co-heating tests. The in-use ventilation heat loss coefficient was calculated based on the pressurisation tests plus an allowance for user behaviour (window opening and the operation of fans). This additional term was calculated in accordance with the UK Government's Standard Assessment Procedure [15]. Viz.: $V_{\mathrm{HL}} = 0.5 + [(I_{\mathrm{R}} \times S_{\mathrm{F}})^2 \times 0.5]$, where I_{R} = the infiltration derived from the pressurisation test ($L_{50}/20$) and an allowance for extract fans (10 m^3/h per fan — $2 \times 10/\mathrm{vol}$), and S_{F} = a shelter factor (0.85 for these houses). The envelope elemental breakdown was allocated in proportion to calculated fabric U-values and areas (U-values were not measured directly).

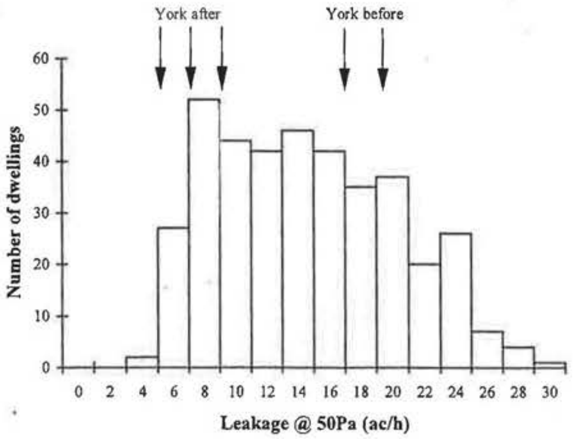

Fig. 2. UK Pressurisation test data (after Ref. [14]).

Table 5
Heat loss coefficient (W/K) broken down by element

Element	Before		After	
	Mean	%	Mean	%
Floor	25	11	25	17
Wall	83	37	37	25
Windows and doors	47	21	40	28
Roof	20	9	9	6
Fabric heat loss coefficient	175	78	111	77
Ventilation heat loss coefficient	50	22	34	23
Total heat loss coefficient	225	100	145	100

Gas House A, 54% in Gas House B, and 51% in Electric House A. The exception was Electric House B where, although delivered energy was reduced in line with the other houses (50%), the expected reductions associated with the application of the heat pump did not to materialise. The measured consumption of almost 12,300 kWh/year in Electric House B compares with a predicted value of just under 9900 kWh/year (some 24% greater than predicted). This was principally because significant problems with the heat pump installation were experienced both in design and use. As a result, the majority of heating was provided by backup electric resistance heaters.

Reliable internal temperature data was available for the two gas houses and Electric House A. Average temperatures in the gas houses (17.3°C in A and 16.9°C in B) were broadly in line with temperatures observed on other schemes in the project (17.6°C, 30-house scheme; 18.8°C, 200-house scheme) with other UK energy modernisation schemes (see for example Refs. [16,17]) and with a UK average (1990–1996) of 17.2°C for centrally heated dwellings [18].[5] The average temperature in Electric House A (19.6°C) was high by UK standards and compares with 18.4°C in the Pennyland new build scheme at approximately the same level of insulation [21].

As would be expected, the reductions in CO_2 were of the same order of magnitude as energy reductions. However, reductions in the gas houses were influenced by an element of fuel switching from electric to gas water heating. Overall, CO_2 from the electric houses remains much larger than the gas houses, reflecting the current large discrepancy between the carbon intensity of the two fuels (see coefficients in the notes to Table 6).

Of particular interest in the 4-house scheme was the performance of the different heating systems and the way they were understood and operated by the occupants and local authority staff. Prior to the demonstration project, the vast majority of tenants chose hydronic gas central heating systems. A few electric storage systems were installed where a tenant expressed a particular preference for electricity. Not surprisingly, the systems which presented the fewest problems for installers and tenants were the conventional gas-fired hydronic and storage electric heating systems. Generally, these systems performed as expected and tenants were clear as to their mode of operation. In the case of Gas House A, the mean annual boiler efficiency was 89% with very little variation regardless of mean daily load. From the tenant's point of view, the system was little different from any other gas central heating system and operation was easy to understand. In Gas House B, the unit heater system was capable of central timing control but this was never used by the tenant, whose previous experience (a single solid fuel fire) and general uncertainty about heating costs, led her to switch heaters on and off individually. Although the house was designed to be heated with three heaters, the tenant, as a matter of convenience, chose to use only two (one on the ground floor and one on the first floor landing). Some discomfort problems were experienced by the tenant, which appeared to have been caused by an uneven heat distribution resulting from the placement of individual heaters. The main difficulty was the inability of the system to provide enough heat to the entrance hall and stairway, a problem which could be solved by the siting of an additional heater in the entrance hall, and by improving the airtightness and U-value of the external door (external doors were a significant source of air leakage, and had U-values between 3 and 4 W/m^2 K). Despite these design problems, the scheme demonstrated a potential, at least in small dwelling modernisation, for unit heater schemes at a cost considerably less than that of a full hydronic central heating system.

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[5] We are grateful to one of the referees for reminding us that the UK average in the Domestic Energy Fact File [18] is not measured directly but inferred from energy calculations on the stock. The only source of measured data on the stock as a whole comes from the English House Condition Survey [19]. This survey recorded average spot temperatures of 19.5°C and 18.3°C in living room and hall, respectively. Although there is some evidence that the hall temperature may be a good guide to whole house temperature at the time of measurement [20], these data are spot measurements (taken in daytime, in mild weather) and do not provide a reliable guide to whole house average heating season temperatures.

Table 6
Long term monitoring results — 4-house scheme

Scheme	Heating system	Before			After			
		Gas (kWh)	Electric[a] (kWh)	CO$_2^b$ (te)	Gas (kWh)	Electric (kWh)	CO$_2^b$ (te)	Int. temp. (°C)
Gas House A	Condensing boiler	23,900	4300	6.73	13,160	1209	3.12	17.3
Gas House B	Gas unit heaters				11,535	1524	2.97	16.9
Electric House A	Off-peak electricity	–	24,800	12.64	–	12,225	6.23	19.6
Electric House B	Air-to-air heat pump	–			–	12,296	6.27	–

[a] Electricity consumption before improvements included on-peak water heating which after improvement was heated by the gas in the gas houses and off-peak electricity in the electric houses.

[b] The carbon coefficients used in this table are taken from the UK Standard Assessment Procedure for the energy assessment of dwellings [15]: Gas 0.19 kg (CO_2)/kWh, Electricity (UK) 0.51 kg(CO_2)/kWh.

The systems in the electric houses presented much greater problems. In common with the gas systems, the electric storage boiler system in Electric House A was easy to understand and presented few problems for the tenant. However, the use of the mechanical ventilation with heat recovery (MVHR) system was less than optimal. This house was the most airtight of the four houses and was sufficiently air-tight to require continuous mechanical ventilation. Although the monitoring data are not conclusive, it would appear that use of the system was very intermittent. This suggests that the introduction of unfamiliar systems requires considerable attention to tenant advice and the training of local authority managers. Evidence from elsewhere [13] indicates, however, that the effective use of MVHR systems by occupants is achievable through appropriate design and occupant advice. The study by Lowe and Johnston [13] also demonstrated the potential CO_2 benefits of efficient MVHR systems over continuous mechanical extract at all levels of air-leakage but particularly at levels below 3 ac/h at 50 Pa.

Monitoring of the air-to-air heat pump system in Electric House B indicated that it contributed only a very small fraction of the space heating requirement. Problems included the frequent cutting out of the heat pump condenser due to excessive condensing temperatures (suggesting inadequate air flow), an inability of the system to maintain adequate temperatures, particularly in the first floor area and difficulties experienced by the occupant in understanding the rather complex control system. It is difficult to be certain about the precise nature of all of the technical problems, but it is clear that the system was not well suited to the needs of the tenants, and that it would have required a further 2–3-fold reduction in design heat load to operate satisfactorily. This is not to say that the various problems cannot be overcome but more research and trial activity would be required in order to build up the necessary experience in the conditions encountered in modernisation work in the UK.

4. The 30-house scheme

This scheme presented an opportunity to monitor energy efficiency improvements against a control group of dwellings in the same modernisation scheme but with no additional energy efficiency works. Good monitoring data was available for 21 experimental houses and 11 control houses and the monitoring period (from the autumn of 1992 to the summer of 1994) included data from two heating seasons. Table 7 sets out the energy characteristics of the two groups, under standard occupancy conditions, both before modernisation and on the assumption that they were improved to the authority's normal modernisation standard. The two groups were remarkably well matched in terms of their energy characteristics, with the expected total energy consumption varying by only 2% before modernisation and less than 1% if both groups were modernised to the normal standard. This analysis would suggest that physical differences in the dwellings are not likely to have had a significant influence on the monitoring results. It was not possible to control directly for occupancy or user behaviour, however a simple occupancy comparison indicates a broadly similar profile in both groups with an average of 3.1 persons per household in the

Table 7
Energy characteristics of 30-house study groups

Group	Before improvement			Improvement to normal modernisation standard		
	Gas (kWh)	Electric (kWh)	Total (kWh)	Gas (kWh)	Electric (kWh)	Total (kWh)
Experimental	26,946	7944	34,890	27,864	3246	31,110
Control	26,290	7818	34,109	27,851	3081	30,932
Difference	656	126	781	13	165	178

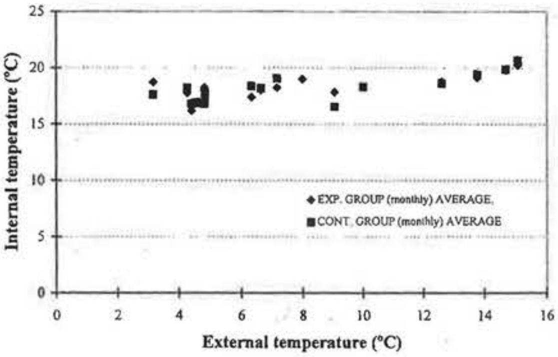

Fig. 3. Internal temperatures.

experimental group (1.86 adults and 1.24 children) and 3.36 in the control group (2.0 adults and 1.36 children). Despite the similarity, occupancy and user behaviour are likely to be an important source of extraneous variability.

4.1. Internal temperatures and energy consumption

Continuous monitoring of internal temperatures and energy consumption was carried out in both groups of houses (see Table 2) and the results compared. Fig. 3 shows average internal temperatures against external temperatures for both groups over the whole of the monitoring period. Despite the difference in levels of insulation, both groups maintained similar internal temperatures. As external temperatures rise into the summer period, the amount of scatter is reduced as internal temperatures become more a function of external temperature and incidental gains rather than levels of heating. Average heating season internal temperatures of 17.9°C in the experimental group and 17.4°C in the control group were recorded. In energy terms, the half degree difference would amount to something in the region of 1360 kWh over a full heating season. The small temperature difference suggests that the majority of the benefits of the energy efficiency measures were taken in real energy savings rather than in higher temperatures.

The results of the energy monitoring together with energy modeling predictions are set out in Table 8. Since the houses were heated by gas, the impact of the insulation and efficiency measures would be expected to result in a significant difference in the gas consumption of the two groups. As can be seen from Table 8, such a difference was observed which was statistically significant.[6] The probability of this difference occurring by chance is less than 3% ($P = 0.022$). The difference in electricity consumption is not significant ($P = 0.201$). Although a significant difference in gas consumption exists, it is considerably smaller than that predicted by energy modeling. This suggests that there are important variations in use which obscure the effects of the energy efficiency measures. Some of these issues are discussed in Section 4.3 below.

Table 8
Energy consumption — 30-house scheme

	Gas (kWh)	Electric (kWh)	Total (kWh)
Measured annual consumption			
Experimental	19,313 (SD = 4367)	3138 (SD = 1375)	22,451
Control	23,092 (SD = 5565)	3529 (SD = 893)	26,621
Difference	3779	391	4170
Temperature Adjusted Difference	5145	391	5536
Predicted annual consumption			
Experimental	16,671	3104	19,775
Control	27,851	3081	30,932
Difference	11,180	−24	11,157

4.2. Cost and pay-back issues

The marginal cost of the energy efficiency works averaged some £1450, at the time the works were carried out in 1992, giving a simple pay-back time of around 17 years based on measured consumption or about 8 years if predicted consumption is used. This contrasts with marginal costs for Gas House A (condensing boiler system) in the 4-house scheme of about £1000 and energy cost savings of £174 over those measured in the control group with a simple pay-back period of between 5 and 6 years. This wide variation in pay-back was largely a function of constructional differences in the house types. Fig. 4 illustrates the most expensive house type (house type C) which had three types of wall construction, cavity masonry for main walls, a timber frame mansard wall/roof, and solid masonry below bay windows and to separating walls be-

Fig. 4. House type C.

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[6] A one tailed t-test was used to test the significance of difference in mean energy consumption between the two groups.

tween the main house and attached (unheated) outhouses. Although the solid and timber walls covered only 13% of the total wall area the costs of insulation (mainly dry-lining work) constituted just over 85% of the costs of wall insulation (£920 out of a total of £1070). Some of this extra cost could be reduced in future schemes with increased volumes and familiarisation with the techniques on the part of contractors but costs are unlikely to fall to anywhere near the £150 for blown fibre cavity fill. This experience highlights the potential benefits of identifying potential upgrade paths at the design stage, particularly in the light of an increasing need to continually reduce the environmental impact of buildings in general.

The likely cost effectiveness of each measure in this house type was established by calculation and the results set out in Fig. 5.[7] The incremental impact of each insulation measure was modeled by removing it from the total package and the resulting increase in energy consumption related to the capital cost of the measure. In the case of the condensing boiler, the measure was added before any insulation. Using this approach, the greatest impact of each measure was determined. It is clear from the analysis that the various dry-lining works were much less cost-effective than cavity wall insulation, loft insulation, and improved boiler efficiency. It is estimated that the omission of dry-lining alone in this house type would reduce the pay-back times by about half, from 17 to 8 years based on measured consumption or from 8 to 4 years if calculated consumption data is used. Although the cost-effectiveness of certain insulation works is poor, their inclusion on comfort or construction grounds (reducing the risk of condensation) may be justified.

The wide variation in energy efficient modernisation costs illustrates one of the particular difficulties which is faced by housing modernisation schemes. The variation stems not only from differences in house construction, as in the case discussed above, but also from some of the design choices made. In particular, the choice of a gas unit heater scheme in one of the 4-house gas schemes resulted in an overall heating system cost of about £780 less than the condensing boiler scheme and some £480 less than a typical heating system in a normal modernisation scheme. If this cost saving were taken into account, the net capital cost of the unit heater scheme would be about £280 with a pay-back of less than 2 years.

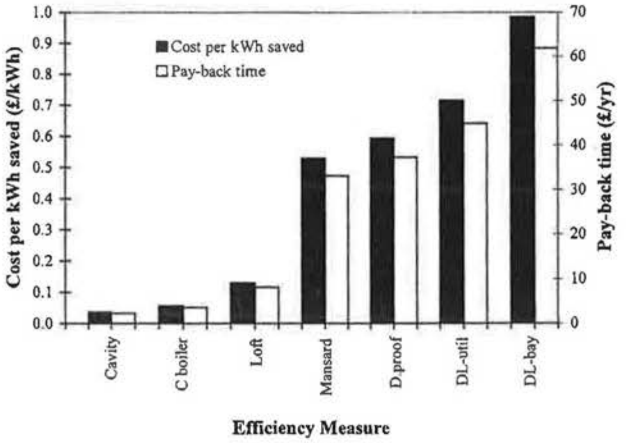

Fig. 5. Cost effectiveness of individual measures in house type C.

4.3. User issues

Large variations in consumption between houses of the same level of energy efficiency are commonly observed in housing energy field trials (see Ref. [22] Chap. 7). This is mainly due to variations in the way houses are used and is likely to go some way to explain the difference between predicted and measured energy consumption observed in this project. A detailed investigation of use was not part of the project, however, in order to gain an insight into the likely impact of use, an open-ended interview was carried out with the occupants of one of the experimental houses. The house exhibited an energy consumption some 40% above the predictions of the modeling program despite internal temperatures similar to those which were predicted by the model. At least part of the discrepancy would appear to relate to the use of the gas fire. As already indicated, modernisation procedures in York provide tenants with a choice of gas fire in addition to a full central heating system (this choice was maintained in the energy project for all but the 4-house scheme). In the case investigated, the fire chosen by the tenant was an enclosed gas flame fire with an efficiency which varied between 59% at high output and 47% at minimum output. The interview indicated that the gas fire was operating on its low setting from about 2:00 in the afternoon to 11:00 in the evening on most days in the heating season and was also on for about 1 h in the morning. The gas fire was used even during the timed heating periods. Since the lounge radiator was fitted with a thermostatic radiator valve, the heat from the gas fire would turn the radiator off for long periods, especially during mild weather. This means that most of

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[7] The capital cost data used in Fig. 5 (taken from contractors invoices) is as follows: cavity wall insulation — £150, condensing boiler (marginal cost) — £300, loft insulation — £210, timber mansard roof/wall insulation — £309, draught sealing to windows/doors — £182, dry-lining to utility room — £339, and dry-lining below the bay window — £274. The energy cost used to determine pay-back time was based on the gas tariff (excluding standing charges) during the monitoring period which was 1.595 pence per kWh (including value-added tax at 8%). A detailed breakdown of cost and energy data for this house is given in Ref. [9]. Since the completion of the schemes, UK energy prices have fallen (in absolute as well as real terms) as have some of the capital costs. For example, the current equivalent gas tariff is in the region of 1.46 pence per kWh (including value-added tax at 5%) and by 1998, cavity wall insulation costs for larger contracts in York had fallen to £100 for similar dwellings. Although these price movements change the detail, the overall picture remains unchanged (cost issues are discussed further in Section 6).

the lounge heat would be provided by the fire running at about 47% efficiency, compared with the condensing boiler at an efficiency between 85% and 90%. A crude assessment of this effect would suggest that the operation of the fire could account for just under half the difference between measured and predicted levels of consumption. A broader analysis of gas fire choices in the experimental and control houses indicates choices of fire, which are similar to that in the above example.

Given the larger efficiency differential between primary and secondary systems in the experimental group, gas fire usage would have a much greater impact in this group than the control group. If, for example, a gas fire was providing 20% of the heating, the increase in consumption would be 14% in the experimental group but only 4% in the control group.

The issue of gas fire choice and use has been discussed in some detail in order to illustrate the potential impact of use on consumption and also to highlight the need for the provision of guidance to tenants and social landlords on both the choice of fire (if any) and its use, particularly in houses fitted with condensing boilers. This need for advice is further reinforced by the findings of a satisfaction survey in both groups, which showed that a very high proportion of tenants (80%) used some combination of gas fire and central heating. One particular fire choice (a decorative open gas flame type) presents a particular problem, not only because it is only 42% efficient at all settings but also because the open chimney increases ventilation losses even when the fire is not in use.[8] In contrast, the gas houses from the 4-house scheme, on the advice of the monitoring team, did not include focal point fires and a much closer match between predicted and measured energy consumption was observed. Other aspects of use in the case investigated related to the opening of windows in bed rooms, hot water consumption, and thermostat settings, most of which would tend to increase consumption in this particular case.

The variation could be further explained by the difficulties of estimating heat losses (both fabric and ventilation). Since (unlike the 4-house scheme) the properties were not pressure tested, it is not possible to assess the likely variation in ventilation heat losses between the two groups. In the case of fabric heat loss, difficulties in estimating the impacts of thermal bridging in existing properties may have contributed to the discrepancy between calculated and observed performance. Evidence from the 4-house scheme, where it was possible to extract a reasonable estimate of the fabric heat loss coefficient (see Table 5) from co-heating and pressurisation tests on two of the houses, gives some support to this possibility. A comparison of this estimate with that from the modeling software indicates that in the before case, the calculations over-estimated fabric heat loss by 27% but after improvements, the corresponding figure was a 9% under-estimate.

The *U*-value calculator in the Evaluator program uses the proportional areas method [23] and ignores thermal bridging around windows and at other junctions. Given the difference in insulation levels (particularly in walls) between the two groups, it is possible that the thermal bridges would have a more marked effect in the experimental group than the control group (as is indicated by the data from the 4-house scheme). We have argued elsewhere, in the context of building regulation [24], that *U*-value calculation methods used in the UK need to take much greater account of thermal bridging and that suitable methods are needed for the design of new dwellings. However, although it would be possible to apply methods designed for new construction to existing dwellings, there are likely to be significant practical problems in establishing construction details with sufficient precision. Internal temperature assumptions are another possible source of discrepancy. The worse the dwelling insulation, the larger the spatial variation in internal temperature. Temperatures based on the average of three point values may therefore not have been a good guide to actual mean whole house temperature in any of the 30-house group, but particularly in the houses before improvement.

5. The 200-house scheme

This scheme sought to achieve a standard of energy efficiency similar to that of the 4-house scheme. However budgetary priorities and tenant choices meant that the standard achieved was somewhere between that of the 30-house and 4-house schemes. The main differences included non-condensing boilers in a number of houses, poor efficiency focal point fires, small areas (about 12 m^2) of solid wall adjacent to covered passage ways between houses which were not insulated and no attempt to improve air-tightness by sealing suspended ground floors.

Good monitoring data was available from 10 houses, one of which was heated electrically. The mean delivered energy consumption in the gas-heated houses was 18,600 kWh (16,700 kWh gas, 1900 kWh electricity). However, internal temperatures were, on average, higher in the 200-house scheme than any of the other schemes. The average temperature in the houses monitored was 18.8°C. This compares with 17.1°C in the 4-house gas houses, 17.9°C in the experimental group (30-house scheme) and 17.4°C in the 30-house scheme control group. Normalising energy consumption against the average temperature observed in the 30-house scheme experimental group, the equivalent

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[8] It would be a considerable achievement on the part of the manufacturers to produce natural gas-fired heating systems that emit more carbon dioxide than electric resistance heating in a fossil fuel fired grid. Nevertheless, against the background of generation efficiencies of modern, combined cycle gas-fired power stations, these fires probably succeed!

consumption would be in the region of 17,200 kWh (15,300 kWh gas, 1900 kWh electricity).

6. Discussion

The objective of the demonstration project was to show the extent to which the application of readily available and well understood technology, as part of housing modernisation, could reduce energy consumption and CO_2. The data from the schemes demonstrate a clear relationship between the level of efficiency work and energy consumption. Figs. 6 and 7 compare the mean energy consumption (temperature corrected) and CO_2 in each of the four schemes.[9] As expected, overall energy consumption and CO_2 declines as the level of energy efficiency increases. In comparison with the normal modernisation standard adopted by the authority at the time of the project, reductions in total energy consumption of 20% (30 house experimental group), 39% (200 house scheme), and 47% (4-house scheme–gas systems) are apparent. In addition to confirming the extent of reduced energy consumption, the monitoring team was also interested in gaining an understanding of the practical implementation problems and how these can be overcome in future schemes.

6.1. Cost effectiveness

Cost is often cited as a barrier to the addition of energy efficiency work to modernisation work programmes. The cost evidence from this demonstration project suggests that although costs and energy savings can result in short pay-back times, this is highly dependent on the house types involved and on the detailed design of schemes. The large variation in capital cost between the relatively simple construction encountered in the 4-house scheme and the more complicated wall arrangement in house type C (30-house scheme) clearly illustrates the difficulties which can arise even in an apparently homogeneous housing estate. In strict economic terms applying cost-effectiveness criteria, together with predicted energy savings, can help to strike a balance between capital cost and reduced energy use costs but this is likely to oversimplify the problem particularly in social housing. House types, which are expensive to insulate, are often mixed with those which are relatively inexpensive and raise ethical questions of fairness and equality of treatment for tenants especially when affordable warmth [25] is an important objective. It is also arguable that, on technical grounds, large gaps in the insulation of the thermal envelope could cause problems of condensation and reduced comfort.

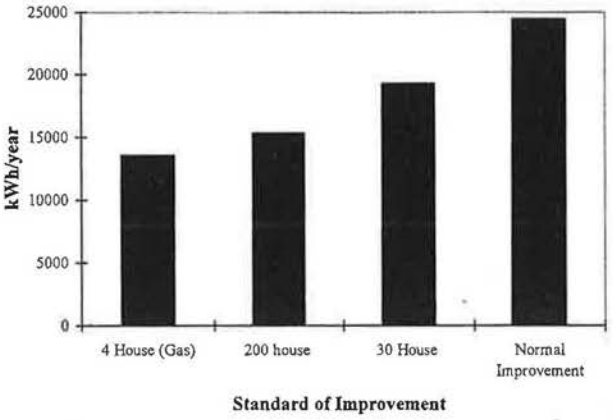

Fig. 6. Comparison of gas consumption — all schemes.

The design of schemes is another area with an important impact on cost-effectiveness. Two examples from the York project illustrate some of the potential issues. Firstly, the design of a gas unit heater scheme in one of the gas houses from the 4-house scheme saved about £780 on the cost of a normal hydronic central heating system and reduced the overall cost of the scheme to only a few hundred pounds above the costs of the normal modernisation standard. However, since the completion of the demonstration project, there has been reluctance on the part of tenants and council officials to follow this example. Such reluctance would appear to be based on long standing expectations about what constitutes an adequate central heating system. The second example concerns maintenance decisions and the way they relate to modernisation cycles. It is self evident that the cost-effectiveness of efficiency works is enhanced if done at marginal cost during other replacement and repair works. However, constraints on the availability of capital often present a dilemma to managers, and lead to results that can only be described as economically perverse. In the 30-house scheme, funds were not available to replace existing window frames and although replacement could be justified on long term maintenance grounds, a decision was taken not to replace but to seek a marginal improvement in comfort and energy consumption by the application of draught sealing. This added some £180 to the cost but with a pay-back time of over 20 years. This can be contrasted with the 4-house scheme where replacement windows with integral draught seals were installed with a marginal pay-back time of around 5 or 6 years.

It is arguable that the use of a simple, single dimension criterion such as pay-back (or even the more sophisticated discounting techniques) are at best crude and at worst miss the point completely. In a review of energy efficient retrofitting, Nilsson et al. [26] point out that energy efficiency, even in the majority of energy demonstration pro-

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[9] The comparisons across the different schemes is presented to provide a broad overview of the standards achieved. However, they must be treated with some caution as there are important differences between the various groups, particularly in the numbers of dwellings involved. The only groups which were matched with respect to their energy characteristics are those in the 30 house scheme.

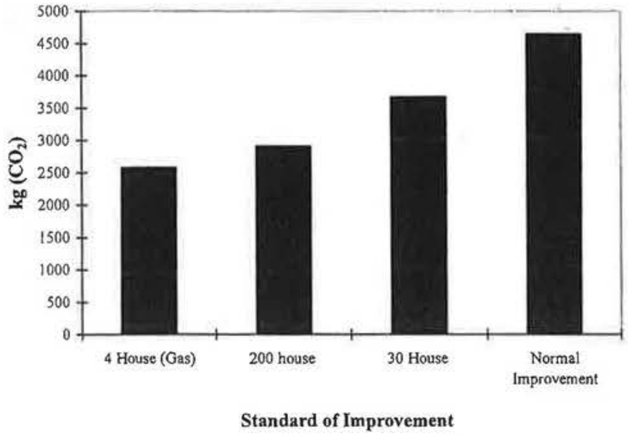

Fig. 7. CO_2 emissions (measured gas consumption) — all schemes.

jects, is not the prime objective of housing modernisation schemes. In most cases, the concerns are about the creation of a high quality internal environment, which fulfills the needs of tenants or prospective purchasers, a situation which also pertained to the York schemes. The vast bulk of modernisation expenditure is not spent on energy efficiency measures but on new kitchens, new bathrooms, the installation of a central heating system, and general repairs and replacements. All of these items are carried out for their amenity value not for reasons of cost-effective payback. The critical point in the context of the need to create a sustainable housing stock is that the required level of amenity and comfort can be achieved in an energy efficient way or an energy profligate way. As was demonstrated in the 30-house scheme, the control group maintained similar internal temperatures to the experimental group because their heating systems had a heat output which was able to counteract the greater heat loss and tenants were able to afford the energy costs involved. Few would argue that the creation of a high standard of comfort should not remain an important target but it is certainly arguable that any extra cost incurred in achieving it in an efficient way should be seen as providing benefits which are wider than the annual fuel bill savings. In order to achieve a more sustainable housing stock, policy makers need to embrace these wider issues. In any case, it is likely that many of the additional capital costs will fall in the longer term as energy efficient technology becomes mainstream.

6.2. Design and buildability issues

In broad terms, the additional energy efficiency works presented few problems for contractors and modernisation management processes. However, the discussion of use factors emerging from the 30-house scheme suggest that considerable care should be taken in the specification of secondary heating appliances particularly when a high efficiency main system is installed. In the context of the provision of choice for tenants, this would suggest a strong case for restricting system choice to ensure that overall efficiencies are not jeopardised. This is also an example of where expenditure has been incurred which, although satisfying a perceived tenant ''need'' (largely an aesthetic one), may well have acted to increase energy consumption rather than reduce it. Advice to tenants may also help to reduce the problem but given the difficulties of providing such advice, it is likely to have only marginal impact [27].

The design of heating systems generally was a matter of some concern in the early stages of the project, with a tendency for individual designers, used to poorly insulated dwellings, to consistently oversize condensing boilers. Although the impact of oversizing on boiler efficiency was very small (see Ref. [9] p. 25) the impact on capital cost was considerable. This indicates a need for industry wide training and education, which would enable designers and installers in the domestic sector to respond to the requirements of a more highly insulated housing stock. Detailed analysis of the heating system in Gas House A (4-house scheme) indicated that mean daily boiler load did not rise above 4 kW with a boiler rated at 9.1 kW and that the boiler was operating at full capacity for only a few days per year [9]. Continuous operation of the boiler in very cold weather could have enabled a significantly lower boiler rating with the potential for significant cost savings. The difficulty with this however, is that there are no condensing boilers available on the UK market with a rating lower than 9 kW [28]. If there is to be a more rigorous approach to the sizing of boilers in modernised dwellings and in new dwellings, where the opportunities for higher insulation standards are much greater, manufacturers need to bring to the market systems which are much better matched to actual design heat loads in typical new and refurbished dwellings. But, perhaps more importantly, the artificial price premium for condensing over non-condensing boilers should be sharply reduced.

6.3. Impact of the demonstration project

The objective of demonstration projects is to encourage the widespread adoption of the technologies being demonstrated and given adequate follow up and dissemination work, they can have an important impact on subsequent practice [29]. At a national level, the York project has played its part along with other schemes in the Greenhouse Programme [3,4] in raising the profile of energy efficient modernisation in social housing. However, its greatest impact has been within the host local authority. The positive impacts have included the instigation by the local authority of a mass cavity wall insulation programme which began even before monitoring work had been completed and saw all cavity walled dwellings owned by the Authority insulated by the middle of 1997. The impact on local authority policy making also resulted in the establishment of a 5-year strategy to improve the efficiency of the local authority stock overall. Modernisation options were widened to include the addition of condensing boilers, additional roof insulation, and window replacements with low emissivity double glazing. Although the demonstration project has been successful in influencing modernisation policy, barriers remain to the whole-hearted adoption of condensing boilers. Problems include budgetary arrangements which militate against the choice of a condensing boiler by the tenant (each dwelling has a small budget for "extras" which can be chosen by the tenant and the additional cost of a condensing boiler is taken from this budget) and a residual scepticism on the part of some surveyors and installers as to their cost-effectiveness and long term performance and reliability. In addition, the aesthetic requirement for a secondary heating appliance (usually a gas fire) has been maintained and very few systems are installed which do not include this element. As already discussed, this adds to capital cost and energy consumption and may have adverse health effects [30]. However, the findings of the project have persuaded the Authority to restrict the choice of fire types so as to eliminate those with very low efficiencies.

The project was also very successful in developing (from a low base) the energy expertise of the technical and management staff in the Authority and also of the contractors involved in carrying out the work. Given that the modernisation team at York is typical of many local authorities in the UK, the incorporation of energy efficiency into the modernisation of social housing requires the maintenance of a high level of training and staff development. Without such a development programme, many opportunities to reduce emissions from existing housing will be lost.

7. The project in context — a conclusion

The York project has clearly demonstrated that there is considerable scope for the improvement of single family housing through the application of well established (early 1980s) technology and that existing modernisation procedures are capable of delivering these improvements. This has been demonstrated through the monitoring results and through the subsequent experience of the authority in implementing the lessons learned. However, if the contribution of this type of modernisation work to the development of a sustainable housing stock is to be understood, it is also important to place the results into the context of other schemes. Fig. 8[10] shows how the highest standard achieved in York compares with the energy efficiency of British housing overall (existing and the current new-build standard implied by the Building Regulations), a European retrofit project (Østerbro) and three low energy new-build housing projects. The Østerbro scheme [31] is one of the most efficient of recent large scale improvement projects, the Pennyland houses [21] represent the best of the UK low energy projects of the 1970s and 1980s, the Longwood House [32] represents one of the most energy efficient UK schemes of the 1990s, and the Passivhaus project at Kranichstein in Germany represents the best of the low energy housing projects undertaken in Europe to date [33]. Pennyland and Longwood addressed the concerns of the 1970s, which were the exhaustion of fossil fuels and security of supply, with the technology of the 1970s and early 1980s. Kranichstein addresses the much more demanding agenda of the 1990s, the stabilisation of atmospheric CO_2 concentration, with the technology of the 1990s. As can be seen, the best of the houses at York outperform the British average by over 30%, are comparable with the current standard for new UK housing and approach the level achieved in the Pennyland scheme. They do, however, fall some way short of the level set by Longwood and the energy retrofit scheme at Østerbro and do not begin to achieve the performance of the Passive Houses at Kranichstein.

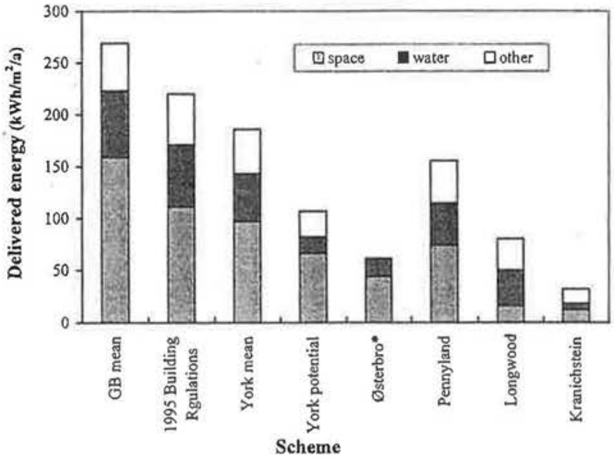

Fig. 8. The York Energy Demonstration Project in context (*data on lighting and appliance consumption, not available).

The agenda at York was to implement an energy efficiency programme at modest cost, that could be undertaken by a Local Authority acting alone within the constraints imposed by existing housing modernisation programmes, concentrating on space heating and to a lesser extent water heating, and using readily available technology. Although significant improvements were made in York, it is possible to identify a number of further improvements in space and water heating which could be carried out. The likely effect of these further improvements is shown in Fig. 8 (York potential).

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[10] The source of the data for Fig. 8 is as follows: GB average — compiled from [2,18]; Building regulations — BREDEM calculation based on the application of The Building Regulations 1995 for England and Wales Approved Document L [5] to the York dwellings; Østerbro — [31] Pennyland — [21]; Longwood — Lowe and Curwell [32]; Kranichstein — [33].

It has been argued that the development of building regulations in England and Wales, within the first decade of the next millennium, could see fabric U-values reduced considerably in new housing. For example, U-values of 0.2 for walls and ground floors, 1.3 for windows, 0.6 for solid doors, and 0.15 for roofs are achievable at reasonable cost [24]. The houses in York lend themselves to further improvements to roofs, windows, and doors without major structural modifications and there is no fundamental impediment to the achievement of radically reduced U-values for these elements in most of the existing stock, especially if carried out during replacement works (roof replacement also provides an ideal opportunity to eliminate thermal bridging particularly if insulation is placed at rafter level to create a warm roof construction). Recent developments in the efficiency of condensing boilers have seen seasonal efficiencies rise to around 90% [28]. In addition to these improvements with respect to space heating, savings in water heating could be achieved by the application of active solar systems, improvements in storage tank insulation and pipe insulation, and the adoption of water saving measures such as aerating taps and showers. Improvements in domestic appliances also offer the prospect of savings in the consumption of electricity for lights and appliances. The net effect of such improvements would be to reduce overall consumption in houses similar to those in York to around 110 $\mathrm{kWh/m^2/a}$, an overall reduction of 60% with respect to the British average and a level which has been surpassed by only a small number of new houses in the UK to date [34]. The difference between the actual and potential performance of the 4-house retrofit at York has implications for policy, since significant opportunity costs are incurred by applying readily available technology which, almost by definition, is below the performance of the best. It is for example, unlikely that the windows actually installed at York, whose U-value exceeds the current state-of-the-art by a factor of at least 2, will be replaced for another four decades. It is reasonable to suppose that if such opportunity costs were considered, alongside initial capital cost the adoption of higher performance technology would be more widespread.

The Østerbro scheme (Fig. 8) illustrates the impact of a more technologically innovative approach to retrofit. This scheme of improvement to a five storey apartment block in, Copenhagen was able to achieve a consumption of 61 $\mathrm{kWh/m^2}$ for space and water heating in a retrofit which included a range of passive solar measures such as an innovative solar wall (incorporation transparent insulation) and active solar water heating as well as insulation and window improvements [31]. This is considerably lower (57%) than that actually achieved in York (143 $\mathrm{kWh/m^2/a}$). However, our assessment of the potential for further improvement in the York houses (83 $\mathrm{kWh/m^2/a}$ for space and water heating) suggests that the achievement at Østerbro could be emulated in dwellings similar to those encountered in York. The economics are, of course vastly different with a 33-year pay-back time in the Østerbro scheme (caused mainly by the solar wall) compared with around 5 years in the 4-house scheme in York.[11]

Although this project has been able to demonstrate that the technology can be successfully applied and that it is well within the capacity of existing technology and construction practice, the major problem facing the UK and many other countries is the transfer of such improvements into the housing stock as a whole. In the UK, the existence of a high proportion of owner occupied dwellings (some 67% of all tenures) make this a particularly difficult task, for it will require policies which encourage and enable millions of individuals to make the required investment. This is a problem which goes far beyond the demonstration of appropriate energy efficient technology.

Acknowledgements

We are grateful for the support of the City of York Council and the Department of the Environment Transport and the Regions in carrying out this project. In particular, we would like to thank the staff of the York maintenance section and the tenants for their invaluable assistance. We would also like to acknowledge the contribution of the referees who made some very detailed and useful comments. Any remaining errors or omissions are the responsibility of the authors.

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