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SIMULATION SUPPORT FOR THE FORMULATION OF DOMESTIC SECTOR UPGRADING STRATEGIES

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ABSTRACT

This paper describes the application of a building simulation program to construct a decision-support tool for use by policy makers addressing the needs of the Scottish domestic housing sector. The process of tool formulation is described and an example given of its use to identify best-value retrofit options while taking factors such as future climate change and improved standard of living into consideration. It is argued that the process of tool formation renders it applicable to the cumulative roll-out of upgrade measures in the long term, both within and outwith the UK.

CONTEXT

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, most national governments have substantial policy instruments focused on the sector. In Scotland, for example, there are 2,232,000 dwellings of which 5% are vacant and 2% due for demolition. The majority of dwellings are houses (52%) and flats (38%). Some 36% (795,000) were constructed within the last 30 years, while 26% (590,000) were constructed between 1945 and 1965. In constructional terms, the breakdown is given in Table 1.

Table 1: Scottish construction types.

Construction system	%
Cavity wall	71
Solid wall	28
Material	**%**
Brick/block	67
Sandstone	18
Whin/granite	4
Non-traditional	10
External finish	**%**
Rendered	71
Stone	18
Brick	5
Non-traditional	5

The latest house condition survey (Scottish Homes 1997) assigned a mean National Home Energy Rating of 4.1 on a scale from 0 (poor) to 10 (good), indicating that there is a significant need for energy efficiency improvements:

- While 80% of dwellings have loft insulation, in only 12% of cases does this meet the 1991 building standards.
- While 92% of dwellings have satisfactory hot water tank insulation, and 74% have satisfactory levels of pipe insulation, there remain 100,000 dwellings with unacceptable levels of the former and 281,000 with unacceptable levels of the latter.
- While 70% of homes (1,559,000) have full gas central heating, and 14% have partial installations, 13% (290,000) have no central heating. This gives rise to concerns about fuel poverty and the health-related problems associated with hypothermia, condensation and mould growth.

Table 2: Scottish house types.

Detached	No adjoining dwelling.
Semi-detached	One other adjoining dwelling.
Terraced	Several adjoining dwellings.
Tenement	Flats within a block with shared access.
Four-in-a-block	Each flat has its own access.
Tower block	Maisonettes and flats in a multi-storey block.
Conversion	Flats resulting from the conversion of a house or non-residential building.

Table 2 lists the existing Scottish house types. For each type, a range of sub-types can be identified depending on the age of the property. This is especially the case for housing constructed between 1945-1964, when there existed a shortfall in supply, and 1965-1982, when the availability of new materials facilitated novel solutions. These dwellings form a large proportion of those currently

Table 3: 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/ Maisonette 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/ Maisonette 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/ Maisonette Four-in-a-block Tower block

requiring refurbishment. In relation to construction types, the categories of Table 3 are relevant.

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 response by the Scottish Executive (SE) to the present need is to use regulatory means to bring about energy efficiency improvements over time. The impetus for the present project was to assist this process while ensuring compatibility with the new EU Directive on Building Energy Performance (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? and 3) how should the deployments be phased over time? SE 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.

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 possible energy efficiency measures. While a simulation-based approach was adopted within the project, for reasons explained in the following section, it was not deemed necessary to simulate directly the many possible permutations.

PROJECT OUTLINE

Contemporary simulation tools are powerful, with features that allow them to quantify the integrated performance of a building when operating under realistic weather 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. While simplified programs do exist—e.g. the EPIQR system which has been designed for the German market to enable the rapid assessment of retrofit options for specific apartment buildings (EPIQR 2002)—these require building specific inputs and are therefore not well tailored to the needs of policy makers.

Even if the interface dilemma can be overcome, there remains anothermaster_esru 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 (e.g. Tables 2 and 3), the task becomes intractable when viewed thermodynamically. Two 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 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 performaster_esrumance 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, thermal capacity level, capacity position and air permeability.

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 this tool will be used by SE personnel engaged in the development of building regulations in response to need and national policy drivers.

The impact of technologies that may largely 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.

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: Consruction-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 permeability. If each parameter can exist at one of three levels (poor, good or advanced; 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 efficiency upgrades, a greater proportion of the TC designs 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 4 summarises the parameter levels for each design, while Table 5 lists the values corresponding to each case. The monthly energy requirements

Table 4: 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	-0.110	0	0.0009	0.0130	22.7
2	0/0/2/2/0	0.181	-0.015	-0.157	0.2350	-0.0020	0.0013	-0.190	0.00010	0.0030	0.0204	17.4
3	1/0/1/1/1	-0.946	-0.005	-0.106	-0.0080	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	-0.0940	0.0028	0.0012	-0.121	0	-0.0020	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	-0.100	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	-0.220	0.00040	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	0.007	-0.113	-0.0240	-0.0020	0.0014	-0.072	0.00020	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	-0.0190	-0.0010	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	-0.0050	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	-0.0060	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 $W\ m^{-2}\ {}^oC^{-1}$), 1 standard (0.6 $W\ m^{-2}\ {}^oC^{-1}$), 2 high (0.3 $W\ m^{-2}\ {}^oC^{-1}$)
P3: thermal capacity level - 0 low, 1 medium, 2 high
P4: capacity position - 0 inner, 1 middle, 2 outer
P5: air permeability (i.e. air change rate) - 0 poor (1.5 h^{-1}), 1 standard (1 h^{-1}), 2 tight (0.5 h^{-1})

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

where E is the monthly energy requirement ($kWh\ m^{-2}$), θ the monthly mean temperature (^oC), 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.

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 4 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 (ESRU 2003). The assumptions underlying this model correspond to an 'average' house as determined from appropriate publications (e.g. Scottish Homes 1997, CIBSE 1999, Bartholomew and Robinson 1998).

Table 5: Values of the five construction-related parameters.

	Value	**Comment**
Window Size		
Standard	10% of floor 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 governing thermal regulations exist and therefore constructions have minimal thermal insulation.
[#]ISBN 91-7257-025-3
[%]Corresponding values for single, double and advanced glazings are associated with windows.

Stage 2: Other considerations

The energy performance of a range of 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 monthly demand profile for each defined appliance. By switching between appliances of different efficiency ratings, it is possible to determine rapidly the impact on the overall energy demand.

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).

MODEL VERIFICATION

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 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 value 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. Table 6 shows the level of agreement attained for a number of cases. As can be seen, the agreement ranges from a best case of 3% to a worst case of -13%. Note that the relatively good performance of the detached house is due to its compliance with recent standards; all other types are in need of upgrading.

Table 6: Comparison of results for real and generic (TC) models.

	Real House Type								
	Detached	Semi-detached		Terrace		Tenement flat		Four-in-a-block	
	As built	As built	#1	As built	#1	As built	#2	As built	#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.

Likewise, the robustness of the supply and heat recovery technologies was tested by comparing the results from detailed simulations with the corresponding predictions to emerge from the HUPS tool-set.

HUPS APPLICATION

The HUPS tool-set comprises two components: a Web-based upgrade evaluation tool and a spreadsheet-based technology evaluation tool. Figure 1 shows the interface of the Applet that comprises the former tool (URL2 2003; original in colour). 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.

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 (approx. 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 (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. A site inspection would then typically be arranged to 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 his way, the tool supports action planning over extended time periods.

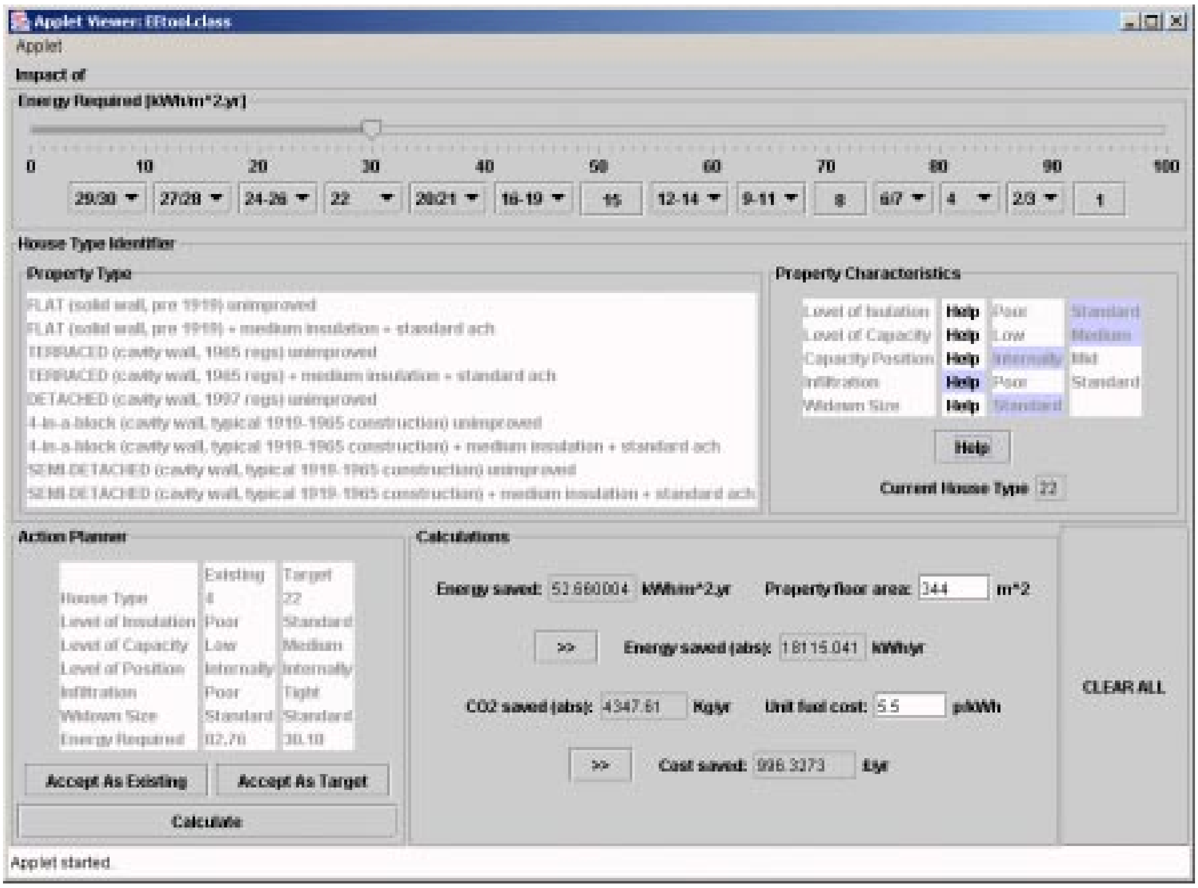

Figure 1: Assessing the impact of housing upgrades.

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 4 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 4 are substituted by a new set constructed on the basis of simulations conducted against an alternative heating control system regime. The result is again a new slider scale enabling the impact appraisal process to proceed as described above.

Figure 2 shows the interface of the second tool (URL3 2003; original in colour) for the case of an assessment of local energy resources. 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 are displayed. A second screen (not shown here) supports an assessment of the impact of energy efficiency measures applied to brown and white domestic appliances.

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 and the simulations may be re-run for any number of anticipated circumstances, including the appearance of new technologies in future.

CONCLUSIONS AND FUTURE WORK

An integrated simulation program has been applied to a set of house designs corresponding to distinct thermodynamic classes established to represent the spectrum of possible house thermal responses. The outcome, when expressed as a set of regression equations, has been encapsulated within a JAVA Applet that supports policy makers concerned with the development of upgrading strategies for the Scottish housing sector. A second decision-support tool has been devised to enable the evaluation of the impact of the adoption of non-design specific technologies such as tank/pipe insulation, solar energy capture and heat recovery. 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. μCHP).

It is envisaged that to be effective the HUPS procedure will require substantial inputs from site inspections. These will be required to assist with the process of parameter setting for the houses comprising a targeted estate and the translation of indicated upgrade measures to action on the ground.

Such activities are fully compatible with the intentions of the EU directive on building energy performance.

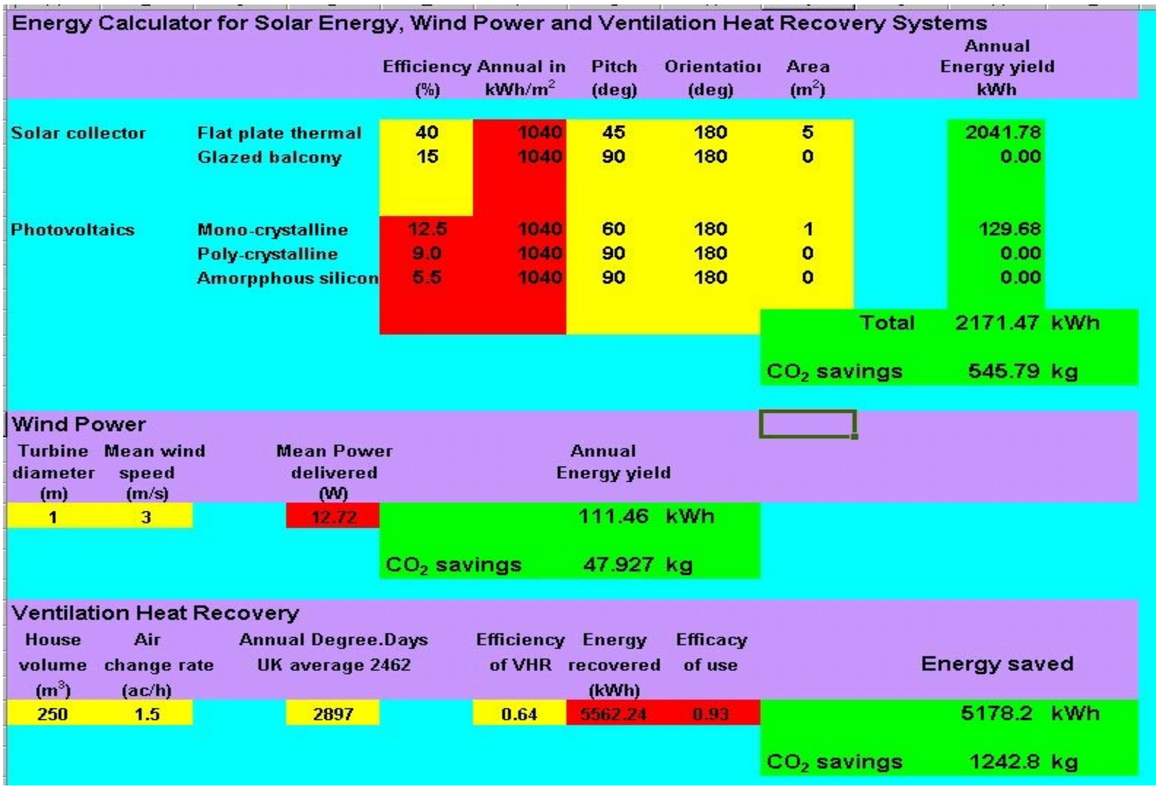

Figure 2: Assessing the potential of local energy resources.

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