Freeman, R. A. J., Yearworth, M., & Preist, C. W. (2012). *Modelling a school as a socio-technical system for the purpose of managing greenhouse gas emissions*. Bristol University. http://hdl.handle.net/1983/1828

Early version, also known as pre-print

Link to publication record in Explore Bristol Research
PDF-document

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available: http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/

Modelling a School as a Socio-Technical System for the Purpose of Managing Greenhouse Gas Emissions

Rachel Freeman, Dr Mike Yearworth, Dr Chris Preist
Systems Centre, Faculty of Engineering, University of Bristol
BS8 1UB, UK

email: {cerajf, mike.yearworth, chris.preist}@bristol.ac.uk

Abstract

There is a need to better understand the dynamic interactions between people, organisation, and physical infrastructure when working to reduce Greenhouse Gas Emissions (GHG) emissions and utility bills in organisations. This paper presents a Systems Dynamics approach to the problem that combines both the social and the technical factors affecting a building's carbon emissions over time in a single model. Through assigning variables to represent both the soft aspects of the building system – organisational culture, roles and responsibilities, energy management attitudes, etc.; and the physical infrastructure – rated power of plug load equipment, building services equipment, building fabric, etc. – a SD model can indicate which factors are most important. We anticipate there will be several long-term benefits from the use of this model, namely: 1) helping to bring clarity to a very messy problem, 2) providing a picture of how carbon and energy issues change over time, 3) getting people within an organisation to incorporate carbon management into their everyday work life. GHG emissions are often overlooked in organisations but we believe that proactive, ongoing carbon management should be as important as meeting legal or health and safety requirements and that it is essential for an organisation's long-term resilience.

Keywords—*sustainability, carbon reduction in schools, organisational behaviour, strategy, consultancy, model-based management*

1 Introduction

Most organisations today operate as linear, open loop systems in which minimising Greenhouse Gas (GHG) emissions, waste streams, and effects on the natural environment are not priorities in everyday decision making, as depicted in Figure 1. Decisions are made according to financial rules that do not consider these three impacts; budget and financial reporting cycles dominate decision-making rather than long-term organisational sustainability or carbon risk reduction. For example, many organisations will not invest in an energy saving measure unless its estimated payback is less than two years, eliminating many possibly beneficial interventions.

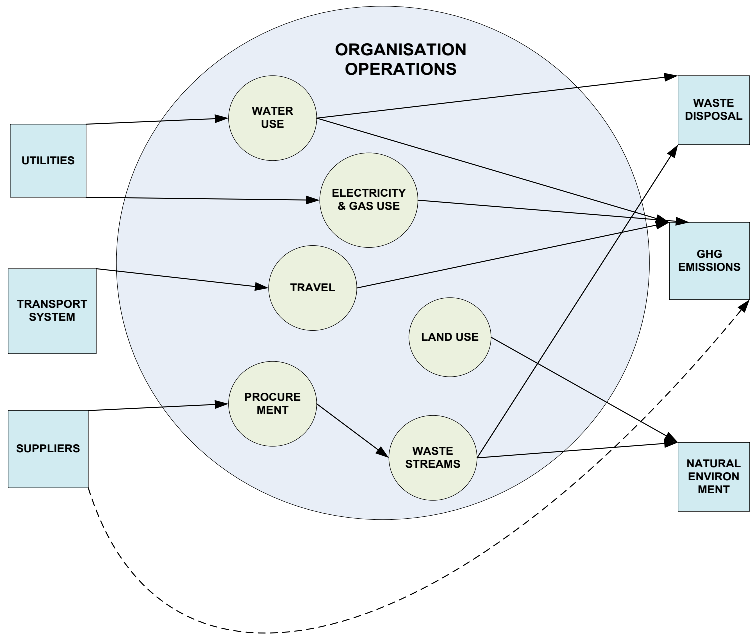

Figure 1: Flows of energy, water and embedded carbon used by an organisation

Commercial buildings, along with the people who use them, can be seen as complex socio-technical systems. Within the building, energy is used to provide the services people need such as indoor comfort, specialist equipment, and ICT. Post-occupancy evaluations have shown that actual energy consumption in buildings can be much higher than planned for at design stage. For example, CarbonBuzz, an online database of performance data for buildings in the UK, shows average actual performance for schools of 56.9 kg $CO_2e/m^2/yr$ versus an average of 29.4 kg $CO_2e/m^2/yr$[1] for design performance[2]. There are many possible reasons for this; for example, Building Management Systems (BMSs) may be programmed incorrectly, specialist equipment and lights may be left on when not needed, and unplanned-for amounts of plug-load equipment may be brought into the building.

Diagnosing where energy is being used and finding ways to reduce it are not straightforward tasks. While the physical infrastructure – energy-using equipment and the building fabric – can be modelled with building simulation software, uncertainty about how occupants use the building is not usually included. Energy management can be made more difficult when a number of different stakeholder groups are involved, such as in a Private Finance Initiative (PFI) school in the UK, where the building is *owned* by a PFI company, *managed* by a Facilities Management (FM) company and other subcontractors, and *used* by

[1] The terms "GHG emissions", "carbon", "CO_2" and "CO_2e" are commonly used interchangeably in industry to mean carbon dioxide gas or equivalent amounts of other greenhouse gases emitted either directly from the fuel combustion process or indirectly via electricity from the grid.

[2] Carbon Buzz (www.carbonbuzz.org) is an online database of building energy consumption data, created to highlight the performance gap between design figures and actual readings.

school staff and students. Each group and/or individual will perform energy management (or perhaps not at all) according to his or her perceived roles and responsibilities, organisational policies and procedures, time considerations, and personal needs.

There is a need to better understand the dynamic interactions between people, organisation, and physical infrastructure. This paper presents a Systems Dynamics (SD) approach to the problem that combines the key inputs, outputs, and endogenous factors that affect a building's energy use over time in a single model. Through assigning variables to represent both the softer aspects of the building system – organisational culture, roles and responsibilities, energy management attitudes, etc.; and the physical infrastructure – rated power of plug load equipment, building services equipment, building fabric, etc. – a SD model can indicate which factors are most important. The SD model is to be used within a consulting practice that engages with organisations to help them reduce their GHG emissions. The purpose is to achieve both deeper and more cost-effective carbon savings through first diagnosing the system, so that the most appropriate interventions can be identified.

Since buildings vary so much by sector it was decided to concentrate on a single building type and the case study chosen is that of a secondary[3] school. Despite a large secondary school rebuilding programme in the UK (Building Schools for the Future[4]) average carbon emissions have been rising. Evidence for this is provided by a review of Display Energy Certificates (Godoy-Shimizu, Armitage, Steemers and Chenvidyakarn, 2011) which revealed that average carbon emissions in secondary schools have risen by 8% since 1995. Looking specifically at types of fuel used, fossil-thermal[5] energy consumption fell by 24% and consumption of electricity rose by 33%, as shown in Figure 2. In other words, this is a systems problem in which improvements in one part of the system (the building) have not led to expected improvements in the whole system (the post-occupancy building combined with the people who use it). Moreover, because electricity tariffs are more than twice those of gas on a per kWh basis, this has led to a rise in energy costs for schools.

[3] 11-18 year old pupils in the UK

[4] http://www.education.gov.uk/schools/adminandfinance/schoolscapital/funding/bsf

[5] Fossil-thermal energy is any non-electrical energy supply such as natural gas, solid fuels (e.g. coal, wood), and biogas.

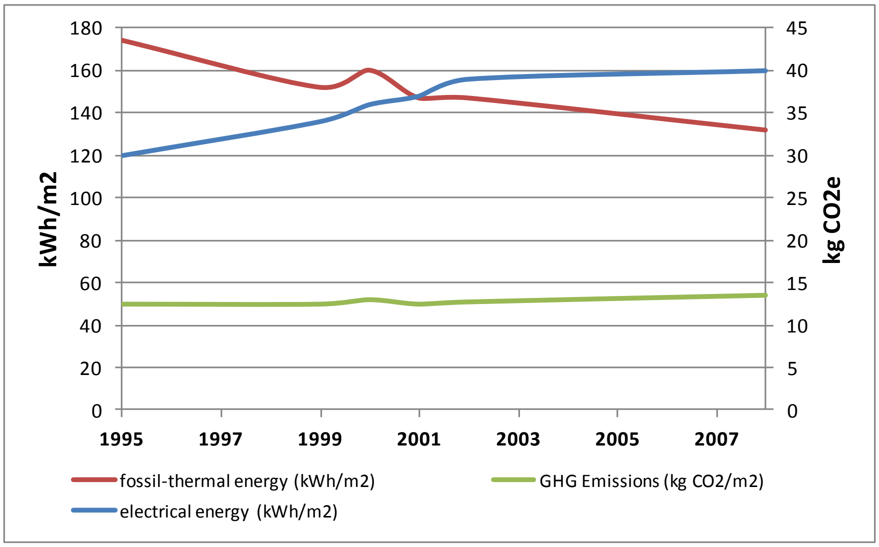

Figure 2: Change in Carbon, Electricity and Fossil-thermal Use in Secondary Schools from 1995 to 2008 (data from Godoy-Shimizu et. al.)

2 Development of the Model

The *purpose* of the model is firstly to diagnose the system (i.e. the school) and identify what are the most important influences on the key metrics – the carbon emissions due to the consumption of natural gas and electricity, and utility bills[6] – and secondly to test interventions designed to improve the system's performance with regard to the key metrics. The *boundary* for the system of interest is the building and its occupants, with utilities supplied and waste disposed of (including GHG emissions put into the atmosphere) crossing the system boundary. The level of *detail* in the model is that of a conceptual model that identifies the main categories of "soft" and "hard" components, but does not go to the level of individual building systems, equipment, or people; thus it is not comparable to a building simulation model. The modelling *period* is 15 years, which is enough time to model long-term changes in building use and the expected rise in energy costs.

2.1 The Modelling Process

The modelling process started with identifying the components in the system that affect the key metrics: i) inputs coming from outside the system and not changeable, ii) attitudes, behaviours and technology control factors existing within the system and potentially changeable, iii) building performance and equipment loads modelled as stocks, and iv) the introduction of feedback which represents carbon reduction strategies. These are summarised in Table 1.

[6] Water use also leads to carbon emissions but much less than for gas and electricity, so to minimise the complexity of the model water use was not considered in this first version of the model.

Category	Components
Inputs	H&S, Legal Concerns; Competitiveness Concerns, Educational Requirements; normal opening hours; Price of Fuels; Carbon Content of Fuel;
Controls, Attitudes and Behaviours	Short-term Budget Concerns; Pro-activeness of FM; Pluralism within the Org Structure; Understanding of How to Use Building and Controls; Org culture towards energy management; percent of controls automated; PL Units Retired; Degradation of Building;
Stocks	PL Equipment Inventory; BS Equipment Load; Theoretical Performance of Building Infrastructure
Feedback	Commitment to Change; Carbon Management

Table 1: Model Components

Qualitative variables such as Demands for Individualised Comfort and Convenience were all set as type Scale 1 to 10. Physical-related variables were set to appropriate units such as kW for equipment rating, percentage of hours in a year for Operating Fraction, and kg CO_{2e}/kWh for Carbon Content of Fuel. The relationships between the variables and stocks were established by entering equations in all the variables that were not constants. The structural validity of the model was confirmed by conducting a rigorous check of dimensional correctness (Coyle and Exelby, 2000).

The central calculation that links the soft and hard elements together is that defined in the Energy Consumption variable:

*Annual kWh = Equipment Rating (kW) * Operating Hours/Year (hours)*

The model is shown in Figure 3. Certain aspects of the model are not self-evident and these are described as follows.

Equipment rating is made up of two types of equipment: Building Services and Plug Load. Building Services includes equipment used for security, lighting, catering, and indoor climate control (heating, cooling and ventilation). The fuel for Building Services is mostly fossil-thermal. Plug Load equipment includes all other equipment such as ICT, interactive whiteboards and projectors, and specialist educational equipment. The fuel for plug load equipment is electricity only.

Operating Fraction is the proportion of each year that equipment is switched on (converted to hours to represent operating hours). It is composed of normal opening hours, scheduled out of hours openings for activities such as after-school clubs, rentals to non-school groups, and unscheduled openings for staff to work out of hours. Operating hours are also affected by the amount of automation in controls and by the engagement of staff in energy management. Although in reality operating hours for Building Services will not be the same as for Plug Load equipment, these hours will be approximately the same and so to simplify the model the same value is used for both.

The organisational-level drivers of the model are competitiveness concerns (e.g. providing the latest technology to attract students to the school), educational requirements (e.g. having a certain number of computers per student), and Health and Safety (H&S) and legal concerns (e.g. security systems, the need to keep the indoor climate within a temperature band). An additional driver, Short-term Budget Concerns, affects efforts to improve efficiency by FM staff by limiting investments to those that obey certain financial rules such as a maximum payback period and also increases the rentals to outside groups.

Individual-level factors affecting operating hours and control settings are the degree of pluralism, or sense of division between different groups that work in the building (which can lead to the attitude that energy management is the sole responsibility of the FM company), demands for individualised comfort and convenience (which drives up demand), and the understanding of how to use controls and equipment.

Most of the variables lead to higher energy use, but there are four that reduce energy use:

1. The higher the percentage of controls automated the lower the operating hours due to removing the uncertainty that exists in manual controls.
2. The higher the pro-activeness of FM staff, the more likely that the efficiency of Building Services equipment will be improved and operating hours will be reduced due to equipment controls being set correctly.
3. The higher the perception of energy management as part of their role, the more likely staff will not demand individualised comfort and convenience.
4. The better staff understand how equipment and building controls are supposed to work the closer the actual efficiency of the building will be to the theoretical efficiency.

The introduction of feedback (the intervention) represents a change to the system designed to reduce the key metrics. In the baseline simulation the feedback has no effect. The driving variable for the feedback is Commitment to Change, but the strength of the feedback is also dependent on the key metrics GHG Emissions and Utility Bills (these are what normally drive a push to reduce consumption).

All of the variables and stocks were parameterised with data taken from the literature to represent a typical secondary school. The following data were used:

1. Percentages of gas and electricity consumption by end-use from the UK's Department for Energy and Climate Change (DECC) document "Energy Consumption in the UK, Service Sector, 2010" for the Education sector.
2. Electricity, fossil-thermal and CO_{2e} use by pupil from (Godoy-Shimizu, Armitage, Steemers and Chenvidyakarn, 2011) in 2008. Values for a typical academy school were used, which is higher than non-academy schools.
3. Growth rates for electricity, fossil-thermal and CO_{2e} between 1995 and 2008 from (Godoy-Shimizu, Armitage, Steemers and Chenvidyakarn, 2011).
4. Assume a school of 1200 pupils.

5. Building Services consumption includes energy for catering (estimated 8% of total energy use).
6. Opening hours of 8am to 5 pm on term days, plus several hours per week of renting out the school, scheduled after-school activities, and out of hours openings due to staff working out of hours.
7. Escalators on electricity and gas prices to match historical data from DECC for 1995 to 2008.

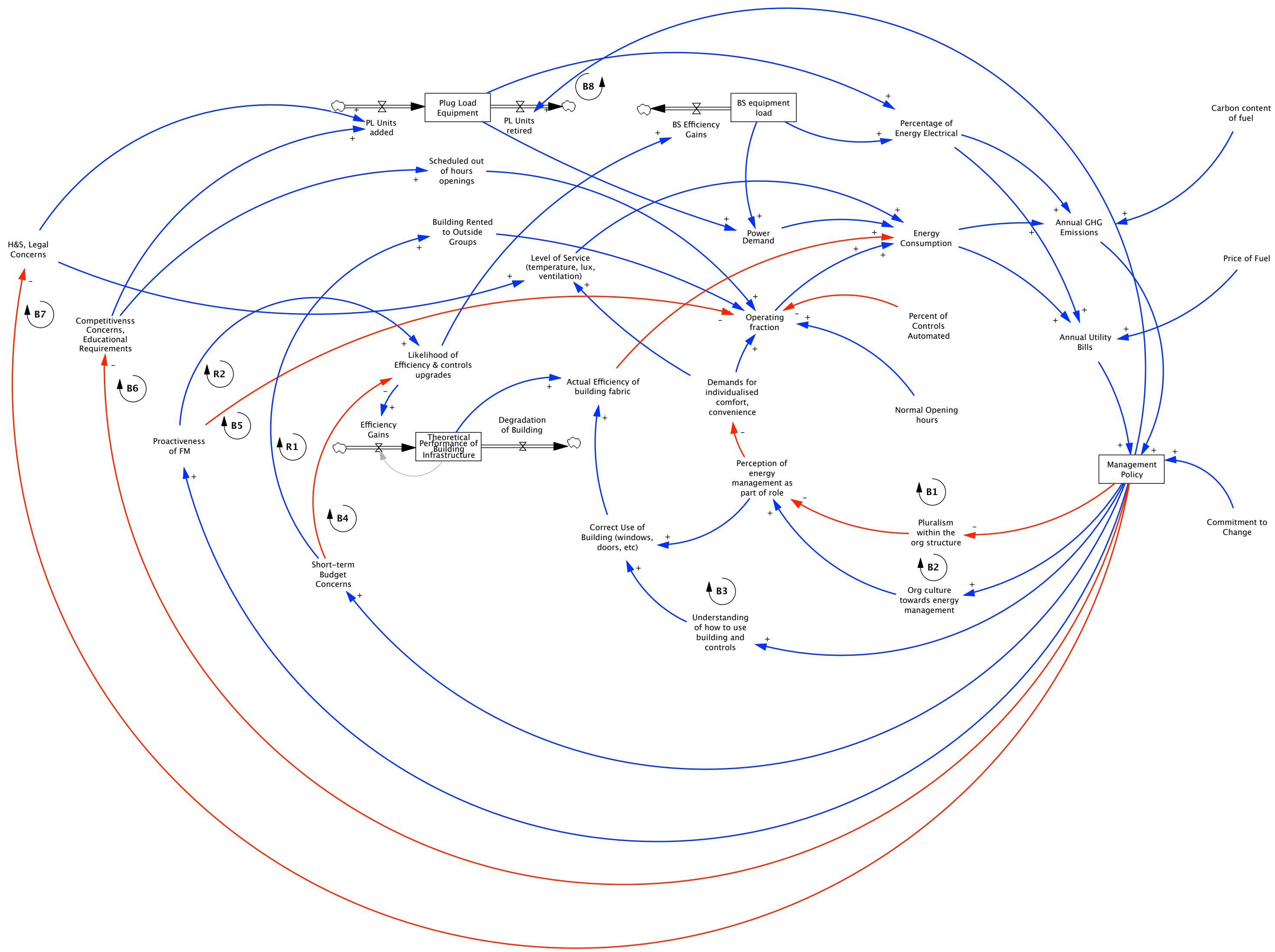

Figure 3: Model of the School as s Socio-Technical System

3 Results

Once the model was parameterised, values for the key variables were calibrated as closely as possible to the empirical data to get a baseline model. The key variables to calibrate were the total kW rating of Plug Load and Building Services equipment, energy consumption, and GHG emissions. Figure 4 shows these values along with Utility Bills for the baseline model over a period of 15 years. Note that although lighting is a Building Services load rather than a Plug Load it was included in the Plug Load category because it is electrical and needs to be calculated with the right carbon content and utility bill conversion values; the model would be improved by lighting being modelled as a separate stock. The graph shows electrical consumption, GHG emissions and utility bills rising over time, while total consumption and fossil-thermal energy use goes down.

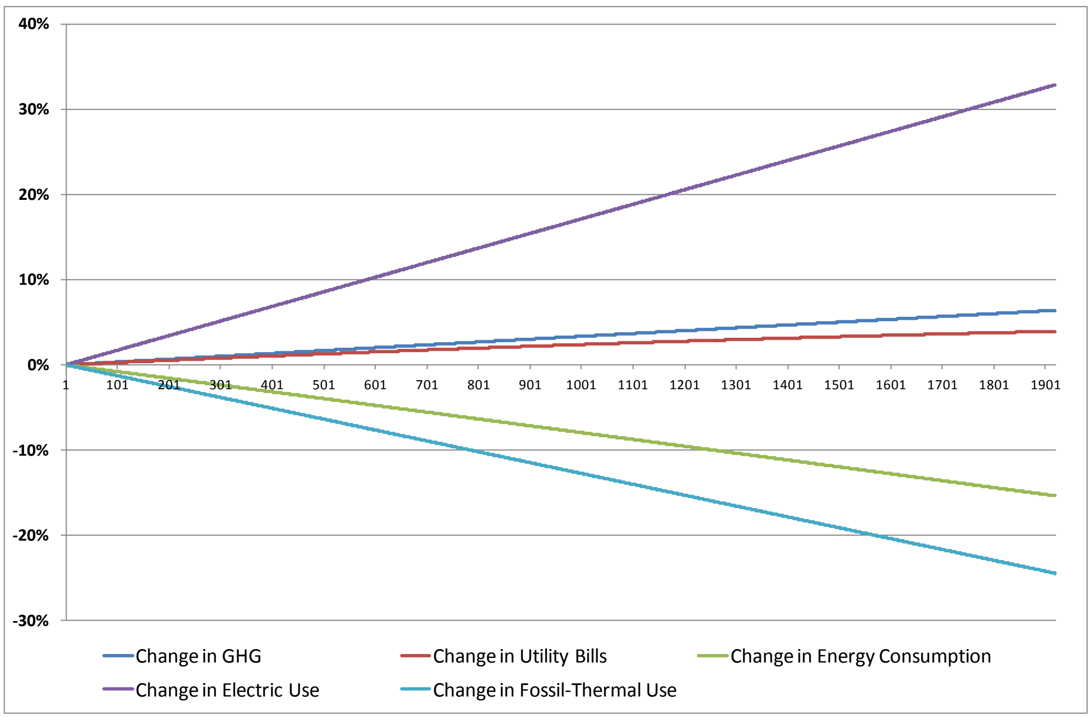

Figure 4: Key Output Variables in Baseline

After the baseline model was calibrated, the effect of changing the variable Commitment to Change was explored. A review of case studies shows that very large drops in energy consumption are not realistically feasible in most cases – 50% reductions have occurred but only in situations where there is a lot of energy wastage in the baseline situation and the interventions are multiple and sustained. Therefore, we chose a best case that has savings of 23% in utility bills, 21% in GHG emissions and 37% in energy consumption. Figure 5 shows a comparison between the baseline case, a medium case, and the best case for the two key metrics GHG emissions (right hand axis) and utility bills (left hand axis). The total savings over the 15 year timeframe of the model could be calculated as the cumulative differences between baseline and best case over the whole period.

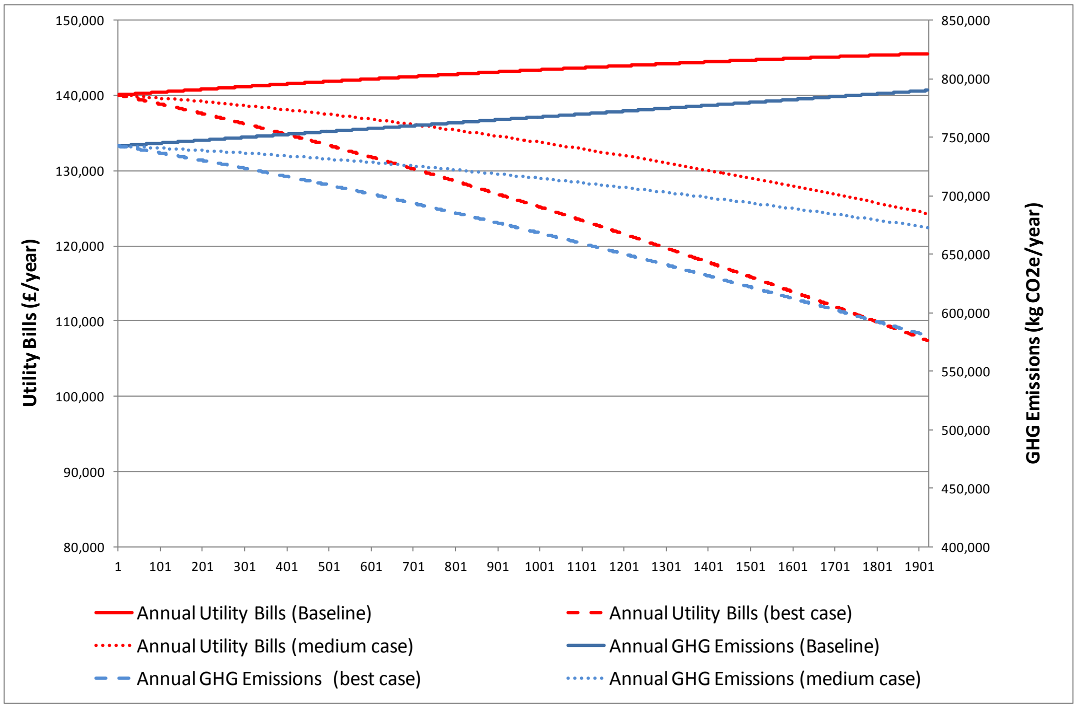

Figure 5: Change in Trends for the Key Metrics, Baseline to Best Case

4 Discussion

Several lessons were learned and several questions arose for discussion during the modelling process:

The difference between energy management and carbon management is important. Concentrating solely on energy can lead to an increase in carbon and utility bills because electricity has more than double the cost and GHG emissions of natural gas. The variable Percentage of Electrical Energy (percentage of the total energy used that is electrical) was not included in the model at first but through the development phase it turned out to be an essential part of the factor in the system.

Exactly which attitudes and behaviours are changeable will vary by organisation. For example, in a school where part of the ethos is to do community outreach rental of school buildings to outside groups would not be changeable.

In the model presented in this paper the attitudes and behaviours are all weighted equally but in a specific school they would not be. Weightings would have to be determined through surveys, interviews and visual inspections.

The data used to calibrate the model was retrospective (1995 to 2008) but the model could be used to forecast future performance by populating it with forecasts for important values. These could include exogenous factors such as carbon tax, the carbon content of grid electricity, energy price rises, improvements in technology efficiency, and local climate change impacts.

The intervention modelled in this prototype is a simplified single effect on controls, attitudes and behaviour. An improvement would be to add different types of interventions and then link them only to those inputs they will affect the most (e.g. staff training on the use of equipment would increase the value of the variable Understanding of How to Use Building and Controls).

The value of Commitment to Change will likely change over time but in this version of the model it does not. In fact, it usually fades unless consistent attention is paid to it from the top of the organisation. One intervention that can improve this is energy information feedback to building users (e.g. via existing displays in the reception area or via the intranet), which could be represented in the model.

Attitudes and behaviours may well be better modelled as soft stocks, as they do in fact build up over time and can be valued as soft capital (Fowler, 2003). For example, it may take years for a school to establish a culture of taking responsibility for carbon emissions and promoting environmental stewardship[7]. This has a value that is much more than just the money savings.

5 Conclusions

The model presented in this paper has attempted to represent the most important technology and people-related factors that impact a school's energy bills and GHG emissions. The model is intended as a tool to support consulting engagements when attempting to reduce these metrics; evidence shows that in the UK they are continuing to rise despite a large amount of investment in new buildings in the secondary school sector. The overall effect of varying a single intervention, Commitment to Change, was explored and compared with evidence from a review of case studies at secondary schools.

Because of the complexity of the system that is "a building and its users" the model only includes the most important factors that lead to electric and gas use, and approximate estimates of their values. This is a functionalist model of a socio-technical system; however, it can be combined with on-the-ground engineering auditing at the building and with people-centred research, to provide a more realistic picture of the physical, cultural and policy-level factors that all have an effect on energy use.

One of the main problems encountered when trying to reducing energy (and therefore carbon) consumption is that energy use is a side effect of performing an organisation's everyday activities. Therefore, to enable the system to be changed, the system must be much better understood *from the perspective of wanting to perform carbon management*. In fact, the system may be quite well understood from the perspective of improving

[7] Anecdotal evidence from the author's research at several schools

educational performance, but this does not help us when GHG emissions are the issue. This model is intended to overcome some of the messiness of carbon reduction work.

Once the system is better understood, a range of different interventions can be introduced. Interventions can be physical (e.g. more efficient equipment), policy (e.g. assigning energy management as part of people's job requirements), or behavioural (e.g. a switch off campaign for equipment). A school may desire to change things for many reasons – because energy bills are rising, or because their overall budgets are being reduced, or because their ethos includes environmental stewardship. These factors all lead to a certain level of commitment to change, which is represented in the model.

The relationships between soft and hard components have been represented as equations entered into the model by the modeller and based on theory, personal engineering judgment, and experience. For use in consultancy, the model will need to be calibrated in each specific engagement. However, it is important not to place too much emphasis on the quantitative value of the model – the question is really about the usefulness of the model in managing GHG emissions for a specific organisation; the model is not "right" in any absolute predictive sense (Sterman, 2002). We therefore see the model being used within an *ongoing process*, supporting both consultants and stakeholders in their efforts to manage GHG emissions. We expect the parameterisation and the structure of the model will constantly evolve to achieve this goal. Validation of the model is therefore more a function of what the model is telling its users about the system, rather than its absolute predictive accuracy (Barlas, 1996).

This prototype model is a first step in developing a tool to aid the process of carbon reduction in organisations using SD, and we anticipate there will be several benefits in the longer term, namely: 1) helping to bring clarity to a very messy problem, 2) providing a picture of how carbon and energy issues change over time, 3) getting people within an organisation to incorporate carbon management into their everyday work life. A detailed sensitivity analysis could shed more light on the dynamic interactions between endogenous, exogenous, and physical factors, and this is a focus for future work. GHG emissions are often overlooked in organisations but we believe that proactive, ongoing carbon management should be as important as meeting legal or health and safety requirements and that it is essential for an organisation's long-term resilience.

Acknowledgements

This work was supported by the Systems Centre at the University of Bristol, UK; the EPSRC funded Industrial Doctorate Centre in Systems (Grant EP/G037353/1); and Sustain Limited, Bristol, UK.

References

Barlas, Y. (1996) Formal aspects of model validity and validation in system dynamics. *System Dynamics Review,* 12(3), pp. 183-210.

Coyle, G. & Exelby, D. (2000) The validation of commercial system dynamics models. *System Dynamics Review,* 16(1), pp. 27-41.

Fowler, A. (2003) Systems modelling, simulation, and the dynamics of strategy. *Journal of Business Research,* 56(2), pp. 135-144.

Godoy-Shimizu, D., Armitage, P., Steemers, K. & Chenvidyakarn, T. (2011) Using Display Energy Certificates to quantify schools' energy consumption. *Building Research and Information,* 39(6), pp. 535-552.

Sterman, J. D. (2002) All models are wrong: reflections on becoming a systems scientist. *System Dynamics Review,* 18(4), pp. 501-531.