Energy and Carbon Performance of Housing: Upgrade Analysis, Energy Labelling and National Policy Development

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ABSTRACT

The area of policy formulation for the energy/carbon performance of housing is coming under increasing focus. A major challenge is to account for the large variation within national housing stocks relative to factors such as location, climate, age, construction, previous upgrades, appliance use and heating/cooling system types.

Existing policy oriented tools rely on static calculation models that have limited ability to represent building behaviour and the impact of future changes in climate and technology. The switch to detailed simulation tools to address these limitations in the context of policy development has hitherto been focussed on the modelling of a small number of representative designs rather than dealing with the spread inherent in large housing stocks.

To address these challenges, the ESRU Domestic Energy Model (EDEM) has been developed as a Web based tool built on detailed simulation models that have been aligned with the outcomes of national house condition surveys. On the basis of pragmatic inputs, EDEM is able to determine energy use and carbon emissions at any scale – from an individual dwelling to national housing stocks.

The model was used at the behest of the Scottish Building Standards Agency and South Ayrshire Council to determine the impact of upgrades and the deployment of new and renewable energy systems. EDEM was also used to rate the energy/carbon performance of individual dwellings as required by the EU Directive on the Energy Performance of Buildings (EU, 2002).

This paper describes the EDEM methodology and presents the findings from applications at different scales.

1. INTRODUCTION

The UK building stock is responsible for over 40% of the country's CO_2 emissions. To achieve the Government's target of 60% reduction by 2050 will require the implementation of radical upgrades. Domestic energy and carbon calculation methods in current use, such as the Standard Assessment Procedure (SAP; BRE, 2005), are based on simple energy balance methods that do not fully account for the dynamic characteristics of buildings. Neither do they adequately represent the many different upgrade options that may be applied individually or in combination. Also, as buildings have extended lifetimes, it is important to assess performance under likely future contexts, such as climate change and the introduction of new technologies.

EDEM has evolved from work previously carried out on the assessment of housing upgrades (Clarke *et al,* 2004). Underlying EDEM is the output from simulations of models representing existing dwellings and all possible combinatorial upgrades. Dynamic modelling gives advantages over static calculations, particularly in the areas of ventilation, comfort, controls and renewable energy integration (Tuohy *et al*, 2006a).

2. SCOTTISH HOUSING

There are around 2,278,000 dwellings in Scotland 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% of all dwellings were built within the last 37 years, with 24% constructed between 1945 and 1965.

The 2002 Scottish House Condition Survey (Scottish Homes, 2003) identified 7 predominant house types: Detached, Semi-detached, Terraced, Tenement Flat, Four-in-a-Block, Conversion and Tower/Slab Block.

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. CO_2 emissions were around 16.2 million tonnes per year. By comparison, the 1996 House Condition Survey established a mean NHER rating of 4.1 and a mean SAP rating of 43, indicating a 10% improvement since 1996, with 12% of all dwellings achieving an NHER rating of 7-9 and no dwellings attaining a rating of 10.

From the 2002 survey, around 86% of dwellings have whole house central heating, with a further 8% having partial central heating. This represents a 6% improvement since 1996, with the number of dwellings with no central heating down from 13% to 5.5%. This small but significant figure gives rise to concerns about fuel poverty and the 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).

3. STOCK MODELLING

While it is a straightforward task to identify house types from an architecture and construction (AC) viewpoint, the task becomes intractable when viewed thermodynamically. Two separate houses, each belonging to the same AC 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 AC groups may have the same energy consumption (after normalisation relative to floor area) because the governing thermodynamic-related design parameters are the same.

The approach adopted was to operate only in terms of thermodynamic classes (TC) so that different AC types may belong to the same TC. A representative model was then formed for each TC and its energy performance determined by simulation using real, representative weather data. Any actual 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.

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

Performance predictions, in the form of regression equations defining energy use as a function of prevailing weather parameters, were encapsulated within EDEM for use by: policy makers engaged in the development of building regulations in response to national policy drivers; building stock owners/managers to appraise the impact of improvement measures; and local authorities in a performance rating context. The impact of technologies that may be considered independent of house type, such as low energy light bulb replacement, local or community CHP and the like, were separately modelled within EDEM.

The evaluation of any given upgrading scenario is a two-stage process. First, the contribution of a proposed fabric upgrade is quantified by assigning the house in question to a TC based on its governing parameters. The energy reduction brought about by its relocation to any other TC may then be simply 'read off' (see Figure 3). 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 energy efficiency measures and/or local sources of energy supply are quantified. This is done by applying house-specific parameter values to the technology in question (e.g. available deployment area in the case of PV). The user is then able to accept or discard either contribution as a function of applicability and cost.

Within the project it was ensured that simulations encapsulated the assumptions underpinning the UK's SAP procedure so that EDEM would give equivalent results when used in SAP emulation mode.

4. EDEM FORMULATION

Model formulation was a two stage procedure covering both fabric and technology parameters. This allows a user to establish the magnitudes of energy and related CO_2 savings likely to be achieved via different combinations of construction and system updrades.

4.1 Stage 1: Fabric Appraisal

The ESP-r system (URL1, 2007) was used to determine the fabric-related energy behaviour of standard house designs, corresponding to the different TCs, when each were subjected to long term weather conditions that typify the range of possibilities for Scotland.

The range of designs to be processed were established as unique combinations of principal parameters that were considered to be the main determinants of energy demand and that may be adjusted as part of any upgrade: insulation level (6), capacity level (2), capacity position (3), air permeability (3) and window size (3) when considering large housing stocks; plus exposure (5) and wall-to-floor ratio (2) when addressing individual dwellings. If each of these parameters can exist at the level indicated in parentheses above then there will be 3,240 (6 x 2 x 3 x 3 x 3 x 5 x 2) potential TCs that represent the universe of possibilities. That is, any possible house design, existing or planned, will correspond to a unique combination of these parameters and therefore belong to one, and only one, TC.

It is important to note that most of the TCs do not yet exist because, in general, the Scottish housing stock may be regarded as poor in terms of energy use and carbon footprint. Instead, the majority represent future possibilities that will result from the application of fabric upgrades to the existing stock.

Long term simulations were then conducted for the 3,240 TCs and the predicted energy demands normalised by floor area to render the results independent of dwelling size and facilitate intercomparison. The TCs were then re-simulated for each of 24 context combinations relating to climate (2), occupancy (2), temperature set-point (3) and appliance efficiency (2).

To enable the simulations, a standard house model was constructed comprising living, eating and sleeping areas with appropriate parametric modifications applied to realise the individual TCs. The assumptions underlying this model correspond to an average house as determined from appropriate publications (Bartholomew and Robinson, 1998; BRE, 2005; CIBSE, 1999; Scottish Homes, 2003; Shorrock and Utley, 2003).

4.2 Stage 2: Technology Appraisal

Dwelling energy demands are extracted from the TC simulations as above. Next, heating/cooling, hot water and lighting systems are selected. In the first case, system type/age and fuel type are used to set an efficiency value in line with CIBSE and SAP defaults (BRE, 2005; CIBSE, 1999), the BRE Domestic Energy Fact File (Shorrock and Utley, 2003) and the Carbon Trust's Building Market Transformation project database (MTP, 2006). Hot water load is determined in relation to standard domestic system capacities and water usage rates (BRE, 2005), while lighting energy use is calculated using a standard model for the UK.

New and renewable energy systems are also selectable: currently mono-/poly-crystalline and amorphous PV, micro wind turbine, solar thermal collectors and CHP.

The mapping of energy use to CO_2 emission is based on UK normalised figures as published by the Carbon Trust, i.e. 0.42 kg/kWh for electricity and 0.19kg/kWh for gas. Such conversions may be redefined where EDEM is being applied in a non-UK or future context.

Unit costs and standing charges are embedded in the tool based on the standards set for SAP. These data are also user definable.

The calculation of the domestic energy rating band and the associated environmental index, as defined within SAP, is output along with an equivalent rating for a similar property built to current building standards.

5. EDEM VERIFICATION

Detailed models of 5 real houses were subjected to simulation, energy efficiency improvements applied and the simulations re-run (such improvements essentially relocating the house to another TC). The houses and their variants were then assigned to a TC based on the level of their governing principal parameters. The predicted heating energy demands resulting from the detailed simulations were then compared to the value associated with the matched TC model. The results indicated discrepancies ranging from 3% to -13%, indicating that the TC approach is a reasonable proxy for the real situation.

A second study compared EDEM output with energy performance as determined using the National Homes Energy Rating (NHER) methodology, which is in common use by UK Local Authorities. A Local Authority Energy Officer carried out detailed surveys using the NHER 'Surveyor' tool and in parallel filled out a questionnaire which gathered EDEM inputs. The EDEM tool was used to calculate carbon and energy performance data for both electric and gas systems and the results compared to those from NHER. Acceptable agreement was found as shown in Figure 1.

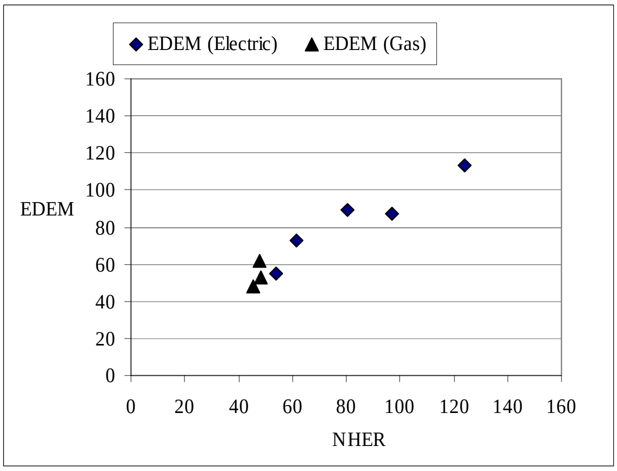

Figure 1: CO_2 emissions (kg /m^2 yr) – EDEM vs. NHER Surveyor.

6. EDEM APPLICATION

EDEM (URL2, 2007) is designed to be flexible in its application. The context is defined, pragmatic input data gathered (Figure 2), a representative TC identified and upgrades/new technologies selected (Figure 3), and the outputs expressed in terms of energy, carbon, cost and a ratings label (Figure 4).

An application will typically proceed as follows. The context of the analysis is set, e.g. 'current UK standard' or '2050 climate with high indoor comfort', and the input data entered. The governing parameters are inferred from the input data and an appropriate TC automatically selected (representing a single dwelling or group of dwellings). The energy demand for the given TC is then determined and modified by appropriate system efficiencies. This demand is used as input to the technology appraisal. Next any upgrades are applied and the calculations re-initiated. Finally, the outputs for the various combinations are collated and presented.

6.1 National Stock Upgrade

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 14.5TWh and CO_2 emission of 5.5MT. The space heating energy demand accounts for 17% of the total Scottish demand. The entire national stock can be classified into 3 TCs groups as listed in Table 1.

The largest housing sector is contained within Group 1, which includes TCs associated with unimproved dwellings constructed prior to 1981. This grouping accounts for 11.1TWh of annual space heating energy.

Practical considerations dictate that any upgrading strategy should focus on low cost technologies initially to maximise the return on investment, and be phased over time thereafter to accommodate technical advances. Reducing fabric and ventilation heat loss are the most effective measures to improve dwelling thermal performance and were assessed in this study.

Table 1: Digest of Scottish dwellings.

1: high thermal mass, poor insulation, large air change rate Number of dwellings: 1,594,600 Heating demand (kWh/m^2yr): 87
2: standard insulation, large air change rate Number of dwellings: 660,620 Heating demand (kWh/m^2yr): 47
3: high insulation, standard air change rate Number of dwellings: 22,780 Heating demand (kWh/m^2yr): 26

An EDEM analysis indicated that the upgrade strategy should be to target Group 1 dwellings by improving their air tightness to standard (e.g. apply draught proofing to windows and doors) and applying insulation measures to improve insulation to standard (e.g. cavity, internal or external insulation plus double glazing and loft insulation). This will shift these properties to a Group 1 category with an associated saving of $40kWh/m^2$.

Further analysis indicated that a second upgrade phase should then be carried out to move Group 2 dwellings to Group 3, again by improving insulation and infiltration (in this case improvements should achieve compliance with all elements of 2002 regulations).

The implementation of the first phase of improvement measures were seen to result in savings in the annual space heating energy demand of 4.7TWh (or 33.2% of the national energy demand). This may be achieved by focusing solely on basic upgrades of dwellings in Group 1. In the second phase of the programme, the annual space heating energy savings would rise to 7.36TWh (51.6%) by targeting Group 2 dwellings. Overall, by improving Group 1 to Group 2 and the original Group 2 to Group 3, a phased programme would reduce the annual space heating energy demand of the Scottish housing stock from 14.5TWh to 7.14TWh (i.e. a 51.6% reduction of the space heating energy demand).

6.2 Regional Housing Upgrade

A Local Authority housing stock comprising 7876 dwellings was evaluated using EDEM to determine the impact on the carbon footprint of a range of upgrades.

The housing stock was decomposed into TCs and the possible upgrades were identified from the Energy Savings Trust's practical help publications (EST, 2007). The upgrades (applied to dwellings as appropriate) were as follows.

0. The current stock with no upgrades applied.
1. Low cost fabric improvement. Where there is a pitched roof and a suspended wooden floor then loft insulation is increased to 300mm and the suspended timber floors insulated to 75mm. All dwellings to have basic double glazing and brought up to 'tight' infiltration standards.
2. Major fabric upgrade. In addition to the low cost measures, flat roofs are upgraded to a U-value of 0.16, cavity wall properties have insulation added to give a U-value of 0.35 and solid wall properties are improved to a U-value of 0.6. (Windows are at current best practice standard with a U-value of 1.5.
3. 2007 heating system. Gas, electric and solid fuel heating systems are upgraded to condensing, instantaneous water heating boiler, air source heat pump with radiators and wood boiler respectively.
4. Upgrades 1+2+3.
5. Upgrades 1+2+3 plus solar hot water heating (delivering 920kWh/yr useful energy applied to properties with an exposed roof.
6. Upgrades 1+2+3+4 (650kWh/yr) plus local renewable energy generation in the form of either PV or wind turbine.
7. Upgrades 1+2 plus CHP (Stirling engine). For groups of dwellings of more than 2 storey height then community CHP was assumed.
8. Upgrades 1+2 plus biomass (comprising individual or community wood boiler systems).

Figure 5 illustrates the impact of each upgrade option on the carbon footprint. These results show the current carbon footprint per dwelling to be 4.9 tonnes of CO_2 per year while future scenarios are presented with emissions below 1 tonne. Further details on the selected upgrade options and a breakdown of the study results by dwelling type are reported elsewhere (Tuohy *et al*, 2006b).

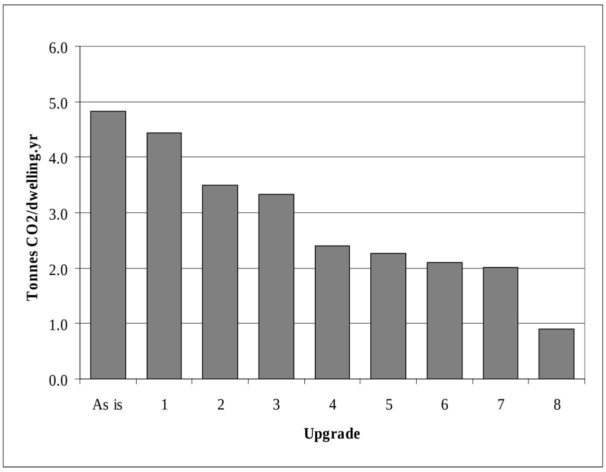

Figure 5: Upgrade impact on carbon footprint.

6.3 Dwelling Energy Labelling

EDEM can be used to provide energy performance ratings. In this case the Environmental Index (EI) and Energy Band (EB) are calculated from the EDEM generated energy demands in accordance with a standard UK method (BRE, 2005).

Table 2 shows an example of EDEM when applied to an electrically heated 1980s top floor flat, which has previously been upgraded with cavity wall fill, double glazing and 200mm of loft insulation. The rating of the base property is 'D'. A number of improvement scenarios were assessed aimed at bringing the fabric up to 2002 insulation and infiltration standards and then applying a range of system upgrades: condensing combi-boiler, ground source heat pump, community biomass heating, community CHP and a gas condensing combi-boiler combined with solar water heating and a PV panel (producing 920kWh thermal and 650kWh of electricity annually). Two options achieved an 'A' rating: upgraded fabric with either community biomass heating or a community CHP system.

7. CONCLUSIONS

A detailed energy simulation program has been applied to a set of house designs corresponding to distinct TCs established to represent the spectrum of house types in Scotland. The outcome has been encapsulated within a Web based tool that supports policy makers concerned with the development of upgrading strategies for the national housing sector or those concerned with enacting the energy rating schemes.

It is envisaged that to be effective the 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 compatible with the intentions of the EU Energy Performance of Buildings Directive.

Table 2: Upgrade energy rating.

Upgrade	kg CO_2/yr	EI	EB
0. As is	3391	57	D
1. 2002 fabric	2778	66	D
2. 1+ gas combi boiler (condensing)	1679	81	B
3. 1+ ground source heat pump	1515	83	B
4. 1+ community biomass	817	93	A
5. 1+ community gas CHP	1000	98	A
6. 1+ 2 + PV + solar water heating	1454	84	B

ACKNOWLEDGEMENTS

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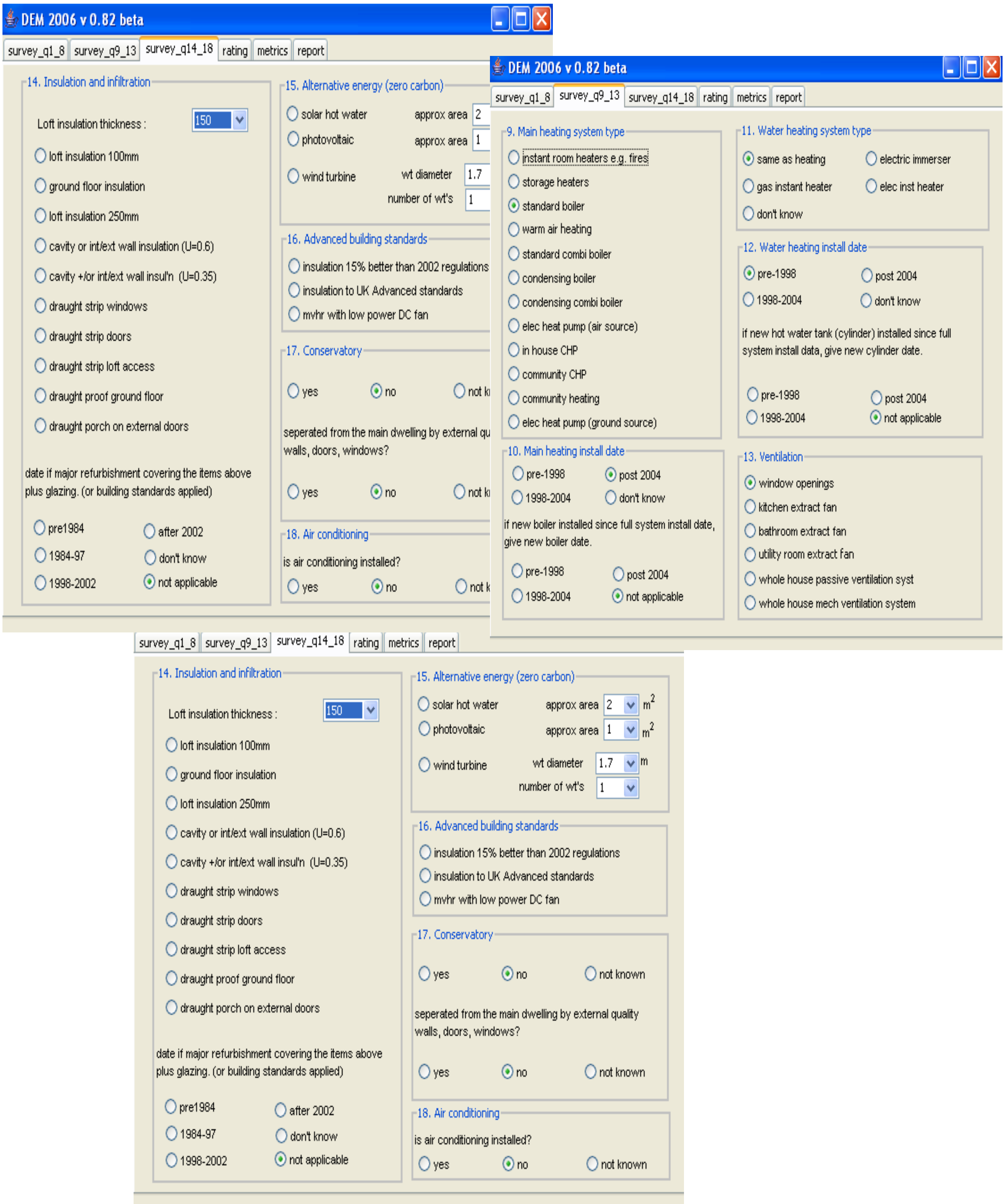

Figure 2: Montage of EDEM inputs.

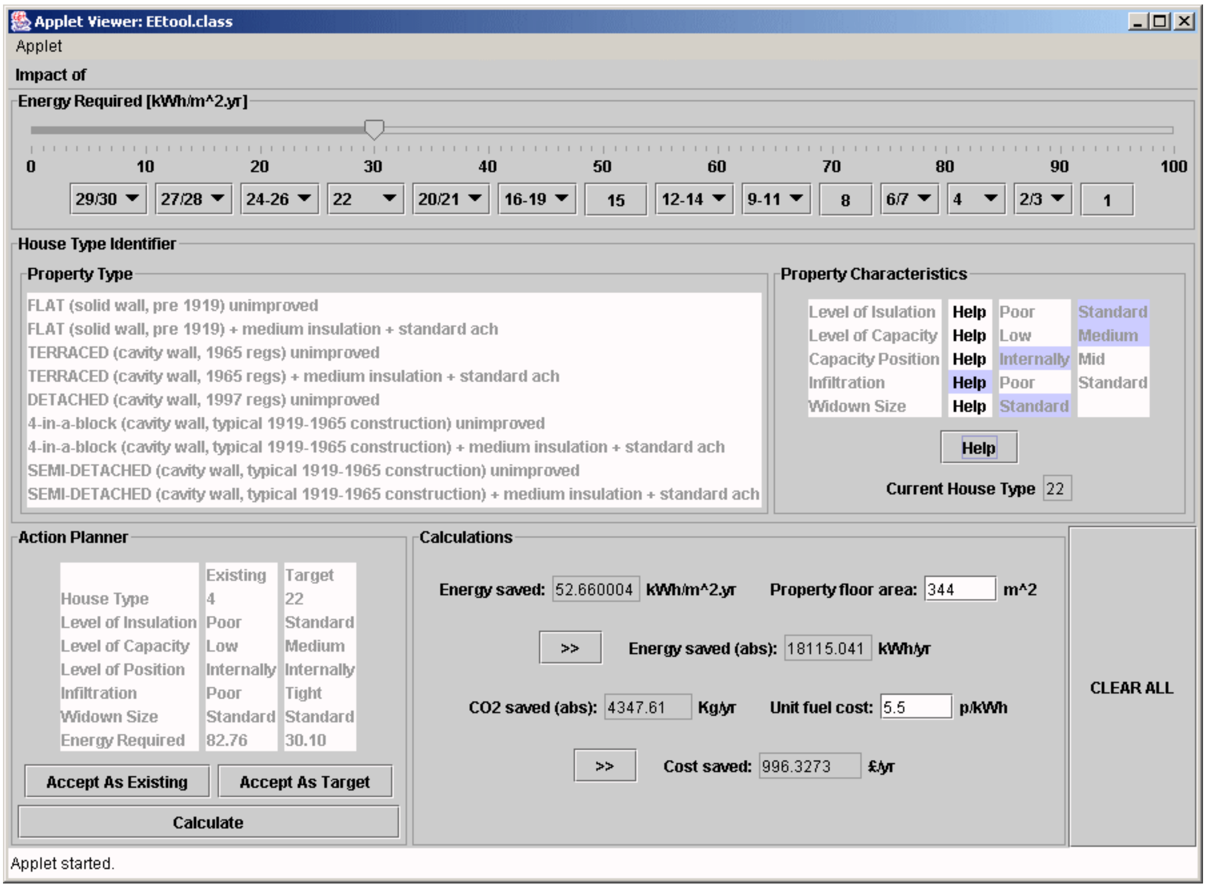

Figure 3: EDEM control screen.

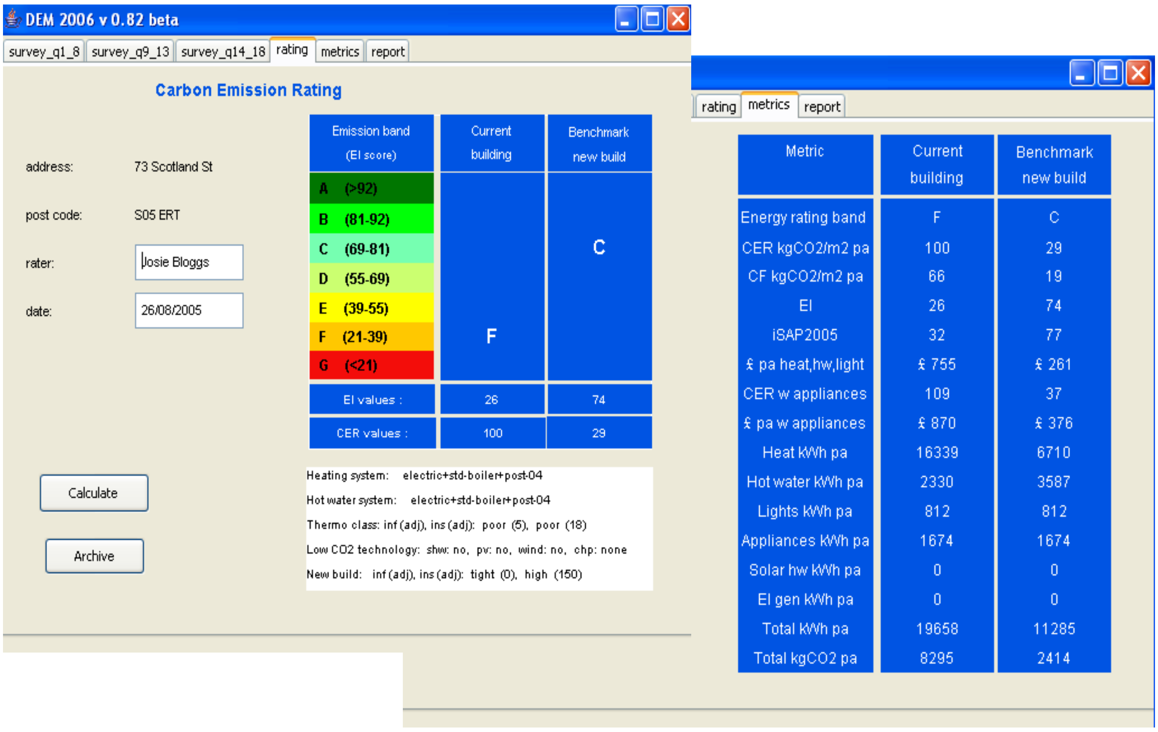

Figure 4: Montage of EDEM outputs.