ESRU

Project Report

University of Strathclyde

Energy Systems Research Unit
James Weir Building
75 Montrose Street
Glasgow G1 1XJ
Scotland, UK

Thermal Improvement of Existing Dwellings

Clarke J A, Johnstone C M, Lever M,
McElroy L B, Prazeres L, and Strachan P A

Energy Systems Research Unit

**Final Report
to the
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Energy Systems Research Unit
Director: Professor J A Clarke

E-mail esru@strath.ac.uk
Phone +44 141 548 3986
Fax +44 141 552 5105

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Executive summary

Sustainable development is driving the political agenda. One possible response by the Scottish Executive (SE) is to use regulatory means to bring about energy efficiency improvements to Scottish homes over time. The impetus for the present project was to assist this process while ensuring compatibility with the new EU Directive on the Energy Performance of Buildings (EU 2002). In enacting such legislation, the key questions to be addressed are:

1) what changes offer best value?
2) what deployment combinations are suited to the different house/construction types?
3) and how should the deployments be phased over time?

SE, and the Scottish Building Standards Agency therefore sought to establish a project that would identify best value approaches to the incremental improvement of energy efficiency within the existing housing stock up to 2020.

This report describes the outcome from a study to determine the impact of energy efficiency measures applied to the Scottish housing stock. Assuming conventional property type classifications, the present performance of the housing stock is quantified using available survey data. Building simulation techniques were then employed to generate a Web-based, decision-support tool for use by policy makers to estimate the impact of deploying energy efficiency measures in different combinations over time. The process of tool formulation is described and an example is given of tool use to identify best-value retrofitting options while taking factors such as future climate change and improved standard of living into account.

The decision-support tool is a significant project output because it enables the different energy saving options to be assessed when deployed separately or together. This, in turn, will allow policy makers to assess the potential of such options in relation to the targets identified in the Government's Energy White Paper: a 20% improvement in domestic sector energy efficiency by 2010, followed by a further 20% by 2020. It also enables a rational response to the EC Directive on the Energy Performance of Buildings, which is due to be implemented by January 2006. In addition to informing the policy development process about the impact of technologies that are at present cost-effective, the tool allows consideration of options that are expected to become so only later as the 2010 and 2020 milestones are approached. It is argued that the nature of the tool renders it applicable to the cumulative roll-out of upgrade measures in the long term, both within and outwith the UK.

To demonstrate the evaluation procedure, the tool is applied to two house types that represent a significant portion of the Scottish Estate.

Finally, the report suggests a mechanism to monitor the cumulative impacts of upgrading measures in future in order to identify and replicate those measures that provide best value.

0. Introduction

The Energy Systems Research Unit (ESRU, www.esru.strath.ac.uk) was contracted by the Scottish Executive to undertake research into the options for, and impacts of, thermal improvements to existing dwellings. The project was undertaken in collaboration with the Scottish Energy Environment Foundation (SEEF, www.seef.org.uk), who was charged to assist with the wider dissemination of outcomes.

The project comprised five inter-related work packages (WP) as follows.

- WP1 reviewed existing data compiled for domestic dwellings within Scotland in order to identify house/construction types and energy saving potentials.
- WP2 developed a decision-support tool to assist with the identification of cost-effective energy efficiency options and their application over time.
- WP3 verified this tool by comparing its outputs with data from other sources.
- WP4 demonstrated the application of the tool to determine cost-effective actions and attainable targets in the short-to-medium term.
- WP5 applies the tool to a representative Scottish housing stock to establish the impact of an upgrading strategy on the energy demands and environmental emissions associated with the thermal performance domestic buildings.
- WP6 elaborated approaches to the monitoring of the impacts of implementing energy efficiency measures over time.

The project team included four academic staff members, each assigning approximately 5% of their time to the project, a Research Fellow (full-time) and a postgraduate student (part-time).

1. WP1: Scottish housing statistics

1.1 Literature review

The purpose of this WP was to categorise the Scottish housing stock by construction type, age, comfort standard, energy efficiency and CO_2 emission. The different possible upgrade options were also identified at this stage for encapsulation within the decision-support tool developed in WP2.

It was recognised at the outset of the project that energy efficiency in housing had been the subject of extensive past research and significant information sources already existed. Data was therefore obtained from the following publications and used in the present work.

- Communities Scotland, Scottish House Condition Survey, 2002, ISBN 1874170 541
- Scottish Homes, Scottish House Condition Survey, 1996, ISBN 1874170 142.
- Thermal Upgrading in House Modernisation, Report prepared for the Scottish Office Building Directorate, 1987.
- T A Markus (Ed), Domestic Energy and Affordable Warmth, Report No. 30, The Watt Committee on Energy, E & FN Spon, ISBN 0-419-20090-8.
- Technical Services Agency, Housing - Raising the Scottish Standard, ISBN 0-95188-34-02.
- BRECSU, Good Practice Guide 79, Energy efficiency in new housing: low energy design for housing associations.
- BRECSU, Energy Consumption Guides 2, 23 and 24.
- BRECSU, Energy Efficiency in Buildings Leaflets 19.1 – 19.6.

- BRE, Domestic Energy Fact File, 1992 and 1993 update and supplements for owner occupied, local authority and private rented homes, 1994.
- CIBSE Guides A and B.
- ESRU, Social Inclusion Study, Report E148 to Communities Scotland, University of Strathclyde, 2001.
- Various communications containing practical information from the industry and emerging possibilities from academia.

What follows is a summary of the findings of the review of the above material.

1.2 Typology profile of housing in Scotland

The housing sector within the UK constitutes a large proportion of the overall energy consumption (Shorrock and Brown 1993). For this reason, and because housing impacts greatly on the health and wellbeing of citizens, the Scottish Executive has substantial policy instruments focused on this sector. In Scotland, there are approximately 2,278,000 dwellings (compared with 2,232,000 in the 1996 survey) of which 4% are vacant and 2.5% are due for demolition. The majority of dwellings are either houses (62%) or flats (38%). Over 40% (905,000) of all dwellings were built within the last 37 years, with 24% (531,000) constructed between 1945 and 1965. In constructional terms, the breakdown is as given in Table 1.

Table 1: Construction types.

Construction system	%
Cavity wall	74
Solid wall	25
Material	**%**
Brick/block	67
Sandstone	18
Whin/granite	5
Non-traditional	10
External finish	**%**
Rendered	61
Stone	18
Brick	9
Non-traditional	12

A typology appraisal of the 2002 House Condition Survey identified 7 predominant Scottish house types as listed in Table 2.

Table 2: Scottish house types.

Detached:	No other dwelling joins any part of the structure.
Semi-detached:	A house attached to one other dwelling only, with both dwellings detached from any other dwelling.
Terraced:	A house forming part of a block where at least one house is attached to two or more dwelling units.
Tenement:	Flats within a block with shared access – generally not over 4 storeys high.
Four-in-a-block:	Each flat in the block has its own independent access. Flats on the upper level are reached by their own internal or external stair.
Tower/slab block:	Maisonettes and flats in a multi-storey or tower with 5 or more levels.
Conversion:	Flats resulting from the conversion of a house or former non-residential building (e.g. a warehouse).

For the 1996 survey, these types were then subdivided into a further 5 categories by age as shown in Table 3. These categories were also employed within the 2002 House Condition Survey.

Table 3: Categorisation of the Scottish house types.

	Pre-1919	1919-1944	1945-1964	1965-1982	Post-1982
Detached	√	√	√	√	√
Semi-detached	√	√	√	√	√
Terraced	√	√	√	√	√
Tenement	√	√	√	√	√
Four-in-a-block	√	√	√	√	√
Tower/slab block	√	√	√	√	X
Conversion	√	√	X	X	X
Construction notes	Typically solid stone wall or rubble filled cavity.	Typically brick/cavity or stone.	Typically brick or block/cavity. Some non-traditional (e.g. timber/ steel).	Some brick or block/cavity. Some innovations (e.g. solid concrete/no-fines/Wilson block *etc*)	Typically brick or block/cavity. Some timber frame (especially post-1990).
Consequences			Some expensive fabric refurbishment options.	Some expensive fabric refurbishment options.	Mainly insulated to minimum 0.6 wall U-value.
Windows	Mainly timber.	Mainly timber.	Timber/metal frames.	Timber/metal frames.	Timber/metal/U PVC frames. Many double glazed.
Original heating	Coal	Coal	Some coal, some central heating.	Few coal, mainly central heating, many electric.	Mainly central heating, many gas but oil or electricity where gas not possible.

Most house types exist in all of the eras identified, with the exception of the Tower/Slab Block, which (including maisonettes) was identified in all eras pre-1982), and Conversions, which were not in evidence post-1945. However, within each house type there is a wide range of sub-categories depending on age. This is particularly the case for housing constructed in the period 1945-64, when needs were great and materials scarce, and also for the period 1965–82, when innovations and the availability of new materials facilitated novel solutions. These houses often relied on solid or un-insulated framed constructions and, due to the availability of low cost electricity (until the mid 1970's), were often heated by electric systems. Such dwellings still form a large proportion of those currently requiring refurbishment and heating system upgrades. While information on these house types is not readily available, a study carried out by Charles Robertson Partnership - Architects for the Scottish Office Building Directorate in 1987 - goes some way to assist in this respect (Scottish Office 1987). Despite the date of publication, this study is relevant as all identified house types relate to the construction periods identified above.

From the data of the foregoing tables, it is evident that the problem is complex, largely because of the many permutations of the observable house types, constructional systems and options for upgrading. While a simulation-based approach was adopted within the project, for reasons explained later, it was not deemed necessary to simulate directly the many possible permutations.

1.3 Heating systems within the existing Scottish housing stock

Of the 2,190,000 inhabited dwellings identified in 2002, around 86% had full central heating (68% had whole house gas central heating, 11% had electric central heating and 7% had full central heating from another fuel). This compares favourably with the 1996 survey, where 74% of dwellings had full central heating, with a further 14% having partial central heating, and the remaining 12% of dwellings having no central heating. The breakdown by heating system and fuel is shown in Tables 4a and 4b.

Table 4a: Breakdown of heating systems within the Scottish housing stock (1997).

Heating Type	Solid Fuel	Electric Storage	Other Electric	Gas	Oil	Other	Total
Central heating	7%	18.5%	3%	57%	1.5%	1%	88% (1.78 million)
Not central heating	2%	N/A	4%	5.5%	N/A	0.5%	12% (0.33 million)
Total	9%	18.5%	7%	62.5%	1.5%	1.5%	100% (2.11 million)

Table 4b: Breakdown of heating systems within the Scottish housing stock (2002).

Heating Type	Gas	Electric	Other	Total
Central heating	68%	11%	7%	86% (1.90 million)
Partial central heating	2%	6%	-	8% (0.17 million)
Not central heating	2%	3%	1%	6% (0.12 million)
Total	72%	20%	8%	100% (2.19 million)

Based on year-on-year surveys, the increase in dwellings with central heating is growing at a rate of 2–5% per year. This is confirmed by the first HECA Report to the Scottish Parliament (HECA 2001), which states that 64,600 old heating systems were replaced in Local Authority housing from April 1997 to March 1999.

1.4 Digest of house types

From the review outcome it was concluded that existing information is diverse in nature, making it difficult to apply to the present problem: how best to assess and compare the energy reduction impacts of the different possible improvements to the housing stock. The review indicated that the existing housing stock could be classified into 7 architectural types and 13 construction systems. As shown in Table 5, this resulted in over 50 permutations as not all construction systems apply to all house types. Further, 6 distinct heating system options were identified resulting in approximately 300 design permutations to which energy saving measures may be applied.

Clearly, this is an unmanageable number of study options and, if processed, would give rise to recommendations that would be impossible to assimilate and implement. A method to reduce the number of options to a manageable number was therefore required. Two reduction techniques were subsequently explored: recombination of options into principal classes, and the mapping of options to a limited set of thermodynamic classes representing all possibilities. This section of the report continues with a description of the former technique while sections reporting work packages 2-4 elaborate the latter, which was adopted within the project.

Table 5: Construction categories.

Category	%	Sub-category	Related house type
Cavity Wall brick/block	67	1. Cavity throughout – plastered on hard. 2. Hybrid - cavity dividing walls with single skin in-fill (brick, block or cladding system) to front and rear – part plaster on hard/part lined.	Detached Semi-detached Terraced Tenement Four-in-a-block Conversion
Solid Wall brick/block sandstone whin/granite	23	3. Sandstone/whin/granite – strapped and lined. 4. Concrete block – plaster on hard. 5. Concrete block – strapped and lined.	Detached Semi-detached Terraced Tenement Conversion
Non-traditional timber concrete metal	10	6. Hollow concrete block – plastered on hard. 7. As above – strapped and lined. 8. Swedish timber or steel frame - not insulated. 9. Swedish timber or steel frame - insulated. 10. No Fines concrete – plaster on hard. 11. As above – strapped and lined. 12. Solid/insitu concrete – plaster on hard. 13. As above – strapped and lined.	Detached Semi-detached Terraced Tenement Four-in-a-block Tower/slab block

BRECSU (1990) has produced a number of Good Practice Guides designed to assist landlords and homeowners wishing to deploy cost-effective thermal upgrades to existing dwellings. These Guides considered only two construction types—solid and cavity wall—and identified 11 upgrading options covering low, medium and high performance measures. While the Guides take no account of dwelling size or occupancy level, an Information Leaflet (BRECSU 1995) advised on typical energy savings achievable in 4 new-built house types ranging from a two bedroom flat ($49m^2$) to a four bedroom detached house ($141m^2$). In order to establish the validity of using such a reduced range of house types, the floor areas of the 4 new dwellings were compared with the floor areas of existing dwellings built from 1919–98 (ESRU 2001). At this stage, it was decided to add 3 additional dwelling types to account for the range of flat types appropriate to the Scottish context. A further refinement of the most relevant house types was made possible by establishing the percentage of the stock in each category (see Table 6), and by accepting that:

- pre-1965 housing can be characterised as having poor insulation levels (albeit in varying degrees of 'poor');
- 1965–97 housing has 'typical' insulation levels; and
- post-1997 housing has insulation levels approaching current practice.

Table 6: Digest of house types.

Type %	20%	< 15% >		< 25% >				< 37% >				3%		TOTALS
	1919	1919-44		1945 – 1964				1965 – 1997				1997 – 2002		
Total 2.1m	Solid	Cavity	Solid	Cavity	Solid	Non Traditional Cavity	Non Traditional Solid	Cavity	Solid	Non Traditional Cavity	Non Traditional Solid	Cavity LW	Cavity HW	
	19.5%	12%	3%	19.5%	1.5%	2.0%	1.5%	27%	0%	6%	5%	1%	2%	
Houses 62%														
Detached (19%)	4%	2%	0%	2%	0%	0%	0%	8%	0%	1%	1%	0.5%	0.5%	**=19%**
Semi (21%)	2%	2%	2%	5.5%	0.5%	0%	0%	6%	0%	1%	1%	0.5%	0.5%	**=21%**
Terraced (22%)	2%	2%	0%	5%	1%	0.5%	0.5%	7%	0%	1.5%	1.5%	0%	0%	**=21%**
Flats (38%)														
Tenement (23%)	8.5%	2%	0%	4%	0%	0.5%	0.5%	5%	0%	1%	1%	0%	0.5%	**=23%**
4 in Block (11%)	1%	4%	1%	2%	0%	0.5%	0.5%	1%	0%	0%	0.5%	0	0.5%	**=11%**
Tower/Slab (3%)	0%	0	0	1%	0	0.5%	0	0	0	1.5%	0%	0	0	**=3%**
Conversion (2%)	2%	0	0	0	0	0	0	0	0	0	0	0	0	**=2%**
Totals	**19.5%**	**12%**	**3%**	**19.5%**	**1.5%**	**2%**	**1.5%**	**27%**	**0%**	**6%**	**5%**	**1%**	**2%**	**100%**

This approach reduced the study scope to 9 construction options and 7 house types, giving 40 combinations overall of which 26 represent cases that correspond to 1% or more of the housing stock. In total, these define 93.5% of the Scottish housing stock. Further scrutiny reveals that within each age band, typical construction types prevail. Typically, for example, dwellings in the pre-1919-64 category were either cavity construction (34% of the stock) or solid (26% of the stock). The balance is fairly evenly split between dwelling types (flats, semi-detached, detached, terraced *etc*), although the largest categories are cavity walled, detached (pre-1919-64) and semi-detached houses (1965-97), and solid walled tenements (pre-1919-64) at 8%, 8% and 9% respectively. Selecting only those combinations that represent a significant proportion of the stock reduces the total number to 4 as identified in bold italic in Table 7:

- semi-detached, cavity wall, poorly insulated, pre-1919-64 (8%);
- terraced, cavity wall, mid range insulation, 1965-97 (7%);
- tenement plus 4 in-a-block, cavity wall, poorly insulated, pre-1919-64 (12%); and
- tenement plus 4-in-a-block, solid wall, poorly insulated, pre-1919-64 (11%).

This selection focuses the study on the existing building stock. However, as the list does not include either a well-insulated or a detached house, it was necessary to add a detached house built to the latest Building Standards to represent current construction trends:

- detached, cavity wall, well insulated, 1997-present (2% and rising).

Between them, these 5 cases represent 40% of the Scottish housing stock. With reference to Table 7, it can be seen that some house types were not selected for modelling even though they represent a high proportion of the housing stock (e.g. detached housing from pre-1919 to 1964). The reason is that a semi-detached and tenement property of similar age and construction were selected, and it was therefore decided that the genre was well represented. A bias was given to dwellings with a cavity wall construction as these represent 70% of the housing stock compared with 30% with a solid wall (Table 7).

1.5 Energy efficiency technologies

A number of upgrading measures may be applied to these house/construction type combinations depending on the particular case. Examples of upgrades include wall, floor, loft, tank and pipe insulation, draught-proofing, heating system and control improvements, double glazing, and low energy consumption lights and appliances. In addition, it is possible to consider local means of supply in the form of solar thermal, solar electric, wind energy and recovered heat.

The 2002 House Condition Survey established a mean NHER rating of 4.5 (on a scale of 0 poor to 10 good) for the Scottish housing stock, with an associated mean SAP rating of 46.5. The associated CO_2 emissions are around 16.2 million tonnes per year. By comparison, the 1996 House Condition Survey established that a mean NHER rating of 4.1 and a mean SAP rating of 43. These data indicate a 10% improvement since 1997, with only 12% of all dwellings achieving an NHER rating of 7 - 9 and no dwellings attaining a rating of 10. Table 8 summarises the performance of the entire Scottish housing estate.

From these data it is clear that there is an urgent need for energy efficiency improvements:

- From the 2002 survey, around 86% (1,902,000) of dwellings have whole house central heating, with a further 8% (169,000) having partial central heating. This represents a 6% improvement on the corresponding 1996 survey, with the number of dwellings with no central heating down from 13% to 5.5% (i.e. 271,000 to 116,000 dwellings). This small but significant change gives rise to concerns about fuel poverty and the

Table 7: Further refinement of house types.

Type %		**< 60% >**				**< 37% >**				**3%**		**TOTALS**
		Pre 1919– 1964				**1965 - 1997**				**1997 - 2002**		
Total 2.1m		**Cavity**	**Solid**	**Non Traditional** Cavity	Solid	**Cavity**	**Solid**	**Non Traditional** Cavity	Solid	**Cavity** Timber	Traditional	
		32%	**24%**	**2%**	**1.5%**	**25.5%**	**0%**	**6%**	**5%**	**1%**	**3%**	
						Houses 62%						
Detached (19%)		4%	4%			8%		***1%***	1%	***0.5%***	***0.5%***	**=19%**
Semi (21%)		***8%***	4.5%			5.5%		1%	1%	*0.5%*	*0.5%*	**=21%**
Terraced (22%)		7%	3%	*0.5%*	*0.5%*	***7%***		1.5%	1.5%			**=21%**
						Flats (38%)						
Tenement (23%)		***6%***	***8.5%***	*0.5%*	*0.5%*	5%		1%	1%		*0.5%*	**=23%**
4 in Block (11%)		***6%***	***2%***	*0.5%*	*0.5%*	1%			*0.5%*		*0.5%*	**=11%**
Tower/Slab (3%)		1%		*0.5%*				1.5%				**=3%**
Conversion (2%)			2%									**=2%**
Totals		**32%**	**24%**	**2%**	**1.5%**	**25.5%**		**6%**	**5%**	**1%**	**2%**	**100%**

health-related problems associated with hypothermia, condensation and mould growth.

- Although around 90% of houses have loft insulation, in only 27% of cases does this meet the 1991 Building Standards (or better), with the most common thickness of insulation being 100mm in 35% of dwellings with lofts.
- 16% of pre-1975 dwellings have cavity insulation (compared with a potential of over 55% of the total stock);
- 4% of pre-1975 dwellings have external insulation (compared with a potential of around 28% of the total stock – although this includes sandstone and granite buildings);
- 6% of post-1975 dwellings have cavity insulation (compared with a potential of 15% of the total stock);
- 1% of post-1975 dwellings have external insulation (compared with a potential of around 2% of the total stock); and
- while 92% of dwellings have satisfactory hot water tank insulation, and 74% have an acceptable level of pipe insulation, there remain 100,000 dwellings without satisfactory hot water tank insulation and 281,000 without an acceptable level of pipe insulation (this information is not updated in the 2002 survey and is presumed to be unchanged).

Table 8: NHER frequency distribution for Scottish housing.

NHER Category	000s	%
0	26	1
1	106	5
2	169	8
3	294	14
4	481	22
5	464	22
6	351	16
7	153	7
8	68	3
9	45	2
10	8	0

The 1996 survey estimated that 738,000 households could be classified as fuel ‘poor’, equating to 35% of the population. By the same definition, this reduces in the 2002 Survey to 262,000 (12%). However, the definition of fuel poverty has been revised, and under the new 2002 Fuel Poverty Statement definition, the actual number is 369,000 (17%), which is nonetheless a significant improvement. Those living in fuel poverty are most likely to be living in dwellings built pre-1982, in rural areas, without central heating, with low levels of loft insulation and/or with single glazing. They are also likely to be living in private rented accommodation, be single pensioners and/or be living on an income of less than £400 per week.

In the 12 month period preceding the survey, around 48% of householders had undertaken some work on their houses. This represents a reduction of 10% compared with the 1996 survey. The most common work addressed heating and insulation– undertaken by 28% of all households, with 23% undertaking general building works. The total amount spent by householders was £3.3 billion, averaging £220 per dwelling. £1.9 billion of this was spent on repairs and improvements, and £1.4 billion on decoration. Only 2% of the work done was grant funded. The most frequent works undertaken included replacement or servicing of heating systems, bathroom/kitchen modernization, window replacement, roof repair/ replacement, render repairs, external painting, platering and floor/joist repairs. Housing Associations and Local Authorities combined undertook around 6 times as many major repairs and improvements as private landlords and owner occupiers (195,000 compared with 33,000).

Although the mean NHER rating varies by house type, tenure, location and age, the range is small (from 3 to 5). The energy efficiency measures to be considered within the present project were divided into two categories: those that are current practice, commercially viable and technically robust, and those that are future practice, technically robust but not necessarily commercially viable. Table 9 lists current practice energy efficiency measures, giving the typical installation costs and simple pay-back period in each case. The costs are based on application of the measures to a semi-detached house when referenced to December 1996 prices, while the pay-back period is the material and installation costs divided by the cost per year of the energy saved (BRECSU 1995).

Measures representing future practice in energy efficiency are listed in Table 10. Here, the costs have been estimated from technical reports corresponding to research and demonstration programmes (Twidell and Johnstone 1993).

In addition to the appraisal of the impact of thermal improvements to existing dwellings, an analysis was undertaken to appraise the energy savings and CO_2 emission reductions that could be achieved through the introduction of embedded renewable technologies supplying power directly to a dwelling and energy efficient 'white' and 'brown' domestic appliances, which reduce a building's energy demand. The development of an assessment tool to quantify the energy impact of such measures, along with the resulting CO_2 emission reduction, is elaborated in the section reporting work package 2.

Table 9: Costs and pay-back of current practice efficiency measures.

Short-term domestic energy saving option	Estimated installation cost	Expected payback period
Hot water tank and pipe insulation	£15/house (DIY) £35/house by contractors	1 – 2 years 3 – 4 years
Draught-proofing	£50/house (DIY) £150/house by contractors	2 – 3 years 6 – 10 years
Loft insulation	£75/house DIY £200/house by contractors	2 years 5 years
Heating system upgrade	£300/house extra cost for energy efficient boiler	3 years if replacing boiler anyway
Heating controls	£300/house for full controls package	4 - 5 years
Cavity wall insulation	£400/house	3 – 4 years
Solid wall insulation	£450/house DIY £650/house by contractors	4 – 6 years 6 – 9 years
Double glazing	£170/house extra cost for double rather than single glazing	5 – 7 years if replacing windows anyway
Lighting	£5 - £15/house	1 year
Appliances	No additional cost	-

Given the large number of design/technology combinations, the categorisation of upgrading impacts by analysing all possible combination is problematic. An approach was therefore established as described in the following section on work package 2.

Table 10: Costs and pay-back of future practice efficiency measures.

Medium to long term domestic energy saving measure	Estimated installation cost	Expected payback period
Exterior insulation based cladding on older buildings.	£80/m^2	11 years
Daylight sensitive lighting control.	£6/m^2 (floor area)	4 years
Introduction of ventilation heat recovery.	£800/house	4 years
Introduction of waste water heat recovery.	£1200/house	6 years
Deployment of community heating.	£2000/house	
Application of Internet based control/ load management (bringing BEMS to the domestic sector).	£350/house	8 years
Advanced solar space heating.	£400/m^2	20 years
Active solar water heating.	£150/m^2	6 years
Integration of embedded renewable technology (PV, wind *etc*).	£3000/kW	30 years

2. WP2: Decision-support tool

2.1 Rationale

Contemporary simulation tools are powerful, with features that allow them to quantify the integrated performance of a building when operating under realistic weather conditions and user influences. That said, these tools have not yet reached a stage of refinement where they can be universally applied by users of different conceptual outlooks. This is especially the case in the present context: the evaluation of housing retrofit options by decision-makers in support of policy formulation.

Even if the interface dilemma can be overcome, there remains another application difficulty: the identification of representative house designs for simulation. While it is a straightforward task to identify house types from an architecture and construction (A/C) viewpoint (Table 5), the task becomes intractable when viewed thermodynamically. Two separate houses, each belonging to the same A/C group, may have substantially different energy consumption patterns as a result of dissimilar energy efficiency measures having been previously applied. (The effects of occupant behaviour are not considered at this point.) Likewise, two houses corresponding to different A/C groups may have the same energy consumption (after normalisation relative to floor area) because the governing design parameters are essentially the same.

The approach adopted in the present project was to operate only in terms of thermodynamic classes (TC) so that different A/C types may belong to the same TC. A representative model was then formed for each TC and its energy performance determined by simulation. Any real house may then be related to a TC via the present level of its governing design parameters.

Should any of these parameters be changed as part of an upgrade then that house would be deemed to have moved to another TC. Within the present study, the design parameters considered as determinants of energy use were window size, insulation level, capacity level, capacity position and air infiltration.

The simulation results for the set of representative models then define the possible performance of the entire housing stock, present and future, for the climate, exposure, occupancy and control assumptions made within the simulations. By varying these assumptions and re-simulating, scenarios such as future climate change and improved standard of living may be incorporated.

The performance predictions, in the form of regression equations defining monthly energy requirements as a function of the prevailing weather parameters, were then encapsulated within a Web-based decision-support tool. The intention is that a tool of this nature could be used by policy makers engaged in the development of building regulations in response to need and national policy drivers and building stock owners/ managers to appraise the impact a variety of improvement measures will have on the energy performance.

The impact of technologies that may be considered independent of house type, such as solar thermal collection, heat recovery, low energy lamp replacement and the like, were separately analysed and the results encapsulated within a second decision-support tool. The evaluation of any given upgrading scenario is therefore a two-stage process. First, the contribution of a proposed building upgrade is quantified by assigning the house in question to a TC based on an estimate of the levels of its governing parameters. The energy reduction brought about by its relocation to any other TC may then be 'read off' as shown later. Because each TC corresponds to a different combination of the governing design parameters, the required upgrade is immediately apparent from the TC relocation. Second, the contribution of generic energy efficiency measures (e.g. pipe insulation) and possible local source of energy supply (e.g. solar thermal) are quantified. This is done by applying house-specific parameter values to the technology in question (e.g. available roof area in the case of a solar thermal installation). The user is then able to accept or discard either/both contributions as a function of their applicability to the case in hand and likely cost. By making the decision-support tool interactive, such trade-offs may be immediately assessed.

The impact of future climate change or enhanced standard of living is assessed by substituting the TC energy consumption data by a set corresponding to the new scenario. In the former case, an assumed temperature increase is applied to the energy regression equations; in the latter case the regression equation set is substituted by one corresponding to a control regime definition that reflects a higher comfort expectation.

2.2 Tool-set formulation

The Housing Upgrade Planning Support (HUPS) tool-set was formulated through to a two-stage process, each stage giving rise to a decision-support tool as follows.

Stage 1: Construction-related considerations

The ESP-r system (URL1 2003) was used to determine the construction-related energy behaviour of model house designs (corresponding to the different TCs) when each were subjected to weather conditions that typify the range of possibilities for Scotland.

The range of designs to be processed were established as unique combinations of the five design parameters that were considered to be the main determinants of energy demand and may be adjusted as part of any upgrade. The parameters are window size, insulation level, capacity level, capacity position and air infiltration. If each parameter can exist at one of three levels (low, medium or high; or small, medium or large) then there will be 243 (3^5) potential designs (i.e. TCs) that, together, characterise the 'universe' of possible house responses. That is, any possible house design, existing or planned, will correspond to a unique combination of the five parameters and therefore belong to one, and only one, TC. It is important to note that most of these TC designs do not yet exist because, in general, the Scottish housing stock may be regarded as poor in energy efficiency terms. Instead, the majority of TC designs represent future possibilities that will result from the application of energy efficiency measures to the existing housing stock. With the passage of time, and the implementation of more energy efficient upgrades, a greater proportion of the TCs will correspond to real cases. Long term simulations were now conducted for a randomly selected, approximately $1/9^{th}$ replicate, sub-set of the 243 possibilities, i.e. 30 representative designs. Table 11 summarises the parameter levels for each design, while Table 12 lists the values corresponding to each case.

The monthly energy requirements extracted from the simulation results were then subjected, along with the corresponding monthly mean weather parameter values, to curve fitting techniques to establish, for each design, a best-fit relationship. Table 11 also gives the equation form and the coefficient values for each design. These equations may now be used to predict the monthly energy demand for any TC model.

The final step in the Stage 1 process was to normalise the predicted energy demands by floor area to render the results independent of house size.

To enable the above process, a standard house model was constructed comprising living, eating and sleeping areas with typical usage patterns, exposures and temperature set-points imposed. The assumptions underlying this model correspond to an 'average' house as determined from various publications (e.g. Scottish Homes 1997, CIBSE 1999, Bartholomew and Robinson 1998).

Stage 2: Non building type specific considerations

The energy performance of a range of 'brown' and 'white' goods/appliances and energy supply technologies were established to support assessments of energy efficiency measures and non-traditional approaches to heat and power supply. These models were then encapsulated within an evaluation tool for use alongside its counterpart established in Stage 1.

In relation to appliances, the tool employs simple models to construct a mean daily demand profile for each defined appliance. By switching between appliances of different efficiency ratings, it is possible to rapidly determine the impact on the overall energy demand, the energy saved and to quantify the CO_2 emission reduction.

The tool also possesses simple models for solar thermal, solar electric, wind power and ventilation heat recovery systems:

- *solar thermal* - the monthly yield is determined on the basis of a solar angle modification applied to the Hottel-Whillier equation (Duffie and Beckman 1980) using reference solar irradiance data;
- *solar electric* - a mean efficiency is assumed for each of the commercially available photovoltaic module types, with reference solar irradiance data employed as above;
- *wind power* - the energy yield calculation is based on the Betz equation for free-stream

air flow (Taylor 1983); and

- *ventilation heat recovery* - is determined from standard heat transfer considerations, with a degree-day modulus applied to factor in the usefulness of the recovered heat (Nifes Consulting Group 1993).

The annual energy yield from a solar thermal system or photovoltaic component is determined from

$$E = E_G * \varepsilon_{SC} * A * Cos\left(\theta_P \pi / 180 - \theta_L \pi / 180\right) * Cos\left(\theta_O \pi / 180 - \theta_X \pi / 180\right)$$

where *E* is the annual energy yield, ε_{SC} the mean efficiency of the collector as stated by the manufacturer, E_G the annual solar energy incident on a south facing surface at a pitch equal to the latitude (kWh/m^2), θ_P the angle of pitch at which the collector will be installed with 0° relating to the horizontal and 90° relating to the vertical, θ_O the orientation of the collector with 0° representing north and 90° representing east *etc*, *A* the collector surface area (m^2), θ_L the site latitude (°), and θ_X = 180° for a site in the northern hemisphere and 0° for one in the southern hemisphere.

For building-integrated wind turbines, the annual energy yield is given by

$$E = 1.651 * d^2 * v_W{}^3$$

where d is the diameter of the turbine rotor (m) and v_W the mean annual wind speed associated with the site of deployment (m/s).

For ventilation heat recovery, the annual energy yield is given by

$$E = 1.625x10^{-6} * ac / h * V * DD^2$$

where *ac* is the mean hourly air change rate for the dwelling type being investigated, *V* the internal heated volume (m^3), and *DD* the annual degree-days for the location.

This part of the tool-set therefore predicts the energy yield associated with the above energy supply systems and correlates these to CO_2 emissions savings. The CO_2 mapping to energy use is based on UK normalised figures as published by the Carbon Trust, equating to 0.43 kg/kWh of electricity and 0.24kg/kWh of gas combusted.

This two stage assessment procedure enables the user to establish the magnitudes of energy and related CO_2 savings likely to be achieved via building upgrade options and compare these with the savings associated with local energy supply and energy efficiency. On the basis of outputs, the user can establish which options are most cost-effective and least site constrained.

Table 11: Design class parameter states and regression equations.

TC	P1/P2/P3/P4/P5	Regression equation* coefficients										
		a	***b***	***c***	***d***	***e***	***f***	***g***	***h***	***i***	***j***	***k***
1	1/0/2/2/0	-1.003	-0.008	-0.115	0.0097	0.0008	0.0052	-0.11	0	0.0009	0.0130	22.7
2	0/0/2/2/0	0.181	-0.015	-0.157	0.235	-0.002	0.0013	-0.19	0.0001	0.0030	0.0204	17.4
3	1/0/1/1/1	-0.946	-0.005	-0.106	-0.008	0.0009	0.0044	-0.107	0	0.0006	0.0128	21.5
4	0/0/0/0/0	-0.755	-0.007	-0.100	-0.094	0.0028	0.0012	-0.121	0	-0.002	0.0171	22.9
5	0/0/0/1/0	-0.969	-0.009	-0.112	0.0387	0.0009	0.0052	-0.105	0	0.0010	0.0127	21.6
6	0/0/1/2/0	-0.889	-0.007	-0.098	0.0155	0.0007	0.0046	-0.096	0	0.0009	0.0130	19.7
7	1/1/1/0/0	-0.857	-0.011	-0.113	0.0048	0.0010	0.0054	-0.102	0	0.0007	0.0127	19.2
8	1/1/0/1/0	-0.854	-0.011	-0.112	0.0060	0.0010	0.0053	-0.102	0	0.0007	0.0127	19.1
9	1/0/0/0/2	-0.855	-0.011	-0.113	0.0064	0.0010	0.0054	-0.103	0	0.0007	0.0128	19.1
10	1/0/0/1/2	-0.856	-0.011	-0.114	0.0078	0.0010	0.0055	-0.104	0	0.0008	0.0129	19.2
11	1/0/1/2/2	-0.800	-0.010	-0.100	0.0093	0.0011	0.0048	-0.1	0	0.0008	0.0123	17.7
12	1/0/2/1/2	0.915	-0.013	-0.229	0.0491	-0.0060	0.0047	-0.22	0.0004	0.0081	0.0194	12.3
13	0/0/2/0/2	-0.685	-0.003	-0.086	0.0552	0.0007	0.0038	-0.083	0	0.0002	0.0105	14.5
14	0/0/1/1/2	-0.742	-0.005	-0.105	0.0579	0.0007	0.0053	-0.083	0	0.0007	0.0103	15.2
15	1/1/2/0/1	0.001	0.0068	-0.113	-0.024	-0.002	0.0014	-0.072	0.0002	0	0.0096	11.0
16	1/2/2/2/0	-0.610	-0.003	-0.087	0.0602	0.0007	0.0043	-0.076	0	0.0008	0.0091	12.4
17	0/1/1/0/1	-0.610	-0.003	-0.087	0.0604	0.0007	0.0043	-0.076	0	0.0008	0.0091	12.4
18	0/1/1/2/1	-0.523	-0.009	-0.097	0.0134	0.0002	0.0051	-0.072	0	0.0006	0.0090	11.6
19	0/1/2/2/1	-0.557	-0.009	-0.096	0.0489	0.0005	0.0053	-0.071	0	0.0007	0.0090	11.5
20	1/1/1/1/2	-0.555	-0.009	-0.096	0.0487	0.0005	0.0052	-0.071	0	0.0007	0.0090	11.4
21	1/1/2/2/2	-0.196	-0.006	-0.092	-0.019	-0.001	0.0034	-0.063	0.00003	0.0013	0.0073	10.0
22	0/1/1/0/2	-0.469	-0.006	-0.084	0.0527	0.0005	0.0045	-0.070	0	0.0009	0.0085	9.7
23	1/2/1/2/0	-0.465	-0.009	-0.102	0.0130	0.0002	0.0053	-0.071	0	0.0006	0.0091	10.5
24	0/2/1/0/1	-0.396	-0.005	-0.088	0.0425	0.0001	0.0047	-0.068	0	0.0010	0.0080	8.7
25	0/1/0/1/2	-0.425	-0.007	-0.076	0.0547	0.0005	0.0042	-0.065	0	0.0094	0.0078	8.6
26	0/2/0/2/1	-0.389	-0.005	-0.086	0.0396	0.0001	0.0046	-0.066	0	0.0091	0.0078	8.6
27	1/2/0/2/2	-0.237	-0.009	-0.074	-0.005	0	0.0040	-0.046	0.00004	0.0002	0.0063	6.0
28	1/2/1/0/2	-0.228	-0.009	-0.069	-0.006	0	0.0038	-0.042	0.00004	0.0001	0.0058	5.6
29	0/2/0/0/2	-0.159	-0.005	-0.053	0.0079	0	0.0032	-0.036	0.00002	0.0004	0.0043	3.9
30	0/2/1/2/2	-0.157	-0.005	-0.052	0.0077	0	0.0031	-0.035	0.00002	0.0004	0.0043	3.9

P1: window size - 0 standard, 1 large
P2: insulation level - 0 poor (1.5 W $m^{-2}K^{-1}$), 1 standard (0.6 W $m^{-2}K^{-1}$), 2 high (0.3 W $m^{-2}K^{-1}$)
P3: capacity level - 0 low, 1 medium, 2 high
P4: capacity position - 0 inner, 1 middle, 2 outer
P5: air infiltration - 0 poor (1.5 h^{-1}), 1 standard (1 h^{-1}), 2 tight (0.5 h^{-1})

$$^{*}E = a\,\theta + b\,R_d + c\,R_f + dV + e\,\theta\,R_d + f\,\theta\,R_f + g\,\theta\,V + h\,R_d\,R_f + i\,R_d V + j\,R_f\,V + k$$

where E is the monthly energy requirement (kWh m^{-2}), θ the monthly mean temperature (^{o}C), R_d the monthly mean direct normal solar radiation (W m^{-2}), R_f the monthly mean diffuse horizontal solar radiation (W m^{-2}), V the monthly mean wind speed (m s^{-1}) and 'a' through 'k' are the least squares coefficients.

Table 12: Values for 4 of the 5 construction-related parameters.

Parameter	Value	Comment
Window Size		
Standard	15% of wall area	1981 Building Regulations
Large	25% of floor area	1997 Building Regulations
Insulation Level	U-value ($W\ m^{-2}K^{-1}$): wall floor roof[%]:	
Poor	1.50 0.86 0.93	pre 1965[*]
Standard	0.60 0.45 0.35	1981 Building Regsulations
High	0.30 0.25 0.16	2002 Building Regulations
Capacity Level	Effusivity ($Jm^{-2}K^{-1}s^{-1/2}$):	Typical construction:
Low	675	Timber
Medium	1095	Cavity wall
High	1285	Solid wall
Air Permeability	Air change rate:	
Poor	1.5	typical
Standard	1.0	1997 Building Regulations
Tight	0.5	Indoor Environment & Health[#]

[*]No national governing thermal regulations exist and therefore constructions have minimal thermal insulation, where quantified in model byelaws.
[#]ISBN 91-7257-025-3
[%]Corresponding values for single, double and advanced glazings are associated with windows.

3. WP3: Tool-set verification

3.1 Approach

To confirm the robustness of the HUPS tool-set, detailed models of five real houses were subjected to simulation. The houses were then assigned to a TC based on the observed level of the five governing design parameters. For some cases, energy efficiency improvements were applied and the simulations re-run. These improvements essentially relocated the house to another TC. The predicted energy demands resulting from each simulation were then compared to the corresponding values associated with the matched TC design. Where agreement was acceptable, this would indicate that the generic TC-based approach offered a reasonable representation of real house performance.

The objectives of this phase of the study were therefore twofold:

1 To calibrate the generic models. By creating a number of detailed models of the most common house types, it is possible to:
   - check against existing measured data to ensure that predicted energy consumption is in line with that expected for that particular house type; and
   - check that the generic models have realistic energy consumption predictions by matching the detailed models with the appropriate generic model and comparing their predicted energy consumption.

2 To develop and archive a number of detailed models of the most common house types that can be used for detailed studies of particular energy retrofit solutions.

The procedure adopted to model the specific house types was as follows. First, the most common house types were selected based on the results of the literature review. Second, computer models were created against standard assumptions on occupancy and construction U-values typically in force within the building regulations for the time at which the houses were built. Third, available monitored data was obtained for each house type and comparisons were undertaken with the predictions from the models, with model calibrations undertaken where required. Fourth, the energy consumption predictions were compared with the corresponding predictions from the generic model. Last, possible upgrades were applied to the model and step four repeated.

Five specific house types were identified that covered a range of different construction types and periods, and which comprised a significant proportion of the current housing stock. The selected house types are listed in Table 13.

Table 13: The five house types chosen for the comparisons.

House Type	Construction type	Insulation level (building regulations)	Proportion of housing stock
Detached	Cavity wall	Well insulated (1997 to 2002)	4% (and rising)
Semi-detached	Cavity wall	Poorly insulated (pre-1919 to1965)	8%
Terraced	Cavity wall	Mid range (1965 to 1982)	6%
4-in-a-block/ tenement	Solid wall	Poorly insulated (pre-1919 to 1965)	11%
4-in-block/ tenement	Cavity wall	Poorly insulated (pre-1919 to 1965)	12%

The total coverage of general house types is therefore around 41%. Note that that no account is taken of variations (e.g. for end-terrace rather than mid-terrace houses) although it is easy to modify the created models to examine the impact of such variations. Certain house types, representing a high proportion of the stock, were not selected: for example, detached housing from pre-1919 to 1965. The reason is that a semi-detached house and a tenement flat of similar age were selected and it was therefore decided that the classification was well represented. A greater percentage of dwellings with cavity wall construction was selected for modelling as this type represents 71% of the stock compared with 28% for solid wall construction. Details of the models are not given in this report; the models have been archived and can be modified and re-simulated as required. The main considerations in model attribution and simulation assumptions to facilitate inter-comparison where appropriate are listed below.

General

Building location:	Scotland Central Belt (56ºN)
Climate data set:	Dundee 1980 (a typical year)
Building orientation:	Living room windows south facing
Internal gains, per occupant:	day - 100W sensible, 40W latent Night - 75W sensible, 20W latent (CIBSE Guide A, Table 6.1)
Small power load:	85W (living room) 115W (kitchen)
Cooker:	200W

	(CIBSE Applications Manual 11, Table C1.1)
Lighting:	200W (18:00 - 23:00) in each zone

<u>Detached</u>

Geometry:	layout based on BRECSU Energy Efficiency in Buildings Information Leaflet 19.6
Modelled as:	5 zones - living room, kitchen, remaining lower, upper, attic
Total floor area:	141.4m^2 (70.5 m^2 per storey)
Approximate dimensions:	9.3m x 7.6m
Living area dimensions:	3.1m x 7.6m x 2.4m
Glazing:	29.15m^2 double glazed
Construction:	1997 Building Regulations
U-values (W/m^{2}K):	walls 0.45, roof 0.25, floor 0.45
Glazing:	21% of floor area
Ventilation:	1 volume air change/hour
Occupancy:	4 people, working household, unoccupied 08:00-18:00 weekdays
Living room heating set-point:	ON at 21ºC 06:30 to 08:30 and 17:30 to 23:00
Bedroom heating set-point:	ON at 18ºC 23:00 to 07:00
Rest of house heating set-point:	ON at 18ºC 06:30 to 08:30 and 17:30 to 23:00 (BRE / BRECSU Information Leaflets)

<u>Semi-detached</u>

Geometry:	layout based on Fuel Poverty Survey (NHER) Survey 53
Modelled as:	5 zones - living room, kitchen, remaining lower, upper, attic
Total floor area:	87m^2 (43.5m^2 per storey)
Approximate dimensions:	6.55m x 6.64m
Living area dimensions:	4.2m x3.4m x 2.3m
Glazing:	8.7m^2 single glazed
Construction:	typical for era (1919-1965) - cavity wall, no insulation
U-values (W/m^{2}K):	walls 1.1, roof and floor no insulation
Glazing:	10% of floor area
Ventilation:	1.5 volume air change/hour
Occupancy:	3 people, working household, unoccupied 08:00-18:00 weekdays
Living room heating set-point:	ON at 21ºC 06:30 to 08:30 and 17:30 to 23:00
Bedroom heating set-point:	ON at 18ºC 23:00 to 07:00
Rest of house heating set-point:	ON at 18ºC 06:30 to 08:30 and 17:30 to 23:00 (BRE / BRECSU Information Leaflets)

<u>Terraced</u>

Geometry:	layout based on BRECSU Energy Efficiency in Buildings Information Leaflet 19.2 and Fuel Poverty Survey 26
Modelled as:	4 zones - living and dining room, kitchen, upper, attic
Total floor area:	90m^2 (45m^2 per storey)
Approximate dimensions:	6.0m x 7.5m
Living area dimensions:	38m^2 x 2.4m
Glazing:	18.2m^2 single glazed
Construction:	1965 Building Regulations
U-values (W/m^{2}K):	walls 1.7, roof 1.42, floor no insulation
Glazing:	20% of floor area
Ventilation:	1.5 volume air change/hour
Occupancy:	3 people, working household, unoccupied 08:00-18:00 weekdays
Living room heating set-point:	ON at 21ºC 06:30 to 08:30 and 17:30 to 23:00
Bedroom heating set-point:	ON at 18ºC 23:00 to 07:00
Rest of house heating set-point:	ON at18ºC 06:30 to 08:30 and 17:30 to 23:00 (BRE / BRECSU Information Leaflets)

<u>Tenement</u>

Geometry:	layout based on BRECSU Energy Efficiency in Buildings

	Information Leaflet 19.1 and Fuel Poverty Survey 42 (NHER calculations)
Modelled as:	2 zones - living room, rest of dwelling
Total floor area:	$60m^2$
Approximate dimensions:	6.7m x 9m
Living area dimensions:	3.0m x 4.5m x 3.0m
Glazing:	$10.4m^2$ single glazed
Construction:	typical for era (pre-1919) - solid wall with internal insulation acting as lightweight construction
U-values (W/m^2K):	walls 1.8, roof and floor - mid-flat
Glazing:	17% of floor area
Ventilation:	1.5 volume air change/hour
Occupancy:	2 people, working household, unoccupied 08:00-18:00 weekdays
Living room heating set-point:	ON at 21ºC 06:30 to 08:30 and 17:30 to 23:00
Bedroom heating set-point:	ON at 18ºC 23:00 to 07:00
Rest of house heating set-point:	ON at 18ºC 06:30 to 08:30 and 17:30 to 23:00 (BRE / BRECSU Information Leaflets)

4-in-a-block

Geometry:	layout based on Fuel Poverty Survey 48 (NHER calculations)
Modelled as:	4 zones - living room, kitchen, rest of dwelling, roof (attic)
Total floor area:	$68m^2$
Approximate dimensions:	7.3m x 9.3m
Living area dimensions:	3.1m x 5.4m x 2.5m
Glazing:	$7.07m^2$ single glazed
Construction:	typical for era (1919-1965) - cavity wall, no insulation
U-values (W/m^2K):	walls 1.1, roof no insulation, floor - top apartment
Glazing:	10% of floor area
Ventilation:	1.5 volume air change/hour
Occupancy:	3 people, working household, unoccupied 08:00-18:00 weekdays
Living room heating set-point:	ON at 21ºC 06:30 to 08:30 and 17:30 to 23:00
Bedroom heating set-point:	ON at 18ºC 23:00 to 07:00
Rest of house heating set-point:	ON at 18ºC 06:30 to 08:30 and 17:30 to 23:00 (BRE / BRECSU Information Leaflets)

3.2 Comparison with monitored data

There is little detailed information available of the energy consumption of typical house types. The Building Research Establishment's Domestic Energy Fact File (Shorrock and Brown 1993) is the most relevant publication, which gives an annual space heating requirement per average household of 48.5 GJ (13472 kWh).

To compare the actual energy used for heating with the predicted value, allowance has to be made for typical boiler efficiencies, for system losses (e.g. from pipework) and occupancy interaction effects (e.g. window opening). Typical boiler efficiencies are set at 60%, system losses at 10% and occupancy interaction effects at 15% (CIBSE 1979). Table 14 lists the annual space heating energy requirements and consumption for the five house types.

The Table also includes the results of additional simulations with upgrades to house tightness and insulation levels, permitting further comparison with the generic models. These data bracket the average reported household space heating energy use in the Domestic Fact File except for the modern detached house, which is built according to higher insulation specifications. It may be expected that heating energy requirements would be less in tenement flats and 4-in-a-block dwellings because of relatively low external façade and roof areas. Also, housing built according to recent building regulations would be expected to have lower heating requirements. The high figure for the terraced house is considered to be a result of the poor insulation standard.

Table 14: Predicted space heating requirements for the reference house types.

House Type	Annual space heating energy requirements		Annual space heating energy use
	kWh	kWh/m^2	kWh
Detached			
- basic model	4143	29.4	8630
- single glazed	6097	43.2	12703
Semi-detached			
- basic model	6138	70.6	12787
- insulated loft	6025	69.3	
- double glazed	5298	60.9	
- cavity insulated wall	5743	66.0	
- 1.0 ac/h	4939	56.8	
- 0.5 ac/h	3766	43.3	
- double glazed, cavity and loft insulation, 1.0ac/h	3713	42.7	
Terraced			
- basic model	7787	86.5	16223
- insulated loft	7222	80.3	
- double glazed	6912	76.8	
- cavity insulated wall	7089	78.8	
- 1.0 ac/h	6387	71.0	
- 0.5 ac/h	5003	55.8	
- double glazed, cavity and loft insulation, 1.0ac/h	3691	41.0	
Tenement			
- basic model	4878	81.3	10120
- double glazed	4291	71.5	
- internally insulated wall	3859	64.3	
- externally insulated wall	3692	61.6	
- 1.0 ac/h	3711	61.8	
- 0.5 ac/h	2585	43.1	
- double glazed, internal insulation, 1.0ac/h	2014	33.6	
4-in-a-block/ tenement flat			
- basic model	4490	66.0	9355
- insulated loft	4129	60.7	
- double glazed	3560	52.4	
- cavity insulated wall	3855	56.7	
- 1.0 ac/h	3491	51.3	
- 0.5 ac/h	2527	37.2	
- double glazed, cavity and loft insulation, 1.0ac/h	2012	29.6	

The percentage improvement for the individual energy retrofit options can be ascertained for the specific house types, as listed in Table 15 for all house types modelled together with the upgrades applied.

Table 15: Energy saving potential for upgrading measures.

Measure	Heating energy reduction (%)
Basic model + double glazing	14.4 ± 6.3
Basic model + insulated loft	5.7 ± 3.9
Basic model + insulated solid wall	22.6 ± 1.7
Basic model + insulated cavity wall	9.8 ± 4.5
1.5 ac/h reduced to 1.0 ac/h	20.9 ± 3.0
1.5 ac/h reduced to 0.5 ac/h	41.3 ± 5.7
1.0 ac/h reduced to 0.5 ac/h	27.3 ± 5.6
Insulation upgrade (poor to current recommendations)	42.4 ± 3.4

As can be seen, basic insulation measures together with increased air tightness results in significant reductions in energy consumption. (The five house models have been archived and are available for future further investigations of the impact of retrofit measures.)

3.3 Checking of generic models

Table 16 sets out the results of comparisons between the five specific house type models and the corresponding generic models in terms of the predicted heating energy requirements. The appropriate generic model was selected in terms of insulation, window size, capacity level, capacity position and infiltration rate. As can be seen, the agreement ranges from a best case of 3% to a worst case of -13%; this is considered to be acceptable, thus indicating that the simple generic models may be used as a proxy for their more detailed counterpart.

3.4 Checking of technology models

To test the robustness of the energy yield predictions from the second stage technology appraisal tool, a comparison was made against monitored data obtained from another ESRU research project.

Figure 1 show's the power delivered from a 10m^2 Photovoltaic (PV) component as installed on the Lighthouse building in Glasgow (Clarke *et al* 2000). The integration of the power over time gives an annual energy yield of 1329 kWh. The estimated energy yield as predicted from the technology tool is 1290 kWh, which agrees within 3%.

The exercise was repeated for ducted wind turbines, which are also installed within the Lighthouse Building. Figure 2 shows the monitored power output, which indicates an annual energy yield of 115 kWh. This corresponds to a prediction of 106 kWh given by the technology tool (within 8%).

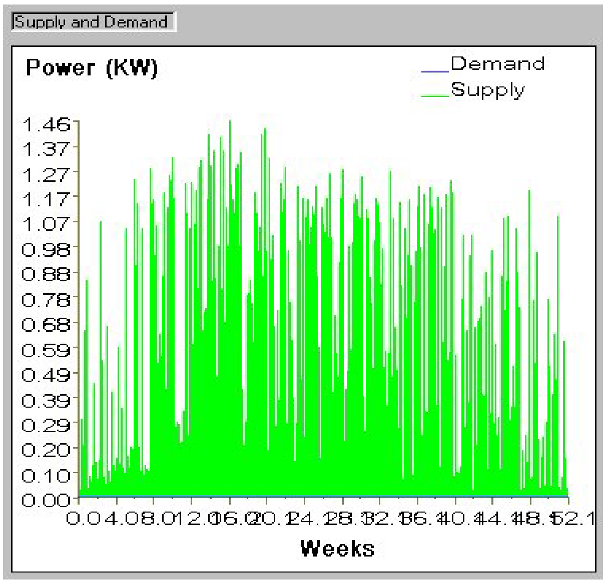


Figure 1: Monitored PV power output.

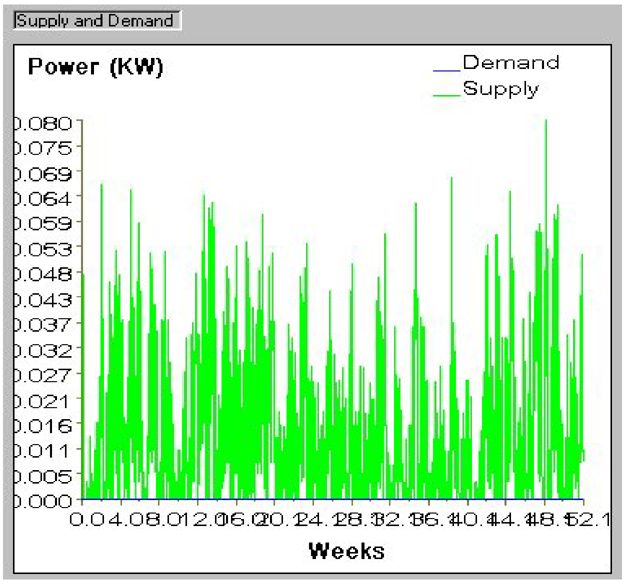


Figure 2: Monitored DWT power output.

Table 16: comparison between specific and generic models.

	House Type								
	Detached	Semi-detached		Terrace		Tenement flat		4-in-a-block/ Tenement	
	Single glazed	Basic model	#1	Basic model	#1	Basic model	#2	Basic model	#1
Predicted heating (kWh $m^{-2}y^{-1}$)	43	71	43	87	41	81	34	66	30
Thermodynamic Class (TC)	13	30	18	28	13	29	21	11	26
TC model heating (kWh $m^{-2}y^{-1}$)	46	76	46	91	46	87	34	67	26
% difference	7	7	7	5	12	7	3	2	-13
#1: with double glazing, cavity and loft insulation and draught-proofing. #2: with double glazing, internal insulation and draught-proofing.									

4. WP4: Tool-set application

4.1 Upgrade evaluation

The HUPS tool-set comprises two components: a Web-based upgrade evaluation tool and a spreadsheet-based technology evaluation tool. Figure 3 shows the interface of the Applet that comprises the former tool (URL2 2003). Only heating energy is being considered here.

Typically, a user might proceed as follows. First, the property to be upgraded is selected from a list using the 'Property Type' entity, or defined in terms of its governing parameters using the 'Property Characteristics' entity. It is envisaged that the parameter levels for a given house would be determined as a function of the age of the property. This is because the building standards in force at the time may be regarded as a proxy for the construction from which the level and distribution of insulation and capacity may be inferred. The infiltration category may be established via visual inspection of the potential leakage paths around windows, doors and other envelope penetrations.

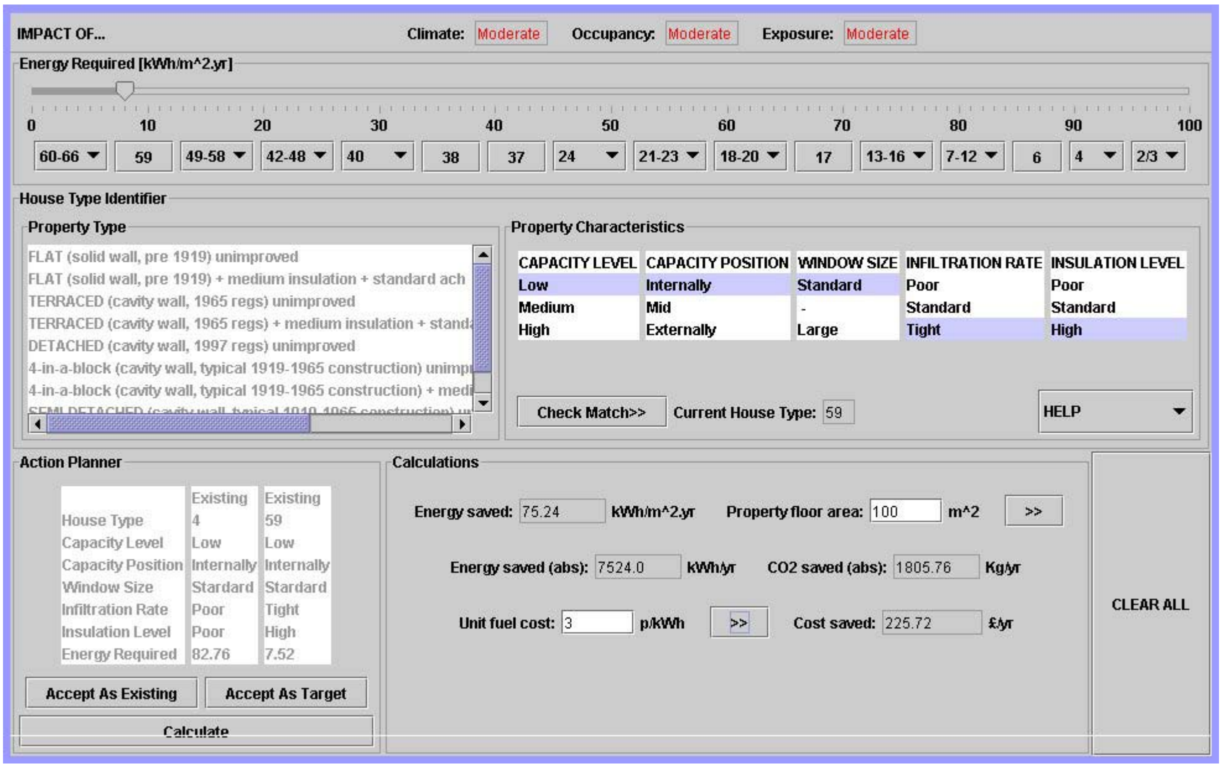


Figure 3: Assessing the impact of housing upgrades.

In either case, menu selection or property definition, the TC is automatically identified within the 'Current House Type' entity (say TC 4). The horizontal slider located near the top of the Applet may then be used to read off the corresponding heating energy demand (approximately 82 kWh $m^{-2}y^{-1}$ for TC 4). The house properties and energy demand data are automatically transferred to the 'Action Planner' entity. The slider may then be moved to another position (say TC 22 as shown here). The design properties and energy demand estimate (here 30 kWh $m^{-2}y^{-1}$) of the target house are then transferred to the 'Action Planner'. After the initial and target properties are accepted by the user, the saving expressed in energy, monetary and CO_2 terms is computed and displayed. The practicalities of implementing these upgrades on specific houses will be established typically via a site inspection if sufficient information on house configurations is not known. This will determine the feasibility of implementing the upgrades as implied by the parameter differences indicated in the 'Action Planner'.

Finally, the cost of implementation would be established as a function of the planned replication extent in order to ensure best value. In practice, the tool may be used strategically to explore alternative upgrade strategies in order to select the most cost-effective options. In some circumstances, it may be desirable to implement upgrades piecemeal over time. For example, a property corresponding to TC 4 might be upgraded to one corresponding to TC 22 in the first instance and then to one corresponding to TC 27 thereafter. In this way, the tool supports action planning over extended periods of time.

To determine the impact of possible future events, such as climate change or improved standards of living, the 'Impact of' pop-up menu may be used. In the case of climate change, this re-invokes the equations of Table 11 but with a user-specified temperature increase applied to the monthly weather data. The result is a new 'Energy Required' slider scale showing the reduced heating demands that would result.

To consider the impact of an improved standard of living, the equations of Table 10 are substituted by a replacement set constructed on the basis of simulations conducted against an alternative heating control system regime. As before, the result is a new slider scale enabling the impact appraisal process to proceed as described above.

4.2 Technology evaluations

Figures 4 and 5 show the interface of the second tool when used to undertake an assessment of the utilisation of local energy resources (renewables and recovered energy) and the application of energy efficiency measures. As a function of the describing parameters of the house type to be upgraded, an assessment of the solar thermal, solar electric, wind power and heat recovery potentials can be appraised and displayed (Figure 4).

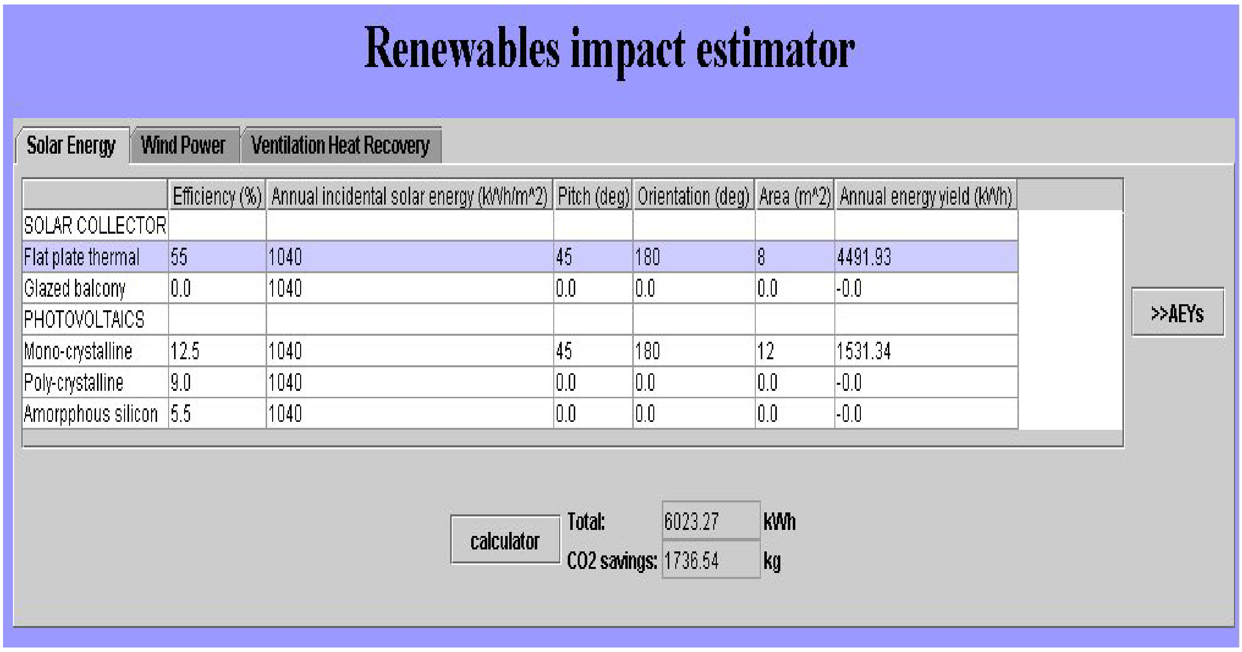
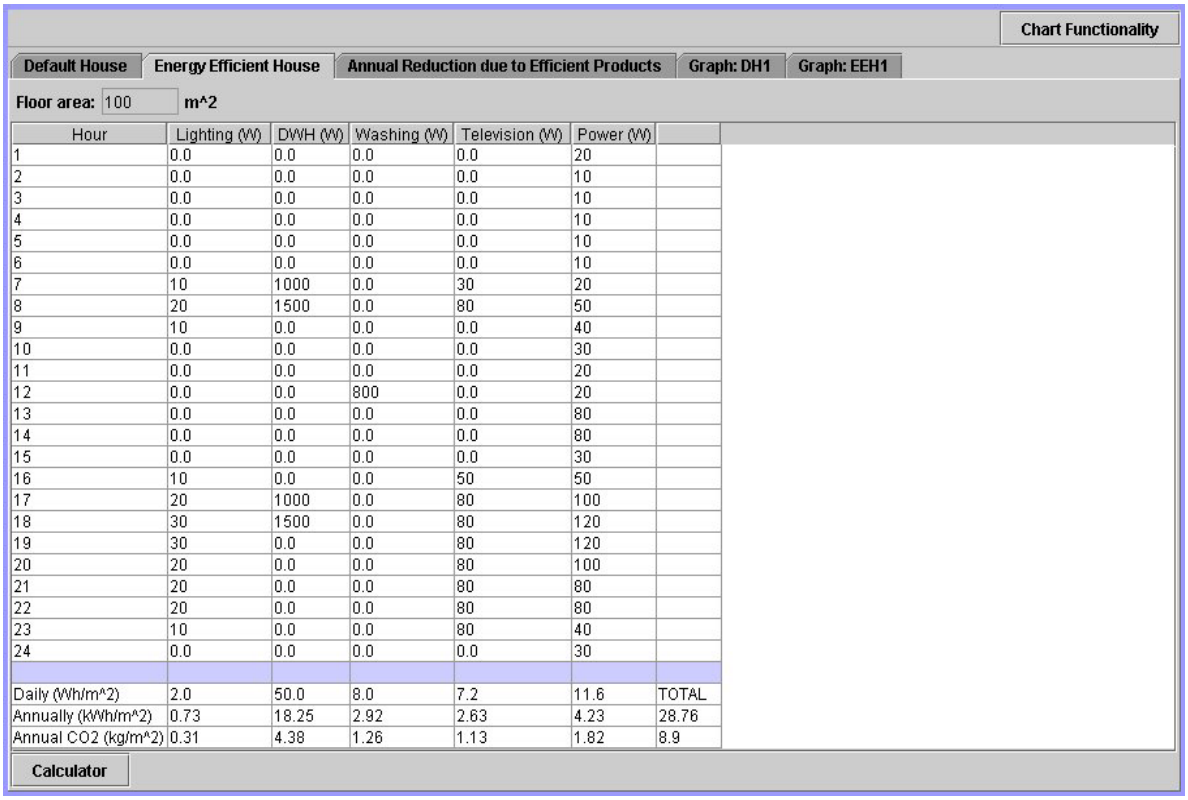


Figure 4: Assessing the potential of local energy resources.

A second screen (Figure 5) supports a floor area normalised assessment of the impact of energy efficiency measures attainable when applying higher efficiency brown and white domestic appliances. The impact the energy efficiency measures have on reducing and reshaping the demand profile can also be assessed as shown in Figures 6 and 7. Figure 6 identifies the demand profile associated with a default house, i.e. one without any energy efficiency appliances installed. Figure 7 identifies the associated demand profile for the same house when modified to include energy efficient lighting and higher efficiency white and brown goods/ appliances. By comparing Figures 6 and 7, the reduction in magnitude and alteration in time of the power demands associated with the energy efficient appliances may be established. The tabularised impact on energy saved and reduced CO_2 emissions resulting from these measures are shown in Figure 3.



Hour	Lighting (W)	DWH (W)	Washing (W)	Television (W)	Power (W)	
1	0.0	0.0	0.0	0.0	20	
2	0.0	0.0	0.0	0.0	10	
3	0.0	0.0	0.0	0.0	10	
4	0.0	0.0	0.0	0.0	10	
5	0.0	0.0	0.0	0.0	10	
6	0.0	0.0	0.0	0.0	10	
7	10	1000	0.0	30	20	
8	20	1500	0.0	80	50	
9	10	0.0	0.0	0.0	40	
10	0.0	0.0	0.0	0.0	30	
11	0.0	0.0	0.0	0.0	20	
12	0.0	0.0	800	0.0	20	
13	0.0	0.0	0.0	0.0	80	
14	0.0	0.0	0.0	0.0	80	
15	0.0	0.0	0.0	0.0	30	
16	10	0.0	0.0	50	50	
17	20	1000	0.0	80	100	
18	30	1500	0.0	80	120	
19	30	0.0	0.0	80	120	
20	20	0.0	0.0	80	100	
21	20	0.0	0.0	80	80	
22	20	0.0	0.0	80	80	
23	10	0.0	0.0	80	40	
24	0.0	0.0	0.0	0.0	30	
Daily (Wh/m^2)	2.0	50.0	8.0	7.2	11.6	TOTAL
Annually (kWh/m^2)	0.73	18.25	2.92	2.63	4.23	28.76
Annual CO2 (kg/m^2)	0.31	4.38	1.26	1.13	1.82	8.9

Figure 5: Assessing the potential of energy efficient appliances.

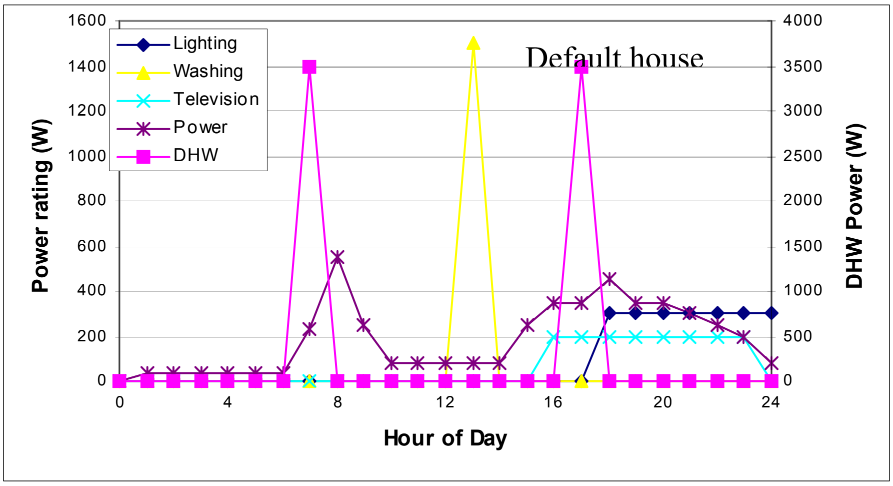


Figure 6: Demand profile for house without energy efficient appliances.

The purpose of this additional analysis is to inform decision makers about the impact the various approaches have on reducing energy demands in order that the most cost-effective options may be chosen.

Taken together, the results from both tools support a reasoned approach to the large scale upgrading of the domestic sector. The approach is widely applicable since the thermodynamic classes are universal while the underlying simulations may be re-run for any number of anticipated circumstances, including the appearance of new technologies in future. This two stage appraisal approach enables policy makers and housing stock owners to identify which options give them the best return, in terms of energy use reduction and CO_2 emissions mitigation, on the investment in the upgrade.

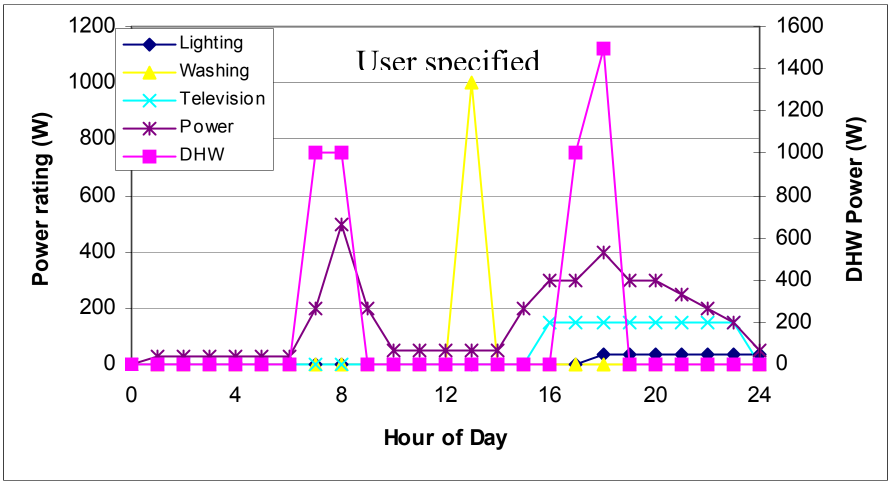


Figure 7: Demand profile for house with energy efficient appliances.

4.3 Applicability

To test the robustness of the HUPS approach and the potential energy and CO_2 savings that might be realised in practice, two test cases were appraised using the tool. The test cases chosen comprised a terraced house constructed with a solid wall, representing 5% of the Scottish housing stock (110,000 units), and a pre-1965 solid wall tenement flat, representing 9% of the housing stock (201,000 units).

Test Case 1: Solid wall terraced dwelling

The house consisted of 90m^2 of floor area and 80m^2 of external wall area. The annual energy use prior to the implementation of upgrading options was 13,710 kWh, equating to 3900 kg of equivalent CO_2 emissions. This breaks down to 8190 kWh associated with space heating (1965 kg of CO_2 emissions) and 5520 kWh associated with domestic hot water, lighting and brown and white appliances (1935 kg of CO_2 emissions).

The first stage is to assess the options available to reduce the energy used for space heating. In this case, the application of double glazing, loft insulation and draught-proofing were identified as feasible options, as shown in Table 17. These measures equate to a cost of £1600, £200 and £150 respectively.

Table 17: Impact of upgrades on annual heating energy demand.

Option	Cost (£)	Revised energy consumption (kWh)	CO_2 emitted (kg)	Energy saved/£ (kWh/£)	CO_2 reductions/£ (kg/£)
Double Glazing	1600	7,249	1,739	0.59	0.14
Loft insulation	200	7,603	1,824	2.94	0.71
Draught-proofing	150	6,722	1,613	9.79	2.35
All above applied	1950	4,308	1,034	1.99	0.48

The application of the above options gives rise to the following outcomes:

- £1600 spent on double glazing reduces the heating energy demand by 11.5% and results in an annual energy saving of 941 kWh (226 kg of CO_2).
- £200 spent on loft insulation reduces the heating energy demand by 7% and results in an annual energy saving of 587 kWh (141 kg of CO_2).
- £150 spent on draught-proofing reduces the heating energy demand by 18% and results

in an annual energy saving of 1468 kWh (352 kg of CO_2).
- Deploying all three measures together (at a cost of £1950) reduces the heating energy demand by 47% and gives rise to an annual energy saving of 3882 kWh (931 kg of CO_2).

The second stage is to assess the impact of the introduction of energy efficient domestic hot water heating, lighting and brown and white appliances. For a standard dwelling with no energy efficient appliances, the annual energy consumption is 5520 kWh (1936 kg of CO_2 emission). The outcomes for the assessment are listed in Table 18.

Table 18: Impact of energy efficient appliances on annual energy demand.

Option	Cost (£)	Revised energy consumption (kWh)	CO_2 emitted (kg)	Energy saved (kWh/£)	CO_2 reductions (kg/£)
Gas boiler	800	4,699	1,739	1.03	0.25
Energy efficient lamps	40	4,905	1,671	15.34	6.63
Energy efficient brown and white appliances	no additional cost	4,955	1,963	-	-
All above applied	840	3,519	704	2.38	0.84

The application of the above options gives rise to the following outcomes:
- £800 for energy efficient boiler replacement, reducing the annual domestic hot water energy demand by 15% and giving a saving of 821 kWh (197 kg of CO_2).
- £40 for energy efficient lamp replacement, reducing the annual energy demand by 11% or 615 kWh (265 kg of CO_2).
- The replacement of brown and white appliances with energy efficient alternatives will result in marginal if any additional costs at the time of replacement but will reduce the annual energy demand by 10% or 565 kWh (243 kg of CO_2).

When applied together, the measures will reduce the annual energy demand by 36% (from 5520 kWh to 3519 kWh) while reducing the associated CO_2 emissions also by 36% (from 1936 kg to 1232 kg).

When assessing the energy saved (or CO_2 emission mitigated) per unit cost of the energy saving measure, the higher the rating the more effective the return on investment. This gives policy makers and housing managers an effective mechanism to produce a sequenced deployment plan.

The combination of the two stage approach demonstrates that the dwelling’s annual energy use can be reduced from 13710 kWh (3900 kg of CO_2) to 7,659 kWh (2,226 kg of CO_2), a saving of 44% and 43% for energy use and CO_2 emissions respectively. If these measures can be replicated throughout Scotland's 110,000 solid wall, terraced dwellings then the scaled-up impact would be considerable. For example, if all three measures are applied, the energy demand would fall from 1508 GWh/annum (429,000 Tonnes of CO_2) to 842 GWh/annum (245,000 Tonnes of CO_2), giving an annual saving of 666 GWh (184,000 Tonnes of CO_2) in an estate that corresponds to only 5% of the Scottish housing stock! In reality, the opportunity to apply these measures to all dwellings in the category would be limited by the fact that the stock is already in varying stages of upgrade. An assessment of the state of the housing stock at any time may be assessed from published data (e.g. Utley *et al* 2001).

Test case 2: Tenement flat

A second case study was undertaken focusing on a pre-1965 solid wall tenement flat. This type of dwelling represents 9% of the Scottish housing stock or 201,000 units. The flat has a floor area of 60m^2, an external surface area of 24m^2 and an annual energy consumption of 8880 kWh (2503 kg of CO_2). The breakdown of the annual energy use gives 5220 kWh for space heating and 3660 kWh associated with brown/white goods and domestic hot water (1252 kg and 1291 kg of CO_2 respectively). If this annual consumption were extrapolated to all dwellings in the sector, the result would be 1,785 GWh/annum equating to 511,143 Tonnes of CO_2 emissions.

The construction technologies considered apposite in terms of reducing space heating energy demands are identified in Table 19 while the results of applying the generic measures are given in Table 20.

The application of energy saving measures to both space heating, domestic hot water and brown/white goods has reduced the annual energy consumption of the tenement flat from 8880 kWh to 4362 kWh, i.e. a 51% reduction. When translated to CO_2 emissions, the reduction is from 2543 kg to 953 kg, i.e. a 63% reduction. If these savings are extrapolated to the Scottish tenement stock, annual energy and CO_2 emissions savings of 908 GWh and 319,590 Tonnes respectively could be realised.

As with the previous case, the opportunity to apply these measures to all dwellings in the category would be limited by the fact that the stock is already in varying stages of upgrade.

Table 19: Impact of construction measures on annual heating energy demands.

Option	Cost (£)	Revised energy consumption (kWh)	CO_2 emitted (kg)	Energy saved (kWh/£)	CO_2 reductions (kg/£)
Double glazing	1,400	4,290	1,030	0.66	0.16
Internally insulated wall	400	3,858	926	3.4	0.8
Externally insulated wall	1,920	3,696	887	0.8	0.2
Draught-proofing to 1a.c./h.	150	3,708	890	10	2.4
Draught-proofing to 0.5 a.c./h.	300	3,600	864	5.4	1.3
Application of double glazing, internal insulation and draught-proofing to 1 a.c./h.	1,950	2,016	484	1.6	0.4

Table 20: Impact of energy efficient appliances on annual energy demands.

Option	Cost (£)	Revised energy consumption (kWh)	CO_2 emitted (kg)	Energy saved/£ (kWh/£)	CO_2 reductions/£ (kg/£)
DHW	800	3,133	1,160	0.66	0.16
Energy efficient lamps	40	3,270	1,113	9.75	4.45
Energy efficient brown/white appliances	no additional cost	3,303	1,309	-	-
All above applied	840	2,346	469	1.6	0.98

Macro impact

In both case studies, substantial energy and CO_2 emission savings of the order of 50% have been demonstrated. Using Scottish average annual energy consumption figures (12000 kWh for space heating, 7500 kWh for domestic hot water and 4500 kWh for electrical power), the estimated annual savings across the entire Scottish housing stock (based on a conservative 35% improvement in a dwelling's energy performance) is of the order of 9.38×10^9 kWh (9.38 TWh) equating to 3.12×10^6 Tonnes of mitigated CO_2 emissions.

Using the decision-support tool, energy policy developers, local authority planners and housing managers have the ability to appraise the impact of potential refurbishment measures and thereby determine which measures give the most effective return on investment. This return may be judged in terms of energy cost reduction, where the focus is fuel poverty alleviation, or CO_2 emissions reduction, where the focus is the attainment of national targets or compliance with legislation.

The HUPS tool set can be accessed via the ESRU web site: http://www.esru.strath.ac.uk. On the left hand side of the ESRU homepage, click on the research icon followed by clicking on Energy Efficiency when asked to select a topic. To run the software a java platform needs to be installed on the computer. The specific software to be downloaded is Java(TM) 2 Runtime Environment, Standard Edition 1.3.1_13, which can be downloaded from URL http://java.sun.com/j2se/1.3/.

5. WP5. Application of the tool

5.1 Breakdown and mapping of the Scottish housing stock.

A digest of the 2002 Scottish house condition survey data has shown that the 2,278,000 dwellings in Scotland translate to a total annual space heating demand of 14.5 TWh and CO_2 emissions of 5.5 MT. The energy demands for space heating account for 17% of the total Scottish demand. The mapping of the Scottish housing stock to thermodynamic types was undertaken based on house architectural type and year of construction. The mapping is shown in Table 21. From the mapping process it can be shown that the entire Scottish housing stock can be represented and classified into 8 thermodynamic classes as listed in Table 22. As can be seen, the largest housing sector is contained within thermodynamic category TC6, representing 42% of the Scottish housing stock or approximately 956,000 units. This is followed by TC2 and TC1 representing 16.5% and 11.5% respectively. TC6 represents dwellings constructed over the periods 1919-65 and 1966-97 using an un-insulated cavity wall, which accounts for a space heating demand of 6.3 TWh/yr. TC2 represents dwellings constructed over a similar period but with a solid wall and no insulation, and accounts for an annual space heating demand of 2.8 TWh. TC1 represents a traditional pre-1919-65 construction using a solid wall of high thermal mass and accounts for an annual space heating demand of 2 TWh.

5.2 Proposed upgrading strategy for existing dwellings

Practical considerations dictate that any upgrading strategy should focus on low cost technologies initially to maximise the return on any investment and be phased over time thereafter to accommodate technical advances. Reducing fabric and ventilation heat loss are the most effective measures to improve the thermal performance of dwellings. In the former case, higher levels of insulation will be required. In the latter case both draught proofing and ventilation heat recovery may be utilized, with draught proofing being the better cost effective option for the Scottish housing stock. The addition of insulation and draught proofing to varying levels was assessed in this study.

When attempting to decide which houses should be tackled first within an upgrading programme, it is necessary to consider the product of the population size within a specific TC and the heating energy demands associated with the TC. The greater this value, the greater the energy saving potential and hence the higher the priority for upgrade. The data of Table 22 indicates that to achieve maximum impact, an upgrade programme should initially target TC6 category dwellings, followed by TC2 and TC1. Targeting of these three TCs will cover 70% of the Scottish housing stock. A second phase of upgrading should then target TC7, which covers 7% of the housing stock and corresponds to 8% of the total heating demand. TC7 represents houses constructed in the period 1965–97 consisting of a cavity wall with thermal mass on the interior, standard insulation and excessive air infiltration rate.

The third phase should target TC17 and TC18 representing 8% and 11% of the Scottish housing stock respectively. These TCs represent dwellings built during 1965-19 that have a cavity wall with standard levels of insulation and air tightness. The main difference is the location of the thermal mass: in TC18 the position of the thermal mass is on the outside of the cavity, while TC17 has the thermal mass located on the inside.

The final phase should target TC19, which represents non-traditional construction types built during the period1965-97. This represents 2.5% of the housing stock. Construction primarily consists of an insulated thermal mass wall with standard levels of insulation and air tightness.

5.3 Quantification of energy savings associated with upgrading

The proposed upgrading schedule features draught proofing and insulation because these measures are cost effective and relatively easy to implement. The initial upgrading phase should target type TC6 dwellings by improving their air tightness. This will result in a change of the thermodynamic class to TC11 and give rise to an 8 kWh/m^2 (from 75 kWh/m^2) reduction in the annual heating energy demand (i.e. a saving of 0.67 TWh or 4.6% relative to the present national annual heating energy demand). The addition of insulation to TC11 moves it to TC18, resulting in a further reduction of 20 kWh/m^2 corresponding to a saving of 2.2 TWh/yr or 15.5% of the national space heating demand.

Table 21: Mapping of Scottish housing stock to TCs.

Type %	60%				37%				3%		
Total housing stock: 2.3 million dwellings	Pre 1919-64				1965-97				1997-2002		
	Cavity	Solid	Non- Traditional Cavity	Non- Traditional Solid	Cavity	Solid	Non- Traditional Cavity	Non- Traditional Solid	Cavity Timber	Cavity Traditional	
	32%	24.5%	2%	1.5%	26 27%	0%	6%	5%	1%	2% 3%	**Total**
Houses (62%)											
Detached (17%) (19%)	4% **TC: 6**	4% **TC: 2, 1**			8% **TC: 6, 7, 17, 18**		1% **TC: 6, 18**	1% **TC: 2, 19**	***0.5%*** **TC: 26**	***0.5%*** **TC: 17, 18**	19%
Semi-detached (21%) (22%)	**TC: 6**	4.5% **TC: 2, 1**			6% **TC: 6, 7, 17, 18**		1% **TC: 6, 18**	1% **TC: 2, 19**	0.5% **TC: 26**	0.5% **TC: 1 18**	22% 1.5%
Terraced (22%) (21%)	7% **TC: 6**	3% **TC: 1, 2**	0.5% **TC: 6**	0.5% **TC: 2**	*7%* **TC: 6, 7, 17, 18**		1.5% **TC: 6, 18**	1.5% **TC: 2, 19**			21%
Flats (38%)											
Tenement (23%)	***6%*** **TC: 6**	**9%** **TC: 2, 1**	0.5% **TC: 6**	0.5% **TC: 2**	5% **TC: 6, 7, 17, 18**		1% **TC: 6, 18**	1% **TC: 2, 19**		0.5% **TC: 17, 18**	23%
4-in-Block (11%)	***6%*** **TC: 6**	2% **TC: 1, 2**	0.5% **TC: 6**	0.5% **TC: 2**	1% **TC: 6, 7, 17, 18**			0.5% **TC: 2, 19**		0.5% **TC: 17, 18**	11%
Tower/Slab (3%)	1% **TC: 6**		0.5% **TC: 6**				1.5% **TC: 6, 18**				3%
Conversion (2%)		2% **TC: 1, 2**									2%
Total	32%	24.5%	2%	1.5%	27%		6%	5%	1%	2%	100%

Table 22: Digest of existing Scottish dwellings.

TC Number	Thermodynamic classification	% of Scottish housing stock	Number of dwellings	Floor area (m^2)	Annual heating demand (kWh/m^2)
1	Solid wall, high thermal mass, large windows, poor insulation and large air change rate	11.5	261,970	22,461,000	90
2	Solid wall, high thermal mass, standard windows, poor insulation and large air change rate	16.5	375,870	31,778,000	87
6	Cavity wall, outer thermal mass, standard windows, poor insulation and large air change rate	42	956,760	83,283,000	75
7	Cavity wall, inner thermal mass, large windows, standard insulation and large air change rate	7.25	165,155	15,934,000	73
17	Cavity wall, inner thermal mass, standard windows, standard insulation and standard air change rate	8.25	187,935	18,087,000	47
18	Cavity wall, outer thermal mass, standard windows, standard insulation and standard air change rate	11	250,580	23,810,000	47
19	Solid wall, standard thermal mass, standard windows, standard insulation and standard air change rate	2.5	56,950	5,159,000	46
26	Timber wall, outer thermal mass, standard windows, high insulation and standard air change rate	1	22,780	2,596,000	26

When targeting type TC2, simultaneously improving air tighness and insulation level will change it to a type TC19 with a saving of 41 kWh/m^2 (from 87 kWh/m^2). This corresponds to a saving of 1.3 TWh/yr (or 9% of the annual national heating energy demand).

In the case of TC1, the addition of insulation to a high standard alters the thermodynamic class to TC16, giving a saving of 43 kWh/m^2 (from 91 kWh/m^2) or 0.9 TWh per year (6.5%). Where draught proofing and an insulation upgrade is applied to TC1 the thermodynamic class would shift to TC21, giving a saving of 35 kWh/m^2 or 1.2 TWh annually (8.7%).

Within the second phase of an upgrade programme, targeting thermodynamic class TC7, by improving both air tightness and insulation, changes the class to TC28. This would reduce the annual space heating demand by 62 kWh/m^2 (from 73 kWh/m^2) giving an annual energy saving of 1 TWh (7%).

The third phase of the programme should focus on TC18 and TC17, both of which may be upgraded in increments. Initially, improving air tightness will change the class to TC22, giving an annual saving of 17 kWh/m^2 (from 47 kWh/m^2) or 0.7 TWh annually (5%). Only upgrading the insulation level for TC17 and TC18 changes the thermodynamic type to TC24, resulting in an energy demand reduction of 21 kWh/m^2, equating to an annual energy saving of just under 0.9 TWh (6%). Applying both measures to TC17 and TC18 changes the type to TC30, which reduces demand by 38 kWh/m^2 or 1.6 TWh annually (11%).

The final phase of an upgrading programme should focus on thermodynamic type TC19 by improving air tightness. This will result in a saving of 35 kWh/m^2 (from 46 kWh/m^2) or 0.06 TWh (0.4%).

Table 23 identifies the range of annual space heating savings that can be achieved by the phased upgrading of the Scottish housing stock.

Table 23: Summary of improvement measures.

TC	Quantity relative to housing stock (%)	Percentage of annual heating demand (%)	Suggested improvement	New TC	Reduction in national heating demands (TWh)	(%)
6	42	43	Air tightness to high standards	**11**	0.67	4.6
11			Insulation to standard levels	**18**	2.2	15.5
2	16.5	19	Standard levels of draught proofing and insulation	**19**	1.3	9
1	11.5	14	High levels of draught proofing and standard levels of insulation	**21**	1.2	8.7
7	7.25	8	High levels of draught proofing and insulation	**28**	1	7
17 & 18	19.25	13.5	High levels of draught proofing	**22**	0.7	5
			High levels of insulation	**24**	0.9	6
			High levels of draught proofing and insulation	**30**	1.6	11
19	2.5	1.5	High levels of draught proofing and standard levels of insulation	**21**	0.06	0.4

5.4: Impact of proposed Scottish housing upgrading strategy

The implementation of the improvement measures in a phased programme will result in savings in the annual space heating energy demand of 4.7 TWh (or 33.2% of the national energy demand) by the end of the first phase. This may be achieved by focusing solely on buildings of type TC6, TC2 and TC1. These savings would rise to 5.7 TWh (40.2%) by the end of phase 2 through the inclusion of type TC7. By the end of phase 3, the savings would have increased to 7.3 TWh (51.2%) by the inclusion of types TC17 and TC18. In the final phase of the programme, the annual space heating energy savings would rise to 7.36 TWh (51.6%) by targeting type TC19 dwellings.

Overall, such a phased programme would reduce the annual energy demand of the Scottish housing stock from 14.5 TWh to 7.14 TWh (or 51.6% of current demand).

6. WP 6. Monitoring to facilitate future decision-making

6.1 Data capture requirements

Appropriate data capture, management and analysis will be required to inform policy makers and housing stock owners of the progress being made in relation to energy and CO_2 emissions reduction. Already, raw statistical data on the Scottish housing stock is being compiled and structured via the Scottish House Condition Surveys of 1996 and 2002. However the format and resolution of these data is insufficiently comprehensive to evaluate the success of improvement measures when applied piecemeal over time. What is required is the routine capture and analysis of energy use data. Fortunately, low cost monitoring and database systems now exist to support such an activity; Figure 8 summarises the concept.

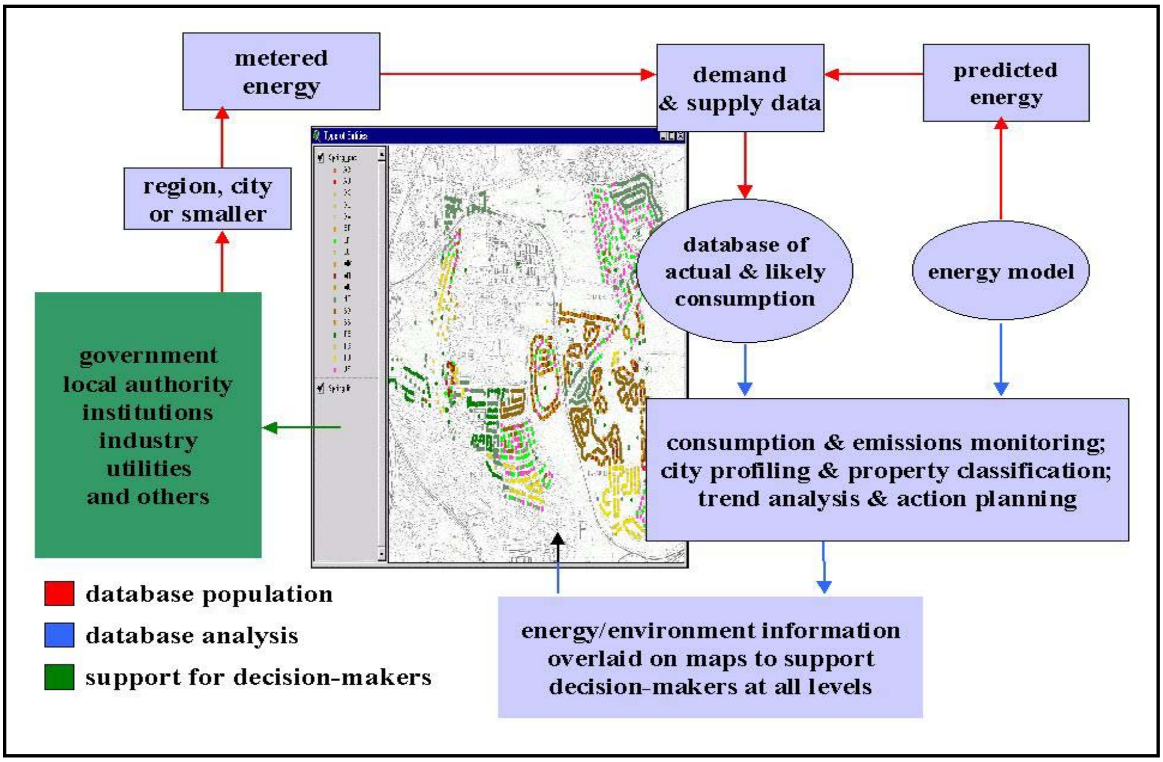


Figure 8: The low cost monitoring concept.

Acting in partnership, utilities, local authorities and others feed information to a shared database covering some geographical area of interest. To accommodate the temporal and scope mismatches between its component parts, the database is distributed, with Internet-resident control agents acting to recover suitable integrations when enquiries at the aggregate scale are submitted (e.g. on domestic sector energy use and gaseous emissions by period, geographical location, property age, fuel type *etc*). These data may then be analysed in order to provide relevant and 'up-to-the-minute' information to a range of possible recipients, from policy makers, through housing stock managers and designers, to citizens. To assist with interpretation, a Geographical Information System may be employed to overlay the energy and environment information on conventional types of information such as street layouts. To assist with policy formulation, an energy model (such as the HUPS toolset developed within this project) is included to enable an appraisal of options for change. Where an option proves beneficial, the reduced energy demand may be returned to the database to be held alongside the present power and fuel use data. This enables the side-by-side display of information relating to the present and future cases in support of extensive inter-comparisons at the large scale before deployment decisions are taken.

In use, such a system would permit the routine monitoring of house performance and thereby identify immediately the benefits (or otherwise) of upgrades as an when deployed in whatever combination.

6.2 Data sources

The central and crucial requirements of such an information system are database construction and maintenance. Two data collection methods are extant: electronic data interchange (EDI) and direct meter reading via the Internet. EDI entails the regular exchange of data via computer files adhering to a pre-agreed format. It is a typical interaction mode between large organisations such as local authorities and utilities. Direct meter reading requires the embedding of sensors throughout the monitored estate and the connection of these sensors to a local electronic gateway device giving access to the Internet. This approach, as summarised in Figure 9, is particularly suited to application at the domestic scale.

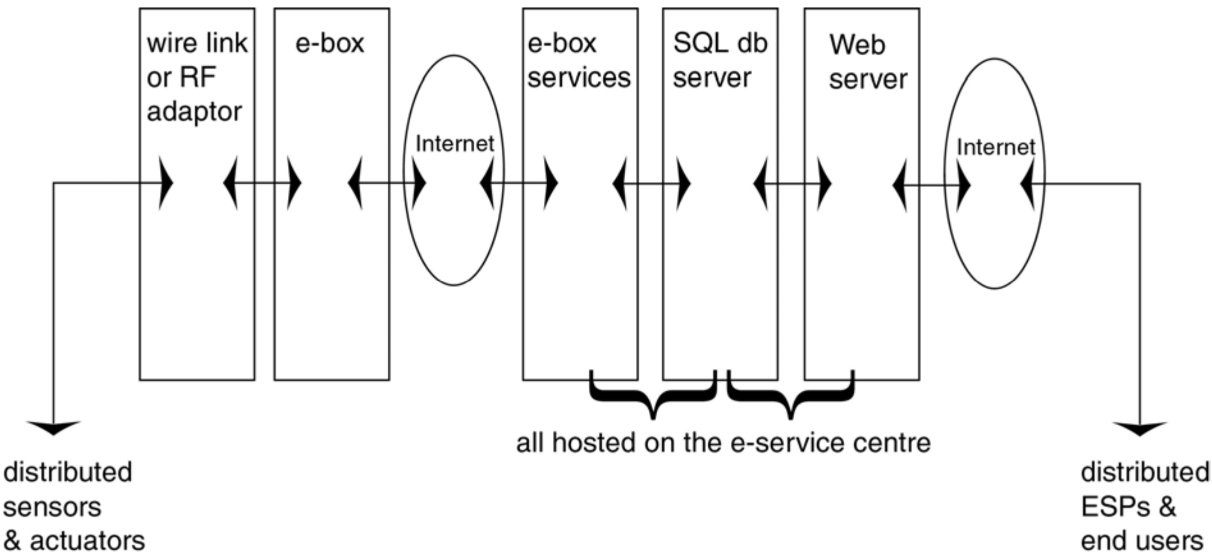


Figure 9: Elements of an Internet energy information system.

Low cost sensors (and actuators if the interaction is two-way) are embedded in each house. Typically, sensors would be deployed to monitor internal and external temperatures and electricity and gas consumption, with data captured as mean values on a half-hourly basis. This enables the energy performance of the house to be quantified while taking changes in thermal comfort levels into account. An Internet access device, or e-box, exists to receive/send information from/to the sensors/actuators and send/receive data to/from an e-service centre located at some arbitrary location on the Internet. At the e-service centre, the private data arriving concurrently from all sites within a given serviced region are brought together and organised (i.e. the e-service centre possesses the software necessary to receive and organise the returns from registered e-boxes). All data are held within a SQL server database with associated software agents acting to extract the information corresponding to the scope defining a particular user enquiry.

Where a permanent Internet connection is not available, Gemini Ultra Tinytag temperature and humidity loggers may be used. This device can be programmed to store 30-minutely, mean temperature/humidity data for up to 3 months. Electricity and gas consumption may be acquired directly from the utility companies supplying the dwellings.

7. Conclusions and recommendations

This project has summarised the existing status of the Scottish housing stock and demonstrated the potential for energy savings and CO_2 emission reductions. To enable policy makers and housing managers to select energy efficiency measures for specific cases, a two part decision-support tool has been developed. One tool supports comparative investigations of the cost-benefit of applying building-specific measures such as draught-proofing, insulation upgrading and so on. A second tool focuses on generally applicable measures such as heat recovery, boiler replacement, tank/pipe insulation, efficient lighting and the like. The former tool operates with thermodynamic classes (TC), which span the range of possible house types, existing and planned; use of the tool requires the mapping from an actual design to a TC. The tool-set is available under Open Source licence (URL3 2003). Future intentions are to deepen the tool-set by extending the underlying model of occupancy interaction and the number of technologies that may be applied (e.g. combined heat and power).

Application of the tool-set has indicated that savings of the order of 50% can be achieved in terms of both energy use and CO_2 emissions, which when scaled to the Scottish housing stock gives a potential energy saving of up to 9.38×10^9 kWh (3.12×10^6 Tonnes of CO_2). In reality, the actual saving will be less than this depending on the level of upgrades that are already in place.

To be effectively applied in practice, the tool-set will require inputs from site inspections. These are required to identify the design parameters from which a matched TC may be identified, and to assist with the translation of identified upgrade measures to the feasibility of implementing these to the specific housing stock being assessed. In whole, such activities as outlined in this report are fully compatible with the intentions of the EU directive on the Energy Performance of Buildings.

The next stage of the work programme should focus on correlating the TC categories within the tool to SAP ratings used in assessing the energy performance of new build housing. This will enable the tool to be used for assessing and labeling the energy performance of dwellings in order that compliance with the EU EPB directive is achieved within the required time frame.

8. Acknowledgements

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