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TG66 - ENERGY AND THE BUILT ENVIRONMENT

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TG66 - ENERGY AND THE BUILT ENVIRONMENT

PAPERS AND POSTGRADUATE PAPERS FROM THE SPECIAL TRACK

Realising that the fraction of total energy consumed in buildings exceeds 35%, that the building sector consumes approximately half of all electricity and that the sector is responsible for at least 33% of global CO^2 emissions, and also realising that in recent years many countries have seen energy demand increase to a point where infrastructure and supply constraints have surfaced and that increasingly hot weather could lead to even higher energy prices and power cuts, the Task Group aims are to coordinate exchange of research activities in matters related to energy usage, impacts on greenhouse gas effects and conservation of energy, so that lessons learned can be shared and more effectively disseminated to stakeholders worldwide and to address the necessary upgrading of energy efficiency of the existing building stock, and not only ways to produce excellent new buildings.

CONTENTS

Papers

Postgraduate Papers

DOCET^{PRO}: Energy Certification and Diagnosis Software on Web Platform

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Abstract

DOCETPRO was born from the experience of national boards ITC-CNR and ENEA, which are in charge of the research activity related to the energy performance of buildings. The new tool aims at defining a national web platform with a calculation engine recognized at regional and ministerial level, that implements the Italian standard UNI TS 11300 concerning the energy performances of buildings, and acknowledges the European standard EPBD (Energy Performance of Buildings Directive) at national level. DOCETPRO is an energy certification software and as such it guarantees the reproducibility of results and the standardization of the calculation methodology. The software produces an XML file that allows the interchange with other software. The tool is based on the monthly balance method. Customers can define the building model, creating several dispersing surfaces with different physical and constructive characteristics: these may be horizontal or vertical, opaque or transparent surfaces. Customers can also define the heating system, with one or more traditional and non-traditional heating generation systems and domestic hot water generation system; it is also possible to define the thermal solar system and the photovoltaic system. The last part of the software is the cost/benefit analysis that allows the economic evaluation of several energy retrofit actions.

Keywords: DOCET^{PRO}, web platform, energy certification, UNI TS 11300

1. Application context

Since mid-2008 UNI TS 11300 part 1 and 2 were issued in accordance with standards developed by CEN under mandate M/343 in support of Directive 2002/91/EC on the energy performance of buildings; the need to define a single national instrument of calculation was generated in this context. The goal is to create an Italian Web portal, called Web Service Channel (WSC), that supports the calculation engine DOCET^{PRO} updated to UNI TS 11300 for energy certification of buildings.

UNI TS 11300 part 2 defines 3 different types of energy assessment:

- Design assessment: the calculation is made on the basis of design data; for the conditions of employment and use of the building and the system a continuous operating system is assumed;

- Standard assessment: the calculation is made on the basis of the data concerning both the building and the real system, as built; for the conditions of occupancy and use of the building and the system a continuous operating system is assumed;

- Assessment under actual use conditions: the calculation is made on the basis of the data concerning both the building and real plant, as built; for the conditions of occupancy and use of the building and the system actual operating values are assumed.

DOCET^{PRO}, as a software of energy certification, is consistent with the design and standard assessment. For the purpose of energy diagnosis it is advisable to carry out the third assessment, integrated with the measurement of consumptions.

2. Software architecture

The software is based on the monthly balance method, aimed at the energy certification of buildings, according to different uses.

The calculation of net energy for heating is carried out according to the UNI TS 11300 part 1, which defines the net energy as the balance of heat losses and heat gains.

The primary energy for heating is calculated according to the methodology laid down in UNI TS 11300 part 2, which defines the primary energy as the balance of heat loss and heat and electrical recovery for every subsystem of the heating and domestic hot water system.

The model building is user-defined as a single thermal zone, thus creating different opaque and transparent, horizontal and vertical scattering surfaces, as detailed as deemed appropriate by setting a minimum number of areas according to the differences between building, physical and exposure characteristics of the individual elements.

For existing buildings, where information retrieval is often an issue, the software gives tips based on the input data and qualitative input entered by the user and according to the abacus contained in the regulations.

DOCET^{PRO} evaluates one or more heating generators, choosing between traditional and non-traditional systems not taken into account in technical standards UNI TS 11300 part 1 and 2, such as thermal solar and photovoltaic systems, heat pumps and micro-cogeneration. The normative references for this type of evaluation are as follows:

- Heat pump: UNI EN 15316-4-2;
- Thermal solar system: UNI EN 15316-4-3;
- Micro-cogeneration: UNI EN 15316-4-4;
- Photovoltaic system : UNI EN 15316-4-6.

The evaluation of multi-heat generation systems is performed with the introduction of allocation factors allocating the thermal energy among the different generators.

The software also contains a cost/benefit analysis, called CBA, for specific types of energy retrofits; starting from a fuel price and a cost manually entered, the certifier can get some economic parameters to determine the specific financial indicators (e.g., payback time, NPV, etc.).

The cost/benefit analysis is therefore an objective tool to evaluate, to compare and to optimize the economic feasibility of possible energy-efficiency refurbishment works identified by the energy diagnosis and fits in the evaluation approach of a building as follows:

- Specific energy diagnosis made by the certifier;
- Identification of performance deficiencies of the building;
- Definition of targets for improvement in performance to be achieved;
- Study of possible alternative technological actions, on equal performances, to achieve the set targets;
- Assessment of the viability of alternative technologies through the CBA identified and definition of the solution allowing the aspects of performance to match at best the economic efficiency.

3. Performance indicators

The methods developed within CEN define three steps of calculation with related performance indicators:

- Net energy;
- Delivered energy;
- Primary energy.

The requirement of net energy is that necessary to meet criteria of comfort, taking into account the thermal losses and gains; this parameter varies depending on the thermal transmittance, orientation, shape factor, profiles of use, etc., and basically indicates that the architectural and construction solutions are fit for the building envelope.

The delivered energy is that actually measurable at the "power meter"; the calculation depends on the type of technological systems installed, their efficiency and the performance factor, and gives comprehensive information on the efficiency of the “building-plant system”.

The third indicator is the primary non-renewable energy, which indicates the actual consumption of non-renewable resources, depending on the fuel used and the actual use of renewable energy sources.

Only the evaluation of all performance indicators described provides comprehensive information on the strategies and the choices made to serve the purpose of increasing the energy efficiency of a building.

3.1 Net energy

The net energy for heating, $Q_{H,nd}$, and for cooling, $Q_{C,nd}$, expressed in kWh, is determined by the balance of losses (transmission and ventilation) and gains (internal and solar gains), according to the following formulas:

$$Q_{H,nd} = \left(Q_{H,tr} + Q_{H,ve}\right) - \eta_H \cdot \left(Q_{int} + Q_{sol}\right)$$

$$Q_{C,nd} = \left(Q_{int} + Q_{sol}\right) - \eta_C \cdot \left(Q_{C,tr} + Q_{C,ve}\right)$$

where:

$Q_{H,tr}$ is the total heat transfer by transmission for heating, expressed in kWh;

$Q_{C,tr}$ is the total heat transfer by transmission for cooling, expressed in kWh;

$Q_{H,ve}$ is the total heat transfer by ventilation for heating, expressed in kWh;

$Q_{C,ve}$ is the total heat transfer by transmission for cooling, expressed in kWh;

Q_{int} is the sum of internal heat gains over the given period, expressed in kWh;

Q_{sol} is the sum of solar heat gains over the given period, expressed in kWh;

η_H is the dimensionless gain utilization factor.

η_c is the dimensionless utilization factor for heat losses.

The net energy requirement depends on the characteristics of the building envelope, such as: geographical location (province, municipality, degrees/day, latitude, altitude, etc.); intended uses of the building; geometry of the building; thermo-physical features of opaque and transparent technical elements (thermal transmittance, surface coloring, solar factor, etc.).

3.2 Delivered energy

The energy delivered for heating and/or for the production of hot water for domestic use depends on the technological systems installed. The heat producing systems can be divided into the following subsystems:

- Heating: emission, regulation, distribution, stoke, generation;
- DHW production: emission; distribution; stoke; generation.

For each subsystem the following shall be determined:

- total amount of energy entering the subsystem;
- total auxiliary energy of the subsystem;
- losses;
- recovered losses.

The calculation is made from the downstream system (emission system) to the heat generator, as defined in figure 1.

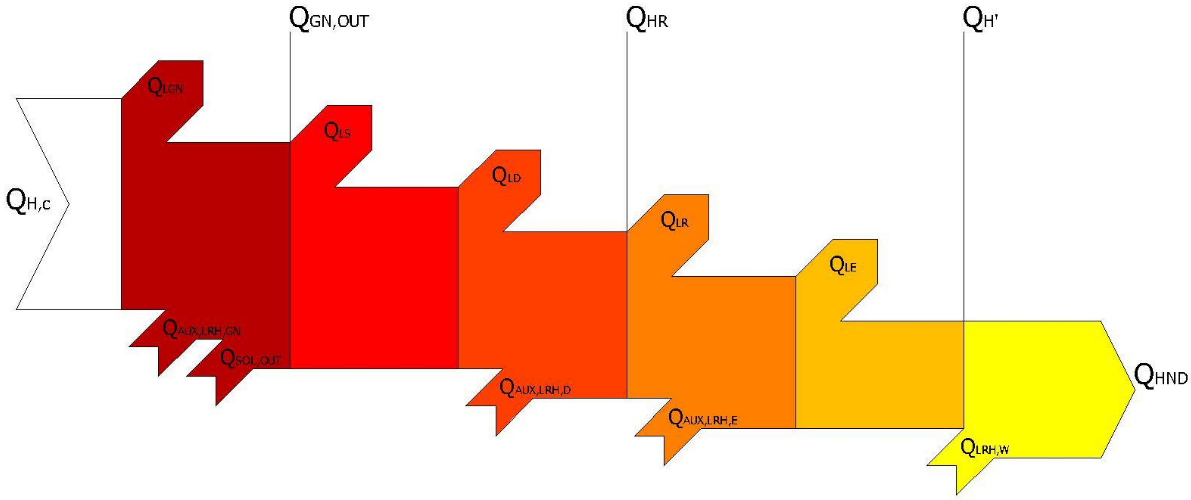

Figure 1: Heat flow of the heating

3.3 Primary energy

The primary energy is defined as the energy potential presented by carriers and energy sources in their natural form, i.e. energy that is not subject to any conversion or transformation process; the tool adds different forms of energy such as fuel (natural gas, oil, biomass, etc.), self-produced or purchased electric energy, derived from renewable sources (geothermal, hydroelectric, wind, etc.) or fossils.

For evaluation of the heating and/or DHW production, the primary energy factors allows the thermal and electrical energy used by the auxiliary systems to be added, according to the following formula:

$$Q_{p,H,W} = \sum Q_{H,c,i} \cdot f_{p,i} + \sum Q_{W,c,j} \cdot f_{p,j} + \left(Q_{H,aux} + Q_{W,aux} + Q_{INT,aux} - Q_{el,exp}\right) \cdot f_{p,el}$$

where:

$Q_{H,c,i}$ is the thermal energy requirement for heating obtained from each energy carrier, expressed in kWh;

fp,i/j is the conversion factor of the energy carrier into primary energy;

$Q_{W,c,j}$ is the thermal energy requirement for DHW production obtained from each carrier, expressed in kWh;

$Q_{H,aux}$ is the electricity requirement for the auxiliary heating system, expressed in kWh;

$Q_{W,aux}$ is the electricity requirement for the auxiliary DHW production system, expressed in kWh;

$Q_{INT,aux}$ is the electricity requirement for any auxiliary systems that use renewal energy sources, expressed in kWh;

$Q_{el,exp}$ is the electric energy exported from the system (photovoltaic, cogeneration), expressed in kWh;

$f_{p,el}$ is the conversion factor of auxiliary energy into primary energy.

4. Financial indicator

According to the European EPBD (Energy Performance of Buildings Directive) normative framework the energy certificate must be accompanied with recommendations for the improvement of the energy efficiency of the building. DOCET^{PRO} contains a section devoted to the cost-benefit analysis, in which possible energy-efficiency refurbishment actions are evaluated from the point of view of improving performance and the economic and financial impact; to this end, the simple payback time of investment is calculated.

4.1 Simple payback time of investment (SP)

The simple payback time is defined as the number of years necessary so that the cash flows (excluding debt payments) equal the total investment, according to the formula:

$$SP = \frac{\text{Initial investment}}{\text{Annual saving}}$$

The simple payback time is one of the most important financial indicators because it determines the time needed to recover the capital invested through the analysis of annual flows of each specific operation.

Since this method does not evaluate the cash flow after capital recovery time and does not take into account the possible currency floating over the time, the value calculated in years for the SP needs to be compared with the expected useful life of the refurbishment; in order for the solution to be economically feasible, the SP must be less than the useful life of the refurbishment.

In the event that the simple payback time is used as a tool to compare and choose the solution that, on equal achievement of energy targets, better meets the financial and economic needs, the solutions with the lower SP value will be preferred.

5. Conclusions

The goal is the realization of an energy platform, called Web Service Channel (WSC), in which DOCET^{PRO} is the tool for energy certification of buildings updated to UNI TS 11300.

WSC is an advanced environment where tools for energy certification are available. It is a user-friendly desktop interface represented by a centralized web-based browser usable operating system; this technology allows the updates to be always available.

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Phase Change Materials (PCMs) - Treated Natural Stone for Thermal Energy Storage in Buildings: Influence of PCM Melting Temperature

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Abstract

The treatment of natural stone with Phase Change Materials (PCMs) provides innovative products with thermal energy storage properties. This allows the storage and release of thermal energy during day/night cycles, contributing to reduce energy demands in buildings, and consequently to CO2 emission reduction. Additionally, health and human comfort indoors can be improved by the reduction of temperature fluctuations between day/night. The objective is to increase energy savings potentials and energy storage capacity of natural stone by improving its thermal properties by means of latent heat storage materials (PCMS). Therefore, PCM treated natural stone can be used as construction materials able to store thermal energy having materials with higher thermal inertia. Energy consumption in buildings (cooling/heating systems) is decreased and negative effects and damages for the environment are reduced. The effectiveness of the treatment with PCM as thermal energy storage system for natural stone has been investigated. A PCM with a melting temperature close to that recommended for human comfort has been used for the natural stone treatment. Different experimental techniques have been used for the characterization of the PCM and for the characterization of the PCM-treated natural stone. Results have shown that these new products based on natural stone have ability to store energy. Temperature fluctuations in the place of use are minimized and the temperature peaks maximum-minimum between day-night are reduced. Moreover, because outdoor temperature changes from summer to winter and in order to have thermal energy storage properties for the full year, the treatment of natural stone with PCMs with different melting temperatures has been carried out.

It has also been demonstrated that the introduction of PCMs with different melting temperatures provides materials with energy storage capacity for different climatic conditions (summer or winter times). In this way, by changing the PCM melting temperature, new stone products can be designed for different climate conditions of different regions and for special exposure conditions. The new products are appropriate for indoor or outdoor applications (tiles, plates and slabs used for cladding, roofing, flooring, systems for ceilings, walls and floors) where energy consumption is crucial for the energy performance of buildings.

Keywords: natural stone, phase change material, thermal energy storage, energy efficiency

1. Introduction

The worldwide economical and technological development requires higher energy demands and higher comfort expectations (heating and cooling systems). However, energy sources are limited and related to harmful gases, which are responsible for climate changes, global warming and environmental problems. PCMs are proposed as a solution to reduce energy demands from buildings by the addition of PCMs to construction materials as concrete, gypsum or plasterboard panels [1, 2].

Several chemical compounds have been found to be useful as latent heat storage materials: paraffin wax, fatty acids, hydrated salts, etc.

The use of PCMs as thermal storage systems for buildings has been of interest since first application in the 1940s. PCMs store latent heat as the ambient temperature rises up to the melting point (PCM changes from solid to liquid state). As the temperature cools down, the PCM return to solid phase and the latent heat is released. This absorption and release of heat takes place at a constant temperature, which is ideal to smooth temperature fluctuations.

The thermal energy storage property of PCMs is based on its capability of latent heat storage, because large amounts of energy can be stored in a small volume of PCM. Therefore, the material containing PCMs can absorb and release heat more effectively than conventional building materials [3]. However, for an effective use of the PCMs for an extended period of the year it is important the selection of the melting point.

Some references have been found about the use of PCMs to improve thermal properties of concrete or gypsum. Some authours [4] have studied the thermal performance of PCMs in different types of concrete blocks. Thermal storage in concrete containing PCMs was increased more than 200%.

Salyer et al [5] have developed different methods of PCM incorporation to building blocks: by imbibing the PCM into porous materials, PCM absorption into silica or incorporation of PCMs to polymeric carriers.

Several applications have been found for PCMs as energy storage systems and coming from a variety of sources. PCMs are currently used for co-generation facilities, air conditioning systems, low temperature solar thermal applications [6], solar collectors, as insulation materials used in clothing, sport clothes [7] or bedding articles [8], cool thermal storage for vegetable cooling [9].

The use of PCMs for the treatment of natural stone in order to improve its thermal properties is due to several reasons:

1) Energy savings in heating/cooling systems; 2) Enhancement of thermal comfort inside the building (reduction of temperature differences between day and night and different rooms inside the building, health and human comfort); 3) Storage of the heat from outdoors; 4) Avoid excessive heat from outdoors.

Directive 2002/91/EC on the energy performance of buildings indicates that the measures to improve the energy savings of buildings should take into account climatic and local conditions as well as indoor climate environment.

Outdoor temperature changes from summer to winter. In this paper, in order to have thermal energy storage properties for the full year, the treatment of natural stone with PCMs with different melting temperatures has been carried out. The influence of the melting temperature of PCMs incorporated to natural stone materials has been analyzed. The choice of the suitable transition temperature for a given application is a fundamental aspect for an optimum effectiveness of the PCMs, as stated by F. Agyenim et al. [10].

It has been demonstrated that the introduction of PCMs with different melting temperatures provides materials with energy storage capacity for different climatic conditions (summer or winter times). In this way, by changing the PCM melting temperature, new stone products can be designed for different climate conditions of different regions and for special exposure conditions.

The new products are appropriate for indoor or outdoor applications (tiles, plates and slabs used for cladding, roofing, flooring, systems for ceilings, walls and floors) where energy consumption is crucial for the energy performance of buildings.

2. Materials and experimental techniques

Bateig azul has been selected as natural stone in order to study the thermal storage properties of natural stone materials after PCM treatment. This material is extracted in Novelda-Alicante-Spain. It is blue and composed of calcite and quartz, with medium porosity size.

Two PCMs have been used for the treatment of Bateig azul with different melting temperature: 1) Micronal DS 5000X (provided by BASF) has been selected as the phase change material. It is a water-based solution with following characteristics: viscosity equal to 30-100 mPa·s, solid content of 43% and meeting temperature ca. 26ºC and 2) Rubitherm RT6. Melting temperature = 8ºC, heat storage capacity=175 kJ/kg, density liquid at 15ºC=0.77 kg/l. For the treatment, Bateig azul has been immersed in these solutions to be impregnated with the PCMs.

Different experimental techniques have been used for the characterization of Bateig azul without and with PCM treatment.

-Scanning Electron Microscopy (SEM). The presence of PCM in the pores of Bateig azul has been observed, distribution and shape. Hitachi S-3000 N.

-Porosimetry. Porosity of Bateig azul before and after PCM treatment has been evaluated (Hg porosimeter, Micromeritcs Autopore IV).

-Differential Scanning Calorimetry (DSC). Thermal behaviour of PCMs, melting temperature, entalphy, decomposition, etc can be evaluated with DSC (Star^{e} SW 8.10, Mettler Toledo).

3. Results and discussion

Some papers in literature indicate that PCMs can be effectively used for the thermal energy storage when incorporated to construction materials such as concrete or gypsum in order to reduce energy demands and to increase human comfort indoors. Therefore, melting temperature of the PCMs used is closed to that of human comfort, ca. 25ºC.

To demonstrate the effectiveness of PCM incorporated to natural stone, a number of pilot stations made out of concrete and Bateig azul (with and without PCMs) as natural stone for the façade have been built and placed outdoors (Figure 1). Bateig azul has been impregnated with PCM with melting temperature of 26ºC.

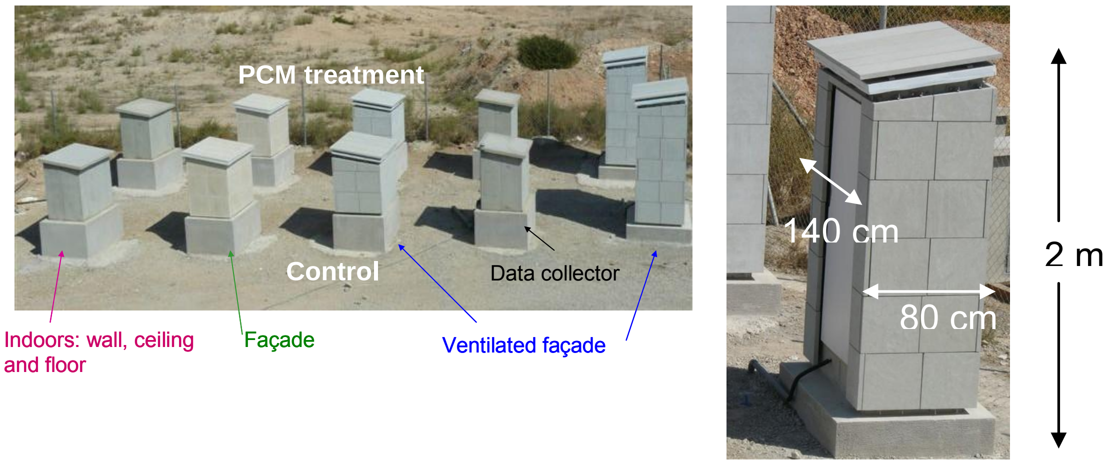


Figure 1. Photographs of pilot stations. Control (without PCMs) and PCM-treated natural stone pilot station.

The objective is to analyze the effect of the PCM-treated natural stones in different parts of the pilot station: south wall, east wall, ceiling, temperature in the air gap, in contact with the concrete or the natural stone, etc. In all cases, sensors have been placed in the control and the "PCM" stations in the same positions. Variations of temperature in different points of the pilot stations have been monitored every 10 min for several day-night cycles during the summer period in Alicante. Figure 2 shows the monitored temperatures for 1 cycle.

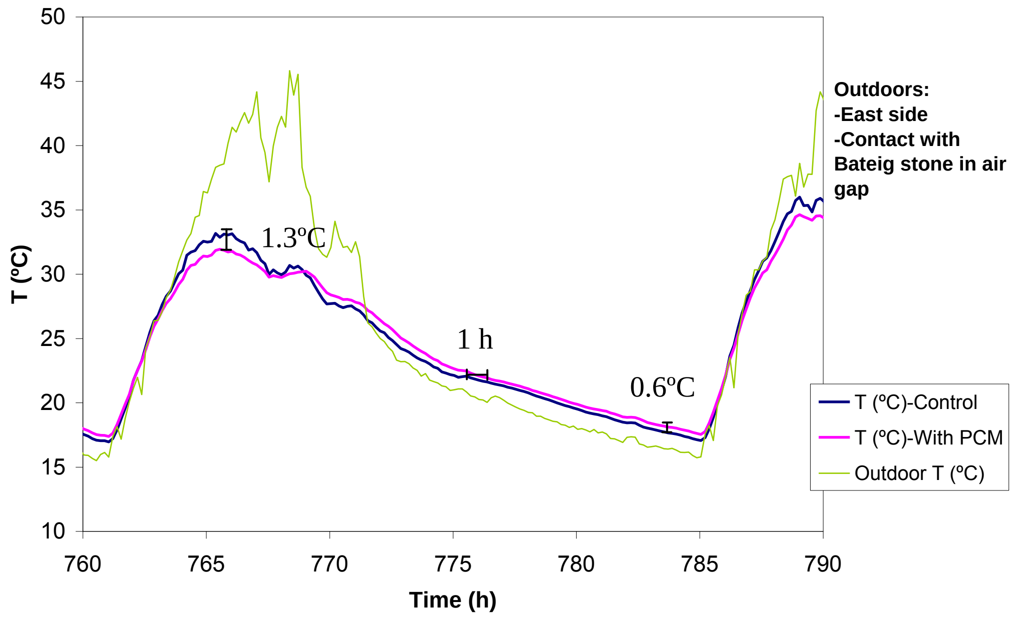


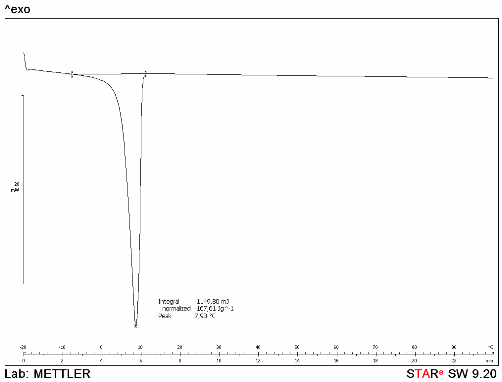
Figure 2. Temperatures in the pilot stations of Bateig azul with and without PCMs as façade materials.

Several differences between the temperatures in the pilot station and the station with PCM-treated Bateig Azul as façade can be observed. The maximum recorded temperature in the PCM treated station – although it occurs at the same time point as in the reference station - it is 1.3ºC lower than for the station without PCMs, demonstrating at pilot scale the energy storage potentials of PCMs. The cooling process is smoother for the pilot station with PCMs (the temperatures occurring in the reference station are reached with an hour's delay in the station with the PCM treated stones), indicating that the stored energy is being released. Minimum temperature in the PCM treated station is 0.6ºC higher compared to the station without PCMs. These two effects are important because the energy demand due to the heating or cooling systems will be decreased by the reduction of temperature fluctuations between day and night, and also because low or high temperatures are achieved with some time delay (at least one hour in these experimental conditions), and thus the working time of air conditioning systems can be also reduced.

Temperatures have been also registered during winter. For this period, temperature does not rise the melting point of PCM (26ºC). Thus, temperatures registered for the control pilot stations are similar to those obtained for the PCM-treated natural stone pilot station. Therefore, PCMs can only be useful for thermal energy storage in a period of the year. To extend the thermal energy storage possibilities of the PCMs to a higher temperature range, natural stone has been treated with PCMs of different melting temperatures: 8ºC, 26ºC and both 8 and 26ºC in the same piece.

PCMs have been characterized by Differential Scanning Calorimetry (DSC) in order to determine the melting temperature and the melting enthalpy (Figure 3 a-c). The information from the provider was confirmed for both PCMs, and melting temperatures of 8 and 26ºC were obtained respectively. Natural stone treated with both PCMs shows also the melting processes corresponding to each PCM.

a)



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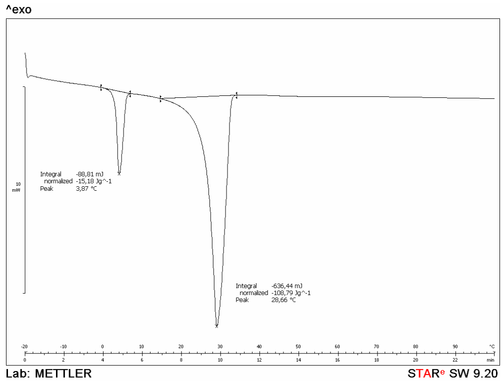

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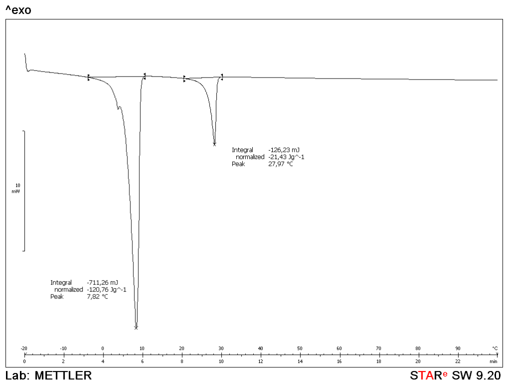

Figure 3. DSC thermographs for a) PCM-8ºC, b) PCM-26ºC and c) PCM-8+26ºC.

The incorporation of both PCMs in the bulk of Bateig azul has been confirmed by mercury porosimetry. Figure 4 shows the pore size distribution for Bateig azul and Bateig azul treated with both PCMs 8 and 26ºC. A decrease in the pore size of Bateig azul can be observed when treated with the PCMs, confirming that the natural stone has been impregnated with the PCMs.

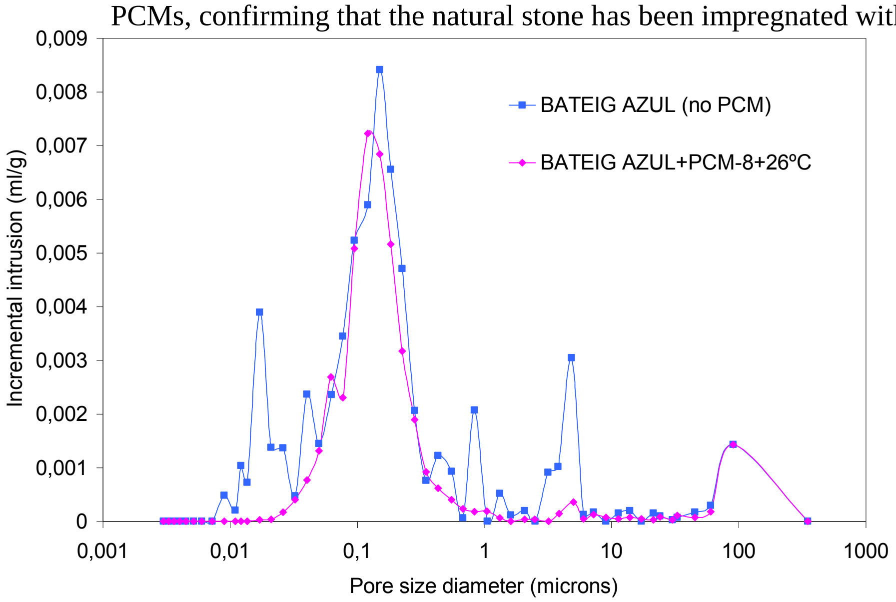

Figure 4. Mercury porosimetry for Bateig azul and Bateig azul treated with PCM-8+26ºC.

Figure 5 includes the SEM micrographs of the cross section of Bateig azul and Bateig azul treated with PCM-26ºC. The presence of PCMs can be observed in the bulk of Bateig azul.

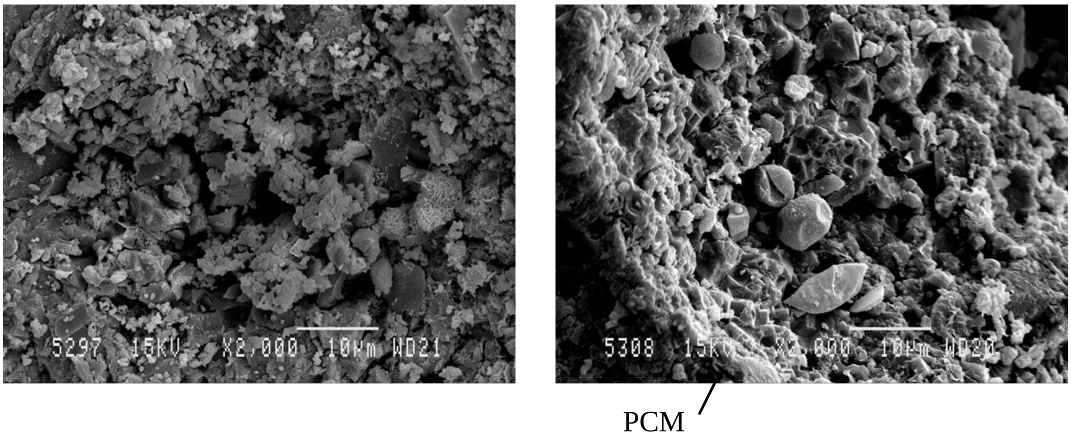

Figure 5. SEM micrographs of Bateig azul and Bateig azul treated with PCM-8+26ºC.

An experimental set-up has been designed using natural stone treated with the different PCMs. The experiment consists of adiabatic cubic boxes (30x30x30 cm), made with isolating materials and one side of natural stone. Temperatures inside the boxes have been registered and compared.

Figure 6 shows the temperature inside the control box compared to the PCM-treated box. A day-night cycle has been selected ranging from low temperatures at night to high temperatures during the day, with the objective to analyze the effect of the different PCMs.

During the summer period, when high temperatures are observed, the Bateig azul treated with the PCM with a melting temperature of 26ºC is more effective for thermal energy storage compared to Bateig azul with the PCM-8ºC, because there is not phase change at this temperature range.

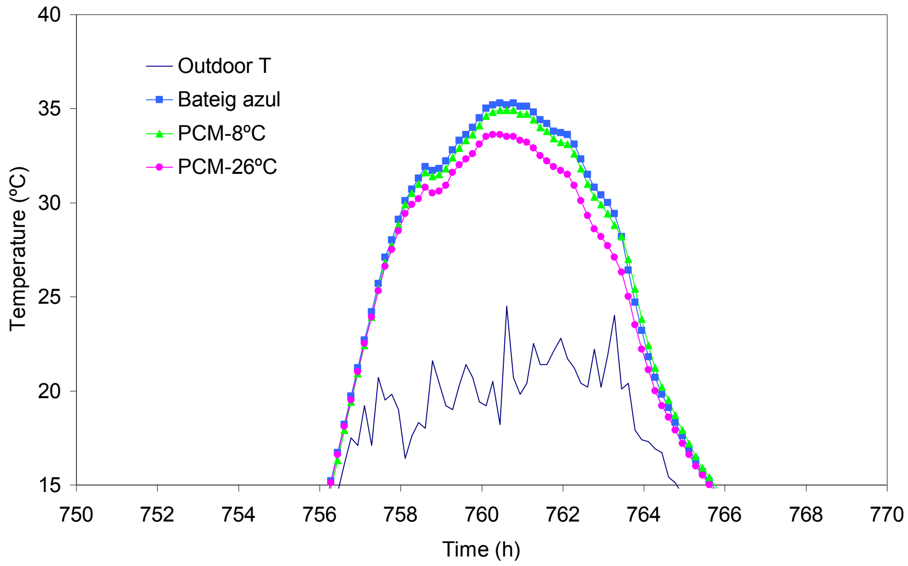

Figure 6. Temperature inside adiabatic boxes with one side of Bateig azul with and without PCMs. Effect of different melting temperature of PCMs during summer.

In order to study the effects of the melting temperature of PCMs in winter, Bateig azul has been treated with both 8 and 26ºC PCMs in the same piece. In this period, because the temperature range is 0-25ºC, the box with Bateig azul treated with PCM-8+26ºC is more effective for thermal energy storage (Figure 7) compared to the PCM-26ºC, because at temperatures lower than 26ºC there is not phase change and it can not store energy.

When going to low temperatures, the PCM-8ºC releases the thermal energy previously stored, and thus not so low temperatures are obtained for the Bateig azul treated with PCM-8ºC (Figure 8). On the other hand, and as a consequence of the reduction in the peak temperatures between day and night, the natural stone will be subjected to lower temperature fluctuations. Therefore, it is expected that durability of natural stone treated with PCMs will be increased.

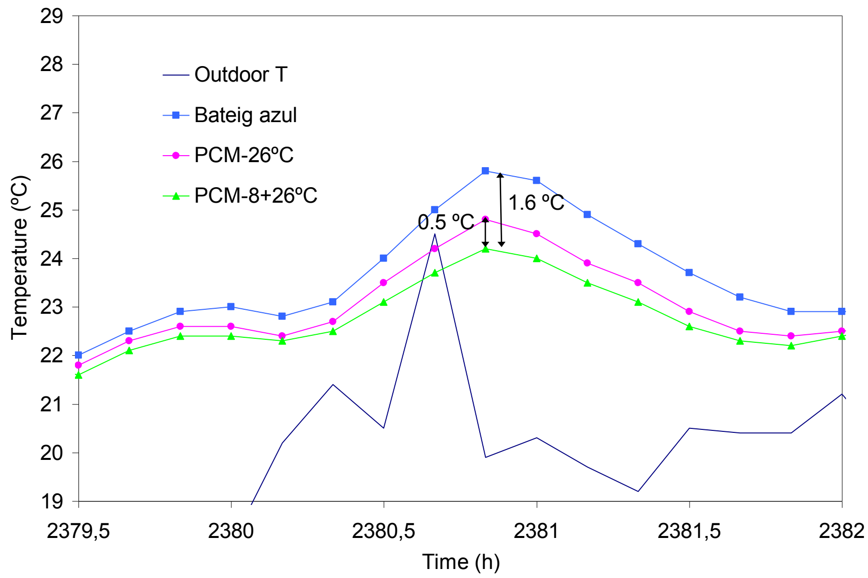

Figure 7. Temperature inside adiabatic boxes with one side of Bateig azul with and without PCMs. Effect of different melting temperature of PCMs during winter.

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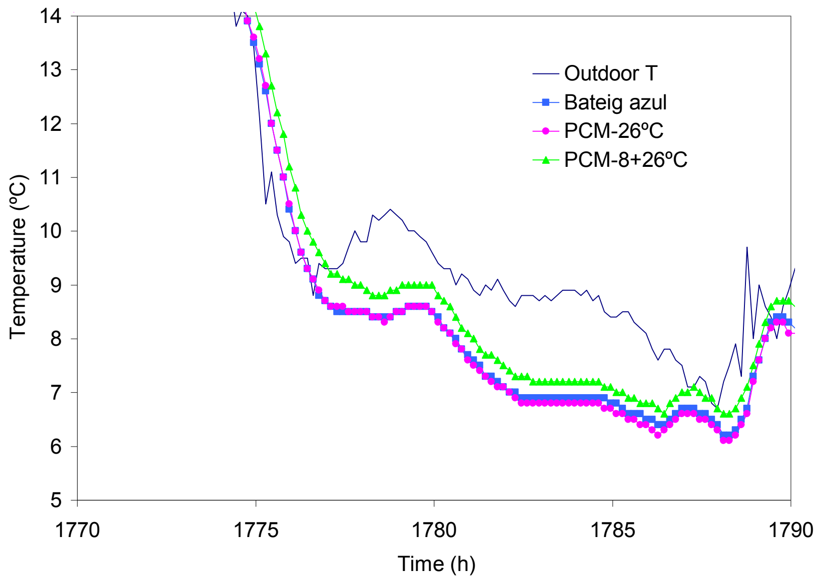

Figure 8. Temperature fluctuations for the box with Bateig azul and Bateig azul treated with PCM-26ºC and PCM-8+26ºC at low temperatures.

4. Conclusions

As a consequence of the PCM treatment, several effects are observed:

-Reduction on the peak temperatures between day-night.
-Delay in the time to go to minimum or maximum temperatures.
-As a result of the experimental observations, a reduction in energy consumption can be anticipated and an increase in human comfort, due to a reduction of temperature variations during day and night.
However, the effectiveness of PCMs as thermal energy storage systems depends on the selection of the melting temperature of PCM, the place where located (i.e northern or southern climates). Treatment with PCMs with different melting temperatures in the same natural stone piece is recommended in order to cover summer and winter periods.

Together with the reduction in energy consumption, an increased durability of the natural stone pieces is expected as a consequence of the reduction in temperature fluctuations between day and night.

Acknowledgement

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Cost-Effectiveness of Energy Efficiency Measures Exceeding Current Standards in New Commercial Buildings

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Abstract

Building energy efficiency has become a top priority for governments across the globe due to the recent energy price volatility and increasing concern regarding climate change. New buildings are considered the easiest and least costly way in which to increase energy efficiency, making new construction an excellent target for efficiency improvements. The goals of this paper are to estimate life-cycle energy savings, carbon emission reduction, and cost-effectiveness of energy efficiency measures in new commercial buildings using an integrated design approach. A total of 1416 energy simulations are run for 12 prototypical buildings in 59 cities, with two building designs, ASHRAE 90.1-2007 compliant and a "Low Energy Case," for each building-location combination. Whole building energy consumption simulations and extensive building cost databases are used to determine the life-cycle cost-effectiveness and carbon emissions of each design. The results show conventional energy efficiency technologies can be used to decrease energy use in new commercial buildings by 10 % to 20 % on average and up to over 25 % for some building types and locations. These reductions can often be done at negative life-cycle costs over a short study period because the improved efficiencies allow the installation of smaller, less expensive HVAC equipment. These improvements not only save money and energy, but reduce a building's carbon footprint by 14 % on average.

Keywords: carbon footprint, energy efficiency, integrated design, life-cycle assessment, life-cycle costing

1. Introduction

Building energy efficiency has come to the forefront of political debates due to high energy prices and climate change concerns. Improving energy efficiency in new commercial buildings is one of the lowest cost options to decrease a building's energy use, owner operating costs, and carbon footprint. This paper uses life-cycle costing and life-cycle assessment with extensive building cost databases and whole building energy simulations to determine the energy savings and cost-effectiveness of energy efficiency improvements and the resulting carbon emissions reduction.

The results of this analysis show that conventional energy efficiency technologies such as thermal insulation, low-emissivity windows, window overhangs, and daylighting controls can be used to decrease energy use in new commercial buildings by 10 % to 20 % on average and up to over 25 % for some building types and locations. Although improving energy efficiency may increase the first costs of a building, the energy savings over the service life of the building often offset these initial higher costs. The first costs can often be lower for the more efficient building designs because, through integrated design, the improved efficiency reduces the size of the heating, ventilation, and air conditioning (HVAC) system required to meet the peak heating and cooling loads.

The energy efficiency improvements not only save money, but also reduce a building's carbon footprint. Carbon footprints are reduced by an average of 14 % across all building types and sizes for a ten-year study period with the greatest reductions occurring in areas relying heavily on coal-based electricity.

2. Study design

Twelve building types are evaluated to consider a range of building sizes and energy intensities. The building types evaluated in this paper represent 46 % of the U.S. commercial building stock floor space (CBECS, 2003). A three-story and six-story dormitory, three-story and six-story apartment building, and fifteen-story hotel represent the lodging category. An elementary school and high school represent education buildings. Three sizes of office buildings (three-story, eight-story, and 16-story) are used to represent the largest building category; offices accounting for 17 % of U.S. building stock floor space. A one-story retail store represents non-mall mercantile buildings while a one-story restaurant represents the food service industry. Building size ranges from 465 m^2 to 41 806 m^2 (5000 ft^2 to 450 000 ft^2).

Life-cycle costing and life-cycle assessment are conducted over four different study period lengths: 1 year, 10 years, 25 years, and 40 years. A one-year study period length represents the time horizon of an investor who intends to turn over the property soon after it is built, such as a developer. The 10-year, 25-year, and 40-year study periods represent long-term owners at different ownership lengths. Longer study periods are effective at capturing all relevant costs of owning and operating a building. However, longer study periods increase uncertainty in the precision of the life-cycle cost estimates due to the assumptions made about costs and occupant behavior in future decades, such as energy costs and energy consumption.

For each building type, energy simulations are run for sixteen U.S. cities located in different *ASHRAE 90.1-2007* sub-climate zones (ASHRAE, 2007). These cities are chosen as representative cities based on geographical location, and population. At least one city from each of the sub-climate zones, excluding Zone 6B and Zone 8, is included in the analysis.

3. Cost data

3.1 Building construction costs

Prototypical building and component assembly costs originate from the RS Means *CostWorks* online database. The RS Means *CostWorks Square Foot Estimator* "default costs" for each building type are used to estimate the costs of a "prototypical building."[1] This prototypical building is used as a baseline to create a compliant building for the two energy efficiency design alternatives being considered in this analysis: the *ASHRAE 90.1-2007* energy efficiency standard design and a higher efficiency "Low Energy Case"' (LEC) design.

The RS Means *CostWorks Cost Books* are used to adapt the RS Means prototypical buildings to the two building designs. The only components that must be changed to meet *ASHRAE 90.1-2007* are insulation and windows. Insulation material and/or thickness in both the walls and roof decks are changed in order to meet *ASHRAE 90.1-2007*. Windows are altered in three ways: increasing the number of panes, adding low-emissivity (low-e) coatings, and adding solar heat gain control films depending on the *ASHRAE 90.1-2007* requirements.

The LEC design increases the thermal efficiency of insulation and windows, and introduces daylighting and window overhangs. The new insulation requirements go beyond *ASHRAE 90.1-2007* by adding up to R-15 to the roof deck and R-16.1 to the wall exterior. The U-factor, solar heat gain coefficient, and visual transmittance are improved by up to 0.10, 0.05, and 0.07, respectively. The LEC also adds daylighting controls and overhangs for window shading where optimal, based on the *EnergyPlus* "Example File Generator" recommendations. Daylighting is included for all building types and locations while overhangs are used in all building types and locations except for the coldest climate zones.[2]

The two building designs have different heating and cooling loads, which leads to differences in the appropriate size of the HVAC system. Whole building energy simulations automatically size ("autosize") the HVAC system to the smallest system that will still meet the ventilation load requirements. Smaller HVAC systems have lower assembly costs, which can offset some or all

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[1] Disclaimer: Certain trade names and company products are mentioned throughout the text. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the product is the best available for the purpose.
[2] Cost data obtained from Winiarski et al. (2003).

of the additional first costs from other energy efficiency measures (i.e. insulation). Based on the costs of the system used in the prototypical building, the HVAC costs are increased or decreased to the appropriate size specified in the energy simulations based on a linear interpolation of assembly costs.

Construction costs for each building are determined by summing the baseline costs for the prototypical building and the changes in costs required to meet the building design. National average construction costs are adjusted with the 2008 RS Means *CostWorks City Indexes* to control for local price variations. Once the indexed construction cost of a building has been calculated, it is multiplied by the contractor "mark-up" rate. This value is then multiplied by the architectural fees rate, resulting in the building's "first costs."[3]

3.2 Maintenance, repair, and replacement costs

Component and building lifetimes and component repair rates are collected from Towers, Dotz, and Romani (2008). Building service lifetimes are assumed constant across climate zones: apartments - 65 years; dormitories - 44 years; hotels, schools and office buildings - 41 years; retail stores - 38 years; and restaurants - 27 years. Insulation and windows are assumed to have a 50-year lifespan. Insulation is assumed to have no maintenance and repair requirements while windows have an annual repair rate of 1 % of window panes. The heating and cooling units have different lifespans and repair rates based on climate. Cooling units have short lifespans and repair frequencies in hot climates and long ones in cold climates. The opposite holds true for heating units, with longer lives and less maintenance in warmer climates.

Future costs are collected from two sources. Baseline average maintenance, repair, and replacement (M, R, and R) costs (excluding HVAC) per square foot for each building type, by year of service life, are from Towers, Dotz, and Romani (2008). RS Means *CostWorks* is the source of M, R, and R costs for the components that change across building designs. In this analysis, HVAC system components are the only components replaced over the study period. Based on the repair rate, windows have an assumed annual repair cost equal to replacing 1 % of all window panes.

3.3 Energy costs

Utility rates for electricity and natural gas are obtained from the U.S. Energy Information Administration (EIA). The state-wide average retail price per 3.6 MJ (1 kWh) of electricity is used as the building owner's/operator's cost of electricity consumption. The EIA *December 2008 Natural Gas Monthly* is used to obtain the average retail natural gas prices by state for 2007. Whole building energy simulations for the 708 building type-location combinations are run in the *EnergyPlus 3.0* "Example File Generator" web interface to obtain each building's annual

[3] Contractor fee and architectural fee rates are the default rates provided by RS Means at 25 % and 7 %, respectively.

energy use for electricity and natural gas. For simplicity, the annual energy use for each fuel type is multiplied by the average fuel cost for the building location to obtain a building's annual energy costs. It is assumed that the building maintains its energy efficiency performance throughout the study period.

3.4 Building residual value

Building residual value -- its value at the end of the study period -- is estimated based on first costs and remaining component and building lifetimes. The baseline residual value is the first cost (excluding any components replaced over the time period) multiplied by the ratio of the remaining life of the building to the study period of the building. The lone additional residual value comes from the HVAC equipment, which is the only component replaced over the study period. Any remaining years in the lifetime of the HVAC equipment is used to estimate a residual value by taking the initial cost of the HVAC system and multiplying it by the ratio of remaining life to estimated lifetime of the equipment.

4. Life-cycle cost analysis

Life-cycle costing (LCC) estimates the net present value of all relevant costs throughout the study period, including construction costs, M, R, and R costs, energy costs, and residual values.[4] LCC of buildings compares the costs from a “base case” building design to costs from alternative building designs.

The “base case” in this paper is assumed to be the *ASHRAE 90.1-2007* design because it is the most recent building energy efficiency standard written into current U.S. state building code requirements.[5] The LEC design is compared to the *ASHRAE 90.1-2007* design to determine the LCC and carbon emissions for this more efficient alternative. This study analyzes LCC results via two measures: net savings as a percentage of base case LCC and the adjusted internal rate of return. Net savings is the difference between the base case (*ASHRAE 90.1-2007*) and alternative (LEC) design's LCCs. The adjusted internal rate of return (AIRR) is the annualized return on the energy efficiency investment costs. The AIRR of building energy efficiency investments can be compared to an investor's minimum acceptable rate of return (MARR), such as gains from competing investments in the stock or bond market over the same study period or, in the case of the federal government, the savings in interest payments from decreasing the national debt. If the AIRR is greater than the investor's MARR, the energy efficiency investment is preferred.

All future costs are discounted to their equivalent present values based on the appropriate discount factors (Rushing, 2008). All costs and values are discounted based on the U.S. Department of Energy (DOE) real discount rate for energy conservation projects (3.0 % in 2008). EIA energy price forecasts are embodied in the discounting of electricity and natural gas

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[4] Source: Fuller et al. (1996).

[5] ASHRAE 90.1-2004 has been implemented by 24 states and Washington, D.C. while 90.1-2007 has been implemented by 3 states, 90.1-2001 by 8 states, and 90.1-1999 or earlier by 15 states.

costs over the study period. National Institute of Standards and Technology's (NIST) *Building for Environmental and Economic Sustainability* (*BEES)* software (Lippiatt, 2007) is used to compute the life-cycle costs for the building design alternatives in compliance with ASTM Standards of Building Economics (ASTM, 2007).

5. Environmental life-cycle assessment

The environmental flows from operational energy use are derived from two sources. The state-level average emissions per 1 MW (3.412 MBtu / h) of electricity for carbon dioxide (CO_2) are obtained from *eGRID* 2007 (EPA, 2007). Natural gas emissions data are collected from *BEES 4.0*. Life-cycle environmental flows from building construction, repair, and replacement are derived from U.S. Environmental Input-Output Tables included in the *SimaPro 7* software. The *BEES* software is used to assess the life-cycle energy and material flows from construction and operation of the building and estimate its carbon footprint.

6. Results

Twelve building types, representing different building sizes and energy intensities, are evaluated over four study period lengths for two alternative building designs. For each building type, energy simulations are run for 59 U.S. cities located across the United States. The resulting energy use and energy costs, life-cycle costs, and life-cycle carbon emissions are discussed below.

6.1 Energy use and costs

As is to be expected, increasing the energy efficiency of a building beyond the *ASHRAE 90.1-2007* standard requirements decreases energy use. Figure 1 shows the LEC leads to reductions across the 50 cities of 6.5 % to 31.2 % relative to the *ASHRAE 90.1-2007* design for a one-year study period.[6] Seven of the twelve building types have an energy savings greater than 10 % for all locations. Eleven of the twelve have at least one location that has a 20 % or greater energy reduction. Seven building types have average energy reductions over 15 %. A 15 % reduction in energy use for most building types relative to *ASHRAE 90.1-2007* appears to be achievable with conventional building technologies.

Energy cost savings are not perfectly correlated with energy use reductions due to differences in the marginal costs of electricity and natural gas across states, region-specific EIA future price projections, and building process loads. The smallest savings in energy and energy costs occurs in colder cities while the greatest savings occurs in cities located in more temperate climates. A

[6] These magnitudes are less than the HVAC energy savings because energy from user demands such as process loads is assumed to be constant across the alternatives.

slight variation in annual energy cost savings across study period lengths occurs because fuel price escalation rates vary over time, but these variations do not alter the interpretations.

6.2 Life-cycle costs

The study period length is important in determining which design alternative is the most cost-effective. The *ASHRAE 90.1-2007* design is the cost-effective choice for only 186 of the 708 (36 %) building type-location combinations relative to the LEC over a one-year study period. This shows how quickly energy efficiency measures -- when applied in an integrated design context -- can pay for themselves.

An increase in the study period length increases the number of building type-location combinations for which the LEC is the optimal design alternative. For a ten-year study period, the LEC is cost-effective for 97 %, or 167 additional building type-location combinations. This number increases to 99 % for a 25-year and 40-year study periods. The LEC design simultaneously decreases building energy use and life-cycle costs for these building type-location combinations. These results support stricter building energy efficiency standards because social gains from reduction in fossil fuel use and carbon emissions will occur at negative costs to the building owner/operator.

Different building types realize different levels of savings. As seen in Figure 2, the LEC is cost-effective over a 10-year study period in all locations for high schools, elementary schools, hotels, six-story apartments, retail stores, restaurants, and all office buildings. The LEC is cost-ineffective in some locations for dormitories and 3-story apartments due to lower overall energy savings.[7]

6.3 Adjusted internal rate of return

An investment in building energy efficiency may lead to lower life-cycle costs but still be a poor investment relative to an owner's/operator's other investment options. For this reason, the AIRR of energy efficiency investments are estimated for comparison with rates of return for alternative investments. Some building types and locations analyzed have an infinite AIRR for the LEC design because first costs decrease. The cost savings from HVAC capacity reduction overcome the costs for additional insulation, daylighting controls, and overhangs. For these buildings, there is a compelling economic case for the energy efficiency improvements even over a one-year study period. Nearly all locations in the following building types have infinite returns in the LEC relative to *ASHRAE 90.1-2007* over a one-year study period: hotels (100%), 8-story office buildings (100 %), 16-story office buildings (100 %), restaurants (100 %), elementary schools (97 %), high schools (97 %), 3-story dormitories (83 %), 3-story offices (68 %), and retail stores (64 %). Apartment buildings and 6-story dormitories have infinite returns in less than 10 % of locations. Of the 708 building type-location combinations, 69 %

[7] The interpretations across building types are the same for all other study period lengths.

have infinite returns over a one-year study period; this figure remains relatively unchanged over other study period lengths.

The longer the study period, the more cost-effective energy efficiency designs become because the energy savings occurs year after year while the first costs are constant and the additional cost of maintaining the building is relatively small. The AIRR on energy efficiency investments varies widely both within and across study period lengths. Of the 708 building type-location combinations analyzed for a 1-year study period, 499 have an AIRR above 3.0 %, the MARR for U.S. federal projects. This increases to 599 with a 10-year and 638 with a 25-year study period. This is an increase from 70 % to 90 % of building type-location combinations. Over 55 % for all study periods have an AIRR greater than 10 %, which is higher than the inflation-adjusted long-term annual return from U.S. stocks of around 7 % (Hammond, 2006).

6.4 Life-cycle carbon emissions

For the LEC design, life-cycle carbon dioxide equivalent (CO_2e) emissions from building materials production (for construction and component replacements) and operational energy use are reduced in nearly all building type-location combinations. Figure 3 shows the range of CO_2e emissions reduction for each building type under the LEC over a 10-year study period. The reduction in CO_2e emissions ranges from 0.3 % to 25.0 %, with a mean of 14 %. Life-cycle CO_2e reductions are slightly lower, in percentage terms, than operational energy CO_2e reductions because material-based emissions often increase with energy efficiency improvements (i.e. more embodied emissions).[8]

Emissions reduction, in percentage terms, is highest for cities that either have reductions in energy use of at least 15 % and/or at least 60 % coal-fired electricity generation. Cities in the central United States have the most significant CO_2e reductions. Cities in this area of the country have middle-to-high ranking in both categories relative to the other locations. The opposite can be said about states with low rankings in both categories, which are the West Coast cities with the lowest carbon emissions reductions. Further support is indicated by an Ordinary Least Squares regression with percentage energy savings and percentage of generation originating from coal as independent variables explaining the percentage of carbon emissions reduction (dependent variable). Both variables are statistically significant at the 1 % level and the R^2 ranges from 0.505 to 0.804 depending on the building type, implying that these two factors explain 51 % to 80 % of the variation in the carbon reduction percentage.

The cost of reducing carbon emissions in the LEC alternative design is negative for all locations with a reduction in life-cycle costs relative to the *ASHRAE 90.1-2007* design, which account for 97 % of building type-location combinations over a ten-year study period. The mean cost under the LEC for a ten-year study period is -\$181/tCO_2e with a range of -\$733/tCO_2e to \$133/tCO_2e.

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[8] Energy-related CO_2e emissions reduction is equivalent to energy reduction in percentage terms due to the constant emissions rate assumed for electricity generation.

Only 21 (3 %) building type-location combinations have a positive cost per metric ton of carbon reduction under the LEC for a ten-year study period (twelve for 3-story apartment buildings, six for 6-story dormitories, two for retail stores, and one for 3-story dormitories). The highest cost per ton of CO_2e reduction for the LEC occurs in cold climate zones due to lower energy savings.

On the contrary, 26 % of building type-location combinations for a one-year study period have positive costs per ton of CO_2e emissions. The shift of 71 % of building type-location combinations from positive costs for carbon reduction for a one-year study period to negative costs for a 10-year study period emphasizes the importance of using life-cycle costing in establishing the business case for energy efficient, carbon-reducing building technologies.

7. Conclusions

There are four conclusions from this analysis that contribute to the current debate over energy efficiency investments in buildings. First, conventional energy efficiency measures can be used to reduce energy use by 10 % to 20 % below *ASHRAE 90.1-2007* requirements on average without any significant alterations to the building design. These results give credence to the cost-effectiveness of building to meet *ASHRAE Advanced Energy Design Guide* recommendations, which advise how to construct buildings 30 % below *ASHRAE 90.1-1999* requirements.

Second, the LEC energy efficiency measures are life-cycle cost-effective relative to *ASHRAE 90.1-2007* requirements for some building types and locations for all study period lengths. This result contradicts recent research by Consol (2008) that found it cost-ineffective to improve energy efficiency by 30 % relative to *ASHRAE 90.1-2004*. The key difference is that this analysis uses an integrated design approach, which allows the HVAC system to be appropriately sized based on the HVAC loads of the building design.

Third, the investor's time horizon determines the cost-effective building design for many building type-location combinations. A short time horizon overlooks many of the realized costs of a building by ignoring the future costs of operating and maintaining the building. As the study period length increases, more building type-location combinations find it cost-effective to adopt a more energy efficient building design, with the greatest change occurring between the one-year to ten-year study periods.

Finally, these energy efficiency investments reduce the carbon footprint of the building by up to 25 % over a 10-year study period. The largest carbon reductions occur in states with the greatest energy reductions and states that rely heavily on coal-fired electricity generation, while states with large amounts of alternative energy use realize much smaller reductions.

In summary, investments in building energy efficiency measures recommended by whole building energy simulations are often cost-effective and have competitive annual investment returns in many areas of the United States, while improving efficiency and lowering a building's impact on climate change.

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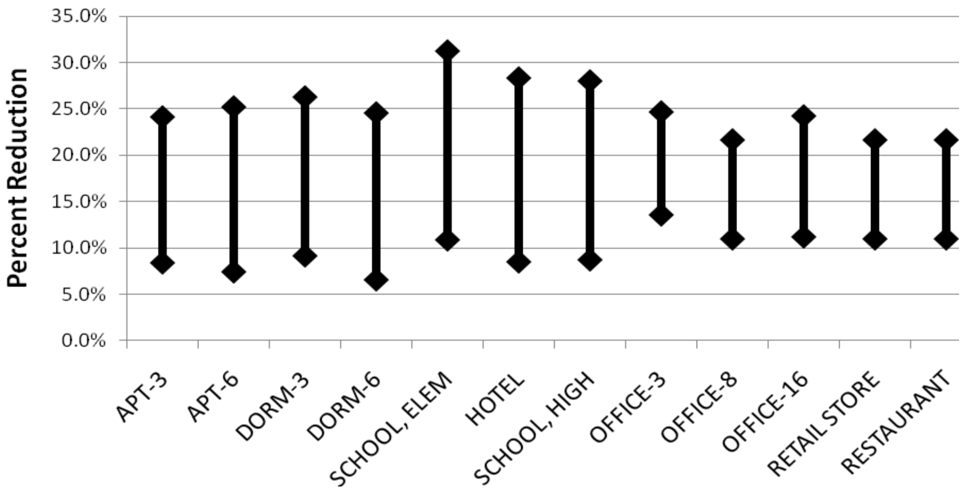

Figure 1: Annual energy use reduction relative to ASHRAE 90.1-2007

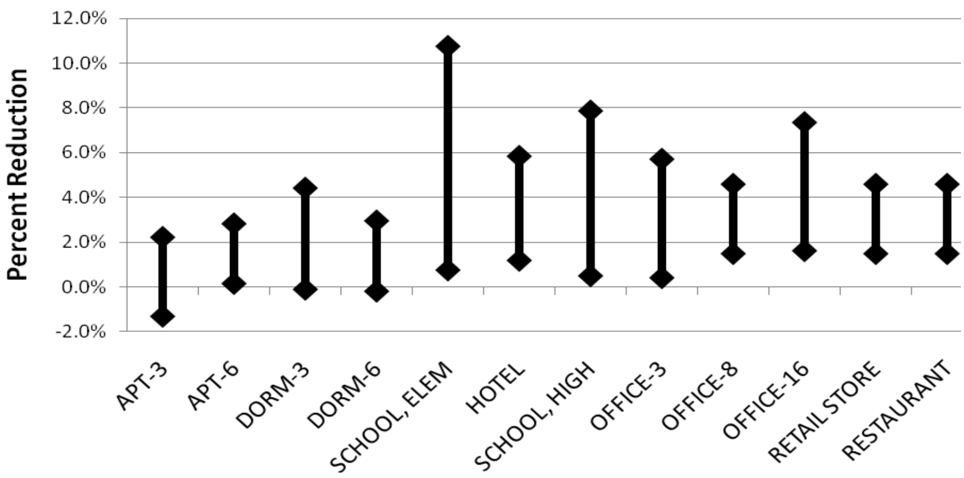

Figure 2: Life-cycle cost reduction relative to ASHRAE 90.1-2007

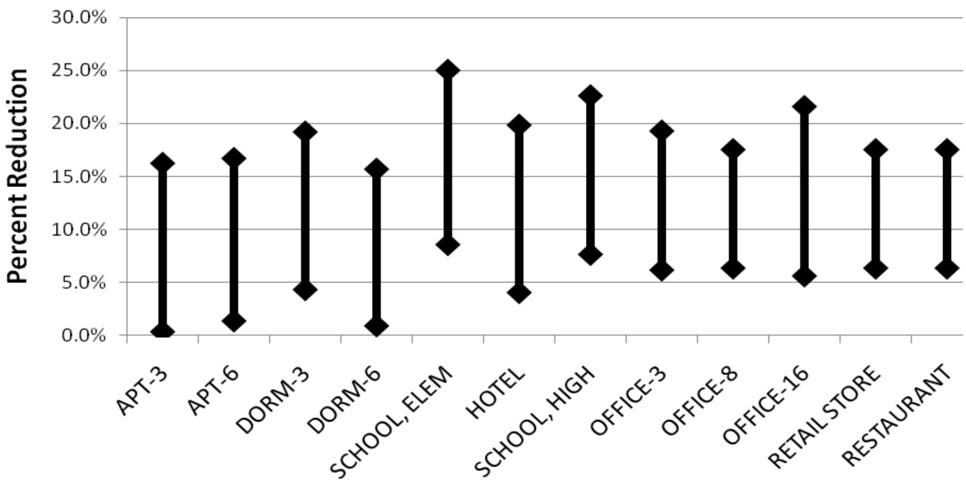

Figure 3: Life-cycle CO2e emissions reduction relative to ASHRAE 90.1-2007

The Effect of Mandatory Insulation on Household Energy Consumption

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Abstract

Insulation has been required in all new houses in New Zealand since 1978, intended to improve energy efficiency, reduce energy consumption and expenditure, and improve comfort and health. Information from the Household Energy Enduse Project (HEEP) is used to compare energy and temperatures in houses built before and after the mandatory requirements to find out how insulating houses has affected energy consumption and temperatures. On its own, insulation has been shown to be associated with less energy consumption. However, increases in heating temperatures, and the larger floor area of newer houses, have taken up some or all of the potential energy savings. There are major differences in the energy reductions depending primarily on the heating type, with little or no overall reductions in electricity consumption, but significant reductions in other fuels. The implications for retrofitting insulation as an energy conservation measure are discussed.

Keywords: energy efficiency, insulation, retrofit, HEEP, energy conservation

1. Introduction and review

In an effort to improve comfort and reduce energy demand and the cost of space heating, since 1978 all new houses in New Zealand have been required to be insulated. So far in New Zealand there has been little research on the effects of this insulation requirement.

The 1971/72 study by the Department of Statistics compared two groups of houses; one group insulated and the other uninsulated (Department of Statistics, 1976). However, it found that energy use was actually higher in the insulated group, although houses in this group were more likely to be in the colder climate of the South Island and were heated to a higher level. Since insulation was not required at the time it is possible that the houses that were insulated had this work carried out because the occupants wanted to heat the house extensively –a self-selected group.

A retrofit study by BRANZ on one staff house found that adding insulation increased indoor temperatures by about 1.4°C in winter, with a reduction in energy use of 300-400 kWh (Cunningham, Roberts and Hearfield, 2001). Another retrofit study by BRANZ on a selection of Wellington City Council owned pensioner flats showed increased indoor temperatures, improved comfort, and less heating energy use (Cunningham, 2000).

The Health and Housing study conducted by the Otago School of Medicine was designed to measure the effects on respiratory health and health care (e.g. hospital admissions, GP visits) from the retrofit of insulation (Howden-Chapman, Matheson, Crane, Viggers et al., 2007). Temperatures were also measured and some limited information on energy use was collected (electricity and gas billing records, self-reported LPG, wood and coal purchase). Analysis of this information showed that during the winter period temperatures in the bedroom increased after the retrofit of insulation by 0.5°C. Metered total electricity and gas consumption (from billing records) in the intervention houses was 8% less than in the control houses, and 19% less with self-reported LPG, wood and coal usage included. The energy data was not of high quality.

The Department of Physics, University of Otago undertook a study of 111 Housing New Zealand Corporation houses in Southland, where they retrofitted insulation and some other energy-efficiency measures (Lloyd and Callau, 2006). Total electricity consumption was reduced by 5–9%, and 24 hour temperatures increased by 0.6° in winter. The total energy reductions were higher, but the variation in non-electricity consumption was too high to make this result significant. Most of the houses already had some ceiling insulation which substantially reduced the improvement in whole-house heat losses achieved.

In overview, all of these New Zealand studies have shown that retrofitting thermal insulation results in winter indoor temperature increases of 0.5°C to 1.4°C, and small or no savings in energy consumption (although electricity was often the only fuel monitored). However, most of these studies were carried out on particular groups of people (e.g. elderly pensioners in council flats, low income households with low health status, Housing New Zealand clients in Southland) so these studies are not representative of New Zealand as a whole.

Most developed countries have introduced mandatory insulation requirements, with many precipitated by the oil shocks of the 1970s. However, there seems to be a lack of research on the effects of these mandatory insulation requirements.

Shorrock and Utley (2003) tracked energy use and thermal comfort in domestic buildings in the UK. The method used surveyed data on appliance types, efficiencies, and house thermal characteristics, and then modelled the temperature that would be required to give energy consumption equal to the known total energy consumption for the domestic sector. From 1970 to 2000 the average temperatures were modelled to increase by 6.2°C, and the penetration of central heating increased from 31% to 90%, but with the improved efficiency of heating systems and improvements to the house insulation energy consumption per house decreased by about 4%. This result is partly due to increasingly stringent Building Regulations for new houses, and partly due to the upgrade of existing houses. While the effect on new houses alone cannot be estimated from this report, it is clear that most of the potential savings have been taken up in increased temperatures and heating.

2. Data

The Household Energy End-use Project (HEEP) is a nationwide New Zealand study of energy use in approximately 400 households (Isaacs, Camilleri, French, et al., 2010). Analysis of the HEEP houses can be used to quantify the differences in energy use and space heating between pre- and post-1978 houses.

2.1 Heat losses and floor area

All the available HEEP houses have been modelled in ALF3 (Stoecklein and Bassett, 1999) to estimate their space heating requirements and heat loss. The required input data were taken from house plans and audit information collected when the monitoring equipment was installed. This was reported in Isaacs, Camilleri, French, et al., 2010.

No clear cut distinction was found between the whole-house heat losses of pre- and post-1978 houses (**Error! Reference source not found.**), although the average heat loss of the post-1978 houses (482 W/°C) is lower than the pre-1978 houses (586 W/°C). The differences are more pronounced in ***Figure 2*** for the heat loss per m² where most post-1978 houses have a heat loss of <4 W/(m²·°C), but most pre-1978 houses have a heat loss of >4 W/(m²·°C).

The post-1978 houses have lower average heat losses but are larger in floor area than pre-1978 houses (Table 1). If these houses were heated to the same temperatures and extent (which they are clearly not) then they would require about 20% less energy to heat.

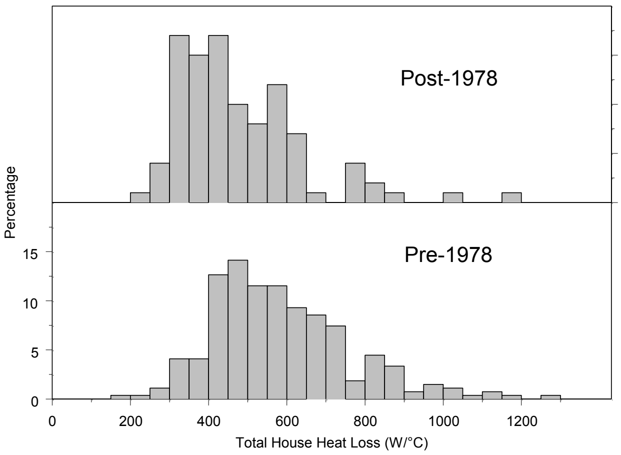

Figure 1: Total house heat loss for pre- and post-1978 houses

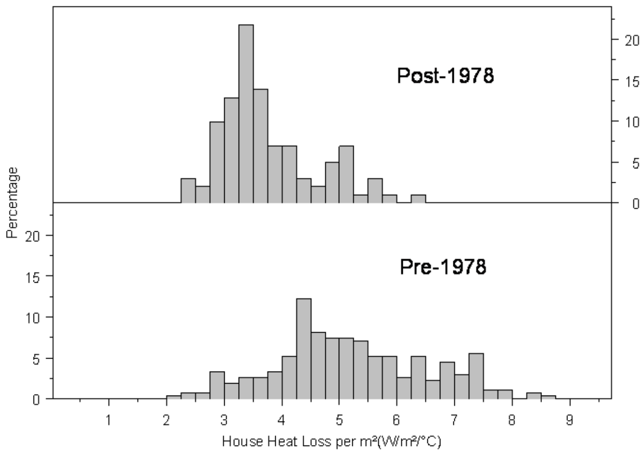

Figure 2: Heat loss per m² for pre- and post-1978 houses

Table 1: Heat losses for pre-and post-1978 HEEP houses

House Period	*Heat loss/m² (W/(m²·°C))*	*SE*	*Total specific loss (W/°C)*	*SE*	*Floor area m²*	*SE*
Pre-1978	*5.2*	*0.1*	*586*	*11*	*119*	*2.5*
Post-1978	*3.8*	*0.1*	*482*	*16*	*132*	*4.6*

2.2 Temperatures and heating pattern

The post-1978 houses are on average 1°C warmer than the pre-1978 houses in the living rooms in winter evenings, and 1.2°C warmer over the whole winter 24 hours, with warmer temperatures for houses with larger heating systems such as natural gas and enclosed solid fuel burners (**Error! Reference source not found.**).

Table 2: Average winter temperatures by heating type

House Period	*Main fuel*	*Mean living evening temp °C*	*SE*	*Mean living 24 hour temp °C*	*SE*
Pre-1978	*Electricity*	*16.8*	*0.3*	*15.0*	*0.3*
Post-1978		*18.6*	*0.3*	*16.9*	*0.3*
Pre-1978	*LPG*	*16.8*	*0.3*	*14.8*	*0.2*
Post-1978		*17.7*	*0.3*	*16.1*	*0.3*
Pre-1978	*Natural gas*	*18.2*	*0.4*	*16.2*	*0.4*
Post-1978		*17.8*	*0.9*	*16.0*	*0.8*
Pre-1978	*Solid fuel*	*18.4*	*0.2*	*16.2*	*0.2*

Post-1978		*19.4*	*0.4*	*17.5*	*0.4*

The heating patterns in New Zealand houses observed in HEEP were usually intermittent, localised, and often poorly controlled. Whole house, 24 hour heating was very uncommon (<5% of houses), with evening only heating in only the living area the most common heating pattern. Temperature control was also usually not good, as many heating systems (e.g. solid fuel burners) do not have thermostatic or timer controls, and with intermittent heating there is considerable warm up time.

The HEEP Heat Index is a synthesised measure of house heating patterns based on heating schedules and zones (Isaacs, Amitrano, Camilleri et al., 2003) designed to quantitatively represent these complex heating patterns. Each heating schedule (nominally evening only, morning and evening, all day, 24 hours) is given a weighting, based on the annual loss factors used in ALF3. For each zone and day the heating index multiplier is applied, then multiplied by the number of days of the week that schedule is used. These are then summed for all zones, and the sum of these for all zones gives the heating index. For example, heating living rooms only in the evening gives a Heating Index of 7 (a weight of 1 for 7 days for 1 zone), while heating all zones (living, bedroom, utility) 24 hours a day gives a Heating Index of 84 (a weight of 4 for 7 days for 3 zones). The most common schedule is winter evening living room heating only (which has a Heat Index of 7).

There is no statistically significant difference in the Heating Index between the pre- and post-1978 houses, suggesting they are heated similarly in terms of schedules and zones (Table 3).

Table 3: Comparison of winter temperatures and Heat Index

House Period	*Mean living room winter evening temp (°C)*	*SE*	*Mean living room 24 hr winter temp (°C)*	*SE*	*Heat Index*	*SE*
Pre-1978	*17.6*	*0.2*	*15.6*	*0.1*	*18.1*	*0.7*
Post-1978	*18.6*	*0.2*	*16.8*	*0.2*	*16.8*	*1.3*

2.3 Space heating energy consumption

Space heating estimates were prepared for all the HEEP houses by comparing the summer energy use baseline (Jan-Mar) with the full year energy use, the difference being assumed to be space heating. This was done for electricity and gas. Space heating for portable LPG heaters and solid fuel burners was monitored directly for all such appliances. This is a different method to the one used for estimating the space heating for the overall HEEP statistical estimates, as the statistical analysis could only give space heating estimates for groups of houses, not for individual buildings. The average of electric space heating used here is about 25% higher, although electricity is a minor heating fuel. Further information on the methodology is in Isaacs, Camilleri, French et al (2010).

Table 4 compares pre- and post-1978 house use of electric and 'all' (i.e. electric, gas, LPG, solid fuel) space heating. This is net energy – electricity is assumed to be 100% efficient[1], an enclosed solid fuel burner[2] assumed to be 60% efficient, an open fire 15%, and a gas appliance 80% efficient.

Comparing the pre-1978 and post-1978 houses, there is no statistically significant difference between their electric space heating energy usage. However this is seriously confounded by the location of the post-1978 houses, as there are more pre-1978 houses in colder climates. Therefore, merely on the basis of the colder climate they would be expected to use more space heating. There is a statistically significant difference in the "All heating" energy in the post-1978 houses, however there are many possible causes, and these are now explored in detail.

Table 4: Comparison of space heating energy

House Period	*Electric heating (kWh/yr)*	*SE*	*All heating (net) (kWh/yr)*	*SE*
Pre-1978	*1,280*	*100*	*3,180*	*200*
Post-1978	*1,060*	*130*	*2,410*	*310*

3. Statistical models of space heating

Statistical models were used to explore the effects of the various physical and socio-demographic input variables, such as pre-1978 status, floor area, income etc, on net energy consumption. These models can be used to attempt to separate the effects of various independent variables to allow the effect of the pre-1978 status to be compared allowing for confounders.

The process of developing these models involves an element of judgement to decide which of the possible model formulations to use. This decision was guided by the data, the goodness of fit, and common sense. Depending on which model was chosen as the final model the effect of the various terms may differ e.g. one model might give an apparently larger effect of the pre-1978 status than another. Hence the estimates of the effect of various variables on energy consumption should not be interpreted as precise estimates. Standard errors are given for each of the variables, which gives some idea of how precisely that particular model defines them, but a slightly different and equally valid formulation of the model might give a slightly different value.

Unfortunately there are several features of the data that make the use of simple linear models problematic. The residuals (the difference between the actual value and the model prediction) are larger for higher heating energy consumption and they are not normally distributed, and the sample variance increases with the energy consumption. Both these features fail to meet two of the major

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[1] Most electric heating was with resistance heaters, with very few heat pumps.

[2] The method for monitoring solid fuel burners and open fires directly measure the net heat output, so the assumed efficiency does not affect the accuracy of their heat output.

criteria for the application of a linear model, which are normally distributed sample measurements with constant variance. The Generalised Linear Model (GLM)[3] is an extension of linear models that can accommodate such statistical distributions by using a non-normal distribution for the sample measurements (e.g. a logarithmic or gamma distribution). They can also fit the data in a non-linear sense by using link functions such as logarithm, inverse or others. These features of the GLM allow the actual underlying structure of the data to be considered in the model and resolve the previous problems noted with the residuals.

The choice of GLM is a matter of finding which type best represents the data. The models used for this analysis use the gamma link function for the statistical distribution of errors, and a logarithmic function to link the predictor to the response. The logarithmic function causes the factors to be multiplicative, not additive as is usual with simple linear models. Overall, these were found to best deal with the non-normal distribution of the residuals and the skewed distribution of the energy consumption.

Statistical models have been created for two different heating energies:

1. Electric space heating only
2. All space heating energy

Although most space heating energy consumption is for non-electric fuels, most houses do use some electric heating (typically in portable electric heaters). As electricity is subject to supply constraints (e.g. peak loads), and some is generated in fossil fuelled power stations, the environmental and supply issues are different to the other fuels (e.g. gas and solid fuel) and it is important to consider the effects of mandatory insulation on electricity alone.

3.1 Electric heating – all houses

There is no significant difference in the national average electric heating energy consumption of the pre- and post-1978 houses (Table 5). However, this takes no account of regional variation or other confounders.

45 houses that used no electric space heating at all were removed from the analysis as the logarithmic transformation of zero is undefined. The final model found the post-1978 houses were associated with (23±15)% less electric space heating, allowing for the confounders of floor area, regional climate, winter heating temperatures, and the type of main heating fuel. The main fuel used for heating (whether electricity, LPG, gas or solid fuel) had a very large effect, associated with a drop of

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[3] See *An Introduction to Generalised Linear Models* (2nd Edition) by AJ Dobson. Chapman and Hall/CRC, New York.

about (45±20)% in electric space heating in houses that mainly use non-electric heating (electric heating is used in most houses, although often only as back-up or secondary heating). The higher temperatures in the post-1978 houses were associated with an increased energy use of about (10±3)% and the larger floor area with a (6±1)% increase. The overall difference between the pre- and post-1978 houses was about (-10±15)%, which is not statistically significantly different from zero.[4]

Table 5: Electric space heating energy and temperature – houses heated mainly with electricity

House period	*Electric heating (kWh/year)*	*SE*	*Mean living room temperature (24 hours) °C*	*SE*
Pre-1978	*2,210*	*260*	*15.0*	*0.2*
Post-1978	*1,470*	*330*	*16.8*	*0.3*

We conclude that there is no significant difference between the amount of electric space heating in the pre- and post-1978 houses, and that the post-1978 houses are achieving higher temperatures over larger floor areas for approximately the same amount of electric heating as the pre-1978 houses, allowing for confounders. If the pre-1978 houses were insulated to the same levels as the post-1978 houses, and heated to the same (higher) temperature, the model predicts that the difference in electric space heating would be (-15±15)%, which again is not statistically significantly different from zero.

Part of the reason for the high statistical uncertainty is the large variation in electric space heating between houses, particularly for those that mainly use other fuels. Looking at houses that mainly heat with electricity should reduce this variation and give a larger difference.

3.2 Electric heating – houses mainly heated by electricity

The analysis was repeated for houses that use electricity as their main means of space heating. Reductions of energy use would be expected to be higher as more electricity is used, and it is used to heat warmer rooms such as living areas instead of being used more often in cooler bedrooms and for occasional heating (Isaacs, Camilleri, French, et al., 2010). This is confirmed as the average electric space heating energy is much lower in the post-1978 houses (Table 5). However, this comparison is seriously confounded by differences in climate, heating temperature and other factors. The final model had independent variables of post-1978 status, floor area, region (representing climate), living room temperature and equivalised income to control for these confounding variables.

The model of the mainly electrically heated houses shows a much larger effect of the post-1978 status on electric space heating – a decrease of (60±25)% in electric space heating. Offsetting these factors were: the higher temperatures – +1.8°C in the post-1978 electrically heated houses and associated

[4] Since these GLMs use exponential functions, the means and standard errors are combined logarithmically. The ratio of standard error to the mean is not used to test for statistical significance; rather the confidence levels generated by the SPLUS GLM models are reported.

with increased electric space heating use of (48±9)%; larger floor areas increasing electric space heating use by about (5±4)%; and higher equivalised incomes[5] associated with an increase in electric space heating use of about (10±4)%.

The net effect of the larger floor areas and higher temperatures of the post-1978 houses is associated with a difference in electric space heating of (-38±27)%, and this is statistically significantly different from zero at a 95% confidence level.[4]

If the mainly electrically heated pre-1978 houses were insulated to the same levels as the post-1978 houses, and heated to the same higher temperature, the model predicts that the difference in electric space heating would be (-41±27)%, which again is statistically significantly different from zero at a 95% confidence level.[4]

Differences in electric space heating energy for houses mainly heated by electricity are quite high. The low indoor temperatures achieved (15°C), and the comparatively small difference between inside and outside temperatures (typically averaging about 4-7°C), means that insulation has a large impact on heating energy use, especially given that internal and solar gains contribute a large proportion of required heating energy.

3.3 All heating fuels – all houses

It has been shown that there are statistically significant differences between pre- and post-1978 houses on a national basis when all heating fuels are considered (electricity, gas, LPG, solid fuel), with the post-1978 houses using less heating energy (Table 4).

A GLM was used to evaluate the effects of the various confounding variables. In isolation the post-1978 status was associated with (45±11)% less space heating energy use. Higher temperatures in the post-1978 houses were associated with an increase in space heating energy use of about (32±3%), and floor area by about (6±1)%.

The net effect of the larger floor areas and higher temperatures of the post-1978 houses is associated with a difference in all fuels space heating of (-23±11)%, and this is statistically significantly different from zero at a 95% confidence level.[4]

If the pre-1978 houses were insulated to the same levels as the post-1978 houses, and heated to the same higher temperature (1.2°C higher), the model predicts that the difference in all fuels space heating would be (-28±11)%, which again is statistically significantly different from zero at a 95% confidence level.[4]

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[5] Higher equivalised incomes are, presumably, not caused by living in a post-1978 house.

4. Summary of model results and discussion

Table 6 summarises the modelling results:

- ‘Post-1978 only’ refers to the % difference in the energy quantity associated with the post-1978 status, allowing for confounders.

- ‘Post-1978, floor area & temp’ are the combined effect of the post-1978 construction, the larger floor area and higher temperatures found in the post-1978 houses, allowing for confounders.

- ‘Pre-1978, post-1978 insulation & temp’ considers the impact if houses built pre-1978 had the same levels of insulation and rooms temperatures as found in post-1978, allowing for confounders.

Note that the differences shown in a bold font in Table 6 are statistically significantly different from zero at the 95% confidence level.

Table 6: Summary of model results

Fuel type	*Quantity*	*House group*	*Post-1978 only (%)*	*Post-1978, floor area & temp (%)*	*Pre-1978, post-1978 insulation & temp (%)*
Electricity	*Heating*	*All houses*	***-23±15***	*-10±15*	*-15±15*
Electricity	*Heating*	*Elect. heated*	***-60±25***	***-38±27***	***-41±27***
All fuels	*Heating*	*All houses*	***-45±11***	***-23±11***	***-28±11***

In all cases, the ‘Post-1978 only’ was associated with a decrease in energy use. This demonstrates with a high degree of confidence that, allowing for confounders, the introduction of mandatory insulation in 1978 has led to improvements in energy efficiency of the housing stock. However, increases in temperatures and larger floor areas in the post-1978 houses have taken up part, and sometimes all, of any potential energy reductions.

The ‘Post-1978, floor area & temp’ results are mixed (Table 6). They give a comparison between the pre-1978 and post-1978 houses allowing for confounders of differences in regional climate, and income and life stage, between the pre-1978 and post-1978 groups. For example, since on average post-1978 houses are in warmer climates, this alone would be expected to reduce space heating energy consumption. With these confounders allowed for it can be seen that the post-1978 houses use less space heating energy for all fuels (Table 6) even though they are on average larger and heated to higher temperatures. However, they use the same amount of electricity (total electricity excluding hot water). The group of mainly electrically heated houses are the only group that show less electric space heating in the post-1978 group compared to the corresponding pre-1978 group.

'Pre-1978, post-1978 insulation & temp' is a prediction from the model of how the energy consumption of pre-1978 houses would change if insulated to the same level as post-1978 houses[6] and heated to the same warmer temperatures. This assumes no change in heating patterns and zones (we have already shown that the pre- and post-1978 houses are heated to about similar patterns and zones). Again, the overall result is mixed, with a similar outcome as the difference between the pre- and post-1978 houses. There are reductions in all fuels for all houses, but no reduction in electricity consumption, except for houses primarily heated by electricity.

In summary, it has been shown that mandatory insulation has led to warmer homes as well as reduced space heating and (total excluding hot water) energy use. However, most of the energy reductions have come from non-electric fuels. The total energy savings for all fuels in the 27% of houses that are post-1978 houses would be about 2–3% of total energy consumption (all fuels), while the total electricity savings in the mainly electrically heated houses (about 8% of households) would be <1% of total electricity consumption.

5. Conclusions

The mandatory insulation of houses in New Zealand since 1978 has resulted in higher indoor temperatures and reduced energy consumption and space heating. Total net energy consumption excluding hot water was (10±6%) lower in the post-1978 houses, however total electricity consumption was not significantly different. Heating energy (all fuels) was (23±11)% lower in the post-1978 houses. Average temperatures in the post-1978 houses were higher, and average floor areas larger, and these factors increased energy consumption. These effects took up ~40% of the potential savings in all fuels, and most or all of the energy savings for electricity.

While the experiment did not retrofit insulation to pre-1978 houses the results give some idea what might be expected. If the pre-1978 houses were insulated to the same levels as the post-1978 houses and heated to the same higher temperatures then the model predicts that total energy consumption of all fuels of these post-1978 houses excluding hot water would be (14±6)% lower, and there would be no significant change for electricity (7±7% lower).

[6] As noted, a pre-1978 house cannot be retrofitted to the same overall insulation level as a post-1978 house of the same design by only installing ceiling and floor insulation. Wall insulation, or double glazing is also required but this is uncommon due to practicality and cost.

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Space Heating in New Zealand Houses

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Abstract

The monitored space heating energy consumption in 398 houses in New Zealand is analysed to determine the effect of various drivers such as climate, house characteristics, occupant characteristics, and other factors. At best the statistical models could explain about 50% of the variation in space heating, with the remainder being of unknown cause or random noise. The heating temperatures, schedules and zones were important determinants of the space heating energy, however only a small amount of the variation in these variables could be explained with statistical models. It appears that households choose their heating temperatures, schedules, and zones by a process that was not captured in this study, and may reflect underlying attitudes or behavioural or cultural practices that defy rigorous analysis. The implications for future energy demand with the recent rapid uptake of heat pumps, and changing comfort expectations are discussed.

Keywords: Space heating, comfort, fuel poverty, energy efficiency, HEEP

1. Introduction

The Household Energy End-use Project (HEEP) is a nationwide study of energy use and temperatures in New Zealand houses. Monitoring began in 1999 and was completed for 398 houses in mid-2005, with each house monitored for about one year (Isaacs, Camilleri, French et al, 2010). This study used a random selection of all New Zealand houses and is statistically representative. The sampling design was for a random selection of houses from the major cities and towns with a population of more than ~50,000 (representing about half the population), then cluster samples of 9 or 10 houses in each of 19 smaller geographical areas (small towns, rural areas) chosen on a random basis to represent the rest of the country. This strategy was used as monitoring a random selection of households outside of the major cities and towns would have been too difficult and expensive.

This methodology was carefully designed and implemented to ensure that the sample was representative of the New Zealand population (Isaacs, Camilleri, French et al, 2010). Special care was taken in the household selection process to avoid bias caused by households choosing not to participate in the survey. Overall, 24% of households approached agreed to participate in the study.

All fuels were monitored (electricity, reticulated gas, LPG, solid fuel, oil and solar water heating). Major circuit loads (total electricity, hot water) were monitored in all houses. Other circuit loads (cooking range, lights, fixed gas and electric heaters etc) were monitored in 100 houses, as well as individual appliances (2-3 randomly selected appliances per house rotated on a monthly basis). All solid fuel burners, portable LPG heaters, solid fuel hot water connections and solar water heaters were monitored. Indoor temperatures were also measured (typically three per house). The installation included a detailed occupant survey, house plans and audit details, and inventory of all electrical appliances.

2. Review of models

In the UK a model of domestic space heating energy consumption has been developed (Shorrock and Utley, 2003). Survey data from the BREHOMES model (Shorrock, Henderson and Brown, 1991) and the English House Condition Survey (DETR, 2000) were used to estimate the indoor temperatures, heating schedules, and house thermal properties, which in turn supported the development of the BREHOMES thermal model to estimate space heating energy.

Total domestic energy consumption in the UK is modelled by BREDEM-12 (Anderson, Chapman, Cutland et al., 2002), including individual end-uses such as lighting, cooking, and appliances. Despite having a complex breakdown of end-uses, and models based on the occupancy, the actual formulas that relate energy use to occupancy and other factors are based on a combination of limited data from other sources or assumptions. For example the formula that relates hot water demand to the number of occupants is (38 + 25 × Number of Occupants) litres per day, and was based on an unpublished formula derived by British Gas.

The Energy Efficiency and Resource Assessment (EERA) Model is a stock based model of energy end-uses for New Zealand (Rossouw, 1997). It has recently been upgraded to take into account information from HEEP, with revised model algorithms that account for the effects of the number of occupants and household characteristic. These algorithms are based on actual monitored energy and temperature data, and surveyed occupant and house characteristics.

3. Data

Data on the occupants was collected using a questionnaire, which included socio-demographic characteristics, heating appliances and usage. A physical audit of the house was conducted, including a detailed house plan, with information on the physical structure, insulation, and windows. Information on space heating appliances was also collected, including the type and heat output. This information was used to develop thermal models in the ALF3 program (Stoecklein and Bassett, 1999).

HEEP temperature data was recorded using single channel battery powered temperature loggers: two in the main living area, and one in the main bedroom. Some houses also had extra temperature loggers for outdoor temperature, otherwise data from a nearby NZ Meteorological Service station was used (CliDB National Climate Database).

The HEEP space heating data consists of the monitored energy consumption of individual space heating appliances including solid fuel burners, LPG cabinet heaters, gas heating systems, and estimates of all other winter space heating derived from total electricity and gas consumption.

Solid fuel burners were monitored using thermocouples, and estimates of their heating output derived from a calibration process using the other monitored energy loads and temperatures and house ALF models to do a heat balance calculation. This process is described in Isaacs, Camilleri, French et al (2010) and has an estimated accuracy or ±20%. These estimates are of the heat released to the room, so do not depend on the efficiency of the solid fuel burner, which varies from ~10% for open fires to 60-70% for enclosed double burners.

LPG cabinet heaters were monitored using thermocouples to detect which panels were lit, and the rate of burn for each panel calibrated by measuring the rate of gas burnt. They are assumed to have an efficiency of 80%. Gas heaters was monitoring directly using gas meters, and the energy input calculated using gas pressure, elevation, and seasonal calorific values supplied by the distribution companies. They are assumed to have an efficiency of 80%.

The method for the estimation of the remaining annual space heating load is described in the HEEP final report (Isaacs, Camilleri, French et al, 2010). The basic process is to compare the summer electricity and gas energy use (excluding water heating and directly monitored heaters) with the winter energy use, with the difference assumed to be primarily space heating. This is known to slightly overestimate space heating, as some of the increase in winter is due to increases in lighting and cooking load, however most of this energy ends up as heat in the building, and most of it is used during times when the building is heated, and so makes a useful contribution to space heating.

4. Heating patterns in New Zealand

The heating patterns in New Zealand houses observed in HEEP were usually intermittent, localised, and often poorly controlled. Whole house, 24 hour heating was very uncommon (<5% of houses), with evening only heating in only the living area the most common heating pattern. Temperature control was also usually not good, as many heating systems (e.g. solid fuel burners) do not have thermostatic or timer controls, and with intermittent heating there is considerable warm up time. Typically, it takes some time for a room to be heated to the desired temperature, then the temperature may or may not be controlled well, then the temperature drops after the heater is turned off. With this type of heating behaviour the concept of a heating set-point is perhaps not appropriate. Instead, the *living room heating temperature* is used, which is defined as the average temperature measured in the living room during winter (Jun-Aug) during the evening (5-11 pm). This room and period was chosen to represent the temperature as approximately 90% of the HEEP households do heat this room during this period.

The New Zealand climate is mild compared to parts of North America and Europe. Average winter evening external air temperatures for the monitored HEEP houses ranged from 4.7°C to 12.5°C, with most of the major populated areas between 8°C and 11°C. The average living room heating temperature was 17.9°C, so the average difference from the outside temperatures is typically 6-9°C. Since this difference is fairly small the amount of heating energy required, and the number of months where heating is needed, are expected to be very sensitive to the living room heating temperature. ALF3 simulations typically show the heating energy doubling for each 2°C increase in heating set-point.

Since heating is often intermittent and localised it is difficult to describe the heating pattern of the whole house quantitatively. Two ways of doing this were used: 1) estimating the area of the house that was heated from the occupant questionnaire information and building floor plan; and 2) A 'Heating Index' synthesised from the occupant questionnaire information on heated zones (e.g. living, bedroom, utility) and heating schedules. Each heating schedule (evening only, morning and evening, all day, 24 hours) is given a weighting, based on the annual loss factors used in ALF3. For each zone and day the heating index multiplier is applied, then multiplied by the number of days of the week that schedule is used. These are then summed for all zones, and the sum of these for all zones gives the heating index. For example, heating living rooms only in the evening gives a Heating Index of 7 (a weight of 1 for 7 days for 1 zone), while heating all zones (living, bedroom, utility) 24 hours a day gives a Heating Index of 84 (a weight of 4 for 7 days for 3 zones).

5. Variations in space heating

The space heating analysed is the *net space heating*, defined as the net energy output to the room from heating appliances. Gross energy input (as measured by gas or electricity meters) is not used, as a lot of space heating is done by solid fuel burners (56% of total gross space heating energy (Isaacs, Camilleri, French et al, 2010)) which have widely ranging efficiencies. The efficiency factors used were 100% for electricity (most heating was resistive), 80% for LPG and reticulated gas, and for solid fuel the net space heating was the quantity measured so no efficiency assumptions were needed.

There are regional variations in net space heating, as shown in Table 1. However net space heating is roughly the same in Auckland, Wellington and Christchurch (the 3 largest cities) despite the large difference in heating degree days. There are major differences in the net space heating energy consumption for the most used heater type (Table 2) and different types of fuels (Table 3). Note that the energy reported is for all fuel types used in the house, not just the fuel of the most used heater. It can be seen that households with natural gas or solid fuel as the most used heater fuel have higher average space heating consumption than houses heated with electricity or portable LPG. This is not necessarily a causative relationship – households using gas or solid fuel may have made a choice to use that fuel to gain comfort, while the data shows that households in colder climates are more likely to have a solid fuel burner.

Table 1: Net space heating energy (all fuels) by climatic region

Region	*Gross Space Heating (kWh/yr)*	*SE*	*Net Space Heating (kWh/yr)*	*SE*	*Degree Days (15°C base)*
Auckland	*3,240*	*500*	*2,370*	*290*	*670*
Hamilton/Tauranga	*3,790*	*730*	*2,820*	*470*	*930*
Wellington	*2,920*	*500*	*2,390*	*420*	*1,120*
Dunedin/Invercargill	*6,200*	*930*	*5,020*	*740*	*1,730*
Warm Clusters[1]	*3,660*	*480*	*2,340*	*280*	*670*
Cool Clusters	*6,920*	*920*	*4,700*	*560*	*1,240*

Table 2. Total space heating energy by most used heater type

Most Used Heater Type	*Gross Space Heating (kWh/yr)*	*SE*	*Net Space Heating (kWh/yr)*	*SE*
Open Fire	*5,050*	*1,840*	*1,520*	*410*
LPG (portable cabinet)	*2,090*	*440*	*1,690*	*300*
Electric	*2,390*	*320*	*2,050*	*230*
Heat Pump	*2,610*	*2,390*	*2,590*	*2,400*
Fixed Electric	*4,100*	*890*	*3,870*	*860*
Gas	*5,450*	*1,180*	*3,870*	*640*
Enclosed Solid Fuel	*6,790*	*630*	*4,420*	*380*
Gas Central	*7,830*	*2,180*	*6,420*	*1,760*

[1] Climatically similar cities and towns have been combined into regions, and the clusters (small towns and rural areas) grouped based on Degree Days into ‘warm’ (≤620 15°C DD) and ‘cool’ (> 620 15°C DD).

Table 3. Net space heating energy (all fuels) by most used heater fuel

Most Used Heater Fuel	*Gross Space Heating (kWh/yr)*	*SE*	*Net Space Heating (kWh/yr)*	*SE*
LPG	*2,090*	*440*	*1,690*	*300*
Electricity	*2,640*	*300*	*2,330*	*250*
Natural Gas	*6,020*	*1,040*	*4,480*	*660*
Solid Fuel	*6,600*	*590*	*4,160*	*350*

5.1 Correlations with single factors

A range of graphs are used to show how the net space heating correlates with a range of single factors. The net space heating ranges widely, from zero or near zero (~5% of households), to nearly 25,000 kWh per year.

Net space heating tends to increase with the living room heating temperature (*Figure 1*, r^2=0.4) and to decrease with external temperature (*Figure 2*, r^2=-0.29), although the scatter is very large. Net space heating energy use tends to increase with the total floor area (Figure 3 , r^2=0.18) and the floor area that is heated (*Figure 4*, r^2=0.27). More space heating tends to be required for houses that heat more extensively, as described by the Heating Index (*Figure 5*, r^2=0.35). The thermal performance of the house also has an influence, with houses with higher total whole building heat losses requiring more heating (*Figure 6*, r^2=0.17).

The one common characteristic in all these figures is the large scatter – although the variables are correlated with the net space heating energy consumption, individually they do not explain much of the variation. Statistical models are used to further explore these influences.

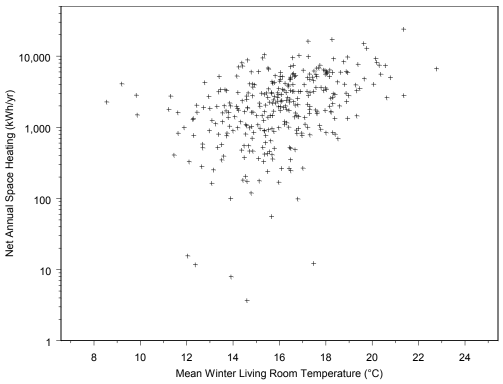

Figure 1. Net space heating by living room heating temperature.

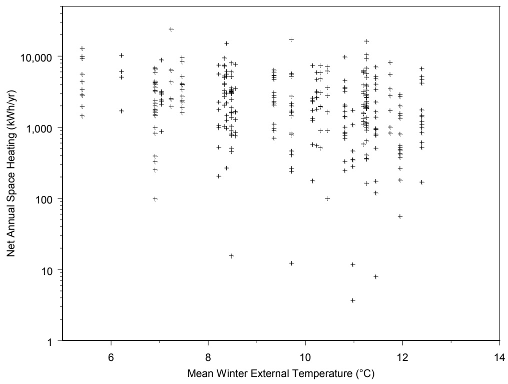

Figure 2. Net space heating by mean winter external temperature.

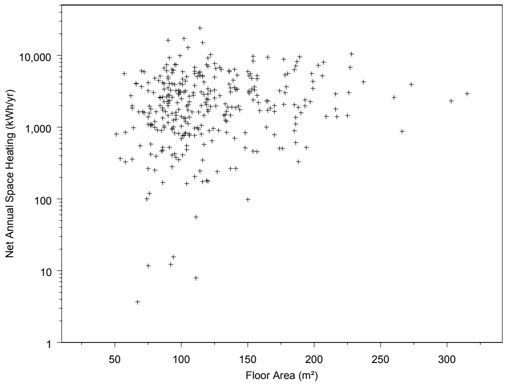

Figure 3. Net space heating by floor area.

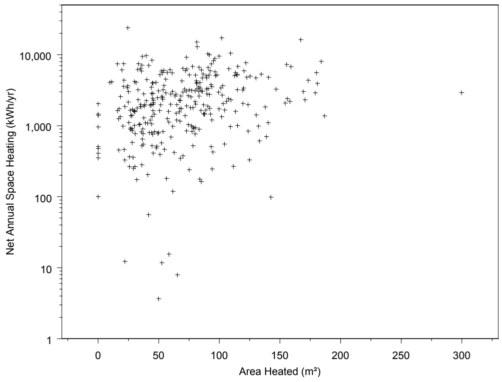

Figure 4. Net space heating by area heated.

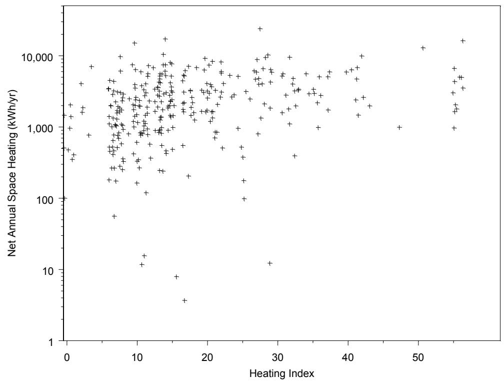

Figure 5. Net space heating by heating index.

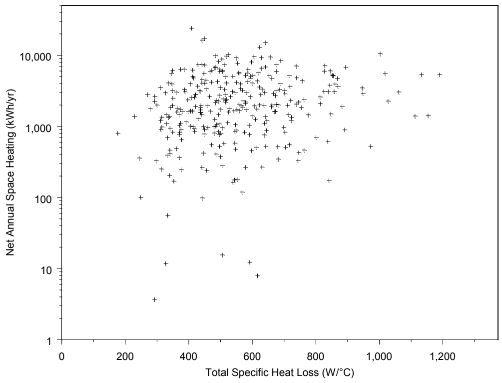

Figure 6. Net space heating by total heat loss.

6. Statistical models of space heating

Generalised linear models were used to explore how the various factors affect space heating energy consumption. This approach was chosen as there are several features of the data that make the use of simple linear models problematic. The residuals (the difference between the actual value and the model prediction) are larger for higher heating energy consumption and they are not normally distributed, and the sample variance increases with the energy consumption. These features fail to meet two of the major criteria for the application of a linear model, which are normally distributed sample measurements and constant variance. Generalised Linear Models (GLM) can deal with these problems[2].

GLMs work in the same general way as linear models, but the underlying statistical distributions are different. For example, a GLM can use a non-normal distribution for the sample measurements (e.g. a logarithmic or gamma distribution). They can also fit the data in a non-linear sense by using link functions such as logarithm, inverse or others. These features of the GLM allow the actual underlying

[2] "An Introduction to Generalised Linear Models" – 2nd Edition, by A. J. Dobson, ISBN 1-58488-165-8.

structure of the data to be considered in the model and can resolve the previous problems noted with the residuals.

The particular choice of GLM is a matter of finding which type represents the structure of the data best, often by trial and error. The models used for this analysis use the gamma link function for the statistical distribution of errors, and a logarithmic function to link the predictor to the response. The logarithmic function causes the factors to be multiplicative, not additive as is usual with simple linear models. Overall these were found to best deal with the non-normal distribution of the residuals and the skewed distribution of the space heating energy consumption.

6.1 Net space heating models

After initial screening of independent variables it was found that normalising net space heating by the floor area (MJ/m²) as the dependent variable gave better model representations than net space heating, as the variation introduced by differences in floor area was reduced. Normalisation using further variables (e.g. degree days) gave no further improvement.

There are some complex correlations and interactions between variables. For example, the type of heating system affects (or is affected by) the living room heating temperature, with higher capacity heaters associated with higher temperatures. The living room heating temperature is, in turn, related to the length of the heating season, as to maintain higher temperatures the heating system must be turned on earlier in the season and be used for longer.

There are a variety of occupant factors that could be expected to be related to space heating, such as the type of household. Rather than include them directly in the model as predictors of space heating energy consumption, they have been used to model the occupant-controlled parameters such as heating living room heating temperature, heating index, most used heater group, and heating season length.

6.1.1 Space heating energy model using physical factors

A base statistical model using only physical factors was developed (occupant factors are considered in separate models). The model was formulated as a generalized linear model with a Gamma family with logarithmic link function (Table 4). This model explained 50% of the variation in net space heating per unit floor area as a function of the variables Heating Index, Living Room Heating Temperature, Heating Degree Days (base 15°C), Heating Season Length, Heat Loss per m², and Most Used Heater Group[3].

It is important to understand that in New Zealand, space heating tends to be intermittent (often evening only) and usually only parts of whole houses are heated (often only the living room). In

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[3] Most Used Heater Group is a factor variable indicating which type of heating appliance is used the most.

combination with the mild climate and short heating season in many areas, this may contribute to the large amount of unexplained variation. The space heating energy will be more sensitive to set-points and schedules than would be the case where a whole house is centrally heated in a cold climate (e.g. as would be the case in colder parts of North America and Europe).

This statistical model clearly shows the importance of the physical factors such as the heating temperature, house heat losses, and heating season.

Table 4. Summary of model terms for space heating energy model (Physical factors only)

Independent Variable	*Factor Category*	*Value*	*Std. Error*	*t-value*
(Intercept)		*-2.551*	*0.479*	*-5.322*
Heating Index		*0.012*	*0.005*	*2.476*
Mean Living room evening temperature		*0.147*	*0.022*	*6.653*
Degree Days (/1000)		*0.565*	*0.157*	*3.590*
Length of heating season		*0.152*	*0.033*	*4.535*
Loss per m²		*0.240*	*0.037*	*6.493*
Most Use Heater Group:	*Portable Electric*	*0.000*	-	-
	Enclosed Solid Fuel	*0.447*	*0.139*	*3.217*
	Fixed Electric	*0.570*	*0.243*	*2.349*
	Gas	*0.167*	*0.216*	*0.775*
	Gas Central	*1.071*	*0.370*	*2.899*
	Heat Pump	*-0.446*	*0.457*	*-0.978*
	LPG cabinet heater	*-0.113*	*0.163*	*-0.694*
	Open Solid Fuel	*0.139*	*0.265*	*0.523*

The ranked importance of the variables in terms of how much variation they explain was determined using single term deletions from the model. The living room heating temperature and total specific loss per m² are the two most important terms, explaining roughly 20% of the variation each. The length of the heating season, heater group, and degree days each explain less variation (5-9%), however the correlation between degree days and the heating season length reduce the importance of the degree days. The Heating Index explains only a small amount of variation (3%), however it is still worthwhile including.

The Most Used Heater Group variable is interesting. Its presence may in part be reflecting efficiency differences for some heating types. The use of net space heating does account for the conversion efficiency of gas and solid fuel burners, however it does not account for the distribution efficiency of central heating systems nor the co-efficient of performance (COP) of the heat pumps (although both these heating types are very uncommon in the HEEP sample, but heat pumps have since undergone a rapid uptake). For gas central heating, the factor of 1.071 corresponds to a multiplicative factor of 2.91, which could account for an efficiency of 34%. The calculated average overall efficiency of gas central heating systems monitored in HEEP was 36%, which is very low, and perhaps is due to poor installation or a lack of maintenance (Isaacs, Camilleri, French et al, 2010). For heat pumps the factor of -0.446 corresponds to a decrease in net space heating of ~35%, which would correspond to a COP of 1.6[4]. For portable electric, portable LPG, gas, and solid fuel heater types where the efficiency has been fully corrected for, the parameters are not significantly different from 0 (which corresponds to a multiplier of 1).

6.2 Living room heating temperature Model

A model of the living room heating temperature was created (Table 5). Variables included in the model were Heating Degree Days, loss per m², life stage, most used heater group, the household type, and the floor area. This model explains 27% of the variation in the living room heating temperature, which clearly leaves a lot of unexplained variation. There appear to be significant regional variations, which might reflect some underlying attitudes to space heating in particular areas, however no hypothesis has been found that can explain these differences. No association between equivalised income (Atkinson, Rainwater and Smeeding, 1995) and living room heating temperatures was found. There may be other underlying reasons why particular households choose to heat how they do, however this is not revealed by this analysis of the HEEP data and survey information.

The ranked importance of the variables in terms of how much variation they explain was determined using single term deletions from the model. The most used heater group explains the largest amount of variation, followed by the type of household. The other variables, although statistically significant in the model, each explain <2% of the variation.

The most used heater group explains the most variation and has a large effect giving differences in living room heating temperatures. For example, using an enclosed solid fuel burner as the most used heater is associated with living room heating temperatures 1.778°C higher than using portable electric heaters.

The household type was an important factor, with one person households were found to be associated with an average 1.9 °C lower living room heating temperature. This is of concern as many of these households are retired people living alone, and low temperatures have been shown to have negative outcomes for health, especially for vulnerable groups such as the very young, the elderly, and the infirm (Howden-Chapman, Matheson, Crane, Viggers et al, 2007).

The life stage variable shows that working age households have lower living room heating temperature than other households, possibly reflecting occupancy patterns. The living room heating temperature decreases with increasing heating degree days, by about 1 °C per 1,000 Degree Days (approximately the range of permanently inhabited locations). Larger floor areas were associated with slightly lower living room heating temperatures, at a rate of -0.5 °C per 100 m² of floor area. This is

[4] The heat pumps were monitored at various times over the period 2000 to 2005, and some were old units.

perhaps due to larger houses requiring larger heating systems, and might reflect some under-sizing in heating systems.

Living room heating temperatures are lower in houses with higher heat losses. In uninsulated houses these were about 0.8 °C lower than in houses insulated to the current Building Code requirements at the time of monitoring. This term explained the least variation in living room heating temperatures, which is curious as it might have expected that this would have been a major influence, given that a fully insulated house would have a total heat loss that is less than half that of an uninsulated house.

Table 5. Summary of model terms for living room heating temperature model

Independent Variable	*Factor Category*	*Value*	*Std.Error*	*t-value*	*Pr(>|t|)*
(Intercept)		*20.539*	*0.869*	*23.635*	*0.000*
Degree Days (/1000)		*-0.900*	*0.300*	*-2.633*	*0.009*
Loss per m²		*-0.195*	*0.099*	*-1.967*	*0.050*
Life Stage	*pre-school age (0-5 years)*	*0.000*	*-*	*-*	*-*
	school age (5-14 years)	*-0.440*	*0.409*	*-1.077*	*0.282*
	working age (15-64 years)	*-0.633*	*0.373*	*-1.696*	*0.091*
	retired (65+ years)	*0.389*	*0.452*	*0.861*	*0.390*
Most Use Heater Group	*Portable Electric*	*0.000*	*-*	*-*	*-*
	Enclosed Solid Fuel	*1.778*	*0.312*	*5.704*	*0.000*
	Fixed Electric	*0.691*	*0.575*	*1.202*	*0.230*
	Gas	*1.112*	*0.475*	*2.341*	*0.020*
	Gas Central	*1.022*	*0.917*	*1.114*	*0.266*
	Heat Pump	*0.697*	*1.108*	*0.629*	*0.530*
	LPG cabinet heater	*0.054*	*0.384*	*0.142*	*0.887*
	Open Solid Fuel	*-1.141*	*0.699*	*-1.633*	*0.103*
	Solid/Liquid Fuel Central	*1.011*	*2.176*	*0.465*	*0.643*
Household Type:	*one family*	*0.000*	*-*	*-*	*-*
	one family with others	*-0.968*	*0.483*	*-2.004*	*0.046*
	more than one family/household	*-1.965*	*1.289*	*-1.525*	*0.128*
	non family (e.g. flatmates)	*-1.327*	*0.717*	*-1.851*	*0.065*
	one person household	*-1.854*	*0.386*	*-4.802*	*0.000*
Floor Area		*-0.008*	*0.003*	*-2.494*	*0.013*

6.3 Discussion

The two models are used in sequence with the living room heating temperature model as input to the net space heating model, and together starts to reveal the underlying behavioural and physical influences. The living room heating temperature is the most important behavioural factor, and the envelope loss per square metre of floor area the most important physical factor. The living room heating temperature, although a behavioural choice, is affected by both behavioural and physical factors, the two most important of these being the type of household and the type of heating system.

So why does a particular house with a particular set of occupants choose a particular heating system? In many cases the type of heating system is determined by what heating system already exists. With about 25-30% of households in New Zealand renting, these people have little or no influence on the type of heating system (Statistics New Zealand, 2006). New Zealand houses also have a high turnover rate, with the average occupation time for owner-occupied dwellings at about 7 years, and shorter for rented dwellings. This means that a lot of households inherit their heating system (or lack of one) from the previous or even original occupants. There are major differences in the type of heating systems used around New Zealand, with solid fuel burners being more common in the colder climates and outside the major cities. This perhaps reflects both the greater need for heating and high heat output in colder climates, and the availability of cheap firewood (often self-harvested or collected) outside the main cities, along with other factors such as the lack of gas supply, high electricity cost, and the frequency of weather related power cuts in isolated rural areas. A level of security can be offered by a solid fuel burner which can supply heat, hot water if connected, and sometimes even cooking.

Although the heat loss per square metre of floor area is a physical characteristic of the house and is affected by the house age, the association of a household with a particular type of house is affected to some degree by the occupant behaviour and characteristics. In New Zealand, post-1978 houses were required to be insulated to comply with the building code and have lower heat losses than earlier houses. Post-1978 houses are more likely to be occupied by households with above average incomes, and this is one example of how a behavioural or occupant factor can influence a physical factor that might at first appear to be independent of the occupants.

Heating patterns and behaviour have been changing rapidly since the HEEP study was conducted. The biggest chance has been a rapid uptake of heat pumps (reverse cycle air conditioners) in response to clean air campaigns (the phasing out of open fires and polluting wood burners) but also in response to consumer demand for more efficient and effective heating. In the HEEP study, only 4% of households had heat pumps – by 2008 this had grown to 19% (French, 2008), and is still growing rapidly. French (2008) found that when people got heat pumps they tended to heat to higher temperatures, for longer periods, over a larger area of the house. Although heat pumps are very efficient heaters, these changes in behaviour are expected to take up most or all of the potential energy savings. Also, since many of the heat pumps are replacing solid fuel burners or gas heaters, this will place additional demand on the electricity network at peak winter times, when fossil fuel generation is at its peak. Research is underway to study the recent changes in heating patterns and the effect on the electricity network.

7. Conclusions

The relationship between space heating energy consumption and the climate, house, and occupants has been shown to be complex. About half of the variation in space heating energy consumption per m² of floor area can be explained by physical factors such as climate (heating degree days), heating zone, schedules and set-point, heating season, type of heating system, and house envelope thermal losses. This is a very successful result given that the amount and extent of space heating in New Zealand houses is highly variable compared to cold climates in North America and Europe climates where 24 hour, whole house heating is common. However trying to explain why a particular household chooses to heat their house the way they do is not nearly as successful. Living room heating temperature models were poor, explaining at most 26% of the variation. It appears plausible that there are underlying attitudes or behaviours that may not be related to socio-demographic factors that determine space heating behaviour. Attitudes to comfort, energy conservation, expenditure, and health may be important influences on occupant behaviour, and the recent rapid uptake of heat pumps shows how quickly these attitudes can change.

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The Building Energy End-use Study (BEES): Study Design and Early Findings

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Abstract

The Building Energy End-use Study (BEES) is a large, multi-year study of the energy use in commercial buildings in New Zealand. The study design is described, including the methods used to overcome some of the major difficulties faced in covering the diverse range of non-residential building types and sizes. Analysis of the building stock characteristics from information derived from public sources including valuation data, Google Earth and Streetview is given. The study aims to develop a complete understanding of the energy use in non-residential buildings that can be used to assist in the development of benchmarks and information for improved building operation for building occupants and managers, and in policy and planning.

Keywords: energy efficiency, commercial buildings, building stock

1. Review

The commercial sector spends over $NZ 900 million/year on energy, accounting in 2008 for 11% of New Zealand's energy and 23% of electricity use (MED, 2009). The sector was responsible directly for 3% of energy Greenhouse Gas (GHG) emissions in 2008 (MED, 2009). In 2008 the sector consumed 22% of total electricity use, making it indirectly responsible for 5% of energy GHG emissions. Thus the sector is directly and indirectly responsible for 8% of national energy GHG emissions. It is important for both macro-economic and environmental management to know where the cost-effective opportunities for energy efficiency and conservation exist.

There is a pressing need to understand where and how energy is used, to help reduce GHG emissions and improve efficiency. To this end, several large scale studies internationally of energy in non-domestic buildings have been undertaken:

1. Commercial Buildings Energy Consumption Survey (CBECS, USA)
2. Commercial and Institutional Building Energy Use Survey (CIBEUS, Canada)
3. Non-Domestic Building Stock (NDBS, UK)
4. Carbon Reduction in Buildings (CaRB, UK)
5. California Commercial End-Use Survey (CEUS, USA)

CBECS is the longest running program, established in 1979 to cover the entire USA and repeated on an approximately four year cycle ever since (EIA, 2009a). The scope and coverage are extensive, encompassing all "commercial" buildings, defined as any building that has at least 50% of the floor area neither residential, manufacturing/industrial, nor agricultural (EIA, 2009b). Therefore there is great diversity in the type and usage of the buildings, and great diversity in energy use and energy intensity. This necessitates a large sample (approximately 5,000 buildings) with sophisticated sampling and analysis procedures to ensure that statistically reliable estimates of energy use and other parameters can be derived for the population as a whole, and sub-populations by building type, building use, geographic region etc. Although participation in the interview is voluntary, a high response rate is achieved, which was 82% for the 2003 survey. Data is collected using Computer Assisted Personal Interviewing (CAPI), where trained field staff conduct the interview on-site with a knowledgeable interviewee. Energy was not directly monitored, but revenue meter data was obtained either from the participants or directly from the energy suppliers[1]. Since energy consumption is only collected at a high level (e.g. building total by fuel) the amount used by various end-uses is not explicitly known but is generated by statistical analysis.

[1] CBECS comes under the EIA's mandatory data collection authority.

CIBEUS was carried out by Statistics Canada, mainly “to collect energy intensity information for the commercial and institutional buildings in Canada for the reference year 2000” (NRC, 2003). This information was used (in part) to assess Canada’s greenhouse gas emissions reduction commitments. CIBEUS was very similar in scale and scope to CBECS, and shared some common definitions and methodologies.

CEUS was a program of comparable scale to CBECS, however conducted only in the State of California for the California Energy Commission (CEC) for the specific purposes of electricity and gas end-use forecasting and energy efficiency market assessment activities (CEC, 2006). Thus the study design was different, although the issues around the sample boundary, sampling, and statistical analysis are similar. In California, many commercial buildings had interval revenue meter data (15-60 minute intervals), and the CEC has a statutory right to access that data. In addition, during the planning stage of the project aggregated electricity data for all commercial buildings in California was obtained supporting enabling a thorough evaluation of the sampling methods. A stratified sample with strata of: energy utility area; building type; size; and climate zone was adopted to both improve the statistical accuracy or estimates and to better match the intended use of the data.

As CEUS required a much greater level of detail than CBECS delivered, different information was collected, extending down to detailed end-use equipment stock and characteristics and the detailed building layout. The information was collected during on-site visits by a trained auditor, so relied more on the expertise of the auditor than the knowledge of the occupants. The data permitted energy models to be created and tuned to match the interval meter billing records By analysis of the load characteristics for the various end-uses in each building, an estimate of the load profile and energy consumption for the different end-uses generated.

End-uses were not directly monitored, though in some cases (~500) time of use meters were installed on dedicated equipment to assist in the modelling end-use disaggregation process. CEUS remains the most detailed large scale study of commercial building energy use.

The NDBS project in the United Kingdom ran from 1991 to 2001, and was designed to support government policy-making for carbon dioxide emissions (Steadman and Bruhn, 2000). Policy making had found that the lack of information on the non-residential stock was a major problem, so one of the main outcomes of the project was a national database of non-residential buildings. More detailed street surveys were also carried out on four central city locations.

The CaRB project started in 2004, built on the methodological foundations of NDBS, extending coverage to all buildings with the long term goal to create a socio-technical model of energy use in U.K. building at scales ranging from national to community level (CaRB, 2009).

In New Zealand a series of field surveys were used to determine energy use in the commercial sector in several major cities: Auckland (Beca Carter Hollings et al., 1979), Wellington (Baird, Donn and Pool, 1983) and Christchurch (R. W. Morris & Associates, 1985), however, unlike CBECS the NZERDC surveys did not achieve nationwide coverage, and the process was not repeated. Subsequent research extended to performance monitoring of end-uses in three large commercial buildings in Wellington (Baird and Pool, 1985).

Each of these projects has had to overcome common methodological difficulties including:

1. Defining what is a "building" or the sample unit
2. Defining the population of buildings
3. Sampling the hugely diverse population efficiently
4. Compiling a list of buildings and occupants to recruit
5. Obtaining accurate and reliable energy data
6. The wide range of energy uses and intensities
7. The wide diversity of the types and levels of service provided

These common difficulties create major issues in sampling and analysis, some of which can be addressed by an appropriate sample scheme (e.g. sample stratified by building floor area, building type, and location) and by sampling a sufficiently large number of buildings.

Only Baird and Pool (1985) directly monitored energy consumption at the end-use level. The end-use estimates for these other studies have been inferred by other methods (e.g. modelling, statistical analysis, time-of-use monitoring, surveys or extrapolations from other research)

2. The building energy end-use study (BEES)

The key objectives of the Building Energy End-use Study (BEES) are to gain an understanding of how and where energy and water is used in non-residential buildings, what level of service is provided and how the efficiency of use can be improved. BEES commenced in late 2008.

Eight key research questions have been identified for this research on the non-residential buildings sector:

1. What is the aggregate energy & water use?
2. What is the average energy and water use per unit area per year?
3. What characterises the largest energy and water using buildings?
4. What is the average energy use per unit area for different building use categories?
5. What are the distributions of energy and water use?
6. What are the determinants of water & energy use patterns?
7. Where are the critical intervention points to improve resource use efficiency?
8. What are the likely future changes as the building stock type and distribution change?

To answer these questions, three complementary data collection methods have been designed and piloted, and are being rolled out in 2010:

1. Aggregate survey: A telephone survey of businesses owners to collect occupant, construction, location, energy and water data for a target of at least 500 buildings.

2. Targeted survey: Detailed monitoring of energy end-use and environmental data for a target of 300 buildings.
3. Case studies: Highly detailed case studies designed to explore the operation of specific buildings, for a target of 5 studies per year.

The data collection is supported and supplemented by: an annotated bibliography of New Zealand and international literature prepared; a systematic review; modelling of all surveyed buildings.

3. BEES sample frame

The sample frame defines the population of buildings which will be studied, which must be specified and sampled appropriately. Even at this most basic level there are difficulties to overcome:

1) Defining what a "building" is
2) Finding an efficient sampling strategy
3) Compiling a list of all valid buildings of interest
4) Finding contacts for businesses in the buildings

There is no commonly accepted definition of a non-residential "building". Non-residential buildings often share common walls and sometimes services, and may have common access arrangements. Sometimes existing buildings are modified and joined to other buildings to create a 'new' building. Buildings could therefore be separated by the architectural boundary (discrete physical structures), the services boundary, or the ownership boundary.

CBECS and CIBEUS used a very similar definition, basically "a structure totally enclosed by walls that extend from the foundation to the roof…" [EIA (2009c); NRC (2003), pg 494)]. NDBS and CaRB used the same definition, basically "…a 'building' encloses space which is accessible and usable for some human activity. …" (Bruhns, Steadman, Herring et al., 2000).

3.1 Information sources

Information on the building stock was gathered from a wide range of sources including:

1. Property valuation data
2. Aerial photos
3. Google Streetview images
4. Internet search of directories and business websites
5. Business directories
6. Brief site visits, to confirm and expand this information

These sources were used initially to get as much information on the buildings in the sample frame as possible, before surveying the buildings or occupants. The intention was to reduce the overall cost for the project and thereby enable a larger sample of buildings and occupants than could have been achieved if site visits were used. This process has turned out to be more difficult than anticipated for various reasons, including incomplete coverage of directories and internet information sources, difficulties identifying the correct land parcel and/or building, and occupant information being out-of-date due to the turn-over of business and buildings.

3.2 Valuation information

Although there is a New Zealand national database of valuations of legal titles[2] (representing land, buildings, parts of buildings, and other structures) used for local government 'rating' purposes[3], this was not in a suitable form for a sample frame. Valuation records are categorised by the principal use of the land at the time a valuation was undertaken. In some cases there may be a number of uses, and a 'multiple use' category is applied. In some cases the use may have changed over time but not yet been changed in the valuation record. A valuation record may include one or more buildings, parts of buildings, or other structures.

BEES purchased a copy of all the valuation records for commercial, industrial service and warehouse and "other" (includes educational, health, and community) categories - a total of 92,555 valuation records. Some buildings have multiple legal titles for different parts (e.g. floors or units) and although these were aggregated to form a parent "building record", without physically inspecting the actual site it is not possible to be 100% certain that this process represents an actual 'building'. This is a similar process to that in used in the NBDS and CaRB, where "hereditaments" (a legal title very similar to that use in New Zealand) were grouped to form a "building". The valuation records were grouped into parent records representing (usually) a single building or campus, yielding 75,400 building records, and various checks and data cleaning performed.

The total floor area for 'Commercial', 'Industrial Service', 'Industrial Warehouse', and the selected 'Other' categories is approximately 75 million m², in these 75,400 valuations (Table 2). The commercial category is the largest with 36 million m² in some 40,000 valuations. The three largest commercial sub-categories are 'Commercial-Retail', 'Commercial-Multiple/Other' and 'Commercial-Office', and their combined floor area is 27 million m², which is 75% of the total 'Commercial' floor area (Table 3). In the 'Other' category, the 'Educational' sub-category has 45% of the total floor area, far larger than any other sub-category.

Using this analysis, and guided by the aims of the study, the decision was made to restrict the main BEES study to the Commercial subcategories: Office, Retail, Mixed, Service Station[4],

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[2] Held by Property IQ - www.propertyiq.co.nz

[3] Rates are local property taxes levied by local and regional councils to provide various services.

[4] A gas or petrol station, nowadays usually also includes a convenience store.

Motor[5], Liquor, and Tourist. These categories seem to best represent those where retail or office activities predominantly occur. The Commercial subcategories of accommodation, rest home, and car park are therefore excluded. 'Educational' and 'Health' categories have been separated out for a sub-study.

After the records in non-BEES categories are removed, it is estimated that in New Zealand there are 50,540 BEES non-residential buildings, with a total of 48.3 million m² total floor area.

3.3 Sampling strategy

These building records were used to investigation efficient options for sampling. Taking a simple random sample of 1,000 building records with equal probability, and assuming energy use was related to the proxy variable of property value, would give an estimated standard error in average total energy consumption of ±17%. In contrast, a stratified random sample of 1,000 buildings with 5 size strata each representing 20% of the total floor area (Table 1) would give a standard error of ±3%. This is caused by the highly skewed distribution of total floor area (see **Error! Reference source not found.**): by count, 87% of all non-residential buildings are under 1,500 m² in floor area, but the remaining 13% by count represent 60% of the floor area. This type of skewed distribution was also observed to occur in the USA in CIBECS and CEUS, and in the UK in the NBDS and CaRB studies, and presumably also applies to other countries. It is expected that other studies of non-residential building energy use in general will have to deal with these kind of sampling issues. Section 4 has more detailed information on the distribution of floor area.

Table 1. Floor area strata used for the BEES sample

Floor area group	*Strata 1*	*Strata 2*	*Strata 3*	*Strata 4*	*Strata 5*	*Total*
Minimum Floor Area	*5 m²*	*650 m²*	*1,500 m²*	*3,500 m²*	*9,000 m²*	
Approx. No. of 'Buildings'	*33,781*	*10,081*	*4,288*	*1,825*	*564*	*50,539*
% of Buildings	*67%*	*20%*	*8%*	*4%*	*1%*	*100%*
Total floor area (million m²)	***9.9***	***9.6***	***9.5***	***9.6***	***9.8***	***48.3***
% floor	*20%*	*20%*	*20%*	*20%*	*20%*	*100%*

3.4 Compiling list of businesses

Implementing the survey design is still not a straightforward process, due to the difficulties of then compiling a list of building and occupants to recruit. There is no near-complete list of building owners or occupants, a problem found and resolved in different ways in other

[5] Motor vehicle sales. Motor vehicle servicing is excluded, and is usually found in the Industrial Service valuation category.

countries. The list of building owners attached to the valuation data is not complete, and many of the owners are trusts or other legal entities which are difficult to contact. Business directories are also not complete, achieving perhaps 50-70% coverage, with some types of businesses unlikely to be listed in general directories.

Statistics New Zealand[6] does hold a list of "enterprises", which are all businesses with GST returns (a value added tax of 12.5%) exceeding $30,000 per annum. This is also incomplete as smaller businesses are excluded, and in addition an "enterprise" can be a business spread across a number of different sites (including fishing boats), so does not always correspond to the BEES sample unit of a "building record". In the absence of a comprehensive directory of businesses, the available business directory was used, supplemented by business names found in Google Streetview or web search, and then followed up with a site inspection to confirm the information, and record any additional businesses.

For BEES, the business level sample unit is called a *premises*, which is a single business operating in all or part of a building record. There can be one or more premises in a building record. Before a phone survey can even commence collecting data, it is necessary to identify all premises and obtain their contact details. Using Google StreetView, the on-line 'Yellow Pages', a web search and purchasing address data from a commercial supplier, a total of 7,682 premises were identified in the 3,043 building records selected for possible recruitment into the study, on average 2.5 premises per building record.

Site visits were then undertaken for the first 800 of these building records to check the information, and search for any additional premises in preparation for the telephone survey. This process yielded a total of 2,568 premises, (3.2 per building record), however 6% of the building records were vacant or not found, and 24% of the premises were not found, leaving 1,943 premises. Of these 1,557 were eligible for the BEES study and had phone numbers. This clearly illustrates how difficult it can be to find a list of survey candidates.

3.5 Websearch

An internet websearch was used to compile information on ~2,400 valuations. The main internet tools used were Google Earth and Google Streetview, which together enabled aerial and street level images to be found, and characteristics of the building inferred, such as the number of floors, floor area, construction materials, glazing etc. Google Sketchup was used to create building models, ready for analysis in the thermal model EnergyPlus, with the information on the building included.

The data collection phase of the websearch was completed in December 2009, and analysis and modelling is continuing.

4. Building stock floor area distribution

The distribution of floor area is highly skewed, as the count of buildings is dominated by small to medium sized buildings, but the floor area is dominated by comparatively few very large buildings. For the Commercial categories, only about 2% of buildings have floor areas larger than 10,000 m², but together they have 20% of the total floor area *Figure 1*. This pattern is seen for all valuation categories, and is particularly pronounced for hospitals and educational buildings, as there are some very large regional hospitals and university campuses. Such a highly skewed distribution creates problems in sampling and estimation.

Table 2. Estimates of total floor area and valuation count – separate and parent records.

Category	*Total Floor Area (m²)*	*Count of 'separate' and 'parent' Valuations with floor area*
Commercial-Accommodation	*3,532,580*	*3,880*
Commercial-Cinema/Hall	*255,530*	*150*
Commercial-Elderly	*2,086,630*	*930*
Commercial-Liquor	*902,150*	*1,080*
Commercial-Motor	*829,130*	*1,490*
Commercial-Multiple/Other	*8,608,160*	*7,020*
Commercial-Office	*7,618,290*	*6,670*
Commercial-Parking	*450,360*	*490*
Commercial-Retail	*10,534,160*	*16,560*
Commercial-Service Station	*571,640*	*1,270*
Commercial-Tourist	*264,170*	*310*
Commercial-Vacant	*58,020*	*220*
Industrial-Service	*8,495,630*	*9,990*
Industrial-Warehouse	*10,328,930*	*6,820*
Other-Assembly Halls	*949,830*	*2,390*
Other-Educational	*8,450,260*	*4,300*
Other-Health/Medical	*2,582,210*	*1,180*
Other-Maori Sites	*431,560*	*800*
Other-Multiple/Other	*3,466,460*	*2,950*
Other-Passive Reserve	*446,600*	*970*
Other-Religious	*1,810,070*	*3,470*
Other-Sporting	*2,063,920*	*2,320*
Other-Utilities	*42,810*	*20*
Other-Vacant	*169,610*	*120*
Total 'Commercial'	***35,710,820***	***40,070***
Total 'Industrial'	***18,824,560***	***16,810***
Total 'Other'	***20,413,330***	***18,520***
Total 'Commercial+Other'	***56,124,150***	***58,590***
Total	***74,948,710***	***75,400***

[6] www.statistics.govt.nz

Table 3. Average floor area by valuation category – 'Commercial' only

Category	*Average Floor Area (m²)*	*Count*	*Percentage of floor area*
Commercial-Accommodation	*910*	*3,882*	*10*
Commercial-Cinema/Hall	*1,681*	*152*	*1*
Commercial-Elderly	*2,249*	*928*	*6*
Commercial-Liquor	*834*	*1,082*	*3*
Commercial-Motor	*558*	*1,486*	*2*
Commercial-Multiple/Other	*1,226*	*7,024*	*24*
Commercial-Office	*1,142*	*6,673*	*21*
Commercial-Parking	*923*	*488*	*1*
Commercial-Retail	*636*	*16,559*	*30*
Commercial-Service Station	*449*	*1,273*	*2*
Commercial-Tourist	*855*	*309*	*1*
Commercial-Vacant	*264*	*220*	*0*
All	***891***	***40,076***	***100***

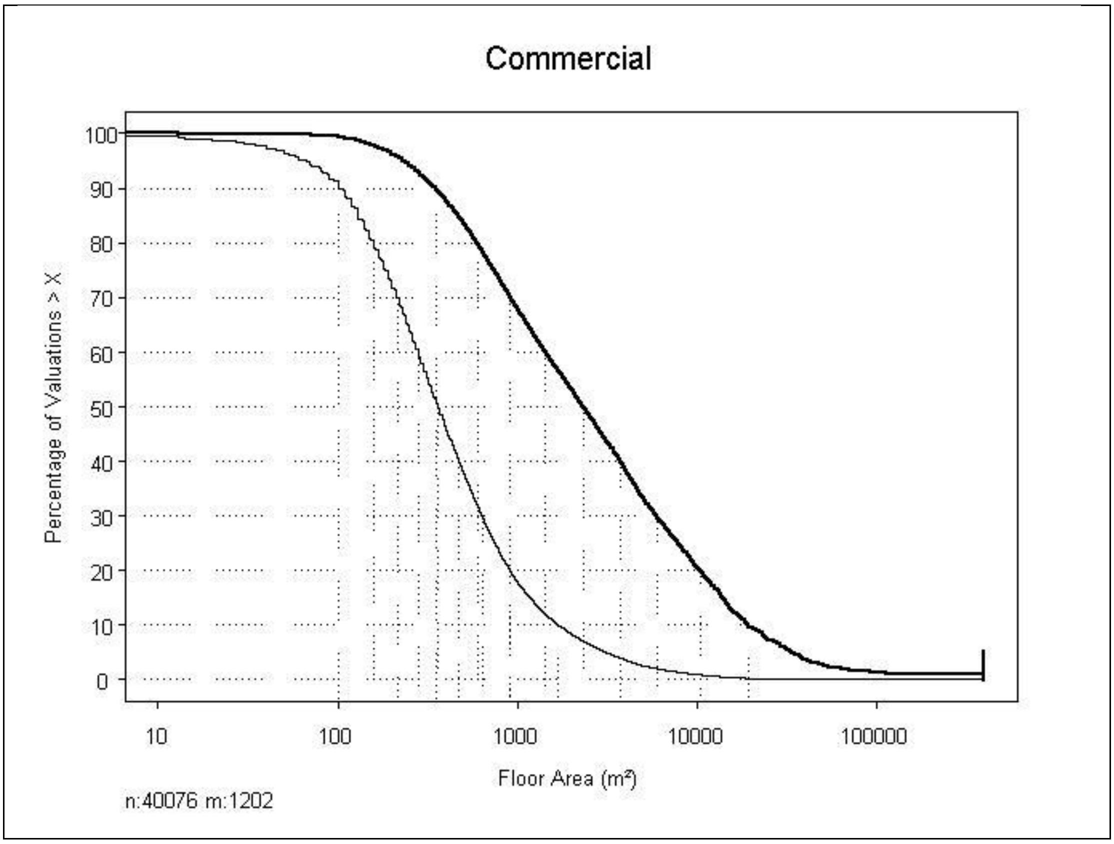

Figure 1. Cumulative percentiles for Commercial valuation categories.
Thin line is cumulative count, thick line is cumulative floor area

5. Energy and environmental data

Energy data for studies of this type is usually sourced from utility billing records, or from interval data (e.g. 30 minutes) from utility interval metering or the building Energy Management System (EMS). Utilising billing records always sounds as if it will be a cheap and easy process, however it does take a lot of time and effort to obtain and process the data. To quote from Beca Carter Hollings et al. (1979):

> "It is often suggested by energy researchers and other interested parties contemplating energy studies that 'energy consumption information can be obtained from supply authorities'. … Any future researcher contemplating a broad multi-fuel type investigation should be prepared for a pot-pourri of classification and accounting systems, as well as considerable variation in accessibility of data."

Energy billing records for BEES premises will be obtained to give a longer time series of data than could be monitored, including revenue records from prior to the commencement of the BEES work. In the 30 years since the Beca Carter Hollings et al. (1979) study was completed this process has become easier as accounts and records are fully computerised but more complex in many other way:

1. The energy market reforms of the 1990s have led to a multitude of energy (electricity and gas) retailers, each with their own systems and requirements
2. Agreeing and trialling information exchange processes
3. Matching account signatory to all matching account and meter IDs
4. Importing, reformatting, and processing data

If the utility suppliers were active participants in the project, or commissioning agents, this process would be much easier as working relationships would already be in place.

Obtaining energy end-use and environmental information (e.g. electricity, gas, temperature, humidity, light) requires a different approach, as these are not usually monitoring in a building unless it has a comprehensive EMS.

For BEES, electricity end-uses are monitored directly at electrical distribution boards around the building using proprietary equipment. The recent commercialisation of Rogowski coils for measuring current has enabled much smaller current clamps than conventional magnetic current transformers. After trials of several systems, the Multivois system was selected, supplied by the French company OmegaWatt (www.omegawatt.fr). This system uses a DIN rail mounted "concentrator" (data logger) which connects to up to nine modules, each with 6 Rogowski coil sensors. The logger and sensors are very small and easy to fit on distribution boards, are accurate (typically ±2%), and cover a very wide power range. The planned monitoring would not be practicable with any other available system due to space restrictions, safety concerns, and likely power interruptions.

Environmental data is collected at several points in each premises using battery powered temperature, humidity, and lux loggers, with carbon dioxide levels monitored by a separate logger at a single point.

6. Conclusions

Planning and piloting of monitoring for the Building Energy End-use Study (BEES) has been largely completed and the full study is underway in 2010. To get to this point some major obstacles have had to be overcome to deal with the huge diversity in building types, size, services, use, and energy consumption - issues that will be common to any similar study. Survey methods for collecting information on buildings and their occupants have been trialled. Methods for monitoring energy end-uses and environmental conditions have been tested and trialled and are being used to monitor buildings. Together these methods should give an unprecedented understanding of how energy is used in buildings, and provide many future opportunities for optimising energy and resource use.

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Urban Rehabilitation of the Coimbra's "Baixinha" Historical Centre – Portugal

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Abstract

Rehabilitation is, in cultural and social terms, an alternative to the substitution of buildings, as an assertion of the urban space's memory and the established social relationships making a unique space within a more global one which is the city as a whole. However we see that the energetic policies are, in a way, more oriented towards a more recent construction, bringing a constant challenge to the rehabilitation being made, also motivated by the complexity involving energetic rehabilitation and the fact that it is still a fairly recent process in our country. The present work exposes studies, its analysis and the evaluation of the measures that should be taken. These should join together rehabilitation and renovation to the carrying out of the energetic-environmental measures, keeping in mind the increase of the buildings energetic performance, the comfort and liveability conditions and the fulfilment of the current legislation without changing the image or the historical and architectural features of old buildings. Researches were made to establish the comfortable thermo conditions and tests to understand the typologies, morphologies and constructive systems influence on the achievement of those conditions. The gathered information was analysed, adjusted and tested in the rehabilitation of historic centre of the Baixa area of Coimbra in order to help the city's administration to accomplish one of their goals: "to assure the environmental and energetic sustainability".

Keywords: rehabilitation, energetic performance, historical centre, sustainability, comfort

1. Introduction

In Portugal during the 20th. century, rehabilitation work was essentially carried out on monuments. It was only after the Revolution of 25 April 1974 that conservation practices began to change, with the recognition of the importance of the idea of that cities should integrate the socioeconomic, cultural and environmental aspects of rehabilitation work and ensure that it was not restricted only to monuments but also included other groups of buildings. Rehabilitation is an important alternative to the replacement of buildings and prevents urban sprawl. In addition, given the impact of buildings in terms of energy consumption, they will now have to comply with minimum energy performance requirements, adapted to local climate conditions. Good practice, in this context, must therefore be aimed at the best possible use of the relevant factors to reinforce energy performance by increasing thermal levels and installing alternative energy supply systems.

Despite the fact that energy policies are not particularly directed towards old buildings and that there are ongoing difficulties involved in implementing domestic energy rehabilitation measures, it is imperative that concerns about energy and thermal comfort are incorporated into rehabilitation, restoration and renovation projects for existing buildings and measures are taken to optimise cost efficient energy-environmental behaviour.

Improving the overall energy performance of an existing building does not necessarily mean total renovation but may be limited to the most important elements of energy performance and those which are cost-effective. Therefore, the search for tools to assess the best building solutions from the point of view of comparative thermal analysis is also very important.

Within this context, this paper presents an assessment of corrective thermal measures implemented through two studies which tested out various thermal corrections applied to two properties, a T0/T1 (studio/one-bedroom flat) (Study 1) and T2/T3 (2/3-bedroom flat) (Study 2) in two separate old buildings in the historic centre of the Baixa area of Coimbra that were due to undergo different rehabilitation strategies.

2. Thermal-energy correction strategies

2.1 The urban environment – climate factors and data

The historic centre of Coimbra stands between nineteen and one hundred and five metres above sea level.

The climate in Coimbra has the typical characteristics of the Beira Litoral region, being temperate and Mediterranean, with moderate temperatures in summer and winter and rainfall throughout the year.

According to Thornthwaite the climate in the area is classified as B1, B’2 s a´, or in other words, humid and mesothermal [1], with moderate water deficiency and little or no concentration of thermal efficiency in the hot season. As classified by Koppen it is a Csb [2] climate, i.e. temperate, humid (Mediterranean) with dry and not very warm summers.

The average annual temperature is 14.8º with slight monthly variations (19.9ºC in July and 9.7ºC in December). Average annual rainfall amounts to 913.8 mm and 75% of the annual total falls between October and March. The relative humidity is high, with an annual average of 82%. The lowest monthly average is 73% in July and August. Annual insolation amounts to 2,392 hours, a value which is not particularly high, and morning fogs and mists are very common. The average wind speed is 10.5 Km/h, with prevailing winds from the south and southwest in autumn and winter and from the northwest in spring and summer. Frosts are rare, occurring only 3.6 days of the year between October and April (Nunes, 2002). The water temperature of the River Mondego varies from 6º C in the coldest months of December and January to 19º C in the hottest months of July and August, averaging 16º C in the Coimbra and Lower Mondego zones and 10º C in the Serra da Estrela and Caramulo zones.

2.2 Identification of main problems

The buildings in the area covered by the study have a low comfort level, independently of its type, due to the poor thermal quality of the building external envelope (walls, frames and coverings) and the actual spatial structure of some of the buildings, which makes it difficult to control natural ventilation and consequently the speed and quality of air in the interior. Their relationship to the outline and width of the streets also affects comfort, since most of the year no direct sunlight comes through the windows, thus reducing solar gain in summer (a positive point) and practically eliminating it in winter (which is very disadvantageous to the performance of the building).

Certain problems related to condensation are also found, either due to the poor quality of the building envelope and lack of heating and ventilation control, or due to climatic factors (with high levels of relative humidity registered). In buildings whose walls have lime-based coatings, the situation is less problematic due to their hydroscopic inertia, which is more permeable to water vapour and releases it more slowly.

2.3 Passive solar strategies

This type of strategy aids the natural heating or cooling down of buildings according to the needs of users. It involves studying the spatial organisation which best favours interior thermal comfort, including constructional mechanisms integrated into the buildings through various measures, namely:

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[1] Humid climate with little water deficiency
[2] Csb – Temperate Humid Climate with dry, temperate summers

1. The use of buffer zones (technical and service areas) to protect living space in terms of solar gain and undesirable losses;
2. Making use of passive solar gains: south-facing collectors to aid insolation in winter and offer protection against the sun in summer;
3. South and north facing openings in opposite facades to allow for cross ventilation in summer and blind facades in the east and west to provide better solar protection in summer;
4. Entrances or interior courtyards to promote passive cooling and provide light for interior areas in summer;
5. Cooling by natural night ventilation or through water evaporation systems;
6. The use of active technologies for transparent or translucent facades to accommodate the relationship between thermal solar gains and natural lighting, favouring gains during the hours of winter insolation and reduction in summer.

Whenever possible passive solar strategies must be applied in rehabilitation work, and even active strategies as well, whilst recognising that their application is limited, given that this involves a built-up area with a defined shape and size. Given these adverse factors and the fact that groups of buildings with great heritage value are involved, various hypotheses and intervention strategies should be tested out from the point of view of increasing comfort and thermal, energy and environmental performance, in order to find the best solution without interfering with the architectural image. For this reason thermal correction applied to the exteriors of walls and external shading are not included in this study;

3. Case study 1

Case study 1 involves a building due to undergo extensive rehabilitation and renovation work, maintaining the facades and altering the entire constructional system and organisation of the interior. It was chosen because it is typical of the cases found in the historic centre of the Baixa area of Coimbra, given the high level of degradation in buildings, which at times leads to maintenance of the facades only and, in addition, because rehabilitation projects are in the applications phase.

3.1 Description of the building

The building stands in Rua na Moeda nº 84-92 / Largo das Olarias, Santa Cruz and was probably constructed at the end of the 19th. century. There is a commercial establishment on the ground floor and residences (7 T0 – studio flats) on the 1st. and 2nd. floors.

Figure 1: Photos / Study 1 localization

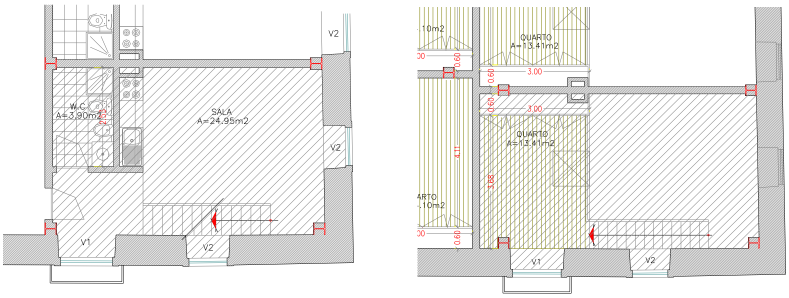

Figure 2: Study 1 target fraction

3.2 Study methodology

In order to assess the most suitable thermal intervention strategies that do not clash with the architectural style of the building, 12 tests were carried out involving the application of the new thermal regulations (DL 80/2006):

3.2.1 Test 1 – existing situation (starting point)

This test served to calculate the thermal performance of the building after alterations to the divisions and the materials stipulated in the architect's plan, without carrying out any thermal correction.

Identification and characterisation of existing construction solutions:

- Outer walls in soft limestone masonry (20 cm thick in the areas below the windows and 70 cm thick in the remaining areas), with traditional coatings on both sides.

- Frames – Glazing with wooden frames, two-pane windows, simple glass and night-time screening with low air permeability (entrance);

- Floors – One-way floor with ceramic filler blocks (0.35 m), levelling cement screed, loose-laid floor covering in the sitting room, mosaics in wet areas and ceiling covering of plaster with metallic finish;

- Coverings - One-way slabs with ceramic filler blocks (0,30m), discontinuous covering of ceramic tiles with well-ventilated area beneath, plastering in interior;

- Water heating system– gas heater.

In this test the effects of installing three different water heating systems were analysed, whilst the remaining features were maintained, in order to determine which was most advantageous.

3.2.1.1 Existing situation + Electric hot water storage heater (TAE)

3.2.1.2 Existing situation + Gas hot water storage heater (TAG)

3.2.1.3 Existing situation + Solar collectors (CS)

3.2.2 Test 2 – Compliance with minimum requirements imposed by new thermal regulations

In this test specific thermal corrections were applied to ensure compliance with minimum regulatory requirements. The corrections made in order to comply with minimum requirements which involved replacing the water heating system with a more efficient one were also tested.

3.2.2.1 Test 2.1 - Minimum requirements + Gas hot water storage heater (TAG)

3.2.3 Test 3 – thermal correction 1

In the test the aim was to comply with the minimum requirements stipulated in the thermal regulations by replacing the frames with more efficient ones and introducing specific corrections which did not significantly reduce indoor space. Certain thermal corrections were therefore carried out, the water heating system was replaced with an electric hot water storage heater with less than 50 mm of thermal insulation and solar collectors were installed in accordance with the Portuguese regulatory programme for the analysis of solar system performance (Solterm).

3.2.4 Test 4 – thermal correction 2

The aim of test 4 was to comply with thermal regulation requirements without replacing framing. Thermal corrections were therefore introduced using thicker insulation material, replacing the existing water heating system with a gas hot water storage heater with 50 mm of thermal insulation and installing solar collectors in accordance with the Solterm programme.

3.2.5 Tests 5, 6, 7 and 8 – thermal correction 3, 4, 5 and 6

In these tests more intrusive and wide-ranging thermal corrections were introduced in order to comply with (and exceed) the thermal regulation requirements by replacing the water heating system an electric hot water storage heater with less than 50 mm of insulation and installing solar collectors in accordance with the Solterm programme.

Table 1 – Summary table with carried out corrections

Test	Frame (glass)	Sealed doors	Ventilation grid	Walls 20 (insulation)	Walls 70 (insulation)	Floor slab (insulation)	Roofing (insulation
1, 1.1, 1.2, e 1.3	Existing	No	No	Without	Without	Without	Without
2 e 2.1	Existing	No	No	60mm	Without	Without	60mm
3 - Correction 1	Double special	Yes	Yes	60mm	Without	60mm	60mm
4 - Correction 2	Existing	Yes	Yes	60mm	60mm	60mm	60mm
5 - Correction 3	Double	Yes	Yes	60mm	30mm	30mm	30mm
6 - Correction 4	Double	Yes	Yes	60mm	30mm	60mm	60mm
7 - Correction 5	Double	Yes	Yes	60mm	40mm	60mm	60mm
8 - Correction 6	Double	Yes	Yes	60mm	60mm	60mm	60mm

4. Results

Using a spreadsheet the thermal regulations were applied to the tests named before and the values for Nic, Nvc, Nac and Ntc in Kwh/m^2.year were calculated. The obtained results are presented in Table 2:

Table 2: Obtained results from the calculation of the thermal regulation

Tes	Ap (m^2)	RPH	Nic	Ni	Nvc	Nv	Nac	Na	Ntc	Nt
1 - Existing	44.89	1.00	187.02	73.47	1.70	18	68.09	52.69	11.30	7.94
1.1 - Exist.+TAE	44.89	1.00	187.02	73.47	1.70	18	42.56	52.69	17.78	7.94
1.2 - Exist.+TAG	44.89	1.00	187.02	73.47	1.70	18	48.63	52.69	9.62	7.94
1.3 - Exist.+CS	44.89	1.00	187.02	73.47	1.70	18	65.16	52.69	11.04	7.94
2 -. Mín Req.	44.89	1.00	138.98	73.47	2.85	18	68.09	52.69	9.91	7.94
2.1 - Mín Req. + TAG	44.89	1.00	138.98	73.47	2.85	18	48.63	52.69	8.24	7.94
3 - Correction 1	44.89	0.85	105.55	73.47	3.97	18	39.62	52.69	14.59	7.94
4 - Correction 2	44.89	0.85	73.42	73.47	3.98	18	45.70	52.69	6.10	7.94
5 - Correction 3	44.89	0.85	84.47	73.47	3.88	18	45.70	52.69	6.42	7.94
6 - Correction 4	44.89	0.85	73.42	73.47	4.60	18	45.70	52.69	6.10	7.94
7 - Correction 5	44.89	0.85	70.37	73.47	4.72	18	45.70	52.69	6.02	7.94
8 - Correction 6	44.89	0.85	66.33	73.47	3.32	18	45.70	52.69	5.89	7.94

Key: Ap (m2) – Floor area in m2; RPH – Renovations per hour; Nic – Nominal energy needed for heating; Ni – Maximum value for nominal annual energy needed for heating; Ncv - Nominal energy needed for cooling; Nv - Maximum value for nominal annual energy needed for cooling; Nac – Nominal energy needed for sanitary hot water; Na – Maximum value for nominal energy needed for sanitary hot water; Ntc – Nominal overall primary energy needs; Nt – Maximum value for nominal overall primary energy;

5. Case study 2

Case study 2 involves a building due to undergo extensive rehabilitation and renovation work, maintaining the facade, floors, support structure and constructional system and only restoring the existing area by implementing thermal correction systems and a specific rearrangement of the interior divisions in order to improve comfort conditions. It was chosen because it is also very typical of the Baixa area of Coimbra, given the poor state of repair of the building and the need to preserve all its features.

5.1 Description of the building

The building stands in Rua da Moeda nº 60-64, Santa Cruz and was probably built at the end of the 19th century. The ground floor serves as a commercial establishment, whilst the 1st. 2nd. and 3rd. floors are residential (3 T3s – three-bedroom flats). In this test we studied the 1st. floor.

Figure 3: Photos / Study 2 localization

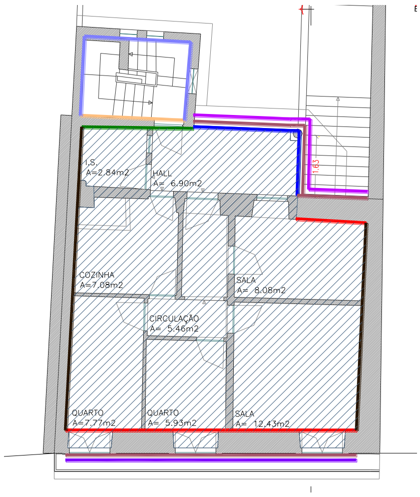

Figure 4: Study 2 target fraction

5.2 Study methodology

In order to assess the most suitable thermal intervention strategies that do not clash with the architectural style of the building, 17 tests were carried out involving the application of the new thermal regulations:

5.2.1 Test 1 – existing situation (starting point)

This test served to calculate the current thermal performance of the property, without introducing any thermal corrections.

Identification and characterisation of existing building solutions:

- Outer walls in soft limestone masonry (15 cm thick in the area below the windows and 60 cm thick in the remaining area), with traditional coatings on both sides (0,25*2).

- Dividing wall with adjacent building on the other side, in soft limestone (50 cm thick) with traditional coatings on both sides (0.25mm*2).

- Dividing wall with stairwell, in soft limestone (22 cm thick) and traditional coatings on both sides (0,25 mm*2).

- Floors – One-way wooden floor (0.35 m) and ventilation space, floor covering (0.03 cm) and wood lathing ceiling (0.02 cm);

- Frames:

  1- Glazing with wooden frames, two-pane windows, plain glass and night-time screening with low air permeability (entrance), south facing (1.10 m x 2.06 m);

  2- Glazing with wooden frames, four-pane windows, plain glass and night-time screening with low air permeability (entrance), north facing (2.66 m x 1.90 m);

  3 - Glazing with wooden frames, three-pane windows, plain glass and night-time screening with low air permeability (entrance), east facing (1.64 m x 1.90 m);

- Water heating system – gas heater (piped, no insulation);

This test also analysed the effects of installing three different water heating systems whilst the remaining features were maintained, in order to determine which was the most advantageous.

5.2.1.1 Existing Situation + Electric hot water storage heater (TAE)

5.2.1.2 Existing Situation + Gas hot water storage heater (TAG)

5.2.1.3 Existing Situation + Solar collectors (CS)

5.2.2 Test 2 – compliance with minimum requirements imposed by new thermal regulations (DL 80/2006)

In this test specific thermal corrections were introduced in order to comply with minimum regulatory requirements. Another correction was introduced: replacement of the water heating system by a more efficient one

5.2.2.1 Test 2.1 - Minimum requirements + Gas hot water storage heater (TAG)

5.2.3 Tests 3 and 4 – thermal correction 1 and 1.1

Tests 3 and 4 aimed to comply with the requirements stipulated in the thermal regulations by replacing the frames by more efficient ones, introducing specific corrections which did not significantly reduce indoor space, replacing the water heating system with an electric hot water storage heater with less than 50 mm of insulation and installing solar collectors in accordance with the Portuguese regulatory programme for analysis of the performance of solar energy systems (Solterm).

5.2.4 Tests 5, 6 and 7 – thermal corrections 2, 2.1 and 2.2

Tests 5, 6 and 7 aimed to comply with the thermal regulation requirements without replacing framing. Thermal corrections were therefore introduced involving the use of thicker insulation, replacing the existing water heating system with a gas hot water storage heater with 50 mm of thermal insulation and installing solar collectors in accordance with the Solterm programme.

5.2.5 Tests 8, 9, 10 and 11 – thermal corrections 3, 3.1, 3.2, 3.3

In tests 8, 9, 10 and 11 other more intrusive and wide-ranging thermal corrections were introduced in order to attempt to comply with (and exceed) the requirements stipulated in the thermal regulations by introducing various thermal corrections, replacing the water heating system with a gas hot water storage heater with at least 50 mm of thermal insulation and installing solar collectors in accordance with the Solterm programme.

5.2.6 Tests 12 and 13 – thermal corrections 4 and 4.1

The aim of tests 12 and 13 was to achieve maximum thermal performance and comfort in the property and exceed the requirements stipulated in the thermal regulations by introducing various thermal corrections, replacing the water heating system with a gas hot water storage heater with less than 50 mm of insulation and installing solar collectors in accordance with the Solterm programme.

Table 3 – Summary table with the carried out alterations.

Test	*Frame (glass)*	*Sealed doors*	*Ventilation grid*	*Walls 20 (isol)*	*Walls 65 (isol)*	*Staircase walls. (isol)*	*Walls separating from other. buildings (isol)*	*Floor slab 1 (isol))*
1, 1.1, 1.2, e 1.3	*Existing*	*No*	*No*	*Without*	*Without*	*Without*	*Without*	*Without*
2 e 2.1	*Existing*	*No*	*No*	*30mm*	*Without*	*30mm*	*Without*	*30mm**
3 - Correction 1	*Special double*	*No*	*No*	*60mm*	*Without*	*30mm*	*Without*	*60mm*
4 - Correction 1.1	*Special double*	*Yes*	*Yes*	*60mm*	*Without*	*30mm*	*Without*	*60mm*
5 - Correction 2	*Existing*	*Yes*	*Yes*	*30mm*	*30mm*	*30mm*	*Without*	*40mm*
6 - Correction 2.1	*Existing*	*Yes*	*Yes*	*40mm*	*40mm*	*40mm*	*Without*	*60mm*
7 - Correction 2.2	*Existing*	*Yes*	*Yes*	*60mm*	*60mm*	*60mm*	*60mm*	*60mm*
8 - Correction 3	*Existing*	*Yes*	*Yes*	*30mm*	*30mm*	*30mm*	*Without*	*30mm*
9 - Correction 3.1	*Double glass*	*Yes*	*Yes*	*30mm*	*30mm*	*30mm*	*Without*	*30mm*
10 - Correction 3.2	*Double glass*	*Yes*	*Yes*	*40mm*	*30mm*	*40mm*	*Without*	*60mm*
11 - Correction 3.3	*Double glass*	*Yes*	*Yes*	*60mm*	*30mm*	*60mm*	*Without*	*60mm*
12 - Correction 4	*Double glass*	*Yes*	*Yes*	*30mm*	*30mm*	*30mm*	*30mm*	*30mm*
13 - Correction 4.1	*Double glass*	*Yes*	*Yes*	*60mm*	*30mm*	*30mm*	*30mm*	*60mm*

*Only the flooring slabs above an unheated/ exterior area were insulated (excluding the part above the commercial establishment)

6. Results

Using a spreadsheet the thermal regulations were applied to the tests named before and the values for Nic, Nvc, Nac and Ntc in Kwh/m^2.year were calculated. The obtained results are presented in Table 4:

Table 4 – Obtained results from the calculation of the thermal regulation

Test	*Ap (m^2)*	*RPH*	*Nic*	*Ni*	*Nvc*	*Nv*	*Nac*	*Na*	*Ntc*	*Nt*
1 – existing	*61.12*	*1.00*	*135.04*	*72.90*	*1.18*	*18*	*125.02*	*77.40*	*14.68*	*11.27*
1.1 - exist.+TAE	*61.12*	*1.00*	*135.04*	*72.90*	*1.18*	*18*	*71.44*	*77.40*	*24.65*	*11.27*
1.2 - exist.+TAG	*61.12*	*1.00*	*135.04*	*72.90*	*1.18*	*18*	*76.94*	*77.40*	*10.54*	*11.27*
1.3 - exist.+CS	*61.12*	*1.00*	*135.04*	*72.90*	*1.18*	*18*	*69.56*	*77.40*	*9.91*	*11.27*
2 – Mín. Req.	*61.12*	*1.00*	*104.71*	*72.90*	*1.68*	*18*	*125.02*	*77.40*	*13.80*	*11.27*
2.1 – Mín. Req.+TAG	*61.12*	*1.00*	*104.71*	*72.90*	*1.68*	*18*	*76.94*	*77.40*	*9.67*	*11.27*
3 - Correction 1	*61.12*	*1.00*	*74.83*	*72.90*	*2.93*	*18*	*15.98*	*77.40*	*6.83*	*11.27*
4 - Correction 1.1	*61.12*	*0.85*	*70.18*	*72.90*	*3.49*	*18*	*15.98*	*77.40*	*6.70*	*11.27*
5 - Correction 2	*61.12*	*0.85*	*70.96*	*72.90*	*2.48*	*18*	*21.47*	*77.40*	*3.93*	*11.27*
6 - Correction 2.1	*61.12*	*0.85*	*65.80*	*72.90*	*2.75*	*18*	*21.47*	*77.40*	*3.78*	*11.27*
7 - Correction 2.2	*61.12*	*0.85*	*50.30*	*72.90*	*2.83*	*18*	*21.47*	*77.40*	*3.33*	*11.27*
8 - Correction 3	*61.12*	*0.85*	*73.56*	*72.90*	*2.33*	*18*	*21.47*	*77.40*	*4.00*	*11.27*
9 - Correction 3.1	*61.12*	*0.85*	*67.93*	*72.90*	*2.82*	*18*	*21.47*	*77.40*	*3.84*	*11.27*
10 - Correction 3.2	*61.12*	*0.85*	*61.13*	*72.90*	*3.31*	*18*	*21.47*	*77.40*	*3.65*	*11.27*
11 - Correction 3.3	*61.12*	*0.85*	*60.20*	*72.90*	*3.34*	*18*	*21.47*	*77.40*	*3.62*	*11.27*

Test	Ap (m^2)	RPH	Nic	Ni	Nvc	Nv	Nac	Na	Ntc	Nt
12 - Correction 4	61.12	0.85	57.54	72.90	2.82	18	21.47	77.40	3.54	11.27
13 - Correction 4.1	61.12	0.85	50.54	72.90	3.34	18	21.47	77.40	3.35	11.27

Key: Ap (m2) – Floor area in m^2; RPH – Renovations per hour; Nic – Nominal energy needed for heating; Ni – Maximum value for nominal annual energy needed for heating; Ncv - Nominal energy needed for cooling; Nv - Maximum value for nominal annual energy needed for cooling; Nac – Nominal energy needed for sanitary hot water; Na - Maximum value for nominal energy needed for sanitary hot water; Ntc – Nominal overall primary energy needs; Nt - Maximum value for nominal overall primary energy;

7. Discussion of results / conclusions

On the basis of the results of the 2 studies, the following conclusions may be drawn:

- The buildings which were tested have very low comfort levels, presenting high values for nominal energy needed for heating (Nic) and nominal energy needed for sanitary hot water (Nac);

- The existing properties and those renovated whilst maintaining the constructional system (Study 2) responded better, from a thermal, energy and environmental point of view, than the properties in which the facades and walls were maintained but the constructional system was altered (Study 1);

- The most advantageous water heating system is the one that uses gas as a source of energy, is the most cost effective and uses solar collectors as a support;

- It is possible for buildings in the historic centre of Coimbra to comply with thermal regulations by using various processes, methodologies and levels of intervention. Methods should be chosen on an individual case basis, in accordance with the budget available, the level of intervention required and the desired thermal and energy performance;

- Thermal correction which involves replacing frames by other, better-sealed ones with low emission double panes does not, in itself, meet the thermal regulation requirements. Moreover, if thermal correction is applied to the surrounding walls, floors and coverings whilst preserving the frames, it is possible to comply with these requirements;

- The installation of ventilation grids with self-regulating openings is a very important corrective measure, as it controls damp, prevents condensation and the appearance of pathologies, and reduces overall energy needs (Ntc) and heating needs (Nic) and, although the values for cooling needs (Nvc) rose, they were still insignificant in terms of the values stipulated in the thermal regulations;

- From a comparison and analysis of the base values and those resulting from the corrections that were introduced it may be concluded that, if care is taken, light intervention introducing improvements within the range of restrictions affecting comfort and energy consumption can produce good results from a thermal point of view and a considerable reduction in consumption;

- The alterations introduced in order to comply with minimum requirements fell considerably short of thermal regulation requirements;

- •The inertia of the properties remained high even when thermal correction was applied to the inside of all the exterior walls;

- It is difficult to make value judgements on which of the tests were most advantageous, although the most balanced studies in terms of cost effectiveness appear to be Test 4 (Study 1) and Test 6 (Study 2), if the intention is not to replace the frames. If a higher level of intervention is intended, Test 9 (Study 1) and Test 11 (Study 2) are best.

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Experimental and Numerical Investigation of Thermal Energy Storage in Natural Stone Treated with PCMs

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Abstract

Improving energy efficiency in buildings is a matter of concern nowadays, since it can essentially contribute to reducing both CO_2 emissions and global energy demand. Towards this direction, the use of Phase Change Materials (PCM) is promoted, as an energy storage solution in the building sector. The application of PCMs in building elements such as wall layers made of concrete, gypsum or plasterboard panels helps in stabilizing abrupt variations of room temperatures within the human comfort zone throughout the day, leading to the reduction of energy demand in buildings. In this work, the potential of PCM treated natural stone to be used as construction material with the ability to store thermal energy, is investigated. At first, and in order to experimentally demonstrate the effectiveness of this concept, a number of “model” pilot stations made of concrete and “Bateig azul”, a Spanish natural stone (with and without PCM) for the façade, have been built and placed outdoors. Temperature measurements were obtained in the interior of the pilot houses for several day – night cycles. Secondly, two simulation models have been developed and are presented, based on MATLAB – Simulink and on the heat transfer analysis computational tool TRNSYS. Their performance is evaluated with respect to the aforementioned measurements. It is shown that a good agreement between computational results and experimental data can be achieved and discussion is mainly focused on (a) the PCM influence, when added to the natural stone façade and (b) the possibility of exploiting the advantages of both implemented models as a future task, by developing an efficient coupled solver combining the TRNSYS platform for the simulation of complex building structures and the MATLAB – Simulink for the prediction of thermal behaviour at a component level. This part of the study is classified under the framework of developing dedicated computational models with the

ability to accurately predict composite wall materials - components thermal behaviour and thus support potential energy saving studies in buildings.

Keywords: phase change materials (PCM), MATLAB - Simulink, TRNSYS

1. Introduction

It is well known that the building sector is responsible for more than 40% of the total EU energy consumption. Thus, it represents today the highest potential in terms of energy savings. Many European studies carried out have assessed the impact of energy saving in the building sector. It has been proven that, by saving 20% of energy consumption, it would be possible to secure 50% of the necessary reductions of CO2 emissions and to save up to 60 billion Euros every year on the energy bill (Green Paper on energy efficiency, 2005)

Specifically, buildings smaller than 1000 m^2 represent 90% of the potential energy, CO_2 and cost savings in the residential sector (EURIMA). Extension of the Directive on the Energy Performance of Buildings to these residential buildings would enable to:

- Save up to 270 billion EURO a year in energy costs at current energy prices,
- Reduce energy use by the equivalent of 3.3 million barrels of oil a day (compared to 6 today),
- Reduce CO_2 emissions of 460 Million tonnes a year by 2032.

Improving energy efficiency in the building sector can drastically contribute to reducing CO2 emissions and EU energy dependence. Significant efforts are currently made to promote the introduction of new technologies around improved materials (such as insulation, glazing, energy storage through phase change materials) that can find direct application in “energy efficient buildings” such as dwellings, offices, hospitals, schools, factories, airports, rail stations, public buildings, for new and retrofitted buildings and retrofitting Cultural Heritage.

Towards this direction, a demo house in Amphilochia, Greece is being built within the frame of the EU-NMP funded projects I-SSB and MESSIB, where innovative elements will be integrated with conventional technologies, RES, and building architecture. Multi-source energy storage systems such as phase change materials for improved active components and ground storage will be installed, monitored and evaluated in the building. The present study can be classified under the framework of developing new dedicated simulation tools for the integrated simulation of a building. These tools will support the construction process of the building and will aid in optimizing its operational parameters. They must consist of discrete reliable computational models, with the ability of accurately predicting the individual phenomena, associated with the technologies that will be integrated in the design of the building. The objective is to achieve maximum performance of the systems and the successful introduction of energy efficient technologies in building under an integral approach.

2. Phase change materials and energy saving

In building applications, PCMs can be used to control internal temperatures. PCMs have a characteristic melting point. When temperatures become warmer, the PCM is liquefied by absorbing and storing heat, leading to the cooling of the house. Conversely, when the temperature decreases and becomes cooler than the PCM's characteristic melting point, the material solidifies and the previously absorbed heat (latent heat) is subsequently released, leading to the warming of the house. By incorporating PCM in the building envelope, they can absorb heat due to the higher exterior temperatures during the day, and dissipate the heat to the interior at night when it is cooler. This absorption and release of heat takes place at a constant temperature, which is ideal to smooth temperature fluctuations. Several building materials exhibit a low heat capacity. Introduction of phase change materials into the building materials will considerably increase the thermal mass of the building.

Properties of PCM that are desirable for residential use include:

- A melting temperature above 25°C,
- low cost material,
- not toxic, corrosive, or hydroscopic, and
- Commercially available in sufficient quantities for producers to incorporate into ordinary building materials.

The addition of PCM in construction materials such as concrete, gypsum or plasterboard panels is promoted, as an energy storage solution to reduce energy demands in buildings. In this work, computational models are built in order to simulate a system for thermal energy storage with walls of natural stone treated with PCM. The computational results are validated against experimental results. The viability of natural stone as a system for thermal energy storage is considered of great importance due to their aesthetic value and their versatile applications in facades, walls, floors, etc.

The use of Phase Change Materials (PCMs) for energy storage purposes in buildings has been proposed since the first applications in the 1940s. However, in the last two decades it has become an object of increasing interest. Several review papers can be found in the literature, providing a thorough analysis on the main characteristics of PCMs and presenting the latest developments in their application for buildings heating and cooling. Zalba *et al.* (2003) have reviewed the history of energy of thermal energy storage with solid – liquid phase change, depicting the materials that have been used as PCMs, focusing on their applications and elaborating on the numerical solution of heat transfer phenomena, occurring in energy storage systems associated with phase change. Farid *et al.*, (2004) have also presented a review of PCM implementation, focusing on their encapsulation, summarizing their applications in buildings and reporting on all the recent technological innovations, that are associated with PCMs. Tyagi and Buddhi (2005), have examined the thermal performance of various PCM systems to evaluate their potential for use in buildings heating and cooling. Other references demonstrating the use of PCMs to improve thermal properties of construction materials, such as concrete or gypsum, can also be found in the literature. Hawes (1990) has studied the thermal performance of PCMs in different types of concrete blocks. Thermal storage in concrete containing PCMs was increased more than 200%. Salyer *et al.*, (1995) have developed different methods of PCM incorporation to building blocks: by imbibing the PCM into porous materials, PCM absorption into silica or incorporation of PCMs to polymeric carriers.

Natural stones are commonly used for external façades and internal (floors, walls etc) building applications. The use of PCMs for the treatment of natural stone in order to improve its thermal properties is proposed for several reasons:

- Energy savings in heating/cooling systems;
- Enhancement of thermal comfort inside the building (reduction of temperature differences between day and night and different rooms inside the building);
- Storage of the heat from outdoors; Avoid excessive heat from outdoors.
- Protection of the natural stone in extreme climatic variations

3. Experimental work

3.1 The pilot stations

In order to demonstrate the effectiveness of PCM treated natural stones, a number of pilot stations made out of concrete and The Spanish marble “Bateig azul”(with and without PCM) for the façade have been built and placed outdoors, in Alicante - Spain (Figure 1). The pilot house model has been selected as a simplified, standard case, fitting for the demonstration of the PCM influence in natural stones.

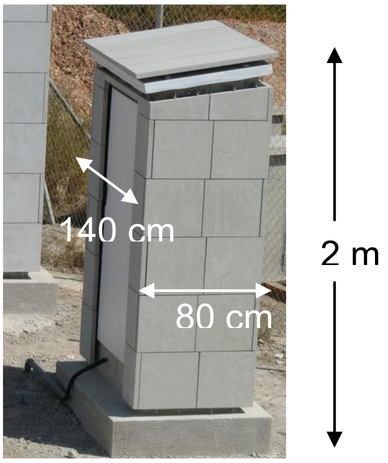

Figure 1: Pilot station made of concrete and Bateig Azul as natural stone for the façade.

Temperature sensors have been placed inside and outside the pilot stations, measuring both ambient and interior temperature for several day-night cycle every 10min. In this work, the period of measurements used for computational simulation is from the 2nd to the 3rd of September 2008.

The measurements show a reduction of temperature variations during the monitored time period, when natural stone is treated with PCM. Hence, an improvement in human comfort and a reduction of energy consumption can be anticipated. (Romero-Sánchez, *et al* 2009).

3.2 Materials

Bateig azul has been selected in order to study the thermal storage properties of natural stone materials after PCM treatment. This material is extracted in Novelda-Alicante-Spain. It is blue and consists of calcite and quartz, with medium porosity size.

The Micronal DS 5000X (provided by BASF) has been selected as the phase change material. It is a water-based solution with following characteristics: viscosity equal to 30-100 mPa·s, solid content of 1-43% and melting temperature ca. 26ºC.

Bateig azul has been immersed in this solution in order to be impregnated with the PCM. The measured thermal conductivity and volumetric thermal capacity of Bateig azul and Bateig azul with PCM are shown in Table 1.

Table 1: Thermal properties of Bateig azul and Bateig azul with PCM.

	Thermal conductivity (W/m·K)	*Volumetric thermal capacity (kJ/m3·K)*
Bateig azul	*1.87*	*2191.7*
Bateig azul -PCM	*1.99*	*2308.7*

The pilot stations have been made of concrete, while Bateig azul (with and without PCM) has been used as façade. The west side of the pilot station is a door. The properties of the materials for the door and the wall layers are shown in table 2.

Table 2: Thermal properties of wall layers and door

	Thermal conductivity (kJ/h·m·K)	*Density (kg/m3)*	*Thermal capacity (kJ/kg·K)*	*Thickness (cm)*
Concrete (wall)	*7.56*	*2400*	*0.8*	*7*
Polyspan Insulation (door)	*0.14*	*10*	*1.40*	*1*
Metal Sheet (door)	*720*	*2700*	*0.86*	*0.2*
PVC Coating (door)	*0.83*	*1500*	*1*	*1*

4. Computational models

4.1 Building a model in matlab – simulink

A simple model has been developed in MATLAB – Simulink for the simulation of the pilot houses. At this stage of the study, a simple case of natural stone without PCM has been considered for the façade. Heat balances taking into account conduction and convection effects are formed for two wall layers (concrete – natural stone), three door sheets (Polyspan – Metal – PVC), the air gap and the pilot stations internal space. Hence, the resulting model contains 7 ordinary differential equations calculating temperature distributions over time and can be written as:

$$\begin{cases} \dot{x}(t) = A * x(t) + B * u(t) \\ y(t) = C * x(t) \end{cases}$$

The u(t) vector is related to the model input, which in this particular case is the measured ambient temperature. The output y(t) vector corresponds to the pilot houses internal room.

The geometry characteristics and thermal properties of the simulated case, as well as the resulting system of energy balances are incorporated in a specific m – file which has subsequently been linked to the Simulink model (Figure 2).

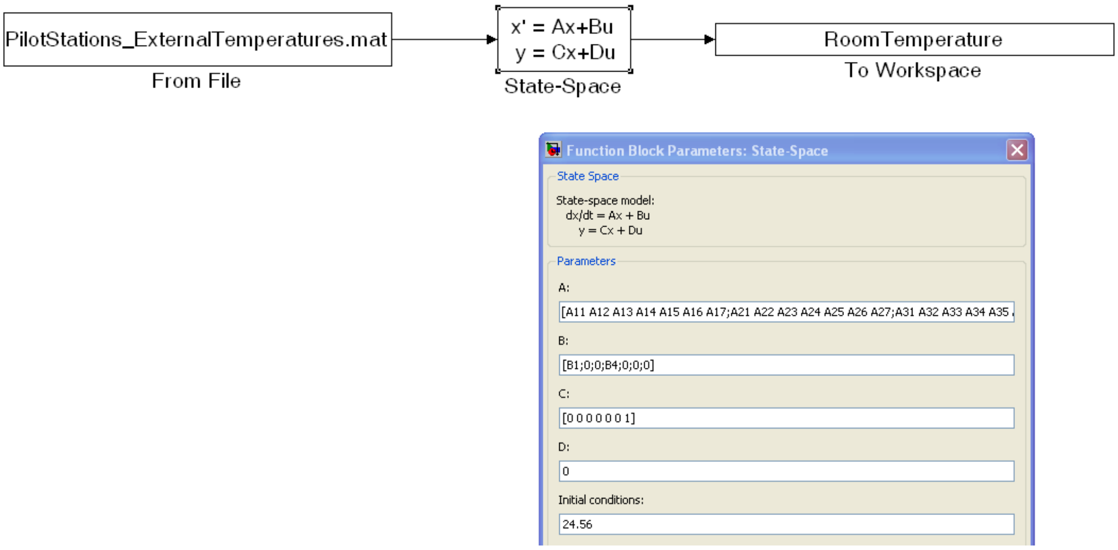

Figure 2: Model scheme by Simulink

4.2 Building a model in TRNSYS

The second model is built using TRNSYS software (TRNSYS). TRNSYS is a complete and extensible simulation program for the transient simulation of systems, including one-zone or multi-zone buildings. The systems are considered to be a set of components linked together to provide the results. Each component is called "Type" and Type 56 is the component which defines a building with different thermal zones. This Type solves a set of differential equations to compute the energy balance of each thermal zone (Ahmad *et al.*, 2005)

Among the components available in TRNSYS, walls of different materials can be chosen. A new wall component (Type 204) was added to TRNSYS to simulate the PCM wall. It was created by a team at Helsinki University, in which the heat equation is solved in 3D for PCM in various phases: solid, liquid or two-phase (Jokisalo *et al.*, 2000).

The pilot stations are modelled as one-zone building, using the properties of the materials given in TRNSYS library. The properties of the Bateig Azul containing PCM are used for Type 204. The pilot stations are located outdoors and are subjected to the local climatic variations. The weather file for Valencia - Spain is used. The file has been altered, in order to include the measured temperatures of 2^{nd} and 3^{rd} of September. The simulation is for three months, but only the results of those specific dates are evaluated. Ground temperature is considered constant.

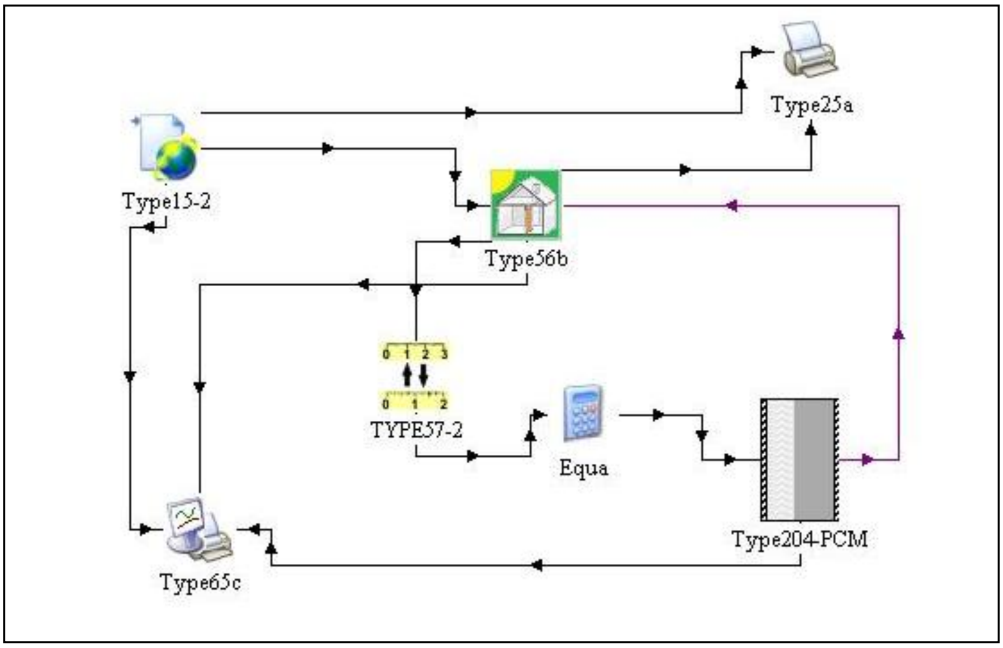

Figure 3: Diagram of the PCM wall simulation showing the links between the components in TRNSYS

Two simulation cases are considered: one pilot station without PCM and one with PCM. The results are then combined and compared to the experimental data. Type 204 is used to simulate the PCM case and takes into account the specific heat capacity (kJ/kg) and the density of the PCM, its melting point and the density and thermal capacity of the other material in the wall layer.

5. Results and discussion

The developed MATLAB – Simulink model has been incorporated for the simulation of the pilot houses thermal behavior during a two – day cycle, between the 2nd and 3rd of September. A simple case without PCM has been considered. Computational results show that the pilot house internal temperatures follow reasonably well the excremental data (Figure 4). However, it should be noted that the temperature distribution tends to be slightly over predicted by the implemented model. Further improvements are expected with the implementation of the ground temperature effect in the model. Additionally, ongoing and future work will focus on the extension of the existing model to take into account possible PCM effects in structural components.

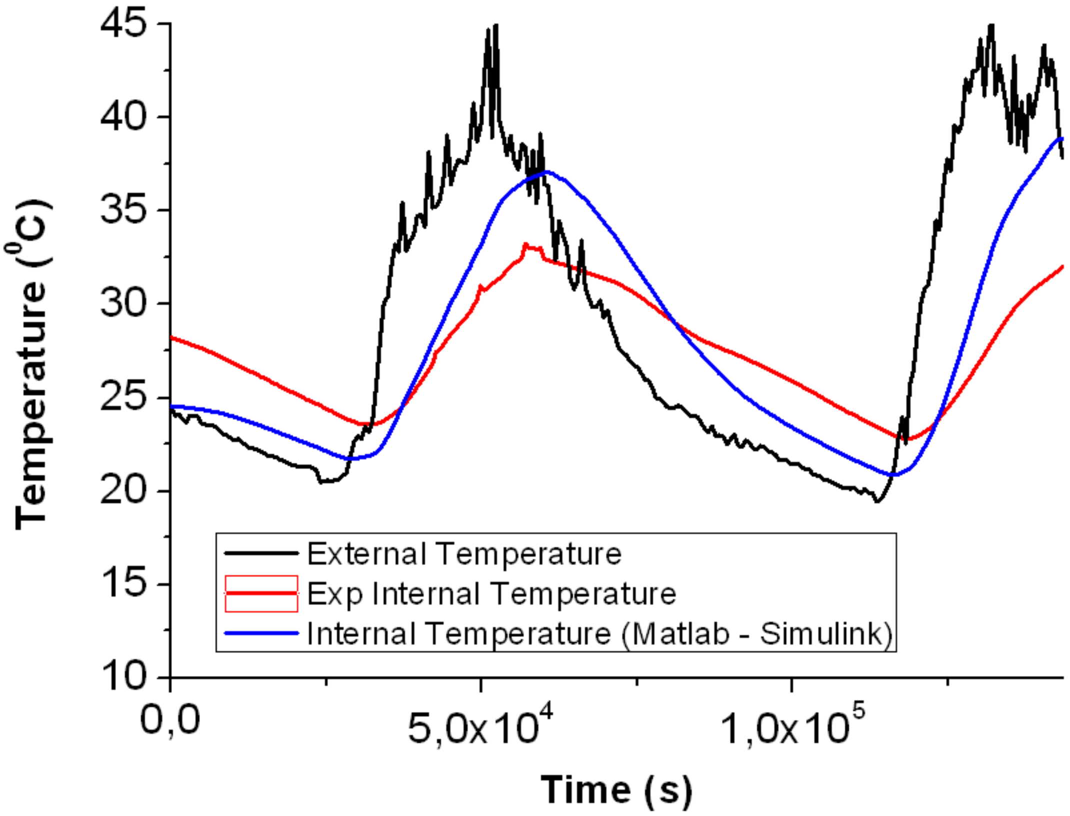

Figure 4: Temperature measurements and Matlab / Simulink model computational results – No PCM case

Fig.5 presents the internal room temperature of both pilot stations (without and with PCM) given by the numerical simulation using TRNSYS for the 2nd of September, compared with measurements for the same day.

Measurements demonstrate that a small but noticeable difference is developed in internal temperatures when the pilot station case without the PCM is compared to the respective case of the PCM façade. The maximum recorded temperature in the PCM treated station is 1.2^{0}C lower than the respective maximum value of the station without PCM, demonstrating, at pilot scale, the application's energy storage potentials. The cooling process is smoother for the pilot station with PCM, indicating that the stored energy is being released. Minimum temperature in the PCM treated station is 0.6 ^{0}C higher compared to the station without PCM. It should be noted though that maximum recorded temperatures do not occur at the same time points as in the reference station and a small shift of approximately 2 hours is observed.

An overall good agreement is found between simulation and measurements. However, some discrepancies are evident, with computational results exhibiting a tendency to under predict the measured temperatures. These discrepancies can be attributed to the following factors: (a) the ground temperature is considered to be constant throughout the simulated cycle, (b) the inability to import the temperature variation curve of the utilized PCM's specific heat capacity (Cp) in TRNSYS. Thus a constant Cp value for the PCM wall has been considered and (c) assumptions made in the pilot house walls and door sheets material properties.

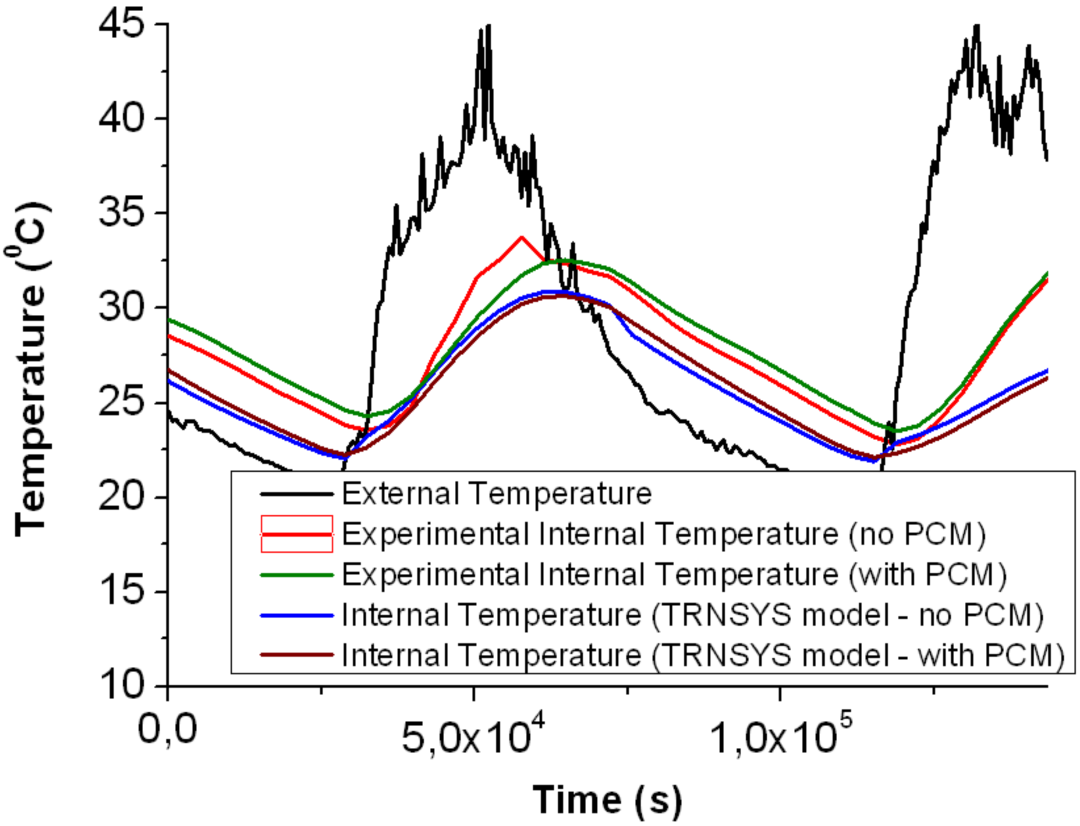

Figure 5: Temperature measurements and TRNSYS model computational results (no PCM / with PCM Cases)

The obtained results and above arguments support the development of a flexible and adjustable, coupled computational tool in a composite approach, which will be characterized by the merging of the two different computational models that have been developed in this study. Hence, the MATLAB – Simulink model will be merged with the TRNSYS software, in order to develop an efficient solver combining the advantages of both implemented components, depending on the specifications and complexities of the examined case. Consequently, the TRNSYS platform will be incorporated, in order to provide detailed information for complex building geometries and accurate predictions of HVAC systems characteristics. On the other hand and during the same simulation, MATLAB – Simulink model will be called by the TRNSYS platform, focusing on the calculation of possible thermal effects associated with PCM incorporation in structural components. Evidently, the combined computational tool will consist of two interacting parts. The first one (TRNSYS platform) will provide useful information on the thermal behaviour of buildings. The second one (MATLAB – Simulink) will concentrate on the accurate prediction of thermal characteristics at a component level.

6. Conclusions

In the present work, the thermal behaviour of two “model” pilot stations of natural stone and concrete, one of which contained phase change material in the natural stone has been experimentally and numerically investigated. The pilot houses have been selected as a simplified, standard case aiming to: (a) highlight the PCM influence when implemented in structural components and (b) be used for the validation of the developed computational tools.

Temperature sensors have been appropriately placed inside the stations, allowing the characterization of their thermal behaviour. Variations of temperature in different spots inside the “model” pilot stations have been monitored every 10 min for several day-night cycles. The resulting measurements demonstrate a reduction of temperature variations during the monitored period of time, when natural stone is treated with PCM. Hence, an improvement in human comfort and a reduction of energy consumption can be anticipated.

Two computational models have been implemented for the simulation of the model pilot houses. A MATLAB – Simulink model has been developed to calculate the energy balances defining the thermal behaviour of the pilot house without PCM. In TRNSYS, a new Type (204) has been implemented and properly modified, allowing for the simulation of the PCM wall. The predictive capabilities of both incorporated models have been assessed by comparing computational results with the aforementioned temperature measurements. In both cases, computational results show an overall satisfactory agreement with the respective measurements, however improvements are still needed.

Future work will focus on the development of an integrated computational tool merging both MATLAB – Simulink and TRNSYS models. The coupled solver will be implemented for the simulation of a demo house in Amphilochia - Greece where innovative elements will be integrated with conventional technologies, RES, and building architecture. The coupled solver will be able to simultaneously use the TRNSYS platform for the simulation of complex building geometries associated with sophisticated HVAC systems and the MATLAB – Simulink tool for the accurate prediction of thermal characteristics at a component level, when PCM are incorporated.

Acknowledgement

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Upscaling Energy Related Innovations

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Abstract

Awareness that fundamental change is necessary regarding our CO_2 output as society has never been higher, as is reflected by results of IPCC, IEA and UFCCC. Governments, as well as local municipalities, are formulating targets in order to diminish energy usage and/or CO_2 emissions. Since 40% of energy usage is related to the built environment, it is an area where important contributions are made and should be made. To be able to achieve the ambitions of major CO_2 reductions the EU has set, energy efficient innovations and concepts need upscaling. In this paper an inventory was made of the possibilities to influence the process of upscaling, as perceived by actors experienced with complex energy related innovations. This consists of an overview of the possibilities of different commercial parties in the building industry and professional clients. In a parallel study possibilities were studied of governmental actors, who are able to define policy instruments. This multi-faceted approach was chosen to reflect on ways to stimulate upscaling, in which the activities of all parties should be included. The inventory presented in this paper is made in relation to energy efficient building concepts, both reducing the total amount of energy used and replacing fossil energy with sustainable energy sources. This topic is chosen due to its urgency and its complexity. Several measures and products have to function together in an integrated approach in order to reach the performance levels required. The research method was a combination of desk research, test sessions and interviews. From this study conclusions will be drawn on the possibilities different parties have for stimulating upscaling energy efficient concepts. Finally some reflections on the results will be added.

Keywords: upscaling, energy, transition management, innovation management

1 Introduction

Important parties and organisations worldwide are underlining the urgency to prevent further increase of CO_2 levels in our atmosphere, in order to prevent global warming (e.g. IPCC 2007, IEA 2008, UNFCCC 2002) and its dramatic consequences. In correspondence with these outlines, other parties and organisations formulated ambitious goals to reduce the use of fossil energy in the built environment (e.g. WBCSD 2004, 2005, 2007, NSTC 2008). The EU aims at an energy neutral built environment in 2040. To fulfil these goals there is an acceleration needed in the process of bringing energy efficient innovations in construction in the phase of full implementation. The built environment contributes about 40% to the emmisions of CO_2, produced especially by operating the older buildings in the existing building stock (WBCSD 2004).

In the construction sector a lot of products and technologies were developed in the last 40 years with the goal to improve the energy efficiency of the built environment. Examples of these innovations are heat pumps in combination with aquifers, geothermal heath, insulation, solar thermal combinations, the application of PV cells on buildings etc. To reach ambitious levels of energy reduction these innovations should be applied in combination with each other. This makes the process of implementation of these innovations complex. At the moment these innovations are applied in demonstration projects and small scale projects. The application on a large scale lags behind expectation, as are activities that complement these new techniques in order to turn them into mainstream business practices. This context of the implementation of these kinds of innovations is the focus for this research because of its urgency and its complexity.

The process in which broad implementation of an innovation is achieved, is called upscaling. In this process the innovation evolves from a niche solution towards a mainstream solution. This means all parties have to become familiar with the benefits of the innovation and have to develop know how on its use and application. In general this leads towards a change of competences and habits of people involved. It also means that all infrastructure has to be put in place and all institutions have to be aligned for mainstream application.

The process of upscaling is known to require long periods of time, taking at least several decades (Bosch 2009). This is especially true for more complex and rigorous innovations, since these types of innovation demand drastic change on several aspects. An example of such an innovation is the alteration of the building production from handy craft towards industrialisation, in which building components will be machine produced. This way of working has influenced the entire value chain in the construction sector. New (combinations of) building materials were used, the organisation of the work was altered (specialisation of activities), production activities relocated from production on site, to production off site in the factory and the knowledge and skills needed by professionals changed accordingly. The upscaling of this new way of working was a process in which a lot of parties were and are still involved. After WW II industrialisation in construction was stimulated with special programs by different governments in order to rebuild the building stock deteriorated during the war (e.g. the Netherlands and Sweden). In this case the process has taken more than several decades. One could easily argue this process of upscaling is still evolving (e.g. see development as described in Girmscheid 2010).

For the innovations we are discussing in this paper we expect even more difficulties in the process of becoming mainstream. The activities needed to overcome the barriers for upscaling towards zero energy building are more difficult to overcome by the parties from the building sector without support from the policymakers, since they are meant to serve society as a whole, with some possible direct benefits for end-users. The market cannot be expected to act automatically in line with this apparent need from society as a whole. Policy making and regulations are therefore necessary ingredients in order to be able to achieve the required goal.

Before we go on, we want to stress that the process of upscaling of innovation is not a smooth and easy process. It is more like a bumpy road with a lot of roadblocks and unexpected holes. A lot of innovations never reach their destination over this bumpy road. It is therefore risky and you cannot guarantee the outcomes when influencing these processes. Innovation processes in the building sector are known to be difficult as it is. Due to fragmentation of the sector, strong regulation, extreme focus on price these processes are even more difficult than in other sectors. In paragraph 3.1 we give an overview of the barriers that can be found for the construction sector.

To better understand the mechanisms that influence the process of upscaling we use the concept of innovation systems. An innovation system is the combination of actors, institutions and infrastructures that interact and shape the conditions for innovations to develop. The dynamics of an innovation system can be understand by analyzing the different functions of the innovation system as defined by Hekkert and others (e.g. Hekkert 2008, Suurs 2009)

In this paper an inventory was made of the possibilities actors in the building industry perceive to have for influencing the process of upscaling. This includes an overview of the possibilities as perceived by the different commercial parties and professional clients, as addressed in this paper. In a parallel study possibilities are studied of governmental actors, who are able to define policy instruments. This approach was chosen while in order to realise upscaling the activities of all parties should be included.

The inventory in this paper is made in relation to energy efficient building concepts, both reducing the total amount of energy used and replacing fossil energy with sustainable energy sources. In this study parties involved in the application of concepts, like passive house were regarded. This is a concept in which the consumption of fossil energy is dramatically decreased towards a level of annual heating requirement that is less than 15 kWh/(m^{2}a) (4755 Btu/ft^2/yr), not to be attained at the cost of an increase in use of energy for other purposes (e.g., electricity). Furthermore, the combined primary energy consumption of living area of a European passive house may not exceed 120 kWh/(m^{2}a) (38039 Btu/ft^2/yr) for heat, hot water and household electricity (www.passiv.de, Feist 1993). Concepts like passive house are seen as important steps towards a built environment which is energy neutral. There have been some discussions about the definition of zero energy buildings and their impact (Torcellini 2006a, 2006b, Rovers 2008). For this study parties with experience with passive house projects and other complex energy concepts were interviewed. The innovation level of these projects had to require multiple measures, for example insulation in combination with improved air tightness, controlled ventilation, low temperature heating, heat pump, etc. Multiparty involvement on design and realisation was another criteria as well as a high impact on energy reduction, with a minimum of a

40% reduction of fossil energy consumption. Concepts in line with these criteria will be referred to as energy efficient concepts.

This criterium for energy efficient concepts ensured that parties who were interviewed had been involved in ambitious projects in which the problems accumulate that need to be solved to make a breakthrough in energy efficient building. The parties in the value chain should cooperate in order to achieve these ambitions. The current status in the Netherlands is that in some area's one pilot house is built or pilot projects are realised with a maximum of dozens of houses. The amount is growing, but it is still at an early stage of upscaling.

1.1 Research question and method

The central research question for this paper is as follows: What opportunities do parties in construction have to upscale the energy efficient building concepts in the Dutch context?

Sub questions in this research were:

- What barriers are there to up-scale innovations related to energy efficient building concepts?
- What roles do different parties in construction see for themselves and which of those do they take on already?
- What opportunities are still left to influence further implementation by other parties in the perception of the interviewees?
- What can we conclude on the opportunities of parties to influence the up-scaling of energy efficient building concepts in general in the Netherlands?

The research method was a combination of desk research, test sessions and interviews. The desk research was carried out in order to construct a theoretical framework to investigate up-scaling and determine barriers to innovation in construction already collected in other studies. The theoretical framework was tested in two sessions with project leaders of complex innovation processes (Oostra 2008). Furthermore, during the summer and early authum of 2009, different actors in the field were interviewed about the interventions they make to forward the energy efficient concepts. They were asked as well what possibilities they saw for other actors to intervene and finally what barriers they encountered.

The reason to limit the implications for this study in this paper to the Netherlands, is the fact that context in the different countries will differ due to differences in policies, even if they respond to similar preconditions as formulated by the European Committee in order to reduce fossil energy consumption in the built environment. More research will be necessary to validate the results for other countries.

2 Theoretical framework

In principle, all parties involved in construction have their own possibilities to influence up-scaling. A general model was developed which can be used for different actors. This model is used as way to reflect with project leaders on up-scaling (Coenen 2008). The model also served as a basis to develop the main steps to design a new policy strategy, which are shown the figure below (figure 1).

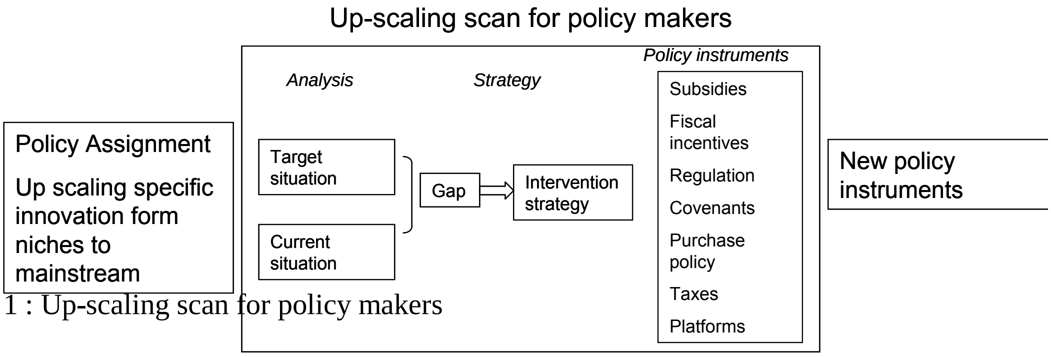

Figure 1 : Up-scaling scan for policy makers

As was argued in the introduction, the concept of innovation system was used for the purpose of analysing the drivers and barriers for up-scaling of innovations. Different frameworks were used to execute this analysis. The first is the System Innovation Policy Framework (Freeman 1995). Klein Woolthuis (e.g. Klein Woolthuis 2005) developed it to analyse the different elements of the framework, as well as to compare the elements in the current situation with the goal situation. For the purpose of this paper the goal situation is the situation in which the innovation is scaled up. The System Innovation Policy Framework distinguishes between the following elements: infrastructure, institutions, interactions, capabilities and market structure.

Infrastructure	Physical infrastructure, products
Institutions	Hard (laws, regulation) and soft (norms, values, implicit rules of the game)
Interactions	To strong or to weak interactions
Capabilities	Entrepreneurship, adequate labour qualifications and the like
Market structure	The way the market is structured and organised

By systematically analysing the different elements a clear view will emerge as to what barriers remain for upscaling.

In order to include the current dynamics of the innovation system, the System Innovation Policy Framework was combined with the functions of innovation systems as developed by Hekkert and others (e.g. Hekkert 2008, Suurs 2009). The functions used in the analysis were the following:

Table 1: Functions of technological innovation systems.

System Function	**Description**	**Event types associated**
F1. *Entrepreneurial Activities*	The role of the entrepreneur is to translate knowledge into business opportunities, and eventually innovations. The entrepreneur does this by performing market-oriented experiments that establish change, both to the emerging technology and to the institutions that surround it.	Projects with a commercial aim, demonstrations, portfolio expansions
F2. *Knowledge Development*	This function involves learning activities, mostly on the emerging technology, but also on markets, networks, users etc. Learning activities relate to both learning-by-searching and learning-by-doing. The former concerns R&D activities, whereas the latter involves learning in a practical context.	Studies, laboratory trials, pilots
F3. *Knowledge Diffusion*	Innovations occur most where actors of different backgrounds interact. A special form of interactive learning is learning-by-using, which involves learning activities based on the experience of users.	Conferences, workshops, alliances
F4. *Guidance of the Search*	This function refers to the activities that shape the needs, requirements and expectations of actors with respect to their (further) support of the emerging technology.	Expectations, promises, policy targets, standards, research outcomes
F5. *Market Formation*	Emerging technologies cannot be expected to compete with incumbent technologies. To support innovation, it is usually necessary to create artificial markets. This involves activities that contribute to the creation of a demand for the emerging technology.	Market regulations, tax exemptions
F6. *Resource Mobilisation*	This function refers to the allocation of financial, material and human capital. The access to such capital factors is necessary for all TIS developments.	Subsidies, investments
F7. *Support from Advocacy Coalitions*	The rise of an emerging technology often leads to resistance from actors with interests in the incumbent energy system. In order for a TIS to develop, other actors must counteract this inertia. This can be done by urging authorities to reorganise the institutional configuration of the TIS.	Lobbies, advice

The functions of innovation systems were used to plot the activities that are taking place in the innovation system with the purpose to implement energy efficient concepts. The functions were also used to categorise the activities mentioned in the interviews. This analysis formed the basis to make an inventory of the strategic gap for upscaling energy efficient concepts.

3 Results

In this section results from theory will be combined with results from the interviews in order to identify barriers for upscaling.

3.1 Barriers for innovation from the literature

There have been quite a few studies on barriers to innovation in construction in general. These barriers appear to be valid for energy efficient concepts as well. Kulatunga ea (2006) have made an inventory on the barriers described in construction innovation literature:

- Fragmentation of the industry (Pries and Janzen 1995) and professional bodies (Winch 1998).
- Isolation and distance between contractors and consultants (Gann 2000).
- Significant coordination and integration problems due to extreme specialisation of functions and/or involvement of various professions (Nam and Tatum 1997).
- Risk aversion due to the long life span of the construction products (Blayse and Manley 2004, Nam and Tatum 1997).
- Opportunities to be innovative are restricted due to technical regulations (Blayse and Manley 2004; Veshosky, 1998). Pries (1995, p: 45) Bowle (1960, cited in Ling, 2003)
- Undue emphasis on cost-cutting measures, economic recession and lowest bidding practice that impeded the actual ability of parties to innovate. (Dulaimi 2005, Veshosky 1998)
- Innovation goes against organisational and industry culture (Veshosky 1998)

3.2 Analysis structure of the innovation system

The first step in our analysis was to clearify the goals to be set for the different system characteristics in order to reach the upscaling of energy efficient concepts. In the interviews with representatives from the building sector we discussed what the goals should be. Interviewed were people from a service provider, a builder, a project developer, a producer of insulation, a producer of heat pumps, a trade organisation of professional clients and an advisor on sustainable buildings. The people chosen were front runners and all had experience with Passive House or other energy efficient concepts.

The results were combined with the results from two workshops with project teams to systematically analyze what possibilities parties have to influence energy efficient innovations (Oostra 2008).

Table 2: overview of the strategic goals to overcome the barriers and develop opportunities for upscaling

System Characteristic	Strategic Goals
Infrastructure	1. Products developments (plug & play, user-friendly, total solutions, 'killer'add-ons, product-service combinations) 2. intelligent energy net suitable for connecting sustainable solutions 3. solid knowledge base in the value chain 4. production and distribution facilities
Institutions	5. Consistent and reliable policy 6. Policy on total costs for housing in stead of rent + energy costs 7. Policy for market creation in the current building sector (regulation, financial incentives) 8. Process of user acceptance (awareness, knowledge, interest, transparency of the costs, risk reduction) 9. Reframing of current framework and habits (transforming the current idea fossil energy is an endless source)
Interactions	10. User participation in building processes 11. Cooperation across the value chain 12. Familiarize people with possibilities and usage (fairs, model homes) 13. Learning sector and society (a problem with an innovation does not legitimise political action to kill it)
Capabilities	14. Combination of technological skills with organisational and commercial skills across the value chain 15. Developing from production sector towards service oriented sector
Market structure	16. Market creation by setting targeting ambitious targets for new buildings 17. Market creation for current building (taxes, etc) 18. Financial constructions to solve current split incentives (split between investor and benefits for end-user, un-balance between investment costs and return on investment, split between budgets for initial investment costs and maintenance & operation costs)

As indicated earlier, the theory of the functions of the innovation system was used as a framework to generate an overview of the current situation of the innovation system and its dynamics. An inventory was made of the activities that already take place in the innovation system. All sorts of activities have been initiated to develop the different functions. As a result there are different energy efficient concepts emerging in Dutch construction. Parties are organizing themselves around concepts (e.g. passivehouse.nl), and value chains (e.g. E.nu). A lot of effort from front runners is being put in disseminating information towards potential clients (e.g. websites, trade markets) and value chain partners. On the other hand governement is trying to stimulate initiatives with special programs (e.g. PeGO, EOS), subsidies (e.g. SDE) and tax measures (e.g. insulation). The inventory of activities is step one in the gap analysis. A general overview of the results can be found in table 4 in the appendix.

3.3 Possibilities of parties to accelerate upscaling

Representatives of the different parties in construction were also interviewed to make an inventory of the possibilities they see to accelerate the process of upscaling. In the appendix a table is presented were a general overview is given of the possibilities parties saw as roles for themselves and roles for other parties (table 5). From analyzing this data we conclude the following:

Entrepreneurial activities:
Frontrunners are very active with energy efficient concepts. These organizations see the necessity to align their products and measurements with others, which requires cooperation. They do see possibilities for cooperation with other parties, but the realisation remains difficult due to the fragmented nature of the building sector. On the other hand existing cooperations, like the Passive House initiative in the Netherlands, is felt to exclude the possibility to cooperate with other parties outside the initiative. To include the next group of entrepreneurs in energy efficient concepts, it is necessary to develop market perspective.

Knowledge development:
Knowledge development should be aimed at the development of products and concepts in which different solutions are combined. This means new fundamental knowledge is not so much required as is the combination of existing knowledge.

Knowledge diffusion:
A lot of emphasis is put on the necessity to disseminate information and knowledge that is already available. Most of the effort of the different parties is to be put in this category of activities. Activities parties take on themselves and see as a role for others are in fact quite similar for knowledge development and knowledge diffusion. One could draw the conclusion these activities are regarded as pivotal in the eyes of the different parties. There is also a need for a more independent source of information in order to legitimate their products and services.

Guidance of the search:
Given the amount of different suggestions for guidance of the search, there is a certain need for direction. Since the interviews were are all from representatives of market parties, and not with policymakers, it is logical a role for policy makers is emerging in guidance of the search. The type of measurements suggested for guidance of the search can be categorized as activities required for market creation. In general parties conclude there is no real sense of urgency felt in society. They feel government, media and independent parties should take their responsibility in order to help to change this. Policy makers are seen as important factors in creating general awareness among the public and

in defining the level of ambition. The best part of their own role is seen in communication towards the market. This in itself is probably not enough to create market for all different niches in construction. There is also a need to objectify the impact of the solutions different parties are proposing.

Market formation:
The split incentive for those likely to pay for energy saving measures and those benefiting from the use of energy saving measures is seen as a problem. No easy solutions are discovered yet. Some niche markets do not have such a split incentive, however. These are the niches markets where the owner is the same party as the user(s) of the building. Clients in these markets are the easiest to convert e.g. the client-users of commercial buildings and client-users of dwellings. In private owned dwellings there is the problem of the long pay-back time. Home owners are not willing to invest in improvements that have a pay-back time that is longer than the period they expect to live in the dwelling. In general the EPC regulation is stimulating market formation since it is clear for the parties what is the norm.

Resource mobilisation:
It is remarkable no activities emerged for the resource mobilization dimension. This can be an indication commercial parties realise government is restricted in its means. Apparently there is no direct need for extra funding, although suggestions are made to create incentives in the form of increasing norms for regulation, applying tax measures and providing guarantees for a good feed-in tariff, similar to Germany, which will remain in place for the long term.

Support from advocacy coalitions:
General awareness and behaviour change is generally seen as the next big step in the reduction of energy consumption. But it is by no means clear how to address this with respect for individual decisions of consumers. How to deal with the freedom of choice for people in relation to a general change of behaviour required to meet ambitious energy reduction levels in the built environment? There is a need to discuss this topic and come to some sort of general consensus on how to approach these issues in the near future. This makes an excellent topic for advocacy coalitions.

3.4 Conclusions: Possible intervention for upscaling energy efficient building concepts

In table 3 the results can be found from the comparison made between the strategic goals (table 2) with the total of activities present in the current situation (table 4 in the appendix) and the activities that were mentioned in the interviews (table 5 in the appendix).

Table 3: overview of the possible activities as perceived by different parties structured along side the strategic goals necessary to upscale complex energy related innovations

System Characteristic	**Strategic Goals**	**Total of activities as mentioned by interviewees to be performed by themselves and others**

Infrastructure	1. Products developments (plug & play, user-friendly, total solutions, ‘killer’add-ons, product-service combinations) 2. intelligent energy net suitable for connecting sustainable solutions 3. solid knowledge base in the value chain 4. production and distribution facilities	1. different initiatives although a lot of work remains 2. not addressed during interviews (although addressed by some actors, policy not yet in place) 3. widely addressed and a demand for support from policymakers 4. not addressed during interviews
Institutions	1. Consistent and reliable policy 2. Policy on total costs for housing in stead of rent + energy costs 3. Policy for market creation in the current building sector (regulation, financial incentives) 4. Process of user acceptance (awareness, knowledge, interest, transparency of the costs, risk reduction) 5. Reframing of current framework and habits (energy is an endless source)	1. The importance is recognized but remains a great challenge to make this reality 2. Idem 3. Is addressed during interviews, parties feel that more attention is required on this topic 4. Interviewees underline the importance of general awareness. 5. Still needs more work, there is a demand for support from media and policymakers
Interactions	1. User participation in building processes 2. Cooperation across the value chain 3. Familiarize people with possibilities and usage (fairs, model homes) 4. Learning sector and society (a problem with an innovation does not legitimise political action to kill it)	1. The importance is only partly seen by some parties, especially those from the demand site. This issue is only addressed partly with solutions / also reframing of end user necessary -> comfort and urgency of the fossil based energy consumption 2. Is seen and addressed by different parties, but is difficult to realize due the fragmentation of value chains 3. Is seen and addressed although more work is seen as necessary 4. Is addressed by some with chain integration, the other problem remains
Capabilities	1. Combination of technological skills with organisational and commercial skills across the value chain 2. Developing from production sector towards service oriented sector	1. Orientation towards organisational options is necessary since most inventors lack the commercial skills 2. Is not addressed by the interviewees. The authors expect this to be the next step in market development.
Market structure	1. Market creation by setting targeting ambitious targets for new buildings 2. Market creation for current buildings (taxes, etc) 3. Financial constructions to solve current split incentives (split between investor and benefits for	1. E.g. “Excellent Areas”, current labels. But a strong stimulus for radical innovation is still required. 2. Extra effort will be needed. What will be acceptable measures in a time of deregulation? 3. Is experienced as a problem, solutions are investigated but still requires work

	end-user, un-balance between investment costs and return on investment, split between budgets for initial investment costs and maintenance & operation costs)	(no easy policy solutions)

Looking at the results of this research we can summarize some of the challenges for the building sector, its clients and policy makers for the upscaling of energy efficient concepts in the built environment. First conclusion would be that a wide variation of actions and measures is necessary to realise the upscaling of complex energy related innovations in construction. Based on the outcomes of this research the most important areas for extra effort for the sector itself would be the following:

On the part of knowledge dissemination, there is a lot of work remaining in the dissemination of why, what and how of the energy efficient concepts; towards different parties in construction, clients and end-users.

Another issue is the development of new products (plug & play, user-friendly, total solutions, ‘killer’add-ons, product-service combinations) in combination with efforts for new business development for both new markets and new products (market creation) including a change towards a more service oriented sector. This will require more cooperation in the value chain, as is indicated, as well as a stronger knowledge base within the value chain and a learning sector. Intelligent grids and production facilities were not addressed during the interviews and are therefore out of the scope of this research.

From the side of policy makers incentives are required to stimulate radical innovation and measures to target existing buildings. In general there is demand for policy making that underlines market creation, this is accompanied by a strong plead for consistency in policy making and the formation of a learning society in which problems with new solution will not automatically lead to political discarding. A role is seen for both independent parties, among which policy makers, and media to underline the urgency of energy reduction and the change towards renewable energy sources towards citizens in general.

The great policy challenge is to create market for the more radical innovations in the new buildings. Especially if these would realize great reduction of fossil energy consumption, while not creating direct benefits for investors and end-users. Radical innovations are not easily implemented, which means parties in the chain naturally avoid these solutions. A strong stimulants combined with regulation can create a market for these innovative solutions. In the Netherlands an important precondition for any regulations would be the acceptability of new regulatory measures. A balance between market creation for energy related innovations and possible market disturbance of the housing market should be closely watched to keep interference acceptable. In the Dutch context the discussion or negotiating between parties (different pressure groups) to reach mutual agreement on the policy approach is necessary (Poel 2009).

Another great challenge is market creation for the current building stock. At the moment building owners are not very willing to invest, especially when they do not use the building themselves. The way present energy labels are implemented does not seem to effect the willingness tot invest. More stimulants (regulation and financial incentives) will be needed in order to create market. A growing or dormant market is a condition for developing new business cases, and it appears the current building stock can be regarded as such. Financial measures to solve the split incentive are needed. Or additional regulation or norms. The acceptance of regulation is of course also influenced by the sense of urgency building and house owners see to invest in energy efficient innovations. This could result in a situation where it is as normal to invest in energy efficient solutions as it is in a new kitchen. Communication can stimulate the emergence of a sense of urgency.

In general there seems to be a good understanding what actions and policy-interventions are needed. The greatest challenge is to coordinate these activities and to take care that actions are really taking place. This means cooperation between the different actors and between market parties and policy makers is necessary in order to align activities for upscaling. Cooperation in the building chain remains an important issue, as was already indicated in the list of the general barriers for innovation in the sector. The actors in the sector play a main role to accomplish this, although policy could support it.

The necessity to coordinate different actions means that a good method of monitoring and designing of the policy approach is needed. A policy approach is required with at the same time a long term horizon and flexibility on an instrumental level. Parties involved in this field (building sector, clients and policymakers) should be able to monitor their activities and adjust depending on the results and external developments.

4 Reflection on the results

The people involved were frontrunners, this means the picture of current activities derived from the research is more positive then can be expected from a general inventory of the sector as a whole. This makes the urgency for upscaling of energy efficient concepts ever more important.

How to handle upscaling remains a complex problem. All parties have their own contribution towards a more energy efficient built environment. No one seems to systematically align these contributions. Together these contributions will be able to realise upscaling. It is a familiar pitfall to suggest that by simply steering this process will lead to a favourable outcome. Yet it would help to:

- tune the different contributions. Not only among commercial parties or among different incentives and rules and regulations from policy makers, but also by bridging between the world of policymakers and building practice.

- have a method for monitoring and evaluation that would provide parties with feedback on how their actions are contributing and how effective they are. This will provide them with the opportunity to adjust and tune their activities, thereby enlarging chances of success in the upscaling process.

Since the fragmentation in the sector has been seen as a hindrance in the sector for years, one starts to wonder if reduction of fossil energy in buildings can be the trigger for real cooperation in the supply chain. Other questions that remain are what actions will work as an accelerator for other initiatives in the different niches, and what policy actions will stimulate these activities?

From the diversity of actions it becomes clear there are no simple answers on the question how to upscale energy related innovation. Clear is that a long-term perspective apart from current party politics is needed. Energy efficiency is a step to make the entire building sector more sustainable. Energy is however only one part of the problem. Yet the built environment could be expected to compensate for other fossil fuel addictions we have as society. It is likely the built environment should compensate for the energy consumption we require for personal mobility for example. One should carefully examine if policy interventions also contribute to this long term goal. One of the interviewees mentioned the need for a ministry of Energy to address the energy related issues. This could be a solution. Germany demonstrates there are possibilities to guarantee a long-term feed in tariff. From their practice we know that the feed in tariff had an amazing impact on the upscaling of PV. From Sweden we know the strong effect pricing policy has had on choice of people for alternative energy sources (Coenen 2010).

Experimenting is necessary in order to learn more about drivers and barriers of upscaling. Recently we have seen a lot of emerging theories around the concept of transition management and innovation management, most of which intends to help policy makers to reflect on their options for steering. Still more work needs to be done in this area. Parallel with this study application for policy makers was investigated. This was concluded with a workshop discussing different policy practices in different European countries (Coenen 2010). An important question on the part of policy making is how to involve ‘technology selection’ as part of innovation policy. New technologies would require more support then older ones. Radical innovations need more support then incremental innovation. But how long should you support new technologies? Only development? Or also the application and new business development that is required? Could there be criteria formulated to assess the new technologies on progress? This could help to legitimize the decision to support certain new technologies and no longer some other technologies. What influencing circumstances are legitimate for setbacks on the forecasted development line of a certain technology?

In a time of deregulation it is hard for government to come up with additional rules and regulations. The easiest way would be to simply increase levels of current standards or to change from several more complicated regulations towards a simpler rule. In the aftermath of the credit crunch policy makers will be reluctant to disturb the current market for construction. New or increased standards should not lead to a complete stand still of the sector. On the other hand small steps for more strict regulations could be accomparied by a clear vision on the direction of these small steps in order to create a sense of urgency among the different parties. If the existing building stocks is included in these steps, parties will be allowed time to anticipate and market creation will be stimulated.

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Appendix

Table 4: examples of current activities in the different functions of the innovation system.

Functions	• **Activities**
Entrepreneurial activities	• Commercial forerunners for total concepts, for example organised in Passiefhuis.nl • Experiments in the subsidiary programs UKR and EOS Demo for Passive House experiments • Local municipalities and commercial forerunners with ambitious plans wanting to implement Passive House (e.g. Almere, Eindhoven, Den Bosch)
Knowledge development	• Research programs EOS (e.g. Rigoreus) • Innovation program of PeGO (3 passive house projects) • Building Future cooperation of TNO / ECN / OTB • Research at universities • European and national research studies
Knowledge diffusion	• Toolkits for knowledge diffusion (concept Passive house) • Senter Novem, Milieukeur • Disseminations programs, conferences, fairs and training programs
Guidance of the search	• Political attention for energy use in the building sector • High standards for new building sector (EPC) • Expectations risen by PeGO, a platform organisation with organisations form the building sector (due to innovation program and regulation workgroup)
Market formation	• Covenants (Lente accord, Convenant between building sector, Ministery of VROM) • Consortia (passiefhuis.nl etc) • Areas with ambitious green goals (excellente gebieden) • Meer met Minder (awareness creation, subsidies and professionalisation of the sector) • Lower VAT for reconstruction/isolation etc • Special financial arrangements for green investments (RABObank, ASNbank etc) • Subsidies for components needed in the Passive House concept: PV, heatpumps, solar thermal combinations etc.

Resource mobilisation	• Money for innovation available (see knowledge development)
Support from advocacy coalitions	• Public opinion is changing towards more sustainability • Umbrella organisations as Bouwend Nederland, Uneto VNI, NEPROM, Aedes etc are supporting goals • Environmental NGOs active (f.e. Natuur&Milieu)

Table 5: overview the interventions as indicated by the interviewees

Functions	**Interventions mentioned in the interviews**	**Interventions mentioned in the interviews**
Entrepreneurial activities	• To inform and advise other supply chain parties • Invest in demonstration projects	• Cooperation in the supply chain offering: ○ coherent information & marketing ○ one-stop-shop for the client ○ integrated package of energy measurements, including additional service (f.e. finance) • Find solutions for split incentive (energy & rent combinations)
Knowledge development	• Investing in knowledge development in the supply chain of construction • Training of the people involved • Redevelop process of realisation • Better performing products • Integrated packages in niches • To co-develop instruments for monitoring and evaluation (BREEAM for example) as branche organisation	• Design and developing new products
Knowledge diffusion	• To inform, educate and advise clients on: ○ the arguments why to invest ○ the different options available ○ how the measurements will be like in practice ○ the measures that suit their situation ○ what measures can be considered as proven technology & cost effective ○ their costs and benefits ○ available subsidies and financial arrangements to implement products and measurements already available • To inform and advise members of branches and create dissemination processes within organisations (Neprom made scheme to promote	• Role of SenterNovem, agency for sustainability and innovation should go beyond energy zero • Stimulate the involvement of maintenance and exploitation costs in investment consideration (education of clients) • To systematically educate end-users of the available options for energy savings (proves to be good for business as well) • Education of the different stakeholders, • Current knowledge should become available for clients of the sector by the different parties involved

	internal dissemination)	

Guidance of the search	• To monitor and evaluate results as branche organisation	• Long term policy goals for the sector
		• Coherent method to balance people, profit, planet & space
		• An independent way to define, to measure and to certify energy efficient houses, with the cooperation of the different parties to actually use these (f.e. real estate agents)
		• An independent way of waying different products and measurements.
		• More regulation is required in the current building sector (from government or EU)
		• EPN could be improved by:
		  o equal rewarding of measures, is now sometimes inequal
		  o skipping double standards for products
		  o energy norms for area's,
		  o increase standard levels
		• Installation of a Ministry of Energy to inform, to stimulate, to manage and steer developments across governments of different political preferences.
		• Providing of (independent) information
		  o To underpin sense of urgency
		  o To provide arguments why it is worth investing in these measures at the moment (needs cooperation of different parties in the entire supply chain, including investors and clients)
		• Financial measures are required
		  o Clever financial incentives like those used to stimulate energy efficient cars, for example low VAT rate for energy efficient buildings.
		  o Check for contraproductive tax measures
		  o Stimulation of green morgages
		  o Subsidies should be in place for longer periods, now they hinder sales of energy efficient measures in times these subsidies are put in place
		  o The feed-in rate for larger quantities should be insured

Market formation	• Raise awareness with clients • Involve different canals to provide information via internet, DIY shops, real estate agents etc; • Improve communication on the effectiveness of measurements by inventing ways to indicate levels of quality • Integrated concepts and products • Branding total concepts, like Passive	• A general and independent Passive House label for energy efficient buildings to distinguish them from ordinary buildings • To create visibility of parties who do have knowledge

	House • Provide calculation tools to prove added value to potential tools to prove added value to potential clients and building parties	
Resource mobilisation	•	•
Support from advocacy coalitions	•	• To nudge people towards energy saving behaviour should become a subject of discussion • To avoid measures that are out of proportion when problems occur (grey water for example) replace this political reflex by communication on how to avoid these problems

Proposed Model for Constructional Design of Photovoltaic Integrated Steep Roof Systems and Case Study: Istanbul, Turkey

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Abstract

Energy consumption in buildings constitutes a considerable part of the total energy consumption in Turkey and electricity constitutes 25% of the energy consumption in buildings. Moreover electricity is the most responsible energy sector for green house gas emissions in Turkey. Energy production by renewable energy sources in buildings was recently referred in energy efficiency policies in Turkey. As a renewable energy technology, photovoltaic (PV) can be replaced with conventional construction materials and this sustainable technology is called Building integrated photovoltaic (BIPV). Roofs are frequently the most attractive opportunity for BIPV installations because of their substantial solar access. Even though there are many constructed BIPV roof systems worldwide; there is only one example in Turkey. This indicates that BIPV is not a common application in Turkey. However, there are some examples of PV applications, in which PV modules are not integrated in the projects during the design process, but they are added during the use of the buildings for retrofit applications. Thus these examples include standoff PV modules attached on roof systems. This design decision results in loss of opportunity of replacing standard construction roofing material with the BIPV system. There are financial barriers on BIPV installations in Turkey. However recent improvements regarding the support of renewable energy source indicate that BIPV applications will be more affordable in future. In this case, lack of experience on the constructional design of BIPV applications may result in improper designs and incorrect detailing of PV roof systems. In addition there is not a guide, regulation or standard regarding the construction of PV systems used in buildings in Turkey. In order to overcome this issue, a model has been developed for the constructional design of PV roof systems, which assists architects, constructers and roof covering material producers to develop correct design alternatives for PV integrated steep roof systems and based on the model, a case study in which PV integrated steep roof system alternatives are designed for Istanbul, Turkey. 5 alternative roof systems were designed with standard PV modules partially integrated in a steep roof system, and their visual impacts, ventilation rates, material consumption rates, self cleaning rates and ease of disassembly are also discussed.

Keywords: photovoltaic, building integrated photovoltaic, renewable energy, roof systems

1. Proposed model for constructional design of photovoltaic integrated steep roof systems and case study: Istanbul, Turkey

1.1 Introduction

In Turkey, 70% of electricity production is supplied by thermal energy and 85% of the thermal energy is being produced from fossil fuels, (Ogulata, 2002). According to 2005-2006 Turkey Energy Report, which was published by World Energy Council Turkish National Committee at 2007, electricity is the most responsible energy sector from green house gas emissions in Turkey. Energy consumption in buildings constitutes almost 30% of the total primary energy requirements and electricity constitutes 25% of energy consumption in buildings, it is the second energy source followed by the natural gas with 29%, (UCTEA, 2008). United Nations Framework Conventions on Climate Change (UNFCCC) was signed by Turkey at 2003 and Turkey signed Kyoto Protocol recently at 2009. This protocol restricts Turkey to decrease green house gas emissions. As well, Turkey has to import nearly more than half of the energy requirement from abroad to meet her needs. In addition, the growth of Turkey's industry is giving rise to a substantial increase in energy demand, (Ogulata, 2002). As a result, renewable energy sources and energy efficiency gained importance in Turkey due to increasing energy demand and environmental concerns.

It was in the year of 1970 when "TS 825 - Conservation Rules of Heat Effects for Buildings" standard regarding thermal insulation of buildings had been activated. In the following years this standard has been revised to increase the U values of the building envelope. Regulation titled "Thermal Insulation in Buildings" has been activated in 2000. The law regarding "Using Renewable Energy Sources for Electricity Generation" has been activated at 2005. A feed in-tariff to renewable energy production which is 5,5 euro cents/kWh for 10 years has been imposed by this law. At 2007, "Energy Efficiency Law" was published and in this law, producing energy by renewable sources is mentioned as an energy efficiency topic. Energy production by renewable energy sources in buildings was first referred in "Energy Performance Regulation for Buildings" regulation at 2008.

As a renewable energy source, photovoltaic (PV) can supply all or a significant part of the electricity consumption of a corresponding building without depletion of finite fossil fuel resources. Hence, they emit no pollution and no greenhouse gases. In order to save on building materials and reduce ecological footprint of buildings, PV can be used instead of conventional roof coverings. This combination of technology and architecture is called Building Integrated Photovoltaic (BIPV). Roofs are frequently the most attractive opportunity for BIPV installations because of their substantial solar access. The benefits of BIPV roof systems are not only functioning as building envelope and generating electricity, but also they do not require any extra land area and infrastructure installations for electric generation. Additionally, losses of electricity during the transmission and distribution are reduced due to short distance between generator and electricity consumer. The first installation of BIPV was carried out in 1991 in Aachen, Germany. The PV elements were integrated into a curtain wall facade with isolating glass, (Benemann, et al., 2001). Following the initial steps in Germany, many BIPV projects were carried on especially in Europe, Japan and USA by support funds of governments and various communities. In 1996, six PV integrated roofs were constructed in Nieuw Sloten, Netherlands, Figure 1a. This was the first city district in the world, where BIPV was demonstrated on such a large scale (Schoen, 2001). In 1999, the worlds' largest urban PV project, Nieuwland was designed and constructed again in Netherlands, Figure 1b. The project consists of over 500 houses and several other buildings with PV modules integrated in their roofs (Pvdatabase, n.d.).

(a) (b) (c)

Figure 1: PV integrated roof system examples.

Although Turkey is one of the regions, which has the most solar electricity generation potential in the Europe (above 1200 kWh/kW per year), (Šúri et al., 2007), and that the benefits of PV integrated roof systems are very well known, there is only one example of PV integrated roof system in Turkey. This PV integrated roof application was constructed on the south faced part of the Mugla University cafeteria building's roof in 2003, Figure 1c. The area of PV covered roof surface is 215 m2. Remaining examples of PV roof systems include systems in which PV had not been integrated to the roof system as a building material but had been attached on the roof coverings of low-slope roofs. Additionally, they had been added during the use of the buildings. This design decision had resulted in loss of opportunity in replacing standard construction material with the BIPV system. The main reason why PV integrated roof systems is not a common application in Turkey is due to financial issues; i.e. initial investment cost is high and payback period of the initial investment cost is too long. Unfortunately financial supports at the governmental or municipality level are not sufficient for the installations of PV roof systems in Turkey. The feed in-tariff to renewable energy production which is insufficient (5,5 euro cents per kWh for 10 years) was implemented recently in 2005. Law proposals regarding the increase of the feed in-tariff are being discussed nowadays by Turkish Ministry of Energy and Natural Resources. Finally, Turkey signed Kyoto Protocol in 2009, which restricts her to decrease green house gas emissions. The aim of this development is to make PV applications more affordable and hence more common. However, when affordable, it will be a challenge for Turkish architects, who are only familiar with the design of PV attached onto the roof coverings of only low-slope roof systems, to design a PV integrated roof system, particularly detailing of the PV modules with the remaining roof components.

Although there are standards regarding the use of solar energy for heating (TS EN 12975 Thermal solar systems and components - Solar collectors, TS 3817 General Requirements for Solar Water Heaters, TS ISO 9459 Solar heating-Domestic water heating systems), there are not any standards or regulations about generating electricity by solar power in buildings. “Energy Performance Regulation for Buildings” and in “Energy Efficiency Law” provide typical details for the design and construction of thermal insulation materials for buildings; and, unfortunately there is no such a guide for the construction of solar power systems for buildings in Turkey.

In order to overcome the above given issues, a model has been developed for the constructional design of PV roof systems, which enables architects to develop correct design alternatives for PV integrated low-slope systems, PV attached on steep roof systems and PV integrated steep roof systems in addition to already known PV attached on low-slope roof systems. The model comprises design processes and inputs for each design process for the architect for the selection of an appropriate type of PV roof system for the building. This paper presents only the sub model proposed for the constructional design of PV integrated steep roof systems and based on the model, a case study in which PV integrated steep roof system alternatives are designed for Istanbul, Turkey.

1.2 Proposed model

Figure 2 illustrates the flowchart of the proposed model developed for the design of PV integrated steep roof systems. Initially, PV module type and PV array size are determined. Module type can be selected according to power output, cell type, number of cells per module, visual impact, module size and module substrate materials. Power output is determined by cell type and also by the module size. Each cell type has different efficiency rate. There are monocrystalline (%14-17 efficiency), polycrystalline (%13-15) and amorphous silicon (%5-10) cells used in PV modules. PV array size is determined according to total energy demand and budget.

Subsequently, PV array orientation and slope, which affect the energy efficiency performance of the PV system, are chosen. Typically, the most favourable orientation is south in the northern hemisphere and north in the southern hemisphere. When the PV surface is perpendicular to sun’s rays, they receive the maximum solar radiation. Based on this knowledge, an optimum tilt angle (slope of the PV system) is defined to generate maximum electricity for whole year or for a specific period of the year (e.g. summer). This decision is dependent on the use period of the building. Additionally, PV modules can be mounted on a movable or sun tracking systems in order to gain a higher yield. Tracking systems are generally used in sun shading systems and systems attached on low-slope roofs. PV simulation programs, which utilize meteorological data based on monthly or hourly measured irradiance, can be used for the calculation of the optimum tilt angle. Some of the commonly used PV simulation

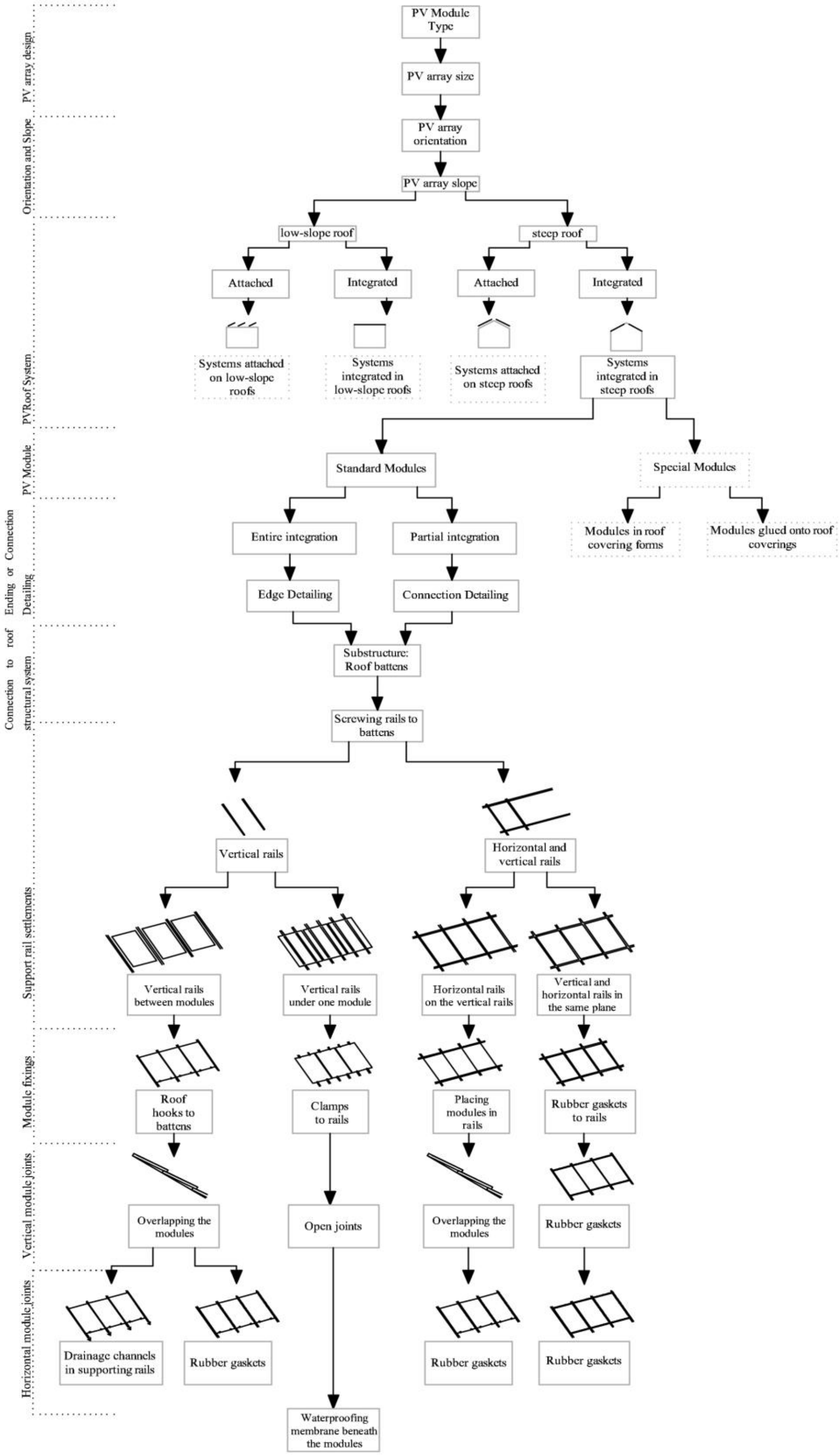


Figure 2: Proposed model for the constructional design of PV integrated steep roof systems

programmes are PV-DesignPro (Mauisolar Software), PV SOL (Valentin EnergieSoftware), PV F-chart (F-Chart Software) and PVSYST software for photovoltaic systems (University of Geneva).

Following, the slope of the roof system is determined based on the criteria, which are climatic conditions, surrounding buildings' roof slopes, roof coverings, local construction methods, regulations and particularly PV array slope. The roof system may be determined as a low-slope or a steep roof system. For example, if the decision making process results in a low-slope roof; i.e. the roof system would be built at a location where the rain intensity indicates dry conditions, and the defined PV array slope remains higher than the defined slope of the roof; then the PV array can be attached at the determined slope separately on top of roof covering of the low-slope roof. On the other hand, if the decision making process results in a steep roof system, the slope can be arranged at the same slope of the PV array and then, the PV array can be attached separately on top of pre-constructed roof covering or be integrated in the roof system as a roof covering, Figure 2. Whether the PV array will be attached or integrated in the roof system are determined according to energy generation efficiency, visual impact, less material consumption, ease of transport, ease of mounting, speed of installation, less tool usage, less labour need, safety during installation, self cleaning, ease of module disassembly in the case of maintenance, etc.

When integration of PV arrays in the roof system as a roof covering is considered, two types of PV modules can be used as a roof covering. These are standard modules and special modules. Special modules are formed like a roof covering or they are glued onto the roof coverings. Special modules are smaller than standard modules. Although the cable consumption increases by the use of these small modules due to cabling per module, they are preferred due to their visual effect. In addition, they are light and their transportation is easier than standard modules. Since standard PV modules are the most commonly produced and used ones in Turkey, the progress of the proposed model will proceed with this type of module in this paper. Standard modules can either be entirely or partially integrated to the roof system, example details are provided in Figure 3. This decision is based on the intended PV array size and roof area. If the roof area is larger than the PV array area, then a partial PV array integration must be considered.

Edge (ending) and connection details differ according to entire or partial PV array installation, as given in Figure 3. The borders and the seams between the last module and the roofing tiles must be ensured to be weatherproof. Weatherproof connections are achieved by metal (tin, zinc or lead) connection plates (flashings) and flexible flashing strips. Generally, connection plates should be specially produced to suit the project. Flexible flashing strips are made from Polyisobutylene (PIB - rubber) with an aluminium rib mesh insert and butyl adhesive strips along both edges.

Standard PV modules are connected to the steep roof structure with a substructure. This substructure enables mounting independently of the rafter spacing and also enables ventilation under the roof covering. An existing roof substructure with suitable spans can also be utilized for construction of the modules. Usually roof battens are used as a substructure. Moisture

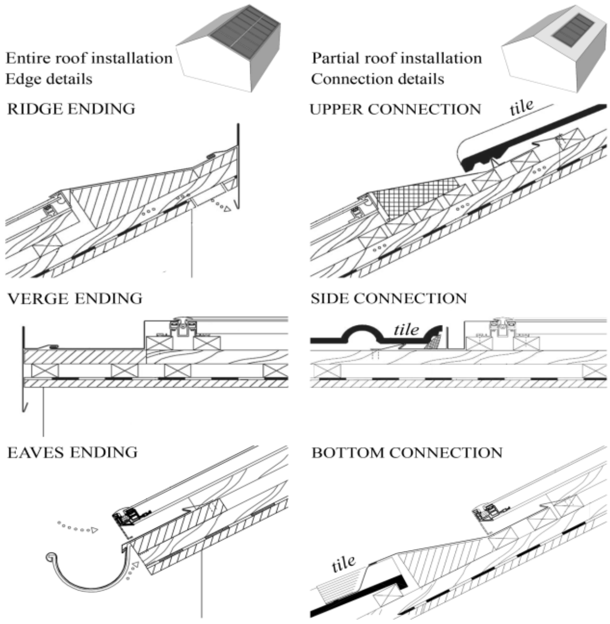


Figure 3: Details of entire and partial PV integrated roofs (Solar World AG, 2008***)***

damage of the components of the roof system due to the condensation occurring at the rear of the modules requires sufficient ventilation behind the modules. Cold roof system, which is usually designed in steep roofs, generally permits rear ventilation. However, the module efficiency decreases in high temperatures, thus the ventilation also affects the efficiency of the system. Ultimately, decision must be taken, whether the existing substructure is going to be used or a new substructure is going to be constructed according to spans and ventilation.

Support rails which are screwed to the roof substructure are used for module fixing. Modules can be placed in or attached on these rails. Supporting rails can be located in four different types. When only vertical rails are used, rails can be located between the modules or vertical rails can be located beneath the modules, Figure 2. In the third type of settlement, horizontal rails are used on the vertical rails. Otherwise, vertical and horizontal rails can be situated in the same plane; a plain roof surface is achieved with in this type of settlement. Settlements are formed due to the module dimensions (spans), impermeability in joints (drainage channels, rubber gaskets, overlapping fashion or open joints) and appearance of the roof surface (overlapping or plain fashion, open joints). In addition to the given factors, material consumption should be taken into account.

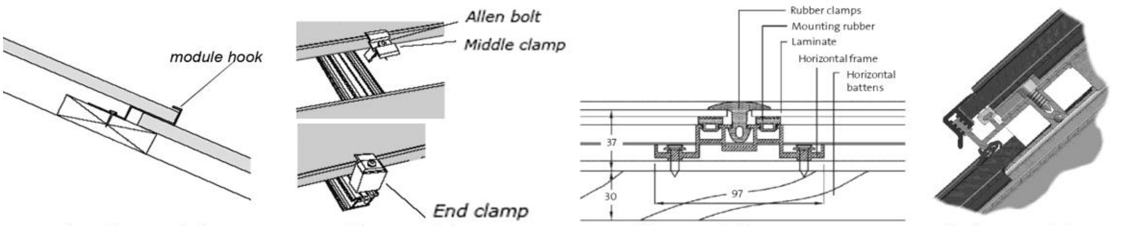
Vertical rails located between the modules can be used with module hooks to fix the modules. Module hooks are mounted on roof substructure and modules are fastened in these hooks. Modules overlap each other by these hooks, Figure 4a. In vertical module joints, water tightness is achieved by this clapboard fashion and with rubber seals between the modules. In horizontal module joints, impermeability is ensured by drainage channels on vertical rails or with rubber gaskets attached to vertical rails, Figure 2.

Another settlement type with vertical rails located beneath modules is used with clamps to fix the modules. Modules are clamped to rails in points, Figure 4b. These point fixing is used when module joints are preferred to be left open. In either case, a waterproofing membrane must be used under the rails. Ventilation underneath the modules can be achieved easily with these open module joints.

In the settlement that horizontal rails are placed on the vertical rails, modules are placed in these horizontal rails, Figure 4d. This type of settlement ensures overlapping the modules in the clapboard fashion. Thus vertical module joints' water tightness is achieved by this clapboard fashion and with rubber seals between the modules. In horizontal module joints, impermeability is ensured by rubber gaskets attached to vertical rails, Figure 2.

When vertical and horizontal rails are situated in the same plane, modules are fixed with rubber gaskets attached to the rails, Figure 4c. Vertical and horizontal module joints' water tightness is also achieved by this rubber seals between the modules. A plain roof surface is achieved with this type application.

Module joint alternatives (open joints, overlapping settlement and flat settlement with rubber gaskets) must be evaluated according to the properties such as visual effect, ventilation rate, ease of installation, speed of installation, labour need, self cleaning and ease of module disassembly.



overlapping modules with module hooks (Ernst Schweizer AG, 2005) | attaching modules with point clamps (Ubbink Solar, 2008) | attaching modules with continuous rubber clamp (Solar World AG, 2008) | placing modules inside the rails (Solare Energiesysteme Nord, 2007)

Figure 4: Module fixings

1.3 PV integrated steep roof system alternatives for Istanbul

A PV integrated roof system is designed for a new building in Istanbul, Turkey. The building is located in Kemerburgaz, which is a suburban area of Istanbul. The function of the building was determined as a residence. Initially, the roof was considered to be a steep roof due to building typology, snowy and rainy climatic conditions of the location and surrounding buildings' forms. Timber was selected as a local construction material. The roof structural system was considered as built-up timber roof. 5-cm thick expanded polystyrene thermal insulation material was designed between timber rafters to provide the required thermal resistance value of the roof system determined by Turkish Standards (TS 825- Thermal insulation requirements for buildings). An APP modified bituminous waterproofing membrane with a thickness of 4-mm was designed on the rigid thermal insulation material and rafters to prevent rainwater entry. Another APP modified bituminous waterproofing membrane with a thickness of 4-mm beneath the rafters was designed as vapour barrier to prevent the occurrence of condensation on the rear side of the waterproofing membrane.

Module type can be selected according to power output, cell type, number of cells per module, visual impact, module size and module substrate materials. PV array size is determined according to energy demand and budget.

PV modules' power outputs vary due to their dimensions, cell types and number of cells in a module. Thus a polycrystalline silicon glass-film framed PV module (80W etc.) was selected due to our total power demand and possible array area. Ease of procuring is also another factor affecting our selection. PV array size is determined based on financial limitations and energy demand. PV array orientation was determined as south to generate maximum energy. Optimum tilt angle in Istanbul for whole year was calculated by PVSYST simulation program. The simulation program specified PV array slope range as 26°-30°.

Building typology, snowy and rainy climatic conditions of the area and surroundings suggested the roof system form as steep roof. PV array was decided to be integrated in the roof system as roof covering due to less material consumption and integrated visual impact. Thus roof slope was arranged at the same slope of the PV array. However, Istanbul construction regulation (bylaws) states that the maximum roof slope can be up to %45 (24°). Therefore, the PV array and roof system slope was determined as 24° for maximum energy generation. As PV module type, standard PV module was selected due to ease of supply and less cable consumption according to its larger sizes than special PV modules. The array size was determined smaller than roof area. Therefore, a partial PV integration system was designed. Connection plates were specially designed to suit the tiles, which cover the rest of the roof. As a new construction, the substructure of the roof (roof battens) was designed according to module spans.

After the above given steps, the rail arrangements, module fixings and joints are studied with possible alternatives. The design alternatives are given in Figure 5. In design A, only vertical rails were used between modules. Module fixings were acieved by roof hooks attached to the battens. Initially, vertical module joints were sealed by rubber seals between overlapping modules and horizontal module joints were drained by drainage channels in vertical rail profiles. Design B differs with its horizontal module joints from design A. These joints in design B were sealed with rubber gaskets clamped continuously to supporting rails. Each of design A and B have clapboard roof surface appearance by lapping modules over each other. This overlapping of modules may also help self-cleaning of module surface. In design C, only vertical rails were used with one difference. They were placed beneath the modules. Module fixings were achieved by clamps to these vertical rails. Therefore vertical and horizontal module joints werearranged as open and a waterproofing corrugated sheet is used underneath support rails. Ventilation rate is better in this design alternative due to its open module joints. This alternative has plain roof appareance. In addition, disassemby is easy for this alternative due to its point module fixings (clamps). Modules can be individually disassembled from each other. On the other hand, PV modules do not provide water impermeability in this alternative. In design D, horizontal and vertical rails were used. Horizontal rails were placed on the vertical rails. Module fixing was achieved by placing modules in horizontal rails. Module joints were sealed with rubber gaskets clamped to rails. This design has clapboard roof surface. In design E vertical and horizontal rails were arranged in the same plane. Rubber gaskets were used for module fixing to rails and for module joints' impermeability. Material consumption of design D and E is over than other alternatives due to both vertical and horizontal rail use.

1.4 Conclusion

Energy policy in Turkey should be based on energy savings and renewable sources to build an energy efficient future. Building surfaces should not be considered only as an envelope conserving energy, but also as an electricity generator. The power generation by PV is still expensive compared with conventional power generation methods. However replacing building materials with PV modules can at least partially offset the cost of building materials. In addition, the reduction of installing cost can be expected. Therefore PV modules integrated with building are effective for cost reduction. Additionally, integration of PV in roofs provide the protection of the system components against weather effects than attached systems, since the components (cables, connection boxes) stay inside the roof system. Furthermore, as a roof covering material PV have longer life-span (20-30 years) and need less maintenance than other conventional roof coverings.

Currently, financial supports are not sufficient to achieve BIPV projects in Turkey. Recent progresses regarding UNFCCC and Kyoto Protocol are expected to affect government policies about renewable energy usage. Power generation from renewable sources is expected to be supported by funds and the insufficient feed in-tariff to renewable energy production is also expected to be increased. These improvements in Turkey are important not only about environmental aspects but also to lessen dependence on importing electricity. Initially, it is suggested that the focus should be on public facilities, where they have the potential for widespread application, such as local government buildings, schools, universities, museums, technical centres, resort buildings, train station buildings, etc. In addition, the mass housing administration shall primarily analyze the possibilities of using solar energy in mass housing projects. When these improvements will be achieved in Turkey, the architects will then be confronted with the challenge of designing correct PV roof systems. Therefore in this paper, a model for the design of PV integrated steep roof systems was proposed and the model was applied for Istanbul as a case study. 5 alternative roof systems were designed with standard PV modules partially integrated in a steep roof system. Their visual impacts, ventilation rates, material consumption rates, self cleaning rates and ease of disassembly are also discussed. The model is considered to be a guide for the architects, constructors and roof covering material producers to assist in the constructional design of suitable steep PV integrated roof system alternatives.

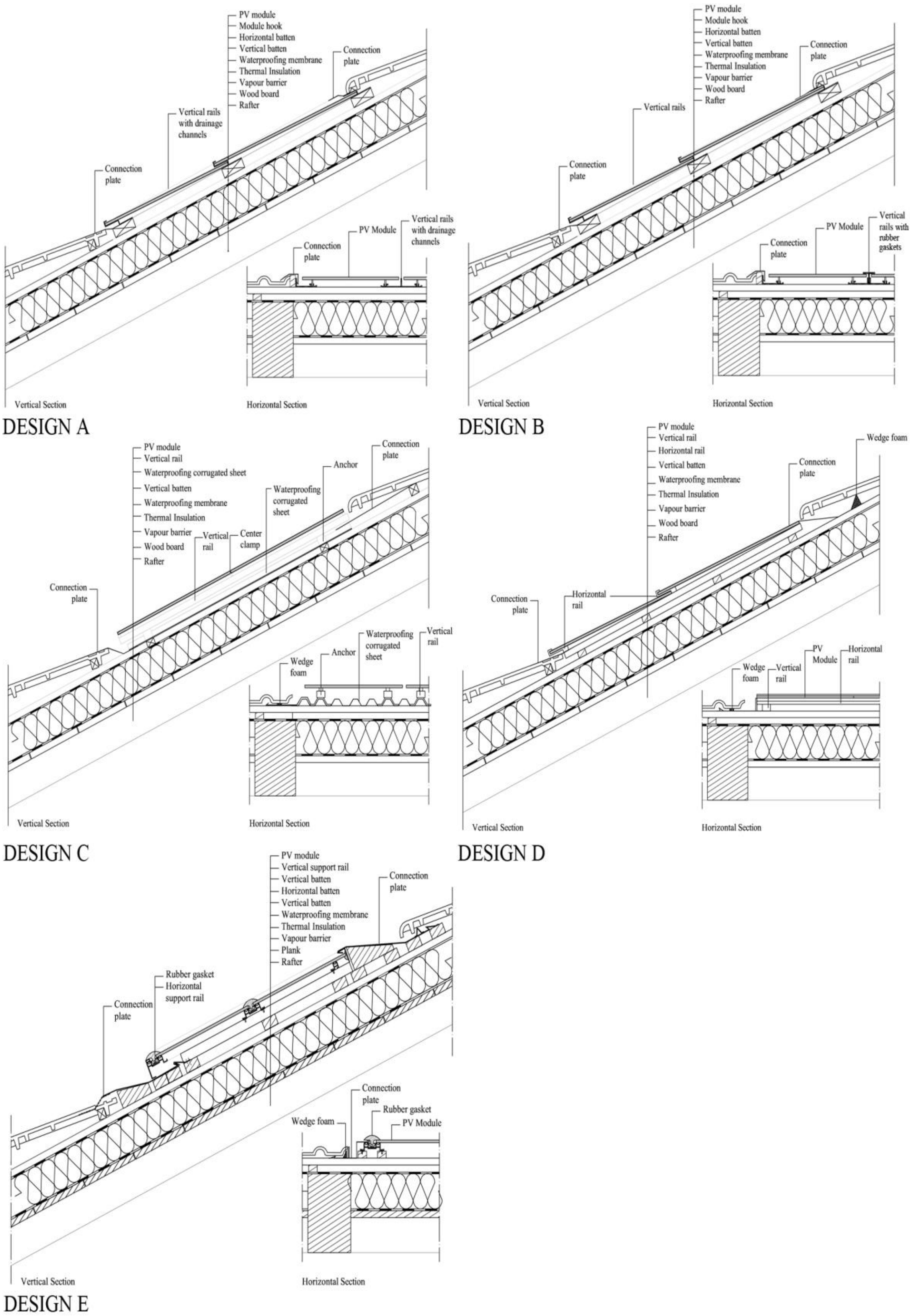


Figure 5: Design alternatives for PV integrated step roof systems for Istanbul, Turkey

Acknowledgement

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An Attitudinal and Behavioural Study of Scottish Pupils in Regards to Energy Consumption in Schools

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Abstract

The UK Government have set a target to achieve a 34% reduction in the UKs Carbon Footprint by 2020 (DECC, 2009b). The education sector makes up a significant component of the UK's public sector buildings, so reducing electricity consumption in school buildings will significantly contribute to achieving this target. The behaviour of building users influences electricity consumption and the underlying worldview frames attitudes to energy consumption. Further to this, an understanding of the perceived responsibility for energy establishes a matrix of how energy is used. A study of pupils in the PFI context explored the perceptions of factors influencing electricity consumption. Factors identified in two workshops were the basis of school wide surveys in two PFI schools. One school is new build and has shown a significant reduction in electricity consumption over the previous year; the other a refurbished building which has shown no reduction. Although the pupils represent the largest user group, in both schools the study identified that they had very little influence on electricity consumption. A positive attitude to reducing consumption was countered by a negative attitude to behavioural change to achieve it. Pupils in the new build school were more environmentally negative compared to the refurbished school. This was surprising, considering the new build school had recently significantly reduced its electricity consumption. The reason for this may be that the new build pupils are more aware of environmental issues. The refurbished school may have suffered from "self-generated validity" (Harrison *et al.,* 1996). The results from both the schools were consistently lower than that found in a university setting (Finlinson, 2005), suggesting an opportunity to implement strategies to increase the factors that encourage environmentally positive behaviours. This study is important to the Facilities Management Company for optimising behavioural change in order to reduce electricity consumption across the entire estate of schools.

Keywords: behaviour change, energy, PFI, schools

1. Schools and the UK energy problem

"We face unprecedented challenges to our environment, our economy, and the future security of our energy supplies and the decisions we make now will affect the planet and our way of life for generations to come." Ed Miliband, Department of Energy and Climate Change (DECC, 2009a).

During the last 10 years there has been a surge in public and political interest in the issue and effects of Global Warming. The diminishing supply of fossil fuels, and the link between the rising global temperature of the earth and the increased concentration of CO_2 in the atmosphere, has led governments to act to reduce energy consumption. There has been a significant shift in the public's attitude towards green issues. They have moved from side issues to central political policy; the public have been a driving force behind this change. The front page of the Conservative Party website claims "environmental issues must be at the heart of politics" (Conservative Party Official Website, 2010).

In July 2009 the UK Government released "The UK Low Carbon Transition Plan" which sets out how it plans to cut the amount of CO_2 released by the UK. A target has been set to reduce the Carbon Footprint by 34% of 1990 levels by 2020 (DECC, 2009b). Every Government Department has been given a specific target for adherence to over the coming years in order to reach this objective. Ward (2008) outlined the current energy usage patterns of various sectors of activity within the built environment. This research showed that the Education sector accounts for 10% of the total energy used in the service industry (which is 66% of the total UK energy consumed). As this is approximately 6.6% of the total consumption in the UK, strategies to minimise it could significantly impact the 34% Government target.

Concurrent with reducing energy consumption, the Government has also initiated an ambitious commitment to the building and refurbishing of schools through the 'Building Schools for the Future' (BSF) programme. Unfortunately, over recent years, it has become apparent that new build schools are consuming more electricity than their older counterparts (Bunn, 2008). A significant proportion of new schools have been procured through Private Finance Initiatives (PFIs) and this form of procurement will continue to be an important component of the Government's ability to deliver their BSF programme (DCSF, 2007). The Scottish Government has followed in this trend. They have set a target to build or renovate 300 schools by 2009. Of the 32 Scottish councils, 28 have used PPPs as a funding mechanism for this renewal strategy with an investment of over £2.2 billion (Scottish Executive, 2004).

1.1 Overview of the study

It is recognised that the amount of electricity consumed depends on both the equipment consuming the electricity and how the users are operating it. For the scope of this investigation, only the user aspect of this two sided coin has been considered. This study sets out to explore and further understand the issue of users' attitudes and behaviours and its subsequent impact on energy consumption in schools

Two Councils in Scotland have recently completed the building stage of PFI projects to rejuvenate their school stock. All of the schools in the project are consuming more electricity than is set out in the Government and Construction Professional benchmarks (Carbon Trust, 2008; CIBSE, 2008). The focus of this research is aimed exploring attitudes to how energy is used by building users. A case study approach investigates two schools, one from each Council. One of the schools is a refurbishment of an older school building and the other is a brand new building.

Due to its financial and environmental costs (ECON73, 1995) this study is focused on electricity consumption. The New Building has seen a reduction in its electricity consumption over 2009 (compared to the previous year). The Refurbished Building has seen no change. By investigating specific users' attitudes and behaviour towards energy consumption, this paper identifies the degree to which pupils seem to have an influence on the reduction of energy and considers measures to adopt for reducing the electricity consumption in the schools.

2. Understanding user behaviour

Electricity consumption in schools has increased in recent years (AECOM, 2009). Undoubtedly this is due to the introduction of new types of equipment powered by electricity, e.g. increased levels of use of ICT, security systems and cooling equipment. A large proportion of the energy consumed by this equipment is in the control of the users of the building. Any intervention into reducing the amount of consumption levels must therefore focus on the user's behaviour. As early as 1981, Morell (1981) discussed that it was naive of organisations to think that energy reduction could only be achieved through simply using technological fixes.

Stern (1981) classifies behaviour into four categories, ranging from those who are actively involved in environmental groups to those who make personal day-to-day decisions. Motivations for environmentally positive behaviour include: cultural bias (Steg, 2000); sympathy for others (alturism) (Allen & Ferrand, 1999; Schwartz, 1973 cited in Stern 2000); expression of post modern materialist values (Inglehart, 1990); religion (Dietz, 1998); and general theories of values (Schwartz, 1994). Using research on the behavioural change models, Stern and his colleagues drew up the Value-Belief-Norm (VBN) Theory by drawing together the concepts of Value Theory, Norm-Activation Theory and New Environmental Paradigm (Scherbaum, 2008). Figure 1 shows the interconnectedness of the different aspect of the theory they developed.

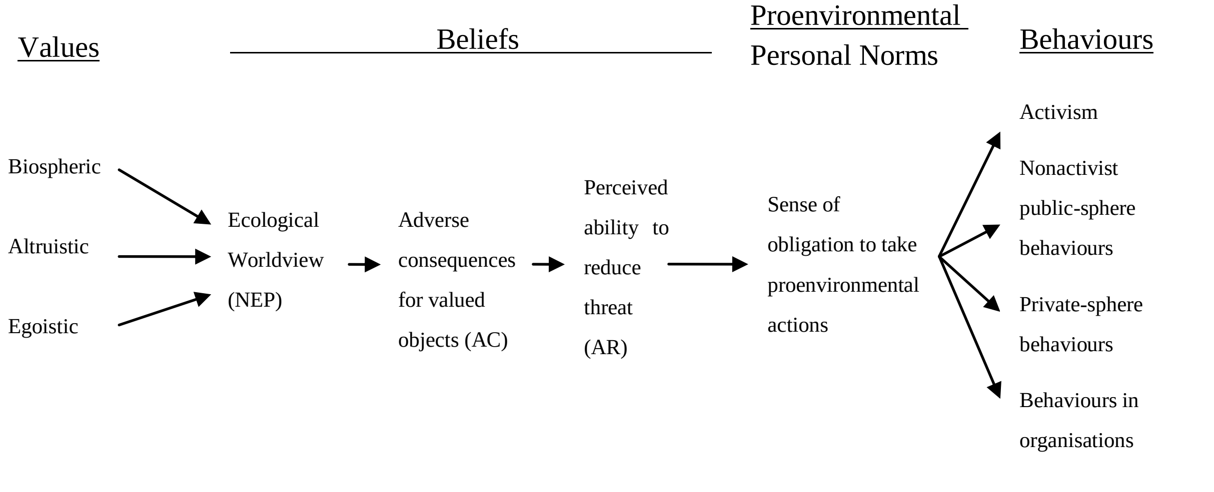

Figure 1 A schematic of the variables in the VBN Theory of environmentalism (from Stern, 2000)

Stern postulated that 'Values' influence 'Beliefs', which in turn influence 'Personal Norms' and therefore 'Behaviour'. This theory has been tested on many occasions over the years (Stern *et al.*, 1999) however all the variables have only been tested once (Steg *et al.*, 2005). Value-Belief-Norm Theory has been proposed as a possible model to assess attitudes towards energy and environmentalism as a mechanism for reducing environmentally negative behaviours, in this instance, overconsumption of electricity. This theory was therefore chosen as a mechanism for assessing the attitude in the two PFI Schools under investigation.

Work undertaken by Scherbaum *et al.* (2008) has shown the relationship of a particular aspect of the VBN Theory. They have shown how individual-level factors have an influence on energy-conservation behaviours, in a university setting. The study methodology used by Sherbaum has been adapted for use in the school setting.

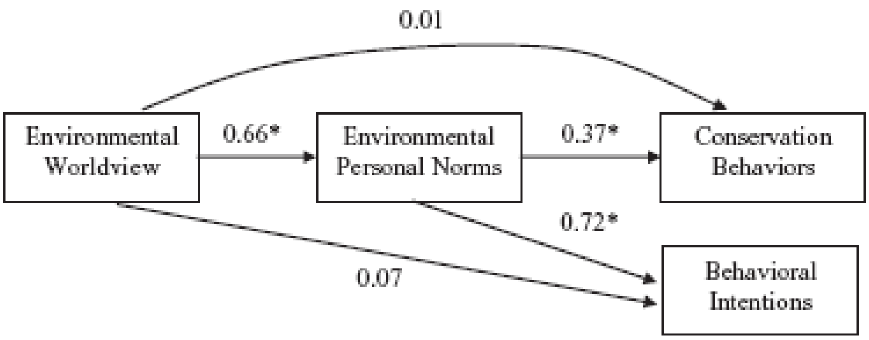

Figure 2. Standardized coefficients from the path analysis ($p < .05$).

Figure 2 Relationships within VBN Theory (Scherbaum et al., 2008, pp830)

Gardner & Stern (1996) reviewed four types of intervention measures aimed directly at behaviours to encourage environmentally positive behaviours. These included:

1. Religious & moral — change world views and beliefs
2. Education — change attitudes and provide information
3. Material Incentives — provide rewards for positive behaviour
4. Community Management — establish shared rules and expectations

They found that no one measure was successful on its own and that a combination of all the approaches was necessary to promote the behaviour on a medium term capacity. Although material incentives (often through external rewards) are very successful at motivating behaviours that reduce energy consumption in the short term (Siero *et al.*., 1989), research by Hellervik (cited by Scherbaum, 2008) found that factors such as personal norms concerning the environment and environmental worldviews are more likely to maintain this motivation. It was therefore decided to investigate the personal norms, environmental worldview and behavioural intentions of the pupils in the schools to determine if there was any opportunity to achieve long term changes in their behaviour.

3. Environmental behaviour study

3.1 Energy consumption profile analysis

Data for electricity consumption in two schools shows that the new build school has reduced its electricity consumption relative to the same period the previous year. Statistical analysis confirmed that the change was significant and sustained over a period of time. The refurbished school shows no significant change in electricity consumption over the same period. No technical changes have been made within the schools, and it is believed that changed behaviour has contributed to the reduction in electricity consumed.

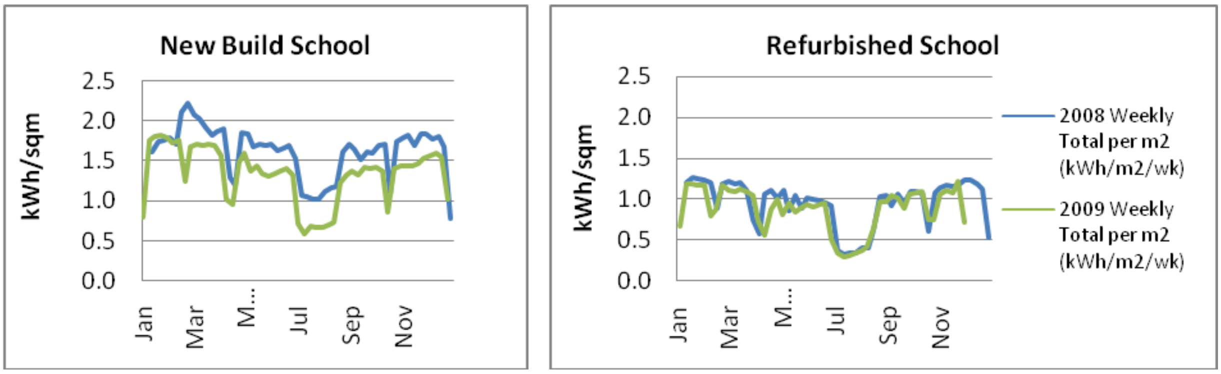

Figure 3 Weekly Electricity Use in New Build and Refurbished School

Analysis confirms that the new build school has seen a significant reduction in electricity consumption. It is therefore important to understand what the causes of this reduction could be and if it could be replicated across other schools.

3.2 Pupil VBN study

As advocated by VBN theory, workshops were utilised to gather information from pupil user groups on electricity consumption. The aim of the workshops was to: identify current knowledge and attitudes related to energy consumption; generate a list of behaviours currently occurring in the schools; generate a list of reasons for engaging in the behaviours; and generate a list of factors considered to be barriers to engaging in behaviours.

The workshops were undertaken in the classroom setting. The pupils were given a brief presentation to introduce them to the subject and to encourage them to begin thinking about energy conserving behaviours and how it affects them. The issues emerging from the workshops formed the basis of the surveys undertaken in the two schools. A scalar ‘scoring’ mechanism was chosen for the survey. The format was adapted to reflect the age groups carrying out the survey. Two schools were surveyed to determine if any differences existed in the attitudes of the pupil groups. Two-hundred surveys were distributed in both schools and the percentage of usable responses was 35% for the refurbished and 51% for the new build. A random sample was taken to directly reflect the view of the entire population.

Table 1 Survey Sample – Year of pupils

School	School Year (proportion)					
	1	2	3	4	5	6
A(refurbished)	0	10	30	19	6	5
B(new build)	12	12	25	17	37	0

3.2.1 Analysis of surveys

The survey was in four parts according to VBN Theory ; Self reported energy-conservation behaviours (ECB), Behavioural Intentions (BI), Environmental worldviews (EWV), and Environmental Personal Norms (EPN). A 6-point scale was used for this section, a score of 0 related to the pupils 'never' engaging in the behaviour, 5 related to the pupils 'always' engaging in the behaviour. A low mean score therefore means the pupils rarely engage in the behaviour.

Self-reported Energy Conservation Behaviours – ECB describes what the pupils do in practice. The users in the New Build scored a lower average score for these categories (2.10). This suggests that they are not likely to engage in energy conserving behaviours. The Refurbished School also had a low score (2.55).

Table 2 VBN - Energy Conservation Behaviours Results

	Question	**Mean (x)**		**Standard Deviation (σ)**	
	What I normally do: (ECB)	*NB*	*R*	*NB*	*R*
3	At the end of a lesson where I have used a computer, I turn it off	3.13	3.56	1.40	1.29
4	When I am not using my computer during a lesson, I turn off the monitor	2.51	2.12	1.56	1.64
5	When I am not using an electric devise, I turn it off at the plug	2.00	2.74	1.68	1.50
6	If there is a bright sky, I ask the teacher to open up the blinds	1.12	1.74	1.55	1.53
7	When I leave a room that is unoccupied, I turn off the lights	1.76	2.61	1.87	1.82
	AVERAGE	**2.10**	**2.55**	**1.61**	**1.56**

It is surprising that the low scores in the New Build School had considering the reduction in energy consumption that has been shown above (figure 3). If changed behaviour of the pupils has contributed to reducing energy consumption, a higher score would have been expected in this category. One explanation for this result could be that the pupils in the New Build School may be more aware of their attitudes and behaviours towards energy consumption through the work of the active Eco-group in the school. As such, they may have been more accurate in the reporting of their behaviours. The Refurbished School, which does not engage their pupils as actively with environmental issues, had a slightly higher score across all categories. The pupils attending this school are demonstrating more environmentally positive behaviours. However this is not materialising in a reduction in electricity consumption which suggests that the behaviour of the pupils is not in direct relationship with consumption, or that the reporting of environmental behaviour is not accurate. As lower scores mean the behaviours are not frequently occurring, there are opportunities in both schools to implement intervention strategies to increase in the scores and thereby reduce the amount of electricity being wasted.

Behavioural Intentions – BI measures the degree to which the individuals' intend to engage in energy conserving behaviours. The results have been included below:

Table 3 VBN – Behavioural Intentions Results

	Question	Mean (x)		Standard Deviation (σ)	
	What I would aim to do: (BI)	*NB*	*R*	*NB*	*R*
8	I would like to help XX School conserve energy	3.29	3.37	0.93	1.02
9	I would change my daily routine to conserve energy	2.84	2.89	1.02	1.00
	AVERAGE	**3.07**	**3.13**	**0.98**	**1.01**

Again the New Build School scored lower than the Refurbished school, although marginally (NB – 3.07 & R – 3.13). It may be that due to the immaturity of school pupils they may not believe it is their responsibility to carry out energy conserving behaviours. The scores for respondents in both schools are quite positive when asked if they would like to help conserve energy, although when asked if they were willing to change their daily routine to achieve this, the scores reduced to the negative side in both schools. The low score is concerning, although it explains why energy conserving behaviours are not more prevalent (as identified in Part 1). VBN Theory shows that if the behavioural intention is low then the frequency of the positive behaviour will also be low. These results show that pupils are more willing to engage in behaviours that will not be inconvenient to them. If they have to make extra effort to achieve the same result individuals are less likely to choose the more difficult approach. This is consistent with the work carried out by Stern (2000) which discussed the effects of 'limiting conditions' which cause barriers to performing environmentally positive behaviours. The more numerous and the more significant the limiting conditions, the less likely it is an individual will engage in the behaviour. This was seen in the lowest scoring question in part 1 – asking the teacher to turn open the blinds. As there are more limiting conditions to this behaviour, it results in a low score. The challenge will be to identify these conditions and mitigate them.

Environmental Worldview – EWV measures the degree to which individuals believe energy conservation is necessary. Having established that the ECB are at present not likely to occur and that the pupils' intentions are not inclined to engage in the behaviours in the future, it is important to analyse their response to the global energy situation to understand what influence this is having on their behaviours. These results are more promising from an energy conservation point of view. A more environmentally positive response to these questions will result in a higher score.

Table 4 VBN – Environmental Worldview Results

	Question	Mean (x)		Standard Deviation (σ)	
	What I think about the world: (EWV)	*NB*	*R*	*NB*	*R*
10	The UK/US is in the middle of an energy crisis	3.12	3.09	1.05	0.89
12	Energy conservation is something to be concerned about	3.46	3.59	1.07	1.01
	AVERAGE	**3.29**	**3.34**	**1.06**	**0.95**

The Schools scored similarly for both of these questions. Although the pupils give a positive response, it is not overwhelmingly in favour of the statements. The Standard Deviations are not as large for these questions; which suggests the spread of results is smaller, giving more consistency to the answers between the respondents. As the opinions are relatively low, there are again opportunities to increase these scores through intervention measures.

Table 5 VBN – Environmental Worldview Results

	Question	Mean (x)		Standard Deviation (σ)	
	What I think about the world: (EWV)	*NB*	*R*	*NB*	*R*
11	News reports about an energy crisis are blown out of proportion	3.10	2.99	0.96	0.85
13	It is my right to use as much energy as I want	2.74	2.91	1.13	1.11
	AVERAGE	**2.92**	**2.95**	**1.05**	**0.98**

Compared to questions 10 & 12, the scores for these questions are lower, showing that the respondents EWVs are consistent. There is not a significant difference between the responses given by the pupils. They seem to be unsure as to whether or not the energy crisis is blown out of proportion (scoring NB – 2.92 & R – 2.95); this is not surprising considering the mixed reports in the media (BBC, 2004). They tend towards disagreeing with the statement that it is their right to use as much energy as they want. As these scores are consistent, it will be important to build on them to influence the pupils' EPNs.

Environmental Personal Norms – EPN measures the degree to which the individuals' feel a responsibility to engage in energy conserving behaviours. According to VBN Theory the EPN are one of the most important factors. They are influenced by the EWVs and in turn influence both the ECBs and the BIs. The scores for questions relating to EPN should be consistent with those for EWV, ECB and BI.

Table 6 VBN - Environmental Personal Norms Results (Part A)

	Question	Mean (x)		Standard Deviation (σ)	
	What I think about energy: (EPN)	*NB*	*R*	*NB*	*R*
14	Conserving energy and natural resources is important to me	3.06	3.23	0.94	1.01
16	I have a responsibility to conserve energy and resources	3.19	3.41	0.99	1.03
17	XX School should conserve energy	3.94	3.81	0.92	0.92
18	I should help XX School conserve energy	3.14	3.27	1.05	1.02
	AVERAGE	**3.33**	**3.43**	**0.98**	**1.00**

Table 7 VBN - Environmental Personal Norms Results (Part B)

	Question	Mean (x)		Standard Deviation (σ)	
	What I think about energy: (EPN)	*NB*	*R*	*NB*	*R*
15	Conserving energy is not my problem	2.51	2.66	0.96	1.09

The responses indicate environmental attitudes that are slightly positive. As has been the case throughout the study the pupils' responses do not vary significantly. The strongest belief is that the school should conserve energy. This has been a consistent message throughout the investigation into the pupils' attitudes toward energy consumption. In this part of the survey they say they believe they should help and that it is their responsibility to do so. Question 15 shows consistency with the other questions in this part of the survey. A lower score indicates the pupils disagree with the statement, therefore they think conserving energy is their problem. Being able to build on these responses will be vital if the school management are to reduce their electricity consumption.

This survey has shown that there are many opportunities for the pupils to reduce consumption. As a holistic approach is needed to change each of the factors incorporated in VBN Theory, it should be possible to achieve real and lasting change. The results of the surveys also agree with what was found in the workshops; that although the pupils are the greatest population in the school, they have limited influence on the control of many of the energy consuming behaviours. This means the staff are more likely to influence the consumption levels. For a FM Company trying to change the behaviour of the users this is advantageous. As the Company is contractually bound to the Council there is a joint responsibility to reduce consumption.

4. Summary of the findings

The analysis could be divided into two broad areas. Firstly, a confirmation that one school was showing a reduction in electricity consumption, and secondly an investigation of the pupils attitudes and behaviours. The analysis of the energy consumption profiles clearly proved that the New Build School had significantly reduced its electricity consumption compared to the same period in the previous year, whereas the Refurbished School had not. The latter area of the investigation was the analysis of the pupils' perceptions of energy. This involved workshops aimed at identifying where pupils perceived energy to be wasted in the school; who they thought was responsible, and what could be done about it. The pupils felt they had very little influence on the electricity consumption, and that it was the teaching staff that had the greatest influence and therefore responsibility to reduce it. They also cited the FM Company as a key stakeholder with significant responsibility towards the reduction.

The workshops fed directly into the surveys that were carried out by a large number of students in both schools. These verified what had been said in the workshops – that they felt they had very little influence on the electricity consumption. But it also showed that although they thought the school should reduce consumption they did not want to change their routine to achieve it. The surveys also showed that the pupils in the New Build School answered in environmentally negative ways compared to the Refurbished School. This was surprising, considering the findings of the consumption profile analysis. The reason for this may be that the New Build pupils are more aware of environmental issues and therefore answered more honestly. The Refurbished School may have suffered from "self-generated validity" (Harrison *et al.*, 1996). This phenomenon should be further explored in future study. Finally, the results of both the schools were consistently lower than that found in the university (Scherbaum study), this suggests ample opportunity to implement strategies to increase the factors that encourage environmentally positive behaviours.

This research set out to identify measures a FM Company can utilise to change user behaviour to reduce electricity consumption in PFI Schools. An extensive Case Study investigation has confirmed that changes in users' behaviours in one school are having a significant impact on the consumption. The research has identified areas where the pupils can reduce consumption e.g. shutting down PCs after use and ensuring lights are off in unoccupied classrooms. It also indicated that the teaching staff have greater influence than the pupils, further research is required to confirm this. By engaging both the staff and pupils in environmentally positive behaviours a FM Company can certainly reduce the Carbon Footprint in school buildings and help the UK Government achieve its Carbon Reduction Target.

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Performance Assessment of PV/T Air Collector by Using CFD

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Abstract

Photovoltaic-thermal (PV/T) air collector, as a device by converting solar energy to electricity and thermal energy at the same time, was assessed by setting up models in the CFD program in this paper. A typical PV/T air collector was composed of glazing covers, PV panel, thermal collector, rear insulation and frame box. Seven models were named and developed after three different aspects, i.e., with or without glazing covers, semi-transparent or opaque PV panels, and air flow directions. Solar radiation on PV panel and thermal collector were pre-calculated and the results were used to input into the CFD program for further simulation. The simulation results were discussed. In general, the air flows in the air passages where its velocity and static temperature increased, however, the static pressure decreased. Maintaining other two variables, the study showed that the unglazed PV/T models would generate more electricity, but less thermal energy than the glazed PV/T models. As to the different transparency of PV panels, the semi-transparent PV panel models would generate more electricity, but less thermal energy than the opaque PV panel models. In terms of the air flow directions, both electricity and thermal energy were highly produced by straight air flow models.

Keywords: photovoltaic, thermal, CFD, electricity, heat

1. Introduction

Solar energy is the most important sustainable energy, which has the potential to meet the whole world's energy needs. The conversion of solar energy to electrical energy and thermal energy has been practiced for many years. By now, the widely used systems are photovoltaic (PV) system and thermal collector (T) system for the electrical and thermal generations, respectively. However, the waste heat from PV panel, high price of both two conventional systems and limited installation space on rooftop of the domestic houses prevent both systems being used simultaneously. An effective combination of both two systems is the photovoltaic-thermal (PV/T) collector system, producing heat and electricity at the same time, which is an advanced technology for the solar energy application. This kind of PV/T collectors has many advantages, i.e., competitive cost, more energy production, better building appearance. (Charalambous et al, 2007)

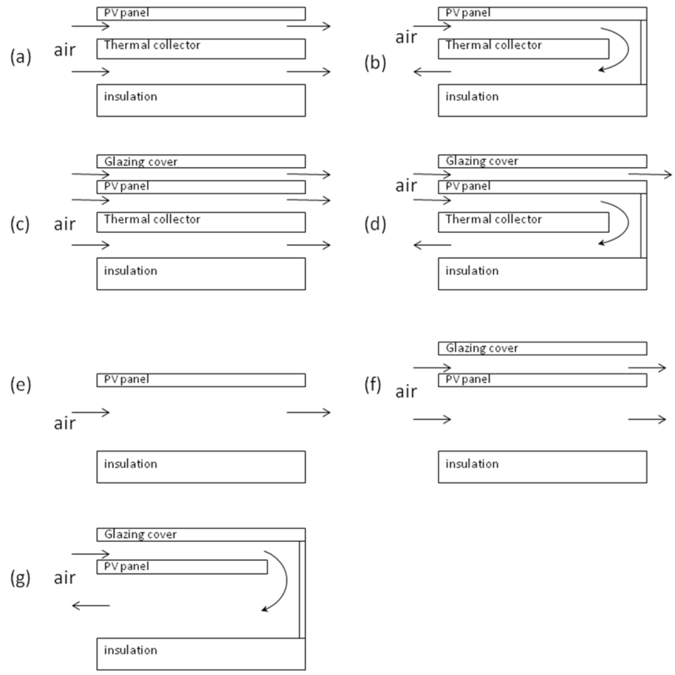
According to the different phase of the working fluid, PV/T collectors can be divided into PV/T liquid collectors and PV/T air collectors. Due to the minimal use of construction material and low operating costs, PV/T air collectors are utilized in many practical applications compared with the PV/T liquid collectors. Until now, many theoretical research and field experiments relating to the performance of PV/T air collectors has been conducted by various authors and has been published in various technical journals.

The aim of this paper is to investigate the performance of seven PV/T air collectors, which were named after with or without glazing cover, the transparency of PV panel (semi-transparent or opaque), and air flow direction (straight or U-shape). Based on flat-plate thermal collectors and photovoltaic panels, these systems were modelled and analyzed by using Computational Fluid Dynamics (CFD) simulation tool. The variation of air flow velocity, static temperature and static pressure were illustrated and the production of electricity and thermal energy were indicated from the simulation results.

2. Description of seven PV/T air collectors

The typical flat-plate PV/T air collectors, constituting of the glazing cover, PV panel, thermal collector, rear insulations and frame materials, are mounted on the rooftop or façades of a building. In general, solar radiation striking on the surface of PV panel, which is upon the thermal collector, is absorbed after transmitting through the glazing cover. Part of the solar radiation will be converted into electricity by PV panel, which, however, will generate heat as a result of its increased temperature. The air passing through the above and under air passages of thermal collector can eliminate the heat. The function of the thermal collector is to cool the PV panel down for more electricity generation and at the mean time produce more thermal energy. The glazing cover, above the PV panel, is to maximize the absorption of solar energy while minimize heat losses from inside to ambient. A metal frame surrounding the system and the rear insulation materials are used to reduce energy losses as well. (Modest, 1993)

The schematic of the proposed seven collectors were shown in Figure 1, which could be named as follows:



(a) Unglazed, semi-transparent PV panel, straight airflow collector
(b) Unglazed, semi-transparent PV panel, U-shape airflow collector
(c) Glazed, semi-transparent PV panel, straight airflow collector
(d) Glazed, semi-transparent PV panel, U-shape airflow collector
(e) Unglazed, opaque PV panel, straight airflow collector
(f) Glazed, opaque PV panel, straight airflow collector
(g) Glazed, opaque PV panel, U-shape airflow collector

Figure 1: Schematic of seven PV/T air collectors

Taking a complicated (d) model as an example to illustrate the structure/configuration of this system, the components of the model and the overall size were shown in Figure 2, the assumption of weather conditions and the geometrical parameters of the components were shown in Figure 3.

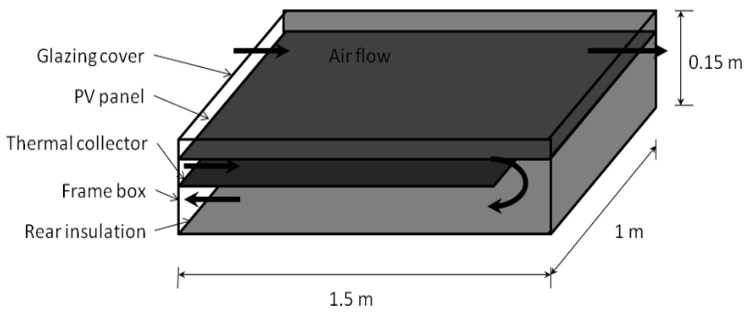


Figure 2: (d) model: system structure and overall size

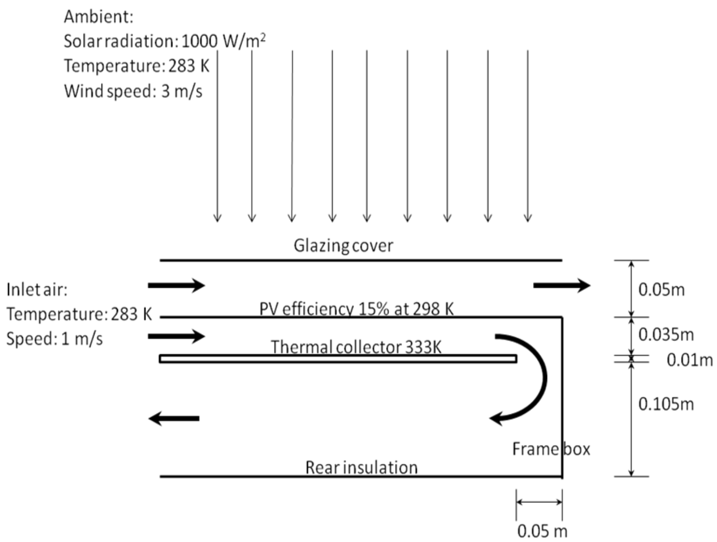


Figure 3: Weather conditions and geometrical parameters of (d) model

3. Mathematical analysis and computer model set-up

In order to use CFD for simulation, two major processes, i.e., solar radiation converted to electricity using PV panel and thermal energy using thermal collector, should be examined. These processes could be illustrated as follows:

3.1 Solar radiation converted to electricity using PV panel

When the solar transmittance of the glazing covers was assumed to be 0.92 for unglazed models and 0.84 for glazed models (Tonui and Tripanagnostopoulos, 2007), the optical and thermal parameters of glazing cover and PV panel were shown in Figure 4.

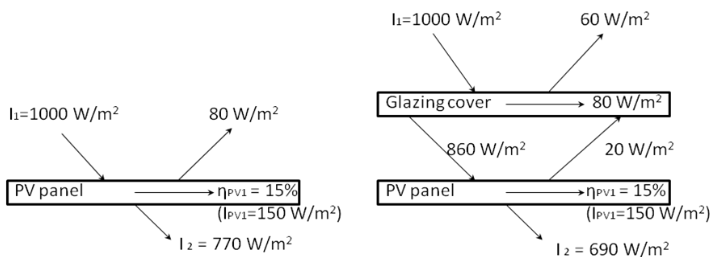


Figure 4: Optical and thermal parameters of glazing cover and PV panel for unglazed and glazed models

Therefore, the solar radiation arriving at the PV panel for the unglazed type and glazed type were 920 and 840 W/m^2, respectively, by deducting the solar radiation absorbed and reflected. The electrical efficiency of PV panel was assumed to 15% at the standard condition with temperature at 15 ^{o}C and the solar radiation at 1000 W/m^2. Therefore, the solar radiation converted to electricity on PV panel surface would be 150 W/m^2. That left 770 W/m^2 and 690 W/m^2 for the thermal energy generation, respectively.

3.2 Solar radiation converted to heat using thermal collector

One hypothesis of this system was no air leaks as the whole system was perfectly sealed, which meant that there were no energy losses.

Energy can be transferred by three means, conduction, convection and radiation. However, as the thickness of PV panel was small, therefore, the conduction can be omitted.

The convective (W_{con}) and radiative (W_{rad}) heat flux can be expressed as follows, respectively (China Tianjin Chemical Engineering Staff Room, 1983):

$$W_{con} = \frac{t_{PV} - t_{air}}{1/h_{con} A_{PV}} \quad (1)$$

$$W_{rad} = \frac{t_{PV} - t_{air}}{1/h_{rad} A_{PV}} \quad (2)$$

Where t_{PV} (PV panel surface temperature), t_{air} (air temperature) and A_{PV} (PV panel surface area) could be considered as fixed. Therefore, the energy flux had a direct relation to the heat transfer coefficient (h_{con} and h_{rad}), which was illustrated below.

Taking the unglazed PV panel (a) model for example as shown in Figure 5, the convective heat transfer coefficients, h_{con}, could be expressed in Eq. (3), when the air flowing over the PV panel and Eq. (4) when the air flowing in the air passages under the PV panel, according to Taine and Petit (1993).

$$h_{con,PV2} = 5.621 + 3.912 v_{air} \quad (3)$$

$$h_{con,PV3} = 0.029 \mathrm{Pr}^{1/3} \mathrm{Re}^{0.8} \lambda_{PV} / L_{PV} \quad (4)$$

Where v_{air} was the air flow velocity across the PV panel, λ_{PV} was the thermal conductivity of the PV panel and L_{PV} was the length of the PV panel in the air flow direction. Re and Pr were the Reynolds and Prandtl number shown in Eq. (5) and Eq. (6), respectively.

$$\mathrm{Re} = \frac{v_{air} D_{PV} \rho}{\mu} \quad (5)$$

$$\Pr = \frac{\mu C_p}{\lambda_{PV}} \qquad (6)$$

Where D_{PV} was the hydraulic diameter of the air passages under the PV panel. ρ, μ, C_p were the air flow parameters related to temperature, representing the density, dynamic viscosity, and specific heat capacity.

The radiative heat transfer coefficient, h_{rad}, could be expressed as follow by using the same equation:

$$h_{rad} = \sigma\varepsilon(t_{PV}{}^2 + t_{air}{}^2)(t_{PV} + t_{air}) \qquad (7)$$

Where σ was the Stefan Boltzman constant at $5.67*10^{-8}$ $W/m^{2}\cdot K^4$ and ε was the emissivity of the PV panel.

Therefore, the heat transfer coefficient could be described as the sum of convective and radiative heat transfer coefficients, which was illustrated below in two different conditions:

$$h_{PV2} = h_{con,PV2} + h_{rad,PV2} \qquad (8)$$

$$h_{PV3} = h_{con,PV3} + h_{rad,PV3} \qquad (9)$$

So the thermal efficiency under the unglazed PV panel, η_{PV3}, can be expressed as:

$$\eta_{PV3} = \frac{h_{PV3}}{h_{PV2} + h_{PV3}} \qquad (10)$$

The solar radiation (I_2) used to generate thermal energy, I_{PV3}, could be expressed in Eq. (11) and illustrated in Table 1:

$$I_{PV3} = \alpha_{PV}\eta_{PV3}I_2 \qquad (11)$$

Where α_{PV} was the transparent factor (0.5 for semi-transparent and 1 for opaque).

In this unglazed case, the solar radiation above the PV panel, I_{PV2}, was 0 as the heat was removed by the ambient air flow.

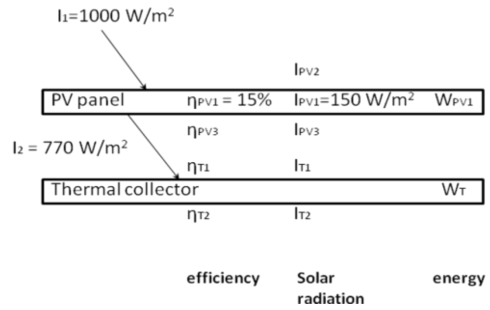


Figure 5: The related parameters of (a) model

According to the equations from (1) to (11), all the solar radiation above and under PV panel (I_{PV2} and I_{PV3}) and above and under thermal collector (I_{T1} and I_{T2}) could also be attained and the results were shown in Table 1 and 2, respectively.

Table 1: Solar radiation above and under PV panel (Units: t (K), D (m), h ($W/m^{2}\cdot K$), I (W/m^2))

	D_{PV2}	Re	$h_{con,PV2}$	$h_{rad,PV2}$	h_{PV2}	D_{PV3}	Re	$h_{con,PV3}$	$h_{rad,PV3}$	h_{PV3}	η_{PV3}	I_{PV2}	I_{PV3}
a	*0*	*0*	*17.36*	*5.01*	*22.4*	*0.035*	*4703*	*16.05*	*5.01*	*21.1*	*0.49*	*0*	*187*
b	*0*	*0*	*17.36*	*5.01*	*22.4*	*0.035*	*4703*	*16.05*	*5.01*	*21.1*	*0.49*	*0*	*187*
c	*0.05*	*6719*	*14.94*	*5.01*	*20.0*	*0.035*	*4703*	*16.05*	*5.01*	*21.1*	*0.52*	*168*	*177*
d	*0.05*	*6719*	*14.94*	*5.01*	*20.0*	*0.035*	*4703*	*16.05*	*5.01*	*21.1*	*0.52*	*168*	*177*
e	*0*	*0*	*17.36*	*5.01*	*22.4*	*0.15*	*20156*	*12.00*	*5.01*	*17.0*	*0.43*	*0*	*333*
f	*0.05*	*6719*	*14.94*	*5.01*	*20.0*	*0.15*	*20156*	*12.00*	*5.01*	*17.0*	*0.46*	*373*	*317*
g	*0.05*	*6719*	*14.94*	*5.01*	*20.0*	*0.15*	*20156*	*12.00*	*5.01*	*17.0*	*0.46*	*373*	*317*

Table 2: Solar radiation above and under thermal collector (Units: t (K), D (m), h ($W/m^{2}\cdot K$), I (W/m^2))

	D_{T1}	Re	$h_{con,T1}$	$h_{rad,T1}$	h_{T1}	D_{T2}	Re	$h_{con,T2}$	$h_{rad,T2}$	h_{T2}	η_{T2}	I_{T1}	I_{T2}
a	*0.035*	*4422*	*15.27*	*6.00*	*21.28*	*0.105*	*13266*	*12.26*	*6.00*	*18.27*	*0.46*	*100*	*86*
b	*0.035*	*4422*	*15.27*	*6.00*	*21.28*	*0.105*	*13266*	*12.26*	*6.00*	*18.27*	*0.46*	*100*	*86*
c	*0.035*	*4422*	*15.27*	*6.00*	*21.28*	*0.105*	*13266*	*12.26*	*6.00*	*18.27*	*0.46*	*95*	*82*
d	*0.035*	*4422*	*15.27*	*6.00*	*21.28*	*0.105*	*13266*	*12.26*	*6.00*	*18.27*	*0.46*	*95*	*82*
e	*0.15*											*333*	
f	*0.15*											*317*	
g	*0.15*											*317*	

3.3 CFD model set-up

Seven computer models were set-up by using CFD program after the predicting calculation of the solar radiation on PV panel and thermal collector. The geometrical parameters, weather conditions and factors relating to air flow, illustrated above, would be input into the CFD program for further simulation.

4. Simulation results and discussions

The simulation results, including the analysis of velocity magnitude, static temperature and static pressure, will be explained below. The key factors judging the performance of the system, electricity generation and thermal energy production, will be discussed further.

4.1 Analysis of velocity magnitude, static temperature and static pressure

Taking (d) model for example, the velocity change of the air flow was shown in Figure 6. The air velocity increased along with the air flowing. As to the constraint of the system structure, turbulence was formed at the corner with the lowest air velocity, which was obvious at the right corner where the air circulating under the thermal collector. After that, the air velocity tended to be maintained at constant.

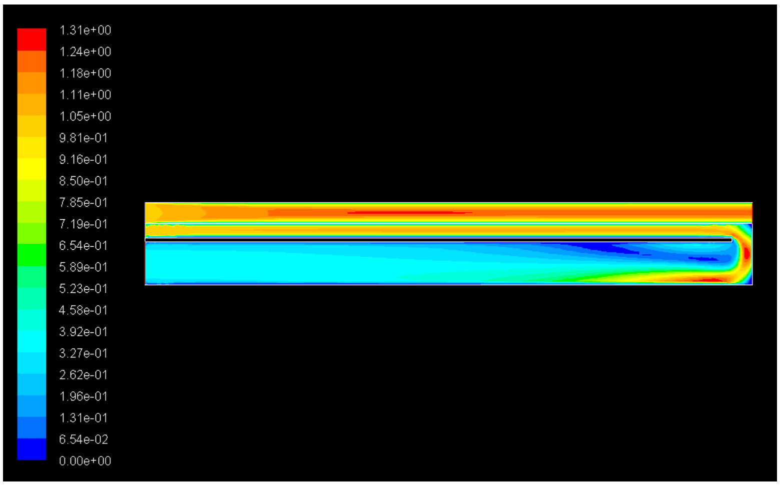


Figure 6: (d) model: image of velocity magnitude

The air temperature increased with the air flowing in the passages, this was because the heat generated by this system was removed by air flow resulting in the air temperature increasing. The air pressure dropped along the air circulating, conversely.

4.2 Analysis of electricity production

The electrical efficiency of PV panel always changed with its temperature. The instantaneous electrical efficiency of PV panel, η_{PV1}, can be expressed as (Godfrey, 2004):

$$\eta_{PV1} = \eta_r (1 - \beta_{PV} (t_{PV} - t_r)) \tag{12}$$

Where η_r and t_r were the reference efficiency and temperature at the standard condition, β_{PV} was the PV panel temperature loss coefficient.

The electricity generated by the PV panel, W_{PV1}, can be expressed as (Wu, 2005):

$$W_{PV1} = \eta_{PV1} I_1 A_{PV} \tag{13}$$

However, in order to maintain the velocity of air flow, part of energy will be consumed by fan (W_f), which can be expressed as (Wu, 2005):

$$W_f = \frac{V_{air} \Delta P}{\eta_f} \tag{14}$$

Where V_{air} was the air volume flow rate, η_f (fan efficiency) was taken as 60% and ΔP was the total pressure drop through the system shown in Eq. (15), including inlet (ΔP_{in}) and outlet (ΔP_{out}) pressure drop caused by air flow velocity and static pressure (ΔP_s) drop from inlet (P_{in}) to outlet (P_{out}), which were expressed at Eqs. (16) and (17).

$$\Delta P = \Delta P_{in} - \Delta P_{out} + \Delta P_s \tag{15}$$

$$\Delta P_{in\,or\,out} = k_{in\,or\,out} \frac{1}{2} \rho v_{air}{}^2 \tag{16}$$

$$\Delta P_s = P_{in} - P_{out} \tag{17}$$

Where $k_{in\,or\,out}$ was the pressure loss coefficient at the inlet and outlet of the system.

The net electricity production, W_{net}, can be described as:

$$W_{net} = W_{PV1} - W_f \tag{18}$$

In this calculation, the average temperature of PV panel and the relevant pressure drops can be attained after simulation as shown in Table 3. The results of net electricity generation were presented in this Table as well.

Table 3: Electricity production

	t_{PV} (K)	η_{PV1}	W_{PV1} (W)	ΔP_{in} (Pa)	ΔP_{out} (Pa)	ΔP_s (Pa)	ΔP (Pa)	W_f (W)	W_{net} (W)
a	*302.135*	*0.1472*	*220.8*	*1.226*	*0.612*	*1.6442*	*2.2582*	*0.56455*	*220.2355*
b	*307.7077*	*0.1434*	*215.1*	*0.613*	*0.306*	*0.905*	*1.212*	*0.0707*	*215.0293*
c	*307.4939*	*0.1436*	*215.4*	*1.839*	*0.918*	*2.4724*	*3.3934*	*1.131133*	*214.2689*
d	*312.741*	*0.1401*	*210.15*	*1.226*	*0.612*	*1.7479*	*2.3619*	*0.334603*	*209.8154*
e	*316.9249*	*0.1372*	*205.8*	*0.613*	*0.306*	*0.2527*	*0.5597*	*0.139925*	*205.6601*
f	*317.0622*	*0.1371*	*205.65*	*1.226*	*0.612*	*1.081*	*1.695*	*0.565*	*205.085*
g	*320.3494*	*0.1349*	*202.35*	*0.613*	*0.306*	*1.4451*	*1.7521*	*0.146008*	*202.204*

From this Table, maintaining two out of three aspects constant and changing only one aspect, the results would be as follows:

For the models with or without glazing covers, it was found that the electricity generation of the unglazed PV panels was higher than the ones with glazing covers. Although the glazing could provide protection for the system, it increased its temperature which minimized the production of electricity eventually.

Comparing the models with semi-transparent or opaque PV panel, it was found that the models with semi-transparent PV panel could generate higher net electricity than the opaque models, this was because the heat generated by PV panel in opaque models were higher than that in semi-transparent models, which increased the system temperature and minimized the capability of PV panel.

About the air flow direction in the models, it was found that the straight flow will eliminate more heat, decrease the temperature of PV panel and maintain a high electricity generation of PV panels than the U-shape air flow models when the air flow velocity constant.

4.3 Analysis of thermal energy production

The thermal energy generated by thermal collector, W_T, could be expressed as follows (Wu, 2005):

$$W_T = \rho V_{air} C_p (t_{out} - t_{in}) \quad (19)$$

The air temperature at the inlet and outlet of the system, t_{in} and t_{out}, were shown in Table 4 with the thermal energy production as well.

Table 4: Thermal energy production

	v (m/s)	V (m^3/s)	t_{in} (K)	t_{out} (K)	Heat recovered	W_T (W)
a	1	0.035	283.0829	293.5174	443.5076	598.8593
	1	0.105	283.0181	284.2364	155.3517	
b	1	0.035	283.0503	295.9069	546.4578	546.4578
c	1	0.05	283.0301	293.9231	661.4242	1233.273
	1	0.035	310.3664	320.3352	423.7135	
	1	0.105	291.8766	293.0383	148.1358	
d	1	0.05	283.0282	293.962	663.8985	1182.493
	1	0.035	283.3918	295.5929	518.5947	
g	1	0.15	283.0336	286.5999	649.6463	649.6463
h	1	0.05	283.0353	293.5208	636.679	1279.624
	1	0.15	283.0058	286.5354	642.9446	
i	1	0.05	283.0788	302.2632	1194.876	1194.876

The variation of thermal energy production with different models can be summarised as follows:

For the comparison of the models with and without glazing, it was found that the one with glazing covers will generate much more thermal energy as to the ability of glazing covers, minimizing the thermal emission, which was thus the key to determine the heat amount.

About the transparency of the PV panel, it was obvious that the opaque models had higher thermal energy generation as the solar radiation was transmitted through the opaque PV panel without the constraint of the materials of PV panel.

About the thermal energy generation with different air flow directions, the straight flow was confirmed as the most efficient way for the heat generation.

5. Conclusion

This paper described seven different models of PV/T collector. CFD program was used to analyse the performance of these models. The major findings could be outlined as below:

For all the seven models, the air velocity raised up gradually as the flow would be enhanced by the structure of the collector. The static temperature increased as the heat generated would be absorbed by the air flow, which would also cause the static pressure decreased along the air flow.

For the models with or without glazing covers, it was found that the unglazed PV panels would generate more electricity than the ones with glazing covers, while less thermal energy. Comparing the models with semi-transparent and opaque PV panel, it was found that the models with semi-transparent PV panel could generate higher net electricity than the opaque models, while produce less thermal energy as well. In terms of the air flow directions in the models, the straight air flow models would generate more electricity and more thermal energy than the U-shape models.

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The Implementation of Condition Monitoring Techniques for the Automated Generation of Display Energy Certificates

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Abstract

The amendments in Approved Document L (Part L) have had a significant impact on the building industry. Monitoring energy consumption and provisions for a logbook are all now mandatory by Part L, additionally further legislation has been implemented that require building owners/operators to demonstrate the energy performance of the building via Energy Display Energy Certificates (DEC). The DEC is only applicable for public buildings with a useful floor space greater than 1000m2; this requires the use of metering data for production of the energy performance of a building. DEC are updated every 12 months, however, in the period between inspections serious degradation in performance could occur only to be uncovered at the next site-based inspection. A more preferable solution would be to monitor the building in real time be alerted to faults or poor performance before they become a serious problem. Condition Monitoring (CM) is the process by which the state of a system is determined by monitoring the parameters that are indicative of its health. The increased levels of monitoring as stipulated by the amendments in Part L now provide the opportunity for introducing CM techniques for building energy performance monitoring. CM would highlight inadequate performance via benchmarking as well as informing the end user of potential maintenance faults via the signals monitored. An automated system would eliminate the need for the time and cost intensive process of generating a manually audited DEC. This paper outlines a CM methodology utilising a numerical covariance analysis technique to evaluate building performance and perform fault detection and diagnosis based upon the energy consumption and external temperature.

Key words: Energy Performance, Buildings, Maintenance, Condition Monitoring, Display Energy Certificates

1. Introduction

The reduction of carbon emissions has become a prevalent issue within developed and developing nations; beginning with the Kyoto Protocol participating states have been set the challenge of reducing CO2 emissions (UNFCCC 1997). The challenge to reduce carbon emissions within the building industry is a significant factor in lowering the overall production of CO2 given that the building sector is the second largest contributor of emissions after the transportation industry with 30% of carbon emissions being generated by buildings (CIB 1999). The commitment to Kyoto and other CO2 reducing initiatives (Defra 2002) have led to the implementation of several legislative changes for the building industry in the UK. As of April 2006 amendments in Approved Document L: Conservation of Fuel and Power (Part L) came into force enforcing the use of Target Emissions Rates (TER) as a benchmark for building performance (Regulations 2006). Furthermore, the recent consultation for Part L 2010 has aimed for even further reductions in CO2 emissions (Government 2009). A key feature of the Part L legislation amendments is the requirement of building owners to account for 90% of energy consumed within commercial buildings. In essence, monitoring of energy consumption is essential for the illustrating and improving of energy performance, without adequate monitoring poor performance is difficult to track and isolate.

In addition to the previously mentioned legislations further performance monitoring initiatives have been introduced, public buildings with a floor space of greater than 1000m2 must now produce a Display Energy Certificate (DEC) illustrating the energy performance of the building (Government 2008). The DEC utilises metering information to compare against typical building based upon the building type and function with a grading system that relates performance into a categorical band. Whilst DEC's are useful for illustrating the performance of a building the auditing process takes place annually, this leaves a significant period of time in which degradation of building performance can occur. Additionally, maintenance faults in the HVAC (heating, ventilation and air conditioning) systems can lead to an increase in wasted energy. Fault detection and early remediation can aid in keeping the energy consumption at the optimal level. It is the opinion of the author that in order to improve building efficiency in the long term, it is necessary to continually audit energy performance.

Condition Monitoring (CM) is process by which the health of a system is derived by measuring/monitoring the parameters that are indicative of the health of the system (Rao 1996). This provides the opportunity to take advantage of the greater levels of metering made mandatory by the amendments to Part L for use as 'health monitoring parameters', allowing for the implementation of an automated system of auditing the energy use of a building in relation to its pre-defined benchmark. Building Energy Management Systems (BEMS) are typically installed in the majority of sizeable commercial buildings, with the primary function of the BEMS being the regulation of the internal environment via the building services systems to maintain occupant comfort. Most commercially available BEMSs possess the ability to log and store data from meters from which analysis can be performed.

2. Application of condition monitoring to building energy performance

The development of condition monitoring methodologies and techniques originated in the manufacturing industry, primarily focussing on signal analysis from manufacturing equipment, the aim of which was to reduce machine downtime and predict costly failures before they occurred. Faults and failures in the majority of technologically dependent industries incurs undesirable cost penalties, CM provides a non-destructive means of the analysing the ‘health’ of equipment whilst delivering the end user with key information on the state of the system. CM has grown in popularity and spread outside the realms of manufacturing into sectors such as the rail and aerospace industries. Traditionally, the monitored parameters were measured using a wide variety of techniques ranging from vibration monitoring to oil wear debris analysis. In its application to the building industry, the monitoring technique shall log process measurement signals. Process measurement signals are those data streams generated by sensors and other systems that relay information about the given system, in the case of DEC’s the metering data forms the main measured parameter. DECs are compiled using energy meter data from the target building, given that the benchmark is also reliant on weather data this shall also be taken to be a the second key process parameter.

Further to CM techniques, CM strategies are an integral element of any CM methodology, these systems, detect and diagnose faults based upon the signals. CM strategies can be placed broadly within 3 categories Knowledge based, Numerical/data driven and model based approaches (Isermann 2005). For the purposes of this paper, Numerical system shall be used to analyse the measured parameters for fault detection whilst a Knowledge Based System shall provide diagnostics. Numerical systems work well at levels with large amounts of data and given the lack of additional points of reference (i.e. sensor data, control information) a Model based analysis would be inappropriate.

Given that DEC’s are based primarily on energy consumption but also takes into account external weather conditions, hence a co-variance numerical analysis system shall be employed as set out in figure 1 shall be utilised.

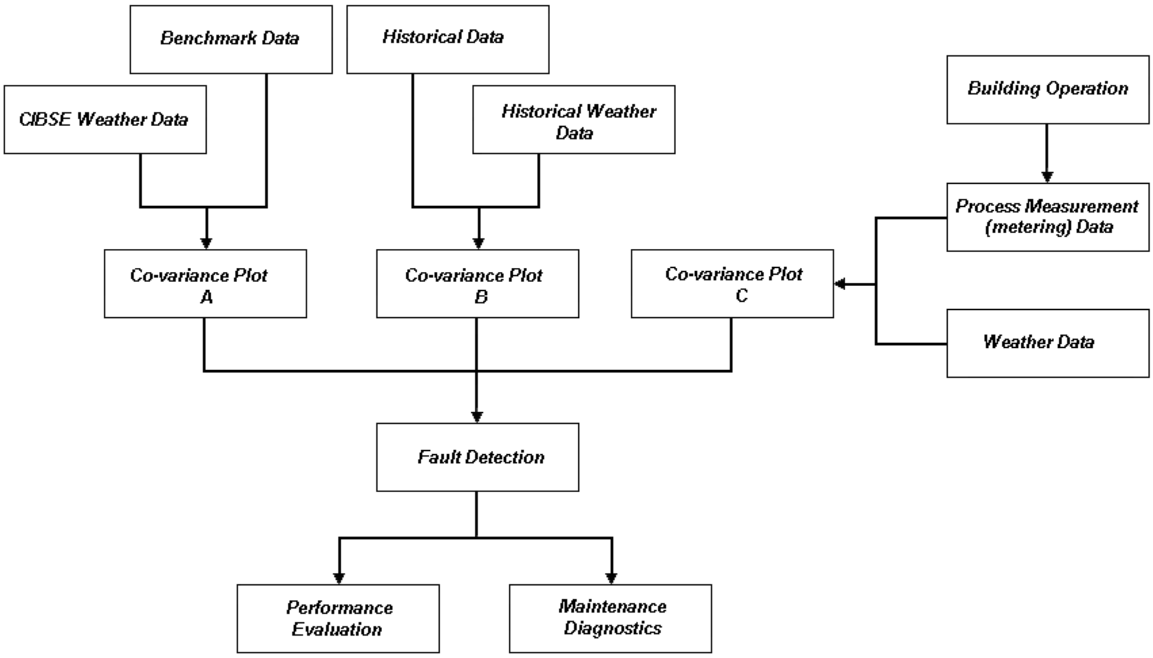

Figure 1 – Condition monitoring overview

The utilisation of process measurement and pre-prepared data allows for automation in the evaluation of performance and maintenance fault highlighting. The current performance is evaluated against the historical (previous year) performance and the benchmark performance. The majority of commercial Building Energy Management Systems (BEMS) have the ability to log data streams such as the past and current energy consumption. Additionally, given that most HVAC plant schedules are based upon the external conditions, outside air temperature is typically logged as well. This allows the covariance analysis tool detect and abnormalities in the current performance. In addition, the actual energy consumption can then be utilised to provide a DEC grading along with potential problems and a theoretical rating of the building should the stated problems be resolved. Maintenance and areas of performance improvement can be delivered through the use of Expert System diagnostics that utilise the process parameter information to deliver a meaningful output to the facilities management for corrective maintenance. However, it must be stated that in utilising the metering/external temperature data as the only process parameter measurement will not allow for in-depth diagnostics hence the output shall primarily be an advisory notice for the facilities management on potential problems that are/could (with extrapolation) cause problems both currently and in the future.

3. Methodology

The application of co-variance analysis for building energy performance evaluation requires the utilisation of the key process measurement data streams, the real-time metering data, historical performance data (addressing the issue of typical external weather conditions) and the Target Emissions Rate (TER) as derived from the governmental standards set out in the legislation. Covariance analysis is limited to measuring the correlation between two data sets and as such can be beneficial in simple aspects of the model, for example, measuring the magnitude of the deviation between the current energy performance and the historical BEMS data (expressed below)(Wildt 1978).

$$Cov_A(B,CW) = \frac{\sum_{i=1}^{n}(B_i - \overline{B})(CW_i - \overline{CW})}{n-1} \quad \text{(EQN 3.1)}$$

$$Cov_B(H,HW) = \frac{\sum_{i=1}^{n}(H_i - \overline{H})(HW_i - \overline{HW})}{n-1} \quad \text{(EQN 3.2)}$$

$$Cov_C(P,WD) = \frac{\sum_{i=1}^{n}(P_i - \overline{P})(WD_i - \overline{WD})}{n-1} \quad \text{(EQN 3.3)}$$

Where the first term of each covariance equation contains the energy consumption (kgCO2/m2) and the second term is the external temperature (oC). B, H and P represent the benchmark, historical and measured process metering parameter respectively. Whilst CW, HW and WD represent the CIBSE, historical and measured weather data respectively. Terms with an overscore indicate the mean value of the data set.

Equations 3.1-3.3 sets out the covariance equations utilised to analyse the trends between energy consumption and weather data in three separate cases. The total number of sample points (n) is to be previous 30 days worth of samples to provide accurate analysis. Typically, BEMS log data at 15 minute intervals, this is sufficient for the purposes of analysis since the rate of change is relatively low. The covariance equations signal correlation between the two variables, a value of 1 means that both variables are increasing or decreasing together; whilst a value of -1 indicates a divergence (a value of zero indicates no correlation).

Comparison of the energy consumption with the external conditions effectively standardises the analysis between each co-variance set, given that other factors such as occupancy is already accounted for within each set of data (consumption trends are relatively predictable for office/school buildings) it allows each covariance set to be compared like for like.

3.1 Fault detection and detection

The detection of faults can be identified as deviations from the expected range of values for the measured parameters. Deviations in energy consumption due to external weather conditions is the most likely cause for false alarms, hence by analysing the variation in the trend against external temperature it is possible to ensure that acceptable increases in consumption are not falsely labelled as faults. Aside from analysing the total energy consumed, the additional monitoring provides for the means of plotting of additional covariance plots for example figure 2 illustrates an example covariance plot between the external temperature and heating energy consumption, as would be expected; during the colder periods there is a clear correlation between the colder external temperature and increase in heating system load. The flat lines represent the weekend periods where the heating system is not utilised. The increase in co-variance value illustrates the increase of energy consumption during the occupied periods (08:00-16:00hrs), whilst the decreasing value indicates the time in which the building is not in use and the HVAC systems are not utilised (16:00 – 08:00).

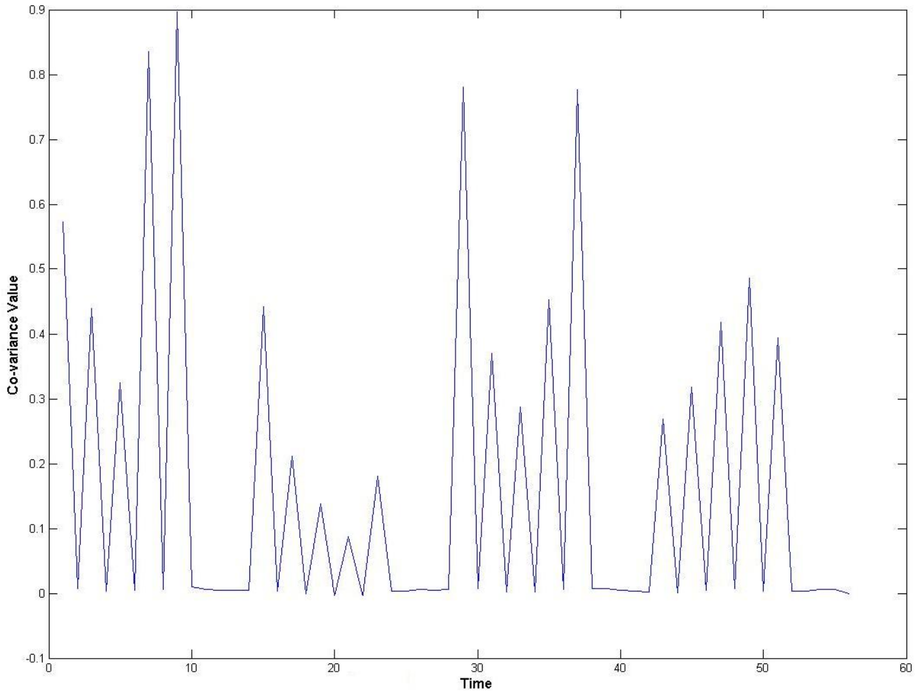

Figure 2 - Covariance analysis performed for January weather data

Whilst diagnosis can be performed, further process signals would be required to provide a confident diagnosis, hence only recommendations can be made in which areas could possible causing excessive consumption and where faults are possibly occurring. Fault data was introduced into the January heating load data set giving producing the following negative value of co-variance as shown in figure 4.

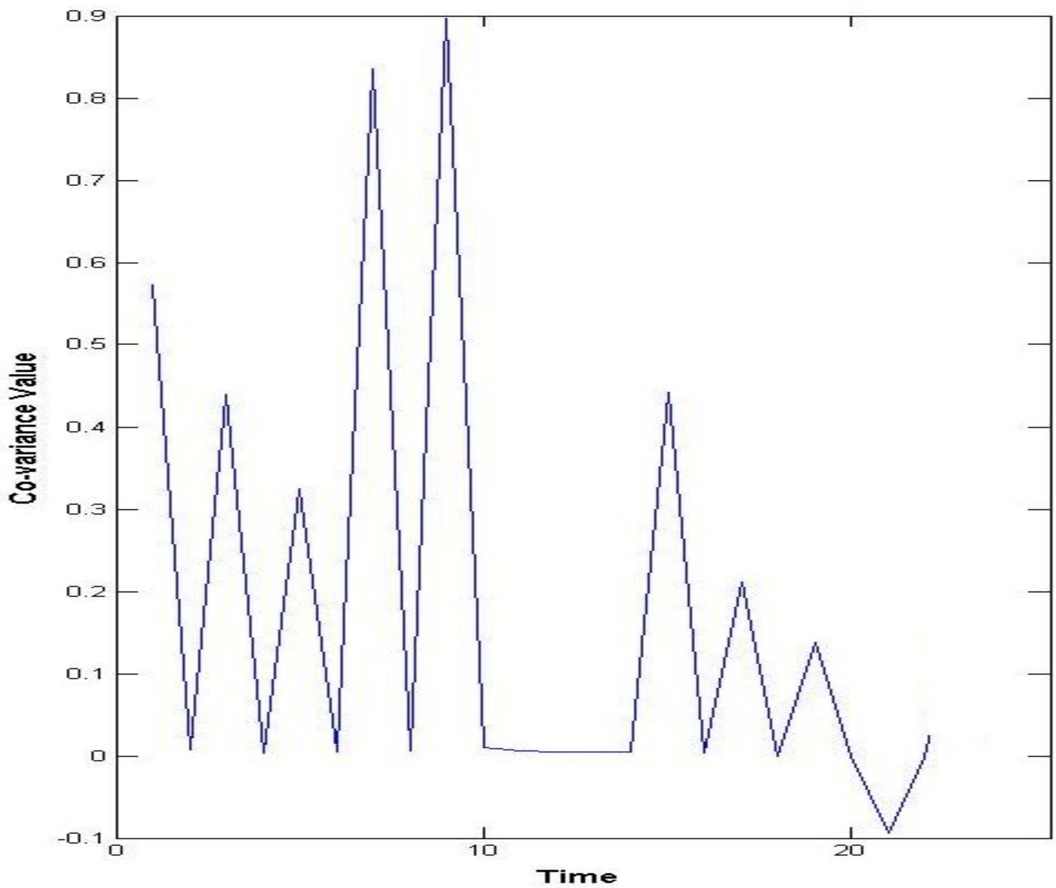

Figure 4 - January co-variance analysis with fault data

In the case of the divergence in figure 4 an expert system could be employed to perform rudimentary diagnostics, expert systems encapsulate human knowledge via a set of inference rules which is converted into software code as IF/ELSE/THEN statements. Typically, the end user provides information to the system from which an output is produced that would mirror an expert in that field. However, to provide a fully automated system rules can be pre-defined to utilise the covariance data points as shown:

NegativeCoVARcounter;

IF CoVAR<0 AND NegativeCoVARcounter>2
Output = Fault Occurred
ELSE
Output = Heating system operational
END

The divergence of energy consumption during colder period highlights a potential fault, the creation of seasonal profiles allow for the detection of faults throughout the year. For example, a prolonged increase in temperature with rising external temperature (surpassing the set point) during the summer period could indicate a faulty sensor or control system.

3.3 Performance evaluation tools

To evaluate the energy performance energy consumption a two step process can be implemented, firstly comparisons can be made with both historical and benchmark data. The covariance analysis determines the level of change between consumption and weather data, by creating adjusted data sets for all three consumption patterns a means is provided to account for variations for external temperature changes. Hence in cases where energy consumption is noticeably higher per unit change of temperature it can be deemed that the building is underperforming. Figure 5 illustrates an example of the use of adjusted data sets for comparison of current energy consumption.

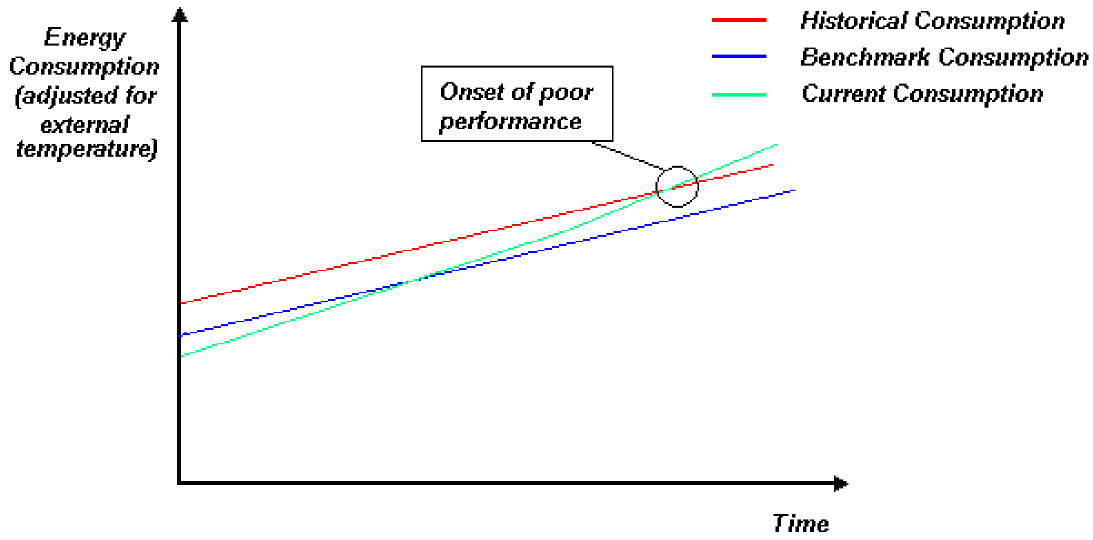

Figure 5 – Performance evaluation compared to benchmark and historical performances

The second performance evaluation tool makes use of the ability to account for external conditions by introducing a varying threshold, the threshold bands provide scope for acceptable variations outside of which are considered to be exceptional or poor performance (lower and upper bands respectively). Figure 6 illustrates the variable threshold adapting to external conditions in the first case of increased energy consumption, whilst in the second case the increase of energy consumed is not caused by changes in external conditions and hence breaches the threshold and can be said to be using excessive energy.

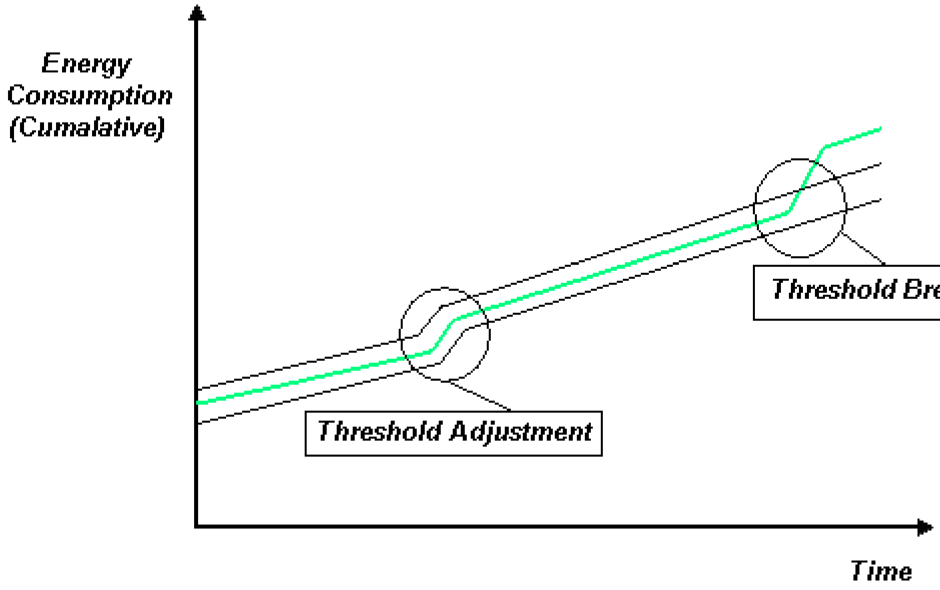

Figure 6 – Performance evaluation with variable threshold

The use of these two performance evaluation tools allow for cross correlation in determining the output, to ensure accuracy both indicators would be used to make a final evaluation of the performance. It must be noted the first evaluation tool is dependent on the historical performance being fault free, in such cases further analytical tools (outside the scope of this paper) could be employed.

4. DEC generation

The grading system of the DEC is based upon the Operation Rating (OR) of the building under consideration, which is based upon the energy consumed over the period of one year. The OR is based on the assessment of building performance compared with a typical building based upon its size and function shown in equation 4.4.1 (Government 2008):

Operational Rating = (BER/Building Area)*(100/Typical CO2 emissions per unit area) (EQN 4.4.1)

OR's that achieve a value between 0-25 are A graded, whilst 26-50 is a B grade and so on. To ensure an fair and appropriate comparison there are several factors that can be adjusted within the calculation process. For the purposes of this paper the relevant factors that would need to be taken into account for automated DEC generation include (Government 2008):

- Weather Data
- Occupancy rates
- Proportion of non-electrical energy used

In the methodology described previously the automated OR rating would be calculated based upon the previous 30 days of energy consumption, allowing for continuous real time performance evaluation. As part of the automated energy evaluation, the integration of such features is not foreseen to be problematic, with the end user initially setting the appropriate information for the typical building calculation.

4.1 Example DEC

Implementation of the previously detailed methodology would aim to provide an improvement to the current system. Figure 7 illustrates a possible output to the end user as opposed to a static certificate currently issued.

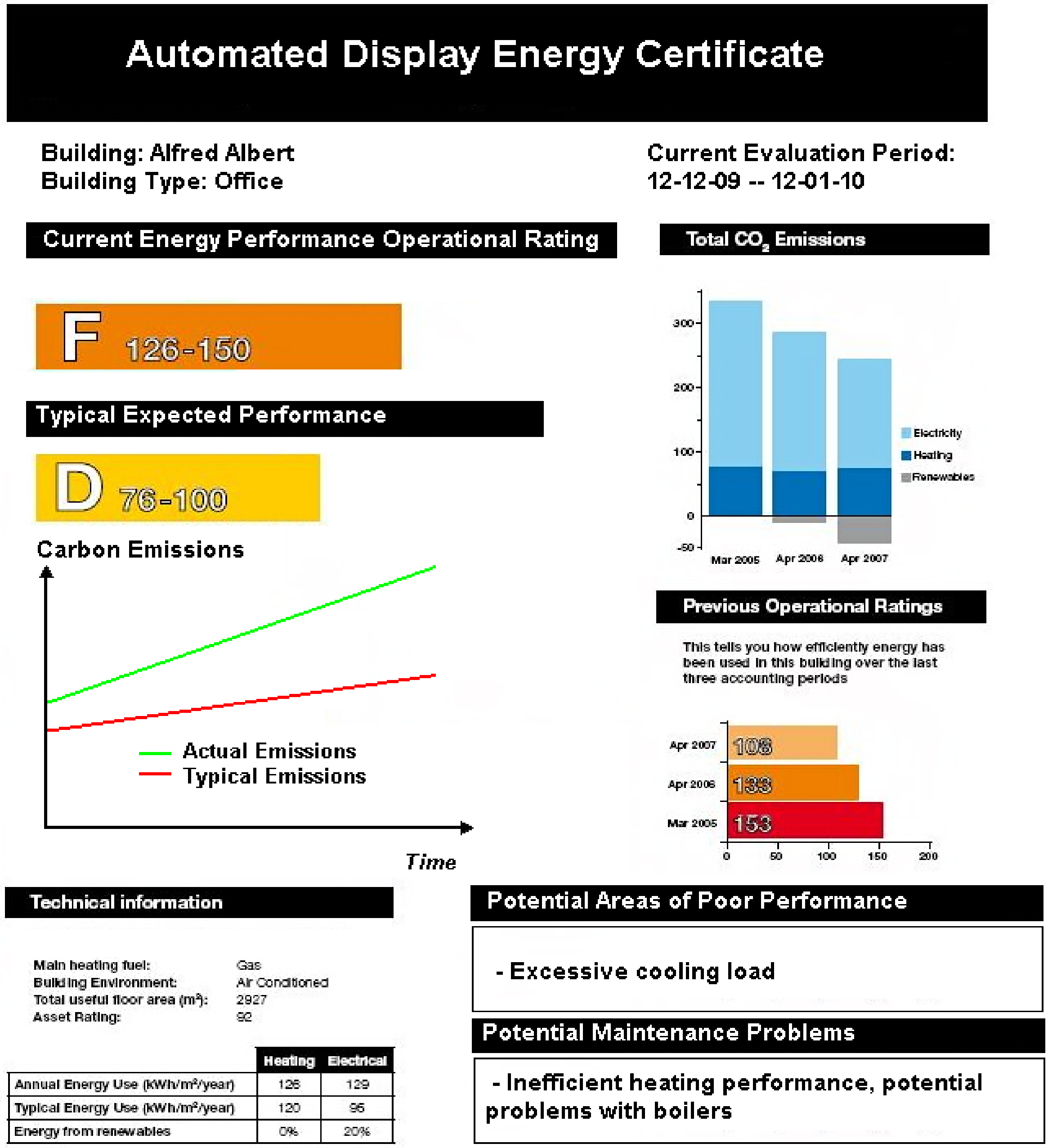

Figure 7 – Example automated DEC (amended from (EU 2009))

5. Conclusion

This paper details a methodology for providing real time energy performance evaluation with maintenance fault highlighting. This paves the way for improving the current system of energy auditing, namely the Display Energy Certificate. Poor performance and faults with the HVAC can be identified with remedial action taken before excessive energy is wasted or occupant comfort compromised. Whilst the numerical analysis is relatively simplistic, it can provide a surface level diagnostics system for the facilities management. Furthermore, the continuous performance evaluation provides the opportunity to not only utilise the extra metering for the very purposes it was made mandatory but to also provide a alternative method to the cost and time intensive method of calculating the DEC. Modern BEMS provide an graphical interface for the end user and with appropriate software amendments the monitor can be utilised to display the self updating DEC.

6. Further work

The next natural evolution would be to employ a system such as Principal Component Analysis (PCA); PCA itself has gained popularity in recent years for the function of providing FDD for HVAC plant. Additionally, the implementation of a pattern extrapolation algorithm will allow for future trend plotting and prognostics of building performance and maintenance requirements.

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Considering the risk factors of reliability, maintainability and product life cycle in a Zero Carbon commercial building

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Abstract

The increased mechanisation of buildings towards the goal of achieving Zero Carbon can be expected to yield certain consequences. This paper was required to investigate the risk associated with the heavy technological load in a building designed to meet the UK 2016 target of Zero Carbon. There is significant motivation for such considerations as the creation of a Zero Carbon building can not only expected to require significantly more investment than a traditional alternative, but the long term financial and environmental benefits will be made redundant if the technologies used fail to function correctly. The case study building was taken from a study into strategies for achieving Zero Carbon performance in commercial buildings in the North West of England. Two solutions from that study were considered in terms of the reliability, maintainability and life cycle of their key sustainability related systems. The paper focuses on comparing the difference in maintenance requirements and anticipated failures between a passive design strategy and a mechanical alternative. This was carried out through building simulations that calculated both the anticipated emissions for each of the strategies and the risk of overheating within the offices themselves. Consideration was given to the potential consequences of failure, including loss of desired user environment, financial and environmental repercussions. The study demonstrated that there is a relatively high risk of additional maintenance issues and increase in components to any reliability analysis when striving for zero carbon performance. It also demonstrated that some of the more passive measures such as the increase in building fabric performance, could increase the severity of the repercussions of failure in the case of a loss of cooling. The paper reflects the need for reliability, maintainability and product life cycle to be considered a major constraint when working towards

performance improvement in buildings and in the allocation of renewable energy generation and that the approach of the building designers and their relationship with a completed building may have to change to accommodate this fully.

Keywords: reliability, maintainability, overheating, zero carbon, commercial

1. Introduction

The need to reduce the energy demand of buildings in order to lower their carbon footprint has become a key issue in modern building design. One benchmark which has received significant interest is that of a building which performs at Zero Carbon in operation. The UK government has set the target in the Part L 2010 Consultation (2009) that all new commercial buildings will achieve this level of performance by 2019 (p.6(1.9)). There are several definitions for this term however for the purpose of this paper the definition employed was that found in CIBSE Guide L (2007). It states that Zero Carbon performance in a building is achieved by a net emission of zero over a calendar year. In practice this means that all energy demand is either met via carbon neutral generation or offset by additional carbon neutral generation to an equal value of the demand (p.9).

In order to achieve this level of performance, building design strategy has been modified to place an increasing emphasis on demand reduction and on site micro-generation. In early examples of buildings which attempted to attain Zero Carbon status the methods used were often non-cohesive and employed untested or uncomplimentary technologies. Clarke et al (2008) asserted that many such attempts were found to be performing at standards well below those laid out in the original designs and simulation results. These findings are also supported by Hinnells (2008) and Glass et al (2008). As such there was perceived to be a need for a more rational and structured set of design parameters that would allow buildings to be designed to favour the reduction of demand and, if necessary, the incorporation of micro-generation in such a way as to succeed in practice. This need for a rational strategy ties the research to the demands of industry, meaning that the numerical definition of Zero Carbon performance must also come from a practical source. In the United Kingdom the emissions are assessed using the National Calculation Method (NCM) as stated in the Approved Document L2A (2006). The building design is modeled and the carbon consumption measured as the Building Emissions Rate (BER) which is then compared to a Target Emissions Rate (TER) which is found by the generation of a notional building of the same dimensions to the 2002 Building Regulations and modified by improvement factors (p.14(23)).

$$TER = C_{notional} \times (1 - \text{improvement factor}) \times (1 - \text{LZC benchmark})$$

Compliance when: BER<TER

Units of BER/TER mass of CO_2 per year per square metre useful floor space ($kg/m^2/yr$) from L2A (2006) (p.14(23)).

A second factor that is of increasing relevance is that of reliability, maintainability and product life cycles. A rational building designer must not only consider the new technologies and design strategies available to improve performance but also the repercussions. The failures observed by Clarke et al (2008) can not only be attributed to poor design methodology. The increased mechanisation of buildings and the use of generation technologies attach a new level of risk to the performance of the building while in use. Each of these new technologies used offers new points of failure and this study was conducted to assess the potential repercussions of applying a zero carbon strategy to a typical office building. The areas of interest were the implications of an increased reliance on the control of internal temperatures via mechanical means rather than by passive design choices (a byproduct of highly insulated and sealed buildings), the risks associated with micro-generation and whether these factors should influence the targets of the low impact building designer and the decision to strive for zero carbon performance.

The study employs a case study building generated within the IES Virtual Environment software which was used to explore the design choices stated above. This was done through a combination of Building Regulations compliance tests and overheating tests. The results of the testing are then examined in order to consider their impact on the reliability and maintenance demands of the building as well as the repercussions of failure.

2. Methodology

2.1 Case study

For the purpose of this study a theoretical building was created that matched the requirements of the strategies to be tested. A simple two storey shallow plan office block was selected so as to allow both a passive and mechanical ventilation strategy to be explored. The building was given a south facing orientation so as to make use of daylight for both light and heating. This method has been described as one of the few proven methods for reducing heating and lighting loads within a low impact building as observed by Andrews et al (2009). Additionally, as noted by Hinnells (2008), it is a factor which the building services engineer (who is often charged with reducing energy demand) can have little control over. The need to control this passive input is a major factor in determining whether the building will require cooling or shading, with the former being another mechanical system which must be considered and the latter a passive design choice which will not. The geometry for this model was derived from the DEFRA's Lion House building which Jones (2009) describes as carbon neutral in operation over a year (which meets the definition of Zero Carbon within this study) through a similar design methodology of demand reduction to that employed within this study. In order to achieve Zero Carbon performance the DEFRA building used both Photovoltaic arrays and micro wind turbines to offset that demand which could not be removed. With this building being a market leader in the UK in terms of performance it was considered appropriate to use this selection of renewable energy sources as the offsetting strategy for this case study. This decision offers two points of interest. If the final performance for either strategy is approaching zero carbon then the methodology itself will be demonstrated to be successful within the capacity of what is considered currently attainable. Additionally, it offers a clear example of the type and size of renewable energy sources required when considering the additional risk that they provide as further technologies that can potentially fail.

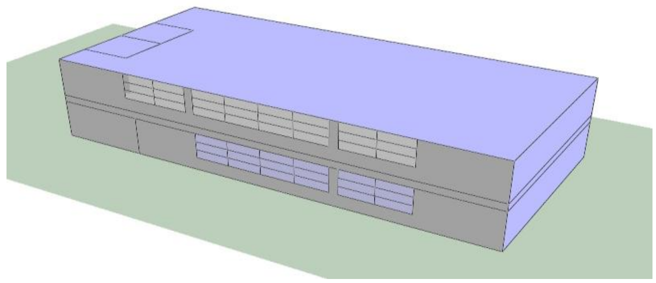

Figure 1: Basic geometry of case study for both naturally and mechanically ventilated strategies.

The image depicts the geometry employed in the case study, with the key features being a ground floor office of 278 m^2 and a first floor office of 294 m^2. Each floor is 2.7m in height with a building depth of 6m and a length of 26m. High thermal mass insulation was used due to the regular hours that the office would be occupied. These hours were assumed to be 0800 – 1800 with a one hour lead in time for heating and cooling (if in place). The building was located in the North West of England due to its part in a larger study within the area. As such the climate was represented by the Test Reference Year (TRY) for Manchester. The key parameters of the building design are included for comparison with the subsequent performance improvement measures.

Table 1: Key Parameters for the Basic Office designs with natural and mechanical ventilation strategies.

Parameters	Wall U-value W/ m^2.K	Floor U-value W/ m^2.K	Roof U-value W/ m^2.K	Glazing U-value W/ m^2.K	Heating Eff. %

Strategy					
Nat. Vent.	0.28	0.16	0.22	2.0	89
Mech. Vent.	0.28	0.16	0.22	2.0	89
Parameters Strategy	Cooling	Specific Fan Power W/(l/s)	Fuel	Air permeability @50Pa m^3 /(h. m^2)	
Nat. Vent.	No	-	Nat. Gas	5	
Mech. Vent.	Electric	2	Nat. Gas	5	

The designs within this study were assessed using the IES Virtual Environment software. This suite of building design tools offers both dynamic simulation of building performance and compliance checking using the NCM in conjunction with both dynamic simulation and empirical assessment. For the purposes of the study the dynamic simulation was employed for both the checking of regulation compliance (and as such the calculation of CO2 generation) and for the overheating tests that are integral to confirming that a building offers the required comfort level for its occupants.

The testing of the basic models revealed that both designs were compliant to L2A 2006 Building Regulations as they produced Building Emission Rates below that of the calculated Target Emission Rates. When the overheating tests were ran using the Design Summer Year (DSY) climate file (which represents a hot summer) it was found that neither mechanical ventilation nor a window opening strategy could provide sufficient cooling. CIBSE Guide A (2006) recommends that no office should be used if it experiences more than 30 hours of occupied time at over 28°C (p.1-11). As such, modifications were made to both the naturally ventilated and mechanically ventilated designs. The naturally ventilated option was provided with shading over the south facing windows in keeping with its passive design ethos. The mechanical ventilation was supplemented by simple cooling. Each design choice has its own perceived advantage, with the passive option still requiring only a heating unit for winter temperature control where the mechanical option will have a lower winter heating demand balanced by a summer cooling energy demand.

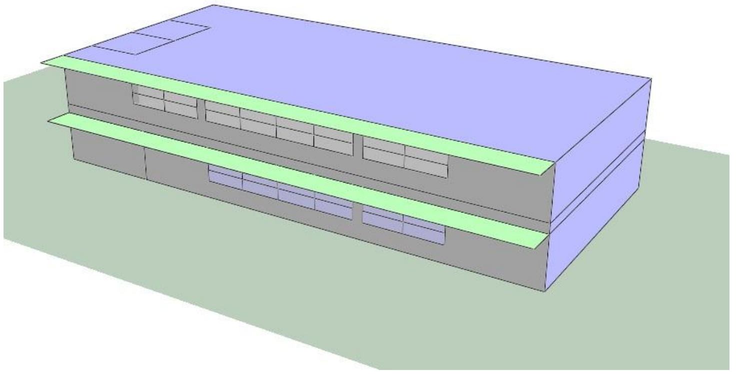

Figure 2: Modified geometry of natural ventilation solution incorporating 2m deep shading on southern windows.

2.2 Zero carbon design methodology

The study targeted the testing of the impact on reliability, maintainability and product life cycle of design improvements aimed at reducing the CO2 emissions of a building. The particular methodology used was taken from an ongoing study and focuses on establishing a maximum demand reduction before employing micro-generation. The justification for this method is itself tied to the risks associated with maintenance factors. It is also to examine the difference between the effects of improving standard design practices through better quality materials, building practices and modeling techniques and the effects of increasing the technological complexity of buildings themselves in order to offer greater control. Combined Heat-Power (CH-P) is a major driver behind the latter. The use of CH-P or even combined cooling, heat and power (CCH-P) requires a level of control over the passive inputs within a building and careful system balancing. If achieved, however, there is evidence to suggest that CCH-P, also known as tri-generation, can be a significant technology for the improvement of building performance as cited by Clarke et al (2008) and Hinnells (2008).

If it is anticipated that a building offering a spread load of heating and cooling is more suited to a CCH-P system than a natural ventilated building with no summer cooling load and (due to the risk of human error with window opening) a significantly higher winter heating load then whether the overall performance improvement is greater than the simpler building with a biogas boiler should b established. Exploring this question fits with the investigation of reliability as the failure of a more complex and less familiar system is a significant risk if the building is provided with traditional maintenance as observed by Glass et al (2008).

The naturally ventilated strategy includes parameters for window opening on the southern face which remains constant throughout all design iterations. It assumes that the windows will be opened when the internal temperature reaches 23°C and subsequently closed once the office temperatures are reduced to 19°C.

Table2: Key Parameters for the Improved Office designs with natural ventilation strategy.

Parameter Design Stage	Wall U-value W/ m^2.K	Floor U-value W/ m^2.K	Roof U-value W/ m^2.K	Glazing U-value W/ m^2.K
Lowered U-values	0.25	0.19	0.13	1.5
Extreme U-values	0.16	0.1	0.1	1.5
Reduced permeability	0.16	0.1	0.1	1.5
Biogas	0.16	0.1	0.1	1.5
CCH-P	0.16	0.1	0.1	1.5
Renewables	0.16	0.1	0.1	1.5
Parameter Design Stage	**Air permeability @50Pa m^3 /(h. m^2)**	**Fuel Type**	**CCH-P**	**Wind Turbines and Photovoltaic Panels**
Lowered U-values	5	Natural Gas	No	No
Extreme U-values	5	Natural Gas	No	No
Reduced permeability	4	Natural Gas	No	No
Biogas	4	Biogas	No	No
CCH-P	4	Biogas	Yes	No
Renewables	4	Biogas	Yes	Yes

The mechanical ventilation strategy employed no window opening so as to make maximum use of the control offered by a complete HVAC system. An additional performance improvement that was included in this strategy was that of smart metering and active controls over the internal conditions within the building. This was considered an example of an unnecessary technology in the passive focussed natural ventilation strategy. In the mechanical ventilation strategy however, it can potentially offer a more balanced heating and cooling profile that will reduce the CO2 generated by the HVAC system.

The renewable energy strategy found in both design strategies uses the same parameters as the Lion House building as discussed above. Jones (2009) states that three 15kW wind turbines and 106 m2 of photovoltaic panels were employed by this building to offset demand and equivalent systems have been included in the relevant simulations. The CCH-P system has been set to meet the demands of the heating and cooling loads rather than the electrical power demands where it provides an offsetting factor.

Table3: Key Parameters for the Improved Office designs with mechanical ventilation strategy.

Parameter Design Stage	Wall U-value W/ m^2.K	Floor U-value W/ m^2.K	Roof U-value W/ m^2.K	Glazing U-value W/ m^2.K	Air perm. @50Pa m^3 /(h. m^2)
Lowered U-values	0.25	0.19	0.13	1.5	5
Extreme U-values	0.16	0.1	0.1	1.5	5
Reduced permeability	0.16	0.1	0.1	1.5	4
Smart Metering and Controls	0.16	0.1	0.1	1.5	4
Biogas	0.16	0.1	0.1	1.5	4
CCH-P	0.16	0.1	0.1	1.5	4
Renewables	0.16	0.1	0.1	1.5	4
Parameter Design Stage	Metering and Controls	Fuel Type	CCH-P	Wind Turbines and Photovoltaic Panels	
Lowered U-values	No	Natural Gas	No	No	
Extreme U-values	No	Natural Gas	No	No	
Reduced permeability	No	Natural Gas	No	No	
Smart Metering and Controls	Yes	Natural Gas	No	No	
Biogas	Yes	Biogas	No	No	
CCH-P	Yes	Biogas	Yes	No	
Renewables	Yes	Biogas	Yes	Yes	

2.3 Testing performance

The performance of the building designs were assessed by the comparison of their respective building emissions rates at each stage of design and the consideration of the reliance that the designs had on each of the technologies. The risk of these technologies as points of failure were then considered and the examination of the consequences of key failures considered. This consideration included overheating tests of the mechanical ventilation strategy in the case of failure of the cooling system as no window opening was offered as part of the cooling and ventilation strategy. For comparison overheating tests were also conducted for the functioning naturally ventilated offices.

The motivation behind staggering the design stages rather than applying all anticipated changes has benefits for both the building designer and those considering reliability, maintainability and product lifecycle factors. For the former it prevents assumptions of significant performance improvement for a specific design due to past successes and prevents the inclusion of redundant or financially inappropriate design measures. For those considering the latter it offers the opportunity to consider the implications of system failures at key stages. The overheating tests carried out in parallel with each compliance check are of interest here as they represent the performance of the building should further system improvements fail.

3. Results

3.1 Natural ventilation method

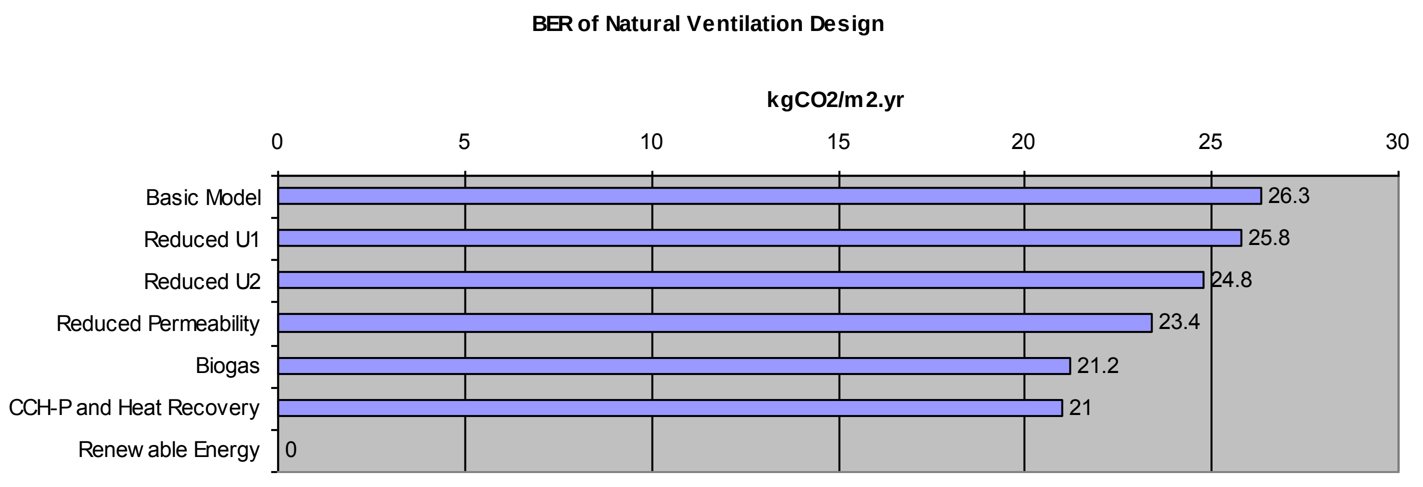

Figure 3: Building Emissions Rates of design stages of the Natural Ventilation design strategy

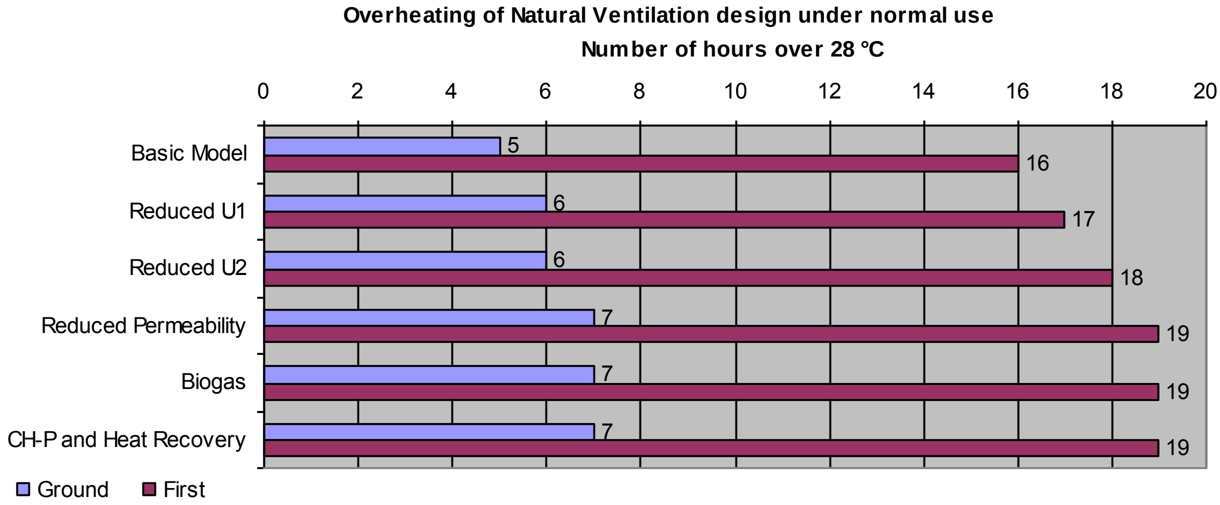

Figure 4: Overheating test for Natural Ventilation design strategy under normal use: number of hours over 28°C during occupied office hours

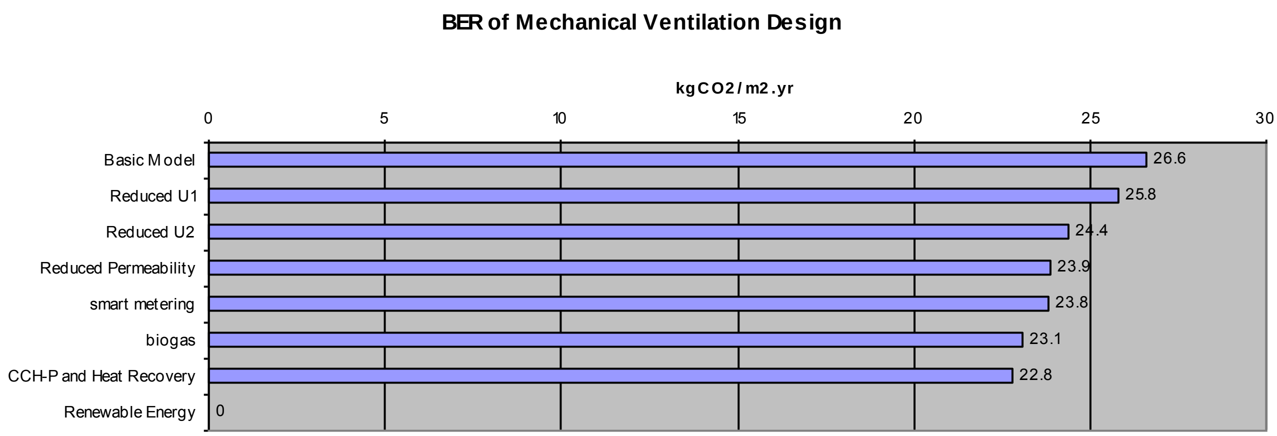

Figure 5: Building Emissions Rates of design stages of the Mechanical Ventilation design strategy

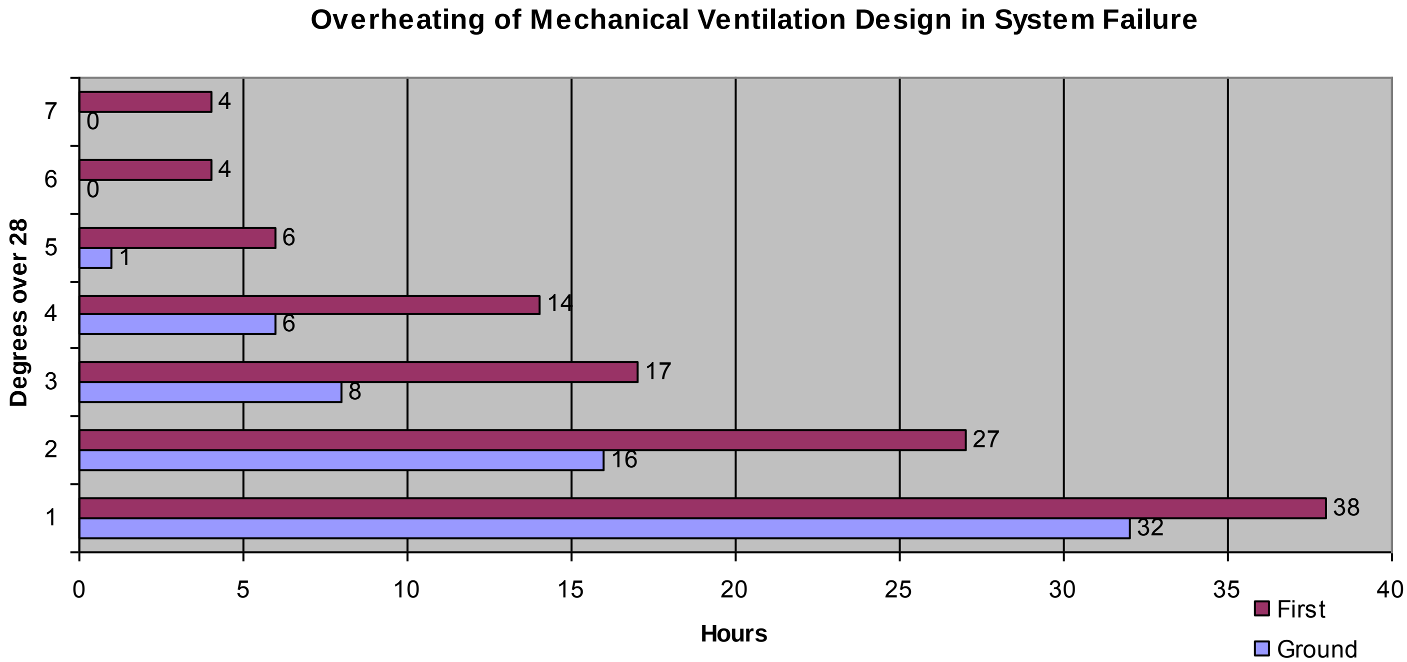

Figure 6: Overheating of final design stage of the Mechanical Ventilation design strategy: number of hours at each degree over 28°C to a maximum of 35°C

4. Discussion

4.1 Comparison of BER for design strategies

The Building Emissions Rates for the mechanical ventilation strategy does not demonstrate an improvement in the performance of the building over those of the natural ventilation strategy. In fact the performance figures suggest that a natural ventilation strategy will offer 1.8 kgCO2/m2/yr less emissions than the mechanical strategy. It should be observed, however that there are risks associated with using the natural ventilation strategy. Such a strategy has an inflexible internal condition that is built around the assumption that cooling will never be needed. Should this prove not to be the case due to unanticipated weather conditions or climate change then there may be the need for aftermarket cooling installation which has the potential to be more expensive and less integrated (and therefore efficient) than a system included in the original design. Additionally, the calculations do not account for the risk of human error and the leaving of a window open, which can have significant effects on the emissions of a building if perpetrated regularly. It can also be observed that despite the goal of balancing the demand over the year as heating and cooling, rather than heating alone, neither strategy gained a significant benefit from the inclusion of a CCH-P system in direct opposition to the suggestion put forward by Clarke et al (2008) and Hinnells (2008). It may be that a greater overall load is required to make use of such a system and make it worth the undoubted risk it poses to building performance through its complexity and requirement of expert maintenance should it fail.

4.2 Overheating analysis

The overheating analysis had its own role in the consideration of each of the design strategies. In the consideration of the natural strategy it was used to confirm that the passive design did not impact on the users as there was perceived to be some risk of overheating as the materials were improved. It can be seen in figure 4 that this is not the case and that even at its highest the overheating for both the ground floor and first floor offices is within the limit of 30 hours over 28°C per year. For the consideration of the mechanical ventilation design it was used to examine what was determined to be the greatest risk of failure and key difference between the two strategies; the loss of cooling. As can be seen in figure 6 there is significant overheating with temperatures reaching as high as 35°C in the first floor office as well as three times the total number of acceptable hours over 28°C per year. This suggests that the failure of this design measure poses a significant problem to the building users and the subsequent need for auxiliary cooling measures poses a risk to the carbon emissions performance of the building.

4.3 Reliance on renewable energy technologies

The two strategies both rely on renewable energy systems to offset four times the CO2 that has been removed through energy reduction strategies and low carbon fuels. This reliance is a major reliability and maintainability issue as these systems require specialist expertise to maintain and the impact of failure will be significant for both the cost of energy provision and the failure to meet targeted emissions rates.

5. Conclusions

The findings of these tests demonstrate the need for the consideration of reliability, maintainability and product life cycle when designing zero carbon commercial buildings. In this simple case study there is the option to focus on passive design choices; however in larger, deep plan buildings this is not available. As has been demonstrated in the testing, system balancing and the use of low carbon fuel can offer only so much performance improvement while increasing both the risk of failure and the severity of the repercussions. This leaves the Zero Carbon building designer relying on renewable energy sources in order to bridge the gap between low impact and truly carbon neutral. This is not an acceptable situation under current building practices as small scale renewable energy requires specialist maintenance and adds an upfront cost premium to the building. Added to these issues are the questions as to the level of understanding of the long term reliability and output of these technologies and their ability to perform to the expectations on which energy assessments are based.

The study demonstrates the need to focus on a change in the way building design is approached, where rather than building to the simplest or most short term cost effective standard, efforts must be made to get the best value from the emerging technologies in order to offset the repercussions of any failures. Additionally, the industry itself needs to look towards a change in its approach towards the provision of solutions and their maintenance. This will allow the successful building designs to continue to do their job of reducing emissions and prevent the shift in building design impacting on the end user.

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Challenges and Opportunities of the Passive House Concept for Retrofit

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Abstract

For newly built houses and renovations European and national ambitions prescribe increasing levels of energy performances, even including achieving the passive house standard, net zero energy or carbon neutral houses. For highly energy-efficient renovation, project information from first demonstration projects is now becoming available. This paper examines experiences of demonstration projects with improved energy performance, in order to diffuse these experiences to reach other innovators and the early adopter market. Innovation diffusion theory is used to analyse examples of residential renovations using passive house technologies. Further the paper examines challenges and opportunities for the diffusion of demonstrated solutions to an early adopter market. Detailed case studies show that passive house retrofit, as well as low energy retrofit, need more holistic approaches, higher skill competence and strong process coordination. The results show that it is technically feasible to reach outstanding energy performance in renovation. However, social, political and economical issues remain important barriers to reach a more substantial market share. In particular there is a need to cluster energy efficiency principles to focus on substantial energy savings. The research leads to ideas for further study of the possible role of change agencies to support substantial energy reduction in retrofit projects.

Keywords: renovation, energy efficiency, passive house, innovation diffusion, building process

1. Introduction

1.1 The urgency of energy efficiency for residential buildings

Promoting energy efficiency in the building sector is essential to achieve the goals of the United Nations Framework Convention on Climate Change and its Protocols, for example Kyoto. The eventual aim in terms of energy reduction in the building sector is to mitigate climate change, and reducing energy use in the building sector is considered to be one of the most important and affordable means to mitigate climate change (IPCC, 2007). Despite signs of improvement, Europe's buildings are still a large energy consumer comprising 40% of final energy use and 36% of EU CO2 emissions (ACE et al., 2009). There are considerable differences between European countries, but on average the residential stock, consisting of households, is responsible for 30% of the total final energy consumption, and proportional to the useful floor areas (Itard et al., 2008). On average, tap water and space heating are responsible for over 60% of the final energy consumption in both residential and non-residential stock (Itard and Meijer, 2008).

The Energy Performance of Buildings Directive, EPBD, also known as Directive 2002/91/EC (EC, 2002), commends Member States to install energy performance policy in the building sector with the aim of reducing energy consumption in buildings caused by heating, hot water production, lighting, cooling and ventilation. The European Parliament (EP, 2009), in its resolution of 31 January 2008, has called for strengthening the provisions of Directive 2002/91/EC, and has called at various times, on the latest occasion in its resolution on the Second Strategic Energy Review, for a 20% energy efficiency target in 2020 to be made binding. The McKinsey Global Institute (2007) has published a comprehensive cost curve for global greenhouse gas reduction measures which states that measures in the building stock are among the most profitable.

It is recommended to look beyond small energy efficiency improvements. With the current atmosphere CO2-equivalent concentrations, not overshooting a 2 K global warming would mean reducing fossil fuel CO2 emissions to almost zero by 2050 (Aitken et al., 2004). Member States are expected to draw up and report national plans for increasing the number of buildings of which both carbon dioxide emissions and primary energy consumption are low or equal to zero, and set targets for the minimum percentage of those buildings in 2020 (EP, 2009). The European Commission (EC, 2006) has highlighted in its "Action Plan for Energy Efficiency: Realizing the Potential", that 'It will take the necessary steps, in collaboration with the building sector, to develop a deployment strategy for very low energy or passive houses, with a view to moving towards this type of houses as a standard in new construction in the medium term, as the appropriate technologies become commercially available.' The document suggests that future adaptations of the Energy Performance of Buildings Directive may be extended to include 'low energy or Passive Houses' as a requirement, setting a target date of 2015. For many countries the passive house level is already seen as a long term political ambition level to reduce energy consumption in the building sector (Dyrbol et al., 2008; Mlecnik, 2008; Mlecnik et al., 2008). The vision of the International Energy Agency was presented at the G8 Summit in Heiligendamm: it states that zero energy buildings are possible but they are still more expensive than traditional buildings, even over the full lifetime of the building, while passive houses are becoming economically attractive because of reduced costs for heating and cooling systems (Laustsen, 2008). This means that the passive house concept, as a basis for the realization of net zero energy buildings or low carbon buildings can certainly not be neglected.

Europe obviously has the ambition to become a global leader in promoting energy efficiency. In order to bring this ambition to fruition, it is important to create the right regulatory and policy framework for industry and the design professions to provide solutions that will reduce energy consumption in Europe's building stock, and particularly in households (ACE et al., 2009).

1.2 Research question

Some countries are advanced in energy policy, have experiences with passive houses and some form of advanced energy performance criteria, and have introduced associated quality assurance schemes (PEP, 2008; Barta et al., 2009). On the other hand, many countries still regard houses with improved energy performance as an innovation. From diffusion theory, it is known that, unless some government, entrepreneurial or non-profit organization makes an innovation available at or near the location of the potential adopter, that person will not have the option to adopt in the first place (Brown, 1981; Miller, 2009). It is important to study more advanced examples and to understand how the findings can be used for further diffusion to reach a more substantial market share of houses with improved energy performance. This is especially important since support measures for the promotion of low carbon and low energy buildings such as fiscal incentives, financial instruments or reduced VAT are to be introduced in European Member States (EP, 2009).

The previous discussion highlights the importance to study already existing examples of renovations that aim towards the low energy, passive house or low carbon level. The main question in this paper is to demonstrate the experiences of the demonstration projects with improved energy performance in order to diffuse them to reach other innovators and an early adopter market.

To answer this question we look at innovation diffusion theory, and take international examples of advanced residential renovations, from the IEA SHC Task 37 and from a Belgian Federal Science Policy project, as case studies. We study those projects as an innovation within an innovation system and insights are provided in the building processes and underlying motivation. In the next paragraph a research strategy is presented applying theory of diffusion of innovations. The following section describes relevant experiences from international research. Further Belgian case studies and experiences from the viewpoint of these theoretical elements are presented. This is followed by a discussion and conclusions.

1.3 Theoretical background

The theory on the diffusion of innovation has only occasionally been applied to the diffusion of demonstration projects (van Hal, 2007). When delving into diffusion research, it appears that there are many different views on this subject. According to Lawrence Brown (Brown, 1981; Miller, 2009), four broad perspectives can be distinguished, each of which with a slightly different take on the matter. Three perspectives explain diffusion by focusing respectively on economic improvement, affordability or communication. The latter perspective is the most popular and defines diffusion as the process by which an innovation is communicated through certain channels over time among the members of a social system (Rogers, 2003).

Advanced renovation projects with improved energy efficiency are currently experimented with on a limited basis in many countries. The following paragraph describes the availability of an innovation segment based on international research: we define the associated principles and technologies for passive house retrofit and discuss the importance of building typologies and change agents. Further, we examine our research question in detail on two case studies, from the communication perspective. Rogers (2003) defines five perceived attributes of an innovation, which can help explain the rate of adoption of an innovation: relative advantage, complexity, trialability, observability and compatibility. We shall take these attributes as a leading guideline throughout the description of the case studies. Learning-by-doing provides insights into the elements that are important considering these attributes.

2. IEA SHC Task 37

The Task 37 of the Solar Heating & Cooling Programme of the International Energy Agency (IEA SHC Task 37) showed that passive house principles and components have been successfully introduced in the retrofitting of existing buildings. For low energy housing retrofit the clustered passive house principles tend to take a more important lead than the strict passive house definition (as defined in: PEP, 2008). These retrofit principles address the minimisation of transmission and ventilation losses, passive and active solar energy, efficient energy supply and overheating control. Following these principles, technologies can be observed in demonstration projects in a clustered way. For example, building systems can include high insulation thickness, triple glazing, special insulated frames and doors, solutions for thermal bridges and building air tightness. Ventilation and heating systems are calculated and adapted to include not only heat recovery and their own energy efficiency, but also domestic hot water production, internal heat gains, passive solar gains, overheating control, passive cooling systems and shading, active systems like thermal collectors or PV-systems.

From the IEA SHC Task 37 research work it is shown that the clustering of these principles into an integrated concept leads to substantial energy reduction. The demonstration projects show that advanced renovation can reduce the energy demand to a level where energy for heating is almost not needed. Twelve Task 37 demonstration projects show energy reductions from 62 to 95% for space heating and domestic hot water, average 75%.

IEA SHC Task 37 demonstration projects that for different pre-war building typologies, the passive house standard of 15 kWh/ m^2a, although easily implemented in new constructions, is sometimes difficult to achieve in a cost-efficient way for retrofit. Especially protected facades, existing thermal bridges and highly valued ornaments are difficult to tackle. On the other side, projects in different countries demonstrate that passive house retrofits can be economically feasible for some building types (E-retrofit-kit, 2008). For typical post-war large block social housing building types, measured energy savings varied between 75 to 95% (IEA SHC Task 37). The specific heating demand is typically reduced from values between 150 and 280 kWh/m²a to less than 30 kWh/m²a. In some cases, pre-defined energy consumption for heating of 15 kWh/m²a is reached. From the technological point of view, a large group of building typologies from the sixties and seventies can relatively easy be transformed into passive houses. Especially prefabrication technologies are considered to have a high potential for advanced housing retrofit of many building typologies, since prefabricated elements allow placement in a limited time frame without hindering occupants too much (IEA ECBCS Annex 50).

The IEA SHC Task 37 demonstration projects showed that social issues can not be neglected. Ownership and decision structures, inhabitants and their characteristics and actual groups of retrofit market players should be involved in the building process, in order to be able to reach a goal of pre-defined energy saving. Also, political issues like national, regional and local regulations and incentives have shown to play a major role in the development of demonstration projects or an early market of advanced housing retrofits. Many countries (IEA SHC Task 37, sub task A) observe the need for a better consumer contact with change agents: individuals who influence clients' innovation-decisions in a direction deemed desirable. For example, the Canadian experience on marketing of advanced renovation, illustrates how to build alliances and a network to increase position and market impact in the renovation sector. A leading agent can take position, spread knowledge and increase the demand within the building industry, local authorities as well as relevant media.

In the following paragraph we discuss the experiences with two Belgian case studies as an illustration of the previous comments.

3. Case studies Belgium

3.1 Innovator case: relative advantage and observability as a driver

We discuss a renovation of a 150 year old row house in the village of Eupen, Belgium, which has been studied in line with the four perspectives described above and the innovation attributes. The case is representative as a best-practice example for the Belgian situation, where the market is mainly dominated by owner-occupants. Although the case study represents the motivated 'innovator' owner-occupant, it can be observed that the main driver for implementation was not necessarily the issue energy efficiency.

The innovator's desire to build a demonstration renovation project was clearly inspired by the increased relative advantage and observability of this kind of project. Instead of only replacing the worn-out roof and glazing, the owner was driven by the desire to increase the habitable area and to add an up-to-date extension. Another major factor that played a role was an asthmatic child. He reasoned that the old convectors and damp walls would certainly give rise to dust, and lead to moisture and health problems. Therefore the owner decided in an early stage of the design process to have mechanical ventilation with filtering, up-to-date with heat recovery. The owner, an architect, further noticed that, since extension, roof and glazing had to be replaced and that the orientation of the building was suitable, the possibility to increase social prestige by opting for a passive house standard. Finally, renovation was preferred to a new built construction because of substantially lower VAT. In conclusion, the owner was driven by relative advantage, i.e. financial advantage, comfort improvement, social prestige factors. Reaching the passive house standard only asked for some minor extra measures, as a logical next step for the owner. The economical and environmental impacts were studied on completion of the project by independent researchers: this showed that the architect's intuitive option was justified for the project.

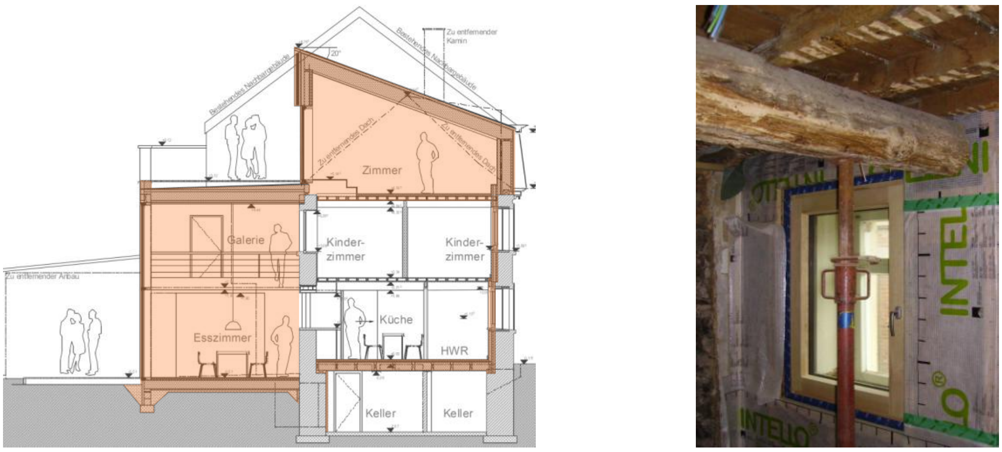

Figure 1: Case study Eupen: section of the row house in Eupen (before and after renovation, left) and detail of interior insulation, air tightness and cutting through carrier beam (right). Source: PHP, FHW architectes (IEA SHC Task 37)

The project proved to be quite a challenge in complexity, trialability and compatibility. Being the first demonstration project of a renovation towards the passive house standard in Belgium, the owner had to find all the technological solutions at regional level. In the design stage, extra care had to be taken with the evaluation and solution of thermal bridges. The city did not grant a permit to insulate the façade on the street side, so a solution for interior insulation on the front façade needed careful study and development. Providing building air tightness was a challenge, as was careful dimensioning and control of the ventilation system.

3.2 Early adopter case: wish for increased comfort leads to phased secondary energy efficiency retrofit

One of the conclusions of the Low Energy Housing Retrofit project (LEHR, 2009) was that, in order to reach Kyoto targets, the whole renovation market has to be augmented in size. For example, in the Brussels Capital Region, it is expected that the low energy renovation market has to increase from 1 to 4%. This means that not only the 'low-hanging fruit' can be addressed. Also, people who already renovated will have to be convinced to do extra building related measures to reduce energy consumption. In this framework, a second example is discussed of a renovation project in Antwerp, Belgium. This urban row house had been renovated in many phases dating back to 1911, with the last renovation in 1996. Nevertheless, the owner-occupants decided to have another renovation in 2006, although its consumption was already lower than average for the same type of building.

The cause of this decision was a perceived lack of relative advantage. It was observed by the owners that the bathroom was difficult to heat in the winter period and that its ventilation system made a lot of noise. The room below the roof was also difficult to heat in winter, it was draughty near the single-pane windows, and had a leaky roller-shutter. This gave the owners the idea to improve the thermal insulation of the roof and the rear façade. Because the owners were aware of the hassle renovation involved, they decided to have an architect do the job.

The project proved to be highly complex. It was difficult to find an architect willing to do the extra work required for the tricky connection details. The architects consulted found their relative advantage regarding cost and benefit to be low, compared with offers in new built construction. The mixed ownership of party walls posed additional social challenges to the appointed architect. On one side of the house the neighbouring owner was not interested in insulating, and on the other side the neighbour tore down a neighbouring, previously heated, space. The owners also wanted to spread the financing. The architect finally came up with a phased solution: first the roof was insulated and extended, the windows in the rear façade were replaced, and then the rear façade was then thermally insulated and plastered. Problems with damp were discovered during the process, which required several separate interventions which irritated the owner-occupants.

In general, the owners perceived a decreased relative advantage, since their main living rooms were uninhabitable for months because the contractors did not stick to the agreed time schedule. The contractors were not familiar with many of the measures taken, e.g. such as extending a roof to connect to future wall insulation, but trialability was included by learning-by-doing. The resulting project was consistent with the existing values, the required comfort and the financial needs of the adopters. As a benefit, the owners now see a decrease in gas consumption and possibilities to have income tax reduction for energy saving measures.

Figure 2: Case study Antwerp: detail of rear insulation (first, intermediate and final steps). Source: PHP, arch. G. Camerlinck; Photo: E. Mlecnik

3.3 Discussion

We discuss the factors that can influence the rate of diffusion from the experiences with the demonstration projects.

Relative advantage: What matters is not so much the ‘rational’ advantage of cost-efficient energy saving, but whether an individual considers an integrated retrofit project to be better than other options. The degree of relative advantage may be measured in economic terms, for example, the availability of associated financial benefits such as reduced VAT (case 1), income tax reduction or grants. Also, social prestige factors (case 1), convenience and satisfaction (case 2) are important factors. We can expect from theory that, the greater the perceived advantage of the retrofit idea, the more rapid its rate of adoption will be. We note that in both case studies improved energy efficiency was not the main driver for renovation. However, comfort improvement was. The relative advantage of the executing parties also plays a role: in case 1 the architect was motivated by his own project to increase social prestige, in case 2 it was difficult to convince an architect to do a complex job.

Complexity: Advanced retrofit projects can be perceived as difficult to understand and implement. Case 1 shows the importance of regional availability of associated technologies and the (political) barrier to insulate the front façade from the outside, leading to complex inside thermal insulation. Case 2 illustrates that a project can become complex when segmented into phases. Some barriers could be removed: for example city officials in Paris and Flemish politicians now voted a law that makes outside insulation possible. Technologies and described (phased) solutions can be made regionally available by change agents. In general, simpler solutions should be stimulated, since they will lead to more rapid adoption.

Trialability: It is important that advanced retrofit projects can be experimented with on a limited basis. Both cases now see the implemented technologies as finality. Providing the possibility for change in demonstration projects (for example industrial, flexible, dismountable solutions), and education by learning-by-doing, is necessary so that executing parties can try out solutions on a partial basis. Better trialability can improve the rate of diffusion. Documenting learning-by-doing experiences can also reduce complexity for other actors.

Observability: Observability of demonstration projects can be a major driver in the innovation phase to convince other innovators, especially when social prestige factors are involved (case 1). The easier it is for innovator-businesses to learn from a colleague-innovator demonstration project, the more likely they will adopt. Market actors perceiving good relative advantage from their involvement in demonstration projects can be expected to be proud of their project and willing to show it to other actors, so this provides an opportunity. However, the visibility will often also be determined by the availability of for example a plaque for the building, project leaflets, easily accessible internet information, media campaigns and the explicit mentioning of the associated actors and change agents in (official) listings and documentation. To convince other early adopters, peer-to-peer contacts are necessary with early adopter demonstration projects. For example case 2 had to start with a tabula rasa since no similar regional demonstration projects with owner-occupants in a similar situation were available. Observability of early-adopter motives and solutions can be improved.

Compatibility: Are the demonstration projects perceived as consistent with existing values, past experiences and needs of potential adopters? From the international research we note that for general marketing a target-group oriented approach might be more interesting than a building typology based approach. But it is also important that potential adopters can recognize their own potential projects in the building types and adopter categories demonstrated. Incompatibility will not lead to adoption unless a new value system is adopted (for example the importance of consuming less), which is a relatively slow process.

4. Conclusion

Techniques and systems for low energy housing retrofit are well developed, even for solutions with occupants remaining and with very limited time frames for renovation. A main barrier for widespread diffusion of such advanced solutions is that the European building sector is characterized by a multitude of regional market actors and different building traditions. Analyses carried out in IEA SHC Task 37 showed barriers according different types of building segments, ownership and decision processes, and national, regional and local regulations and incentives.

Generally, advanced renovation is progressing, but at a much slower rate than that needed to reach national and international goals in time. There are many reasons for this. Passive house retrofit has to compete with products where the “costs” of CO_2 emissions are not taken into account. Work in Task 37 shows that compared to ordinary renovation, passive house retrofit needs more holistic approaches, higher skill competence and stronger coordination in the planning and renovation process.

Clustering of energy efficiency principles can lead to substantial energy reduction. This opens a pathway to promote an integrated package of innovation. This provides an interesting opportunity since, according to theory, it can be expected that technology clusters can be adopted more rapidly than individual innovations (Rogers, 2003). To secure market penetration, it is important to make the market understand what the whole product consists of, per building typology, and to organize a marketplace to provide a whole product offering (Moore, 2002). Advanced renovation and increased renovation rate represent big business opportunities for proactive planners, consultants, building companies and suppliers of building components materials. So far only a few companies have seen and taken this opportunity.

In order to develop a whole system approach new political and social challenges are appearing. Resources mobilization and creation of legitimacy have to be tackled (Alkemade and Hekkert 2009).

In order to diffuse experiences from demonstration projects to a larger audience, it is important to increase the relative advantage and observability of actors involved. There is a need to showcase solutions compatible with existing building types and different target groups. Energy savings can be associated with improved comfort, citizen action, children's future,.. and should not always be reduced to money savings, as this can be counter-productive (Bartiaux, 2006). Complexity should be reduced by learning-by-doing, and subsequently providing information to other parties about the lessons learned.

In order to develop well from demonstration to volume market, one should not neglect that there is a symbiotic relationship between the existence of market infrastructure and consumer finance, both being equally important (Miller, 2009). In this framework, a specific role for change agencies seems appropriate. On a political level, the availability of a legal or instrumental framework for the introduction or diffusion of demonstration projects, and the development of the diffusion by change agents, can be stimulated. Change agencies might be the appropriate vehicle to bring more advanced retrofit into a wider practice, but then they should also address the motivations and desires of early adopter categories.

The focus in this article has been upon the process by which innovations and the conditions for adoption are made available to individuals or households, that is the supply aspect of diffusion. For future research, it can be interesting to study the activities of public or private entities through which the innovation can be distributed or made available to society at large, i.e. local diffusion agencies.

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Protocol for Embodied Energy Measurement Parameters

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Abstract

The building construction industry consumes large amount of resources and energy and owing to current global population and affluence increase trends, a trend projected to aggravate in the near future. Buildings consume approximately 37 percent of total global energy; during the construction phase in the form of embodied energy and during the operation phase as operating energy. Recent studies have considered the significance of embodied energy inherent in building materials and have proven that improved technology could reduce operating energy but embodied energy could only be reduced if low energy intensive materials are preferred and used in buildings. Existing embodied energy templates, parameters and inventories differ in the measurement standards and are inconsistent, fragmented and often incompatible. Therefore there is no reliable protocol regarding embodied energy measurement parameters that could contribute to energy conservation practices, environmental decision-making, eco-labeling and low embodied energy material preference. Embodied energy measurement is a part of Life Cycle Assessment (LCA). Current standards and codes of practice for LCA could provide direction to the process of embodied energy calculation. International Standardization Organization (ISO) and the Society for Environmental Toxicology and Chemistry (SETAC) are among noteworthy institutions that are responsible of standardization and scientific development of LCA respectively. However recent research has pointed out shortcomings in international standards for LCA thereby indicating the need for protocol improvement. This paper focuses on identifying parameters that are causing variation and inconsistencies in embodied energy results and on pointing out issues that need to be addressed.

Keywords: building materials, embodied energy, life cycle assessment, energy consumption in construction industry, embodied energy protocol.

1. Introduction

The construction industry consumes two-fifths of the globe's raw stone, gravel, and sand and one-fourth of virgin wood. It consumes 40 percent of total energy and 16 percent of water annually (Ding, 2004; Horvath, 2004; Urge- Vorsatz and Novikova, 2006; Langston and Langston, 2008; Lippiatt, 1999). An anticipated radical shift in global population from 6.5 billion in 2005 to approximately 9 billion in 2035 (Fernández-Solís, 2008) indicates the graveness of the situation of material and energy consumption as a result of an eventual increase in construction activities. The total energy consumed by the building throughout its life cycle includes embodied energy (EE) and operating energy (OE). Embodied energy (EE) is embedded in building materials during all processes of production, on site construction and final demolition and disposal while, operating energy (OE) is consumed in operating and maintaining the inside environment (Crowther, 1999; Ding, 2004).

Until recently, the share of operating energy was considered larger in the total life cycle energy of a building. However, due to advent of energy efficient equipments and high performance envelope materials, the potential for curbing operating energy has increased and current emphasis of energy conservation has shifted towards embodied energy in building materials (Keoleian et al., 2001; Ding, 2004; Hannon et al., 1978; Nassen et al., 2007; Crowther, 1999; Sartori and Hestnes, 2007). According to Ding (2004), the production of building components offsite accounts for 75 percent of the total energy sequestered in a building (Spence and Mulligan, 1995). This percentage of energy is gradually increasing due to the use of high-energy intensive materials (Sartori and Hestnes, 2007; Langston and Langston, 2008).

Langston and Langston (2008) suggest that the calculation of embodied energy is more complex and time consuming than determining operating energy. Furthermore, there exists no apt method that could calculate embodied energy accurately and consistently (Miller, 2001; Crowther, 1999). Moreover, the process of embodied energy analysis lacks standardization and requires more clarification and guidelines (Pullen, 1996; Pears, 1996; Menzies et al., 2007). Standards like ISO 14040 and 14044 and SETAC (Code of Practice) present requirements and guidelines for the process of Life Cycle Assessment (LCA) of materials or products (Udo de Haes and Heijungs, 2007; Fava, 2005; Rebitzer et al., 2004; Ross et al., 2002: Zamagni et al., 2008; Horne et al., 2009: Dooley, 2001; SETAC, 2008; Levan, 1995). EE analysis is a subpart of LCA that appears in life cycle energy analysis stage (Lawson, 1996; Atkinson et al., 1996). LCA guidelines could be used to provide direction to EE analysis, but parameters like feedstock energy and primary and delivered energy need elaboration. Furthermore, issues such as, system boundary selection and embodied energy calculation methodology are not addressed by these standards. Various factors such as temporal, technological, and geographic representation of the energy data cause wide variation in the embodied energy data (Crowther, 1999; Ding, 2004; Langston and Langston, 2008; Miller, 2001; Lenzen, 2001).

This paper is focused upon identifying differing parameters that cause variation and inconsistency in embodied energy results and identifies the need to develop a protocol to standardize the embodied energy calculation process.

2. Research method

The research method adopted is similar to Literature Based Discovery (LBD), widely used in the realm of biomedical science, which was proposed by Dr. Don R. Swanson from the University of Chicago. In 1986, Swanson adopted the LBD research method in biomedical science studies, and was successful in creating new knowledge (Weeber et al., 2001). The concept of LBD demonstrates great potential that has been widely acknowledged by research communities (Weeber et al., 2001; Weeber, 2007; Kostoff et al., 2008). Kenneth A. Cory from Wayne State University, Detroit, has demonstrated that this research method of creating new knowledge is valid outside of the biomedical science field (Weeber et al., 2001; Weeber, 2007). This paper applies a similar approach by referring to various literature sources such as, journal papers, conference papers, dissertations and scientific and technical reports, in order to identify parameters that are causing variations in the embodied energy database and to point out issues that need to be addressed for standardization of embodied energy calculation. The information is presented in the form of a matrix after identifying the parameters and issues. Furthermore, respective sources are mentioned in the matrix, which are referenced to extract the required information.

3. Literature review

3.1. Interpretation of embodied energy: difference of opinion

Buildings are constructed with a variety of building materials that consumes energy throughout their stages of manufacture, use and deconstruction. These stages consist of raw material extraction, transport, manufacture, assembly, installation as well as its disassembly, deconstruction and decomposition. Miller (2001) reveals that, the term “embodied energy” has been interpreted in a variety of ways, and its published measurements are quite unclear. Crowther (1999) defines embodied energy as “the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings”. Treloar et al. (2001b) explain, “embodied energy (EE) is the energy required to provide a product (both directly and indirectly) through all processes, upstream (i.e. traceable backwards from the finished product to consideration of raw materials).” Likewise, a more comprehensive definition, provided by Baird, 1994; Edwards and Stewart, 1994; Howard and Roberts, 1995; Lawson, 1996; Cole and Kernan, 1996 (As cited in Ding, 2004), proposes that “embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building.” These definitions represent the difference of opinion about the system boundaries to be included in embodied energy analysis.

3.2. Embodied energy modeling

Buildings consume a total energy that is compose of (Ding, 2004; Fay and Treloar, 1998; Treloar, 1998):

Direct Energy: Energy consumed in various onsite and offsite operations like construction, prefabrication, transportation and administration. This includes energy inputs in construction and assembly on site, prefabrication of building components offsite and transportation involved in various onsite and offsite processes.

Indirect Energy: Energy consumed in manufacturing the building materials, in renovation, refurbishment and demolition processes of the buildings. This includes initial embodied energy, recurrent embodied energy and demolition energy. Initial embodied energy is consumed during production of materials and components and includes raw material procurement, building material manufacturing and finished product delivery to the construction site. Recurrent embodied energy is used in various maintenance and refurbishment processes during the useful life of a building. Demolition energy is expended in processes of building's deconstruction and disposal of building materials.

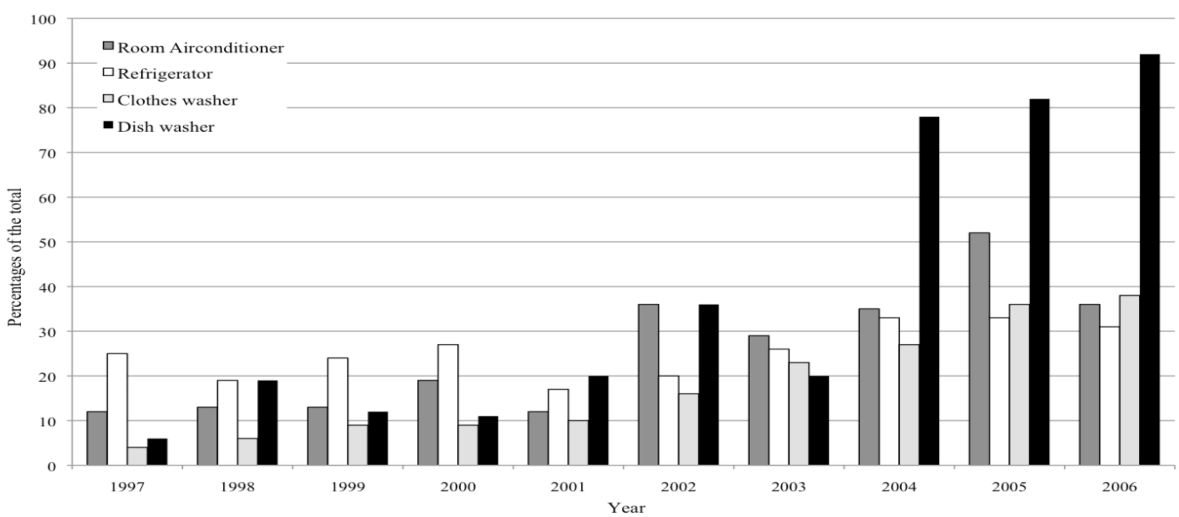

Figure 1: Growing number of Energy Star approved home appliances (based on USDOE 2008 data

3.3. Significance of embodied energy

Until recently, the emphasis of energy conservation research was on the operating energy of a building. However, current research disproved this assumption and found that embodied energy accounts for a significant proportion of total life cycle energy (Crawford and Treloar, 2003; Crowther, 1999; Pullen et al., 2006). Operational energy conservation could be accomplished with energy efficient appliances and advanced insulating materials, which are available more readily (Nassen et al., 2006; Sartori and Hestnes, 2007; Ding, 2004). For example, an increase is observed in the number of Energy Star labeled home appliances in the United States over a ten-year span (see figure 1), which could reduce operating energy gradually (US Department of Energy, 2008). However, preferring low energy intensive materials can only reduce the embodied energy. Commonwealth Scientific and Industrial Research Organization (CSIRO) research has demonstrated that the embodied energy content of an average household in Australia is nearly equivalent to 15 years of operational energy (Commonwealth of Australia, 2005). Crawford and Treloar (2003) insinuate that, in Australia, the embodied energy contained in a building is 20 to 50 times the operational energy needed for the building annually.

Table 1: Embodied energy figures, showing variability, derived by various authors (Source - Ding [7])

Embodied Energy (GJ/m^2)	*Building Type*	*Source*
3.6	*Residential*	*Hill, 1978 (cited by Pullen, 2000b)*
3.9	*Residential*	*Edwards et al., 1994*
4.3 – 5.3	*Residential*	*D' Cruz et al., 1990 (cited by Pullen, 2000b)*
4.9	*Residential*	*Pullen, 1995*
5.0	*Residential*	*Lawson, 1992 (cited by Pullen, 2000b)*
5.9	*Residential*	*Pullen, 2000b*
6.6	*Residential*	*Ballantyne et al., 2000 (cited by Pullen, 2000b)*
6.8	*Residential*	*Treloar 1998*
8.76	*Residential*	*Treloar 1996b*
3.4 – 6.5	*Commercial*	*Honey and Buchanan, 1992 (cited by Pullen, 2000c)*
4.3 – 5.1	*Commercial*	*Cole and Kernan, 1996*
5.5	*Commercial*	*Oppenheim and Treloar, 1995*
8.0 – 12.0	*Commercial*	*Oka et al., 1993 (cited by Pullen, 2000c)*
8.2	*Commercial*	*Tucker and Treloar, 1994 (cited by Pullen, 2000c)*
10.5	*Commercial*	*Yohanis and Norton, 2002*
18.6	*Commercial*	*Stein et al., 1976 (cited by Pullen, 2000c)*
19.0	*Commercial*	*Tucker et al., 1993 (cited by Treloar, 1996b)*

3.4. Variation and inconsistency in embodied energy measurement results

Buchanan and Honey (1994); Crowther (1999); Crawford and Treloar (2003); Ding (2004); Horvath (2004); Crawford and Treloar (2005); Nassen et al. (2007); and Langston and Langston (2008) suggest that the embodied energy results from research studies show significant variation in embodied energy figures, which are derived from information from disparate sources and different countries. Ding (2004) present embodied energy figures derived by various research studies that demonstrate variations in embodied energy figures of a typical residential unit and a commercial building (see table 1). The mean of residential units' embodied energy is 5.506 and standard deviation is found to be 1.56, while commercial buildings' embodied energy figures demonstrate a mean of 9.19 and a standard deviation of 5.4. This indicates that the commercial buildings show greater variability than the residential units in embodied energy terms (see figure 2 and 3).

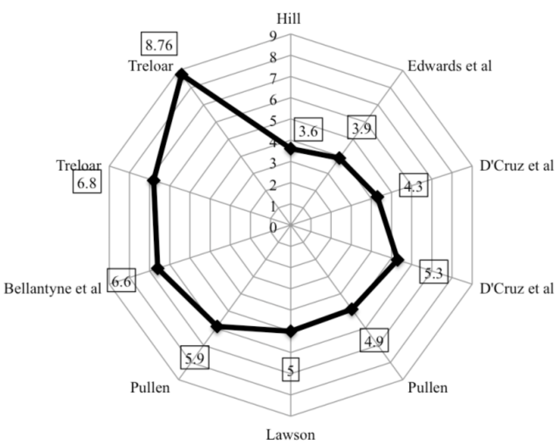

Figure 2: Differing embodied energy figures in residential buildings (based on Ding, 2004)

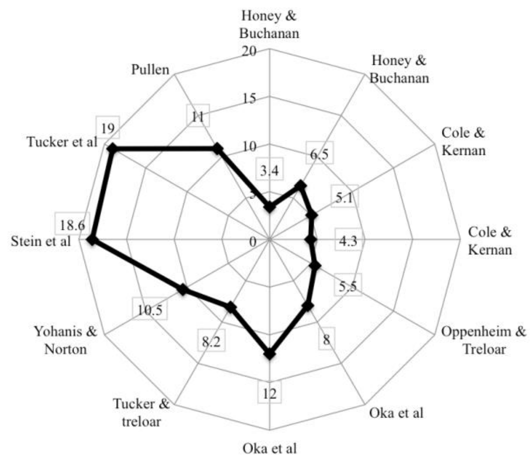

Figure 3: Differing embodied energy figures in commercial buildings (based on Ding 2004)

4. Findings: factors causing variation and inconsistency

The literature search suggests 10 parameters that are responsible for affecting the quality of embodied energy results adversely. These parameters are presented in the form of a matrix along with the research studies supporting them (see Table 2). Life Cycle Analysis (LCA) is referred at various places in the following paragraphs, as embodied energy analysis is a part of LCA. Following section describes these parameters in brief.

4.1. System boundary

In past embodied energy analysis, whenever it becomes difficult to acquire necessary reliable and consistent information, a boundary is drawn and further analysis in upstream is truncated (Crawford and Treloar, 2003). This boundary defines the number of energy and material inputs that are considered in the embodied energy calculation and could include stages such as raw material extraction in distant upstream and demolition and disposal in farthest downstream. Research studies have adopted different system boundaries and, as a result, their measurement figures vary and could not be compared (Miller, 2001; Ding, 2004; Horvath, 2004; Lenzen, 2001).

Table 2: Matrix of parameters causing variation and authors

Authors and Year of Study/ Research	*Parameters*									
	(1) System	*(2) Method of EE Analysis*	*(3) Geographic Location*	*(4) Primary and Delivered Energy*	*(5) Age of Data*	*(6) Data Source*	*(7) Completeness of data*	*(8) Manufacturing Technology*	*(9) Feedstock Energy Consideration*	*(10) Temporal Representation*
Buchanan and Honey, 1994			√		√			√		
Pears, 1996		√		√		√		√		
Pullen, 1996		√	√			√	√			
Alcorn and Wood, 1998			√		√	√	√			√
Lippiatt, 1999			√					√		√
Pullen, 2000a				√						
Pullen, 2000 b		√	√		√			√	√	
Treloar et al., 2001a		√	√	√				√		
Miller, 2001	√	√								
Glover et al., 2002	√									
Junnila and Horvath, 2003	√		√			√				√
Ding, 2004	√		√		√	√				
Horvath, 2004	√	√								
Suh et al., 2004	√									
Crawford and Treloar, 2005		√								
ISO 14040, 2006	√		√		√		√	√	√	√
Lenzen, 2006	√		√		√			√		√
Holtzhausen, 2007		√	√					√		
Menzies et al., 2007			√		√	√	√	√		
Nassen et al., 2007		√								
Sartori and Hestnes, 2007			√	√		√			√	
Hammonds and Jones, 2008	√	√	√		√					
Peereboom et al., 2008			√		√	√		√		√

4.2. Methods of embodied energy measurement

Process analysis, statistical analysis, input output analysis and hybrid analysis are among the major methods used for embodied energy computation (Ding, 2004; Alcorn and Baird, 1996; Lenzen, 2001; Treloar, 1998; Crawford and Treloar, 2003; Fay and Treloar, 1998; Pullen, 2000 b). These methods possess different limitations and their level of accuracy varies. As a result their embodied energy results differ and cannot be juxtaposed (Pullen, 2000 b; Miller, 2001; Treloar et al., 2001a; Horvath, 2004; Crawford and Treloar, 2005; Nassen et al., 2007).

4.3. Geographic location of the study

Research studies performed in different countries differ from one another in term of data relating to raw material quality, production processes, economy, delivered energy generation, transportation distances, energy use (fuel) in transport, and human labor. This eventually affects the determination of energy consumption and their results vary radically (Buchanan and Honey, 1994; Ding, 2004; Lenzen, 2001; Sartori and Hestnes, 2007; Lawson, 1996; Pears, 1996; Pullen, 1996). Processes of industrial and economic sectors differ greatly and thus influence the calculated embodied energy values (Buchanan and Honey, 1994). Different locations of data could affect the embodied energy results because of variations in production processes and energy tariffs (Pullen, 2000 b).

4.4. Primary and delivered energy

Primary energy is defined as "the energy required from nature (for example, coal) embodied in the energy consumed by purchaser (for example, electricity)" and delivered energy is defined as "the energy used by the consumer" (Fay and Treloar, 1998; Fay et al., 2000). The measurements of embodied energy are consistent if those are based on primary energy (Fay and Treloar, 1998), but if the delivered energy is considered, the results could be misleading and ambiguous (Fay and Treloar, 1998; Sartori and Hestnes, 2007). Furthermore, both the operating and embodied energy must be measured in terms of primary energy consumption in order to attain consistency and to acquire the most appropriate environmental implications (Fay and Treloar, 1998).

4.5. Age of data sources

Research studies based on old and current data sources could differ significantly as a result of changing technology of manufacturing and transportation. Consideration of old transportation energy data could affect the energy values, as new vehicles have more fuel efficiency and a different fuel structure. Any study that is based on such conflicting data sources could be misleading and uncertain (Peereboom et al., 1998; Alcorn and Wood, 1998)). Building material performance and material production efficiency will be enhanced over time and could be responsible for variations in measurement figures (Buchanan and Honey, 1994; Crawford and Treloar, 2003; Pullen 2000b). Hammonds and Jones (2008) attempt to consider current data sources in establishing the inventory of carbon and energy because of their relevance, certainty and temporal representativeness.

4.6. Source of data

Research studies use data that are collected using different approaches. Some studies derive their own data by calculating the energy intensiveness while; some utilize energy figures calculated by other studies. This subjective selection of data influences the final results significantly (Ding, 2004; Junnila and Horvath, 2003). Peereboom et al. (1998) suggests that practitioners of Life Cycle Analysis (LCA) rely on various sources of information and do not have access to primary data that leads to uncertainty and variability in LCA results. Data source is an important parameter, and its reliability, uncertainty, and transparency must be considered when performing LCA (Alcorn and Wood, 1998; Lenzen, 2001).

4.7. Data completeness

According to Menzies et al. (2007) and Peereboom et al. (2008), research studies often could not access primary data sources and rely on secondary data sources that may or may not be complete. This incompleteness is due to either the limitations of calculation method or subjective selection of system boundaries. Menzies et al. (2007) assert that, the accessibility of data, methodology adopted, and selection of system boundaries govern the completeness of data could affects the reliability of end results significantly. Alcorn and Wood (1998) suggest that the completeness of data needs to be considered while choosing one material dataset over another.

4.8. Technology of manufacturing processes

Differing technologies of material manufacturing possess varied level of energy consumption, as advanced technology could consume less energy due to energy efficient processes. In the similar geographic location and during the same time period, two studies could generate different results if they are extracting information from two material manufacturers using different technologies (Pears, 1996). Technological representativeness is an important quality of data that should be taken into account in order to eliminate inconsistency and variability of results (Peereboom et al., 1998; Holtzhausen, 2007; Lippiatt, 1999; Menzies et al., 2007; Lenzen, 2001).

4.9. Feedstock energy consideration

Feed stock energy is the energy embedded in the ingredients used in the process of manufacturing a material. Petrochemicals like oil and gas are used as a material input in the manufacturing process of products like plastics and rubber. Feed stock energy needs to be considered in the calculation of the total embodied energy in a material (Hammonds and Jones, 2008). Inclusion of feed stock energy in embodied energy calculation or LCA could cause variations in embodied energy figures, and such figures are not comparable across research studies (Pullen, 2000b).

4.10. Temporal representativeness

A significant data quality indicator in Embodied energy analysis and LCA is temporal representation (Junnila and Horvath, 2003; Peereboom et al., 1998; Alcorn and Wood, 1998; Weidema et al., 1996). Some of the energy studies are based on recently developed technology, and some studies consider a mix of new and old technology (SAIC, 2006). The end results of such studies differ and are not consistent.

This list of parameters is not exhaustive and may include more factors that are responsible for variations. Alcorn and woods (1998) and Peereboom et al. (1998) do not rule out possibility of existence of other parameters.

4.11. Current standards: issues of conflict

There exist a set of standards for the process of LCA derived by International Standardization Organization (ISO). The first effort to standardized LCA came with the publication of “a code of practice” by Society of Environmental Toxicology and Chemistry (SETAC) in 1993. This document later formed the basis of ISO standards such as ISO 14040 and ISO 14044 (Berkhout, 1996; McDougall and Hruska, 2000). Owens (1996) asserts that the ability of SETAC code is questionable in explaining interaction between the study system and the environment. Ayres (1995) asserts that the methodology for LCA described by, both the ISO standards and SETAC code, is flawed. Researchers like Weidema et al. (2008), Zamagni et al. (2008), Reap et al. (2008), Suh et al. (2009), Rebitzer et al (2004) and Raynolds et al. (2000) point out the problems associated with the issues of system boundaries and allocation in current ISO standards for LCA. Referring to literature regarding critical reviews of SETAC and ISO standards identifies following issues.

System boundaries: there is a lack of clarity, subjectivity and issue of truncation error in the current selection criteria and procedures mentioned by LCA standards (Weidema et al., 2008; Zamagni et al., 2008; Reap et al., 2008; Suh et al., 2009; Rebitzer et al., 2004; Raynolds et at., 2000).

Allocation: It is still unclear which approach must be adopted for the purpose of allocation as there is disagreement regarding current approaches. The feasibility of the current method of allocation is questionable according to critiques (Weidema et al., 2008; Zamagni et al., 2008; Reap et al., 2008; Suh et al., 2009; Rebitzer et al., 2004; Raynolds et at., 2000).

Methodology for embodied energy calculation: the literature suggests that the methodology prescribed by the LCA standards is still unclear (Curran and Young, 1996; Smith and Peirce, 1996; Trusty, 2004; Zamagni et al., 2008); and

Sensitivity and uncertainty analysis: according to the literature, the current standards mention conducting a sensitivity and uncertainty analysis but fail to provide an appropriate method for performing this analysis (Reap et al., 2008; Zamagni et al., 2008; Ross et al., 2002).

5. Conclusions

The current environmental practices such as environmental selection of building materials, eco-labeling, and green building assessment, in the construction industry, depend mainly on the results of LCA of the buildings. Embodied energy analysis is an integral part of the process of LCA. The literature suggests that the results of neither embodied energy calculation nor LCA are valid and comparable. Therefore, these environmental practices can no longer fulfill their sustainability and energy efficiency goals accurately. The lack of comparability of the energy intensiveness of two building materials or products seriously hampers the process of selecting low-energy building materials and products. The literature indicates that there is a stated need to adapt a tradition of selecting building materials that are low energy intensive. However, given the incomparable and differing embodied energy data, a decision to select a material no longer remains valid.

The ISO, SETAC, and the American Society for Testing and Materials (ASTM) are among pioneer institutions that are responsible for advancements in standardization and scientific development of LCA. However, literature suggests that LCA studies that follow current standards have differing results. Moreover, the critical appraisal of these standards suggests the need for major improvements and modifications in their current status. The literature in the field of embodied energy analysis reveals that there exist no standards that can address the problems of embodied energy calculation and there is a strong need to develop a protocol or standard that can be utilized for embodied energy analysis. This paper identifies the urgent need to establish a protocol to standardize and guide the process of embodied energy analysis and recommends that this protocol needs to address the issues identified by this paper. Research studies discussed in the paper have stated the need to introduce standardization and global comparability to analysis of EE in building materials. Future research endeavors can focus on the creation of a protocol that facilitates a reliable, consistent, comparable, and current database of EE.

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Necessity of Modernization of Modern Buildings

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Abstract

Due to the environmental and economical processes of the world the architectural thinking is started to change radically in the last decades. The danger of the global warming and the climate change motivated us to revalue our activity and its impacts. The concept of sustainability came into being and its role became more and more important in the architecture. It isn't visible that the sustainable architecture will emerge as a new architectural style in the future or only its tool system will build in the architectural practice. Anyway the environmental problems are waiting for the reaction of the mankind, especially of the architects having a special role, because they can form the built environment. So architects have to know, use and improve the tools of the sustainable architecture. The new buildings have to comply with strict norms today. They have to be cost and energy efficient. These features are also welcomed at the existing buildings, which represent the dominant part of the built environment. Unfortunately there are a lot of modern houses among the energy wasting buildings. This is especially true in the case of the buildings of the 1970s and 1980s. This paper presents two case studies on Hungarian public buildings, which were designed in the 1970s. It reveals the origins, concepts and values of the buildings, then it summarises their problems emphasizing the necessity of their modernization. It is visible from the description of the designed modernizations how the houses will be able to fulfil the recent functional and energetic requirements.

Keywords: modernization, energy efficiency, existing building stock, public buildings.

1. New challenges of architecture

The contemporary architecture is under pressure. The aspect system of the architectural design is getting more difficult during the last century. It does not mean architects have to mind new aspects, but some requirements existing throughout all ages are as emphasized now as never before in the architectural history. These new emphases have an influence on the character of the buildings, and in some cases these become important elements of the architectural concept.

The energy efficiency of buildings associated with the maintenance cost is a more and more important demand today. At the beginning of its existence humanity started utilizing the gifts of nature. Due to the populating of Earth and the increased demands of the customer society the utilizing of the goods of Earth changed to the exploitation of it, which took humanity on thin ice and threatened with global disaster. This threat is the idea of sustainability originated from. Sustainability is a very complex concept, which came from economics, but nowadays it has got also a social and environmental meaning *(Figure 1)*. According to the usual definition sustainability aims to meet human needs while preserving the environment so that these needs can be met not only in the present, but in the indefinite future, too.

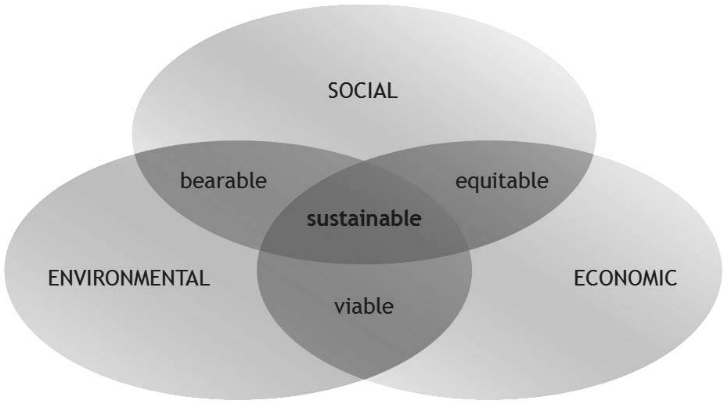

Figure 1: Complexity of sustainability

A significant part of the raw material consumption of mankind is related to the production and the maintenance of the built environment. Execution of buildings needs the 40-50% of the raw material consumption of the word in a year and the maintenance of residential and public buildings requires more than 40% of the world energy consumption. Having these facts it is understandable that using of the sustainability principle is important in the architectural design.

In the twentieth century a lot of trends of modernism emerged. After the turn of the century a completely new direction seems to advance on non-aesthetic basis, which is called as sustainable design. But sustainable architecture has to mean more than a new architectural style in all likelihood, the realization of sustainability is a global social demand, which have to influence all architects related to whatever style or direction. By now a lot of concepts were formed in order to reach the sustainability. The two most important concepts are the ecologic architecture and building passive houses. Former one thinks in autonomic settlements living in harmony with their environment. On these settlements the houses are made of natural building materials of the local area corresponding to the average energetic requirements. The energy demand of the whole settlement is usually satisfied in an ecologic and centralized way. In contrast of this the passive house concept thinks in individual buildings. Passive houses can save the heat which was generated inside using special building structures. To reach this goal extremely good heat-insulated building bordering structures, excellent heat-insulating windows and doors, reduced thermal bridges and air-tight details are needed. In this kind of buildings innovative building service system operates in which the heat recovery ventilation is an obligate element.

In the recent architectural practice new buildings are not made according to these sustainable concepts, but the rules become even stricter expressing the demands and possibilities of the society. Therefore new houses are usually built based on much stricter energy aware aspect having a high level of comfort and low maintenance costs. Designing a new building architects have to satisfy indispensable strict demands according to the actual standards.

Usually an existing building cannot fulfil these actual standards so the designers also have the task to determine which features of the building should be improved in which rate. In this view the protected old, historical monuments have moderated demands also in laws and in standards. For modernizing a not protected building the requirements of energy and cost efficiency are quite as strong as at a new building. Because of these strong requirements building modernization is getting to be more and more important and frequent task today. In order to increase the energy efficiency of existing buildings difficult conversions are needed with a lot of trouble. Such problems can be solved only by means of good architectural and structural designing. The physical survival of the buildings can be ensured with their precise renovations besides the spiritual worth, hidden and coded in materials, in spaces, in masses, in forms *(Winkler and Fejérdy, 2005)*.

There are a lot of great masterpieces among the not protected buildings waiting for modernization. The products of modernism are in a special situation. They were made in an architectural age in which structural knowledge increased as never before. The static exploitation of bearing structures reached the extremity. Bearing and dividing structures started to be separated. More and more layers were built in structures having different functions. These changes caused that some modern buildings don’t have so good energy efficiency than the former built ones. The modernization of these buildings will be a very important and interesting object for the architects.

In the main part of this paper two case studies are summarized presenting the necessity and the possibility of the modernization of modern buildings. Both of them are public building for education and they were made in the 1970s. But they represent different architectural values and they have different problems. Therefore the answers for the problems are also different.

2. Modernization of herman ottó primary school

2.1 Building description

The Herman Ottó Primary School is located in Budaörs, in a suburb of Budapest *(Figure 2, 3)*. In summer of 2009 an architectural competition finished which had the goal to find the right way of the expansion and the facelift of school *(Csík, 2009)*. The presented design participated in the competition. It was not remunerated but it was praised its energy aware aspects.

The school is situated on the south downhill of Budaörs, between a panel housing estate and a shopping area and a gardened residential area is on its west side. The surround shows heterogeneous image, but it is good to see that the vegetation is very abounding on the area.

Figure 2, 3: Herman Ottó Primary School in Budaörs

The design of the school was probably made adapting a design of a ready-cut school at the end of the 1970s by the Council Consulting Company of Pest County. On the site of the school the buildings stand in north-south direction. The buildings are situated on the north side and the play-field is on the south side. The school has three parts: an educational building, a kitchen and dining building and a gymnasium. The house bears the marks of the preferred building practise of the era: It was made using a precast reinforced concrete building system so the fixity of the system is clearly visible on the building. The design concentrates only to satisfy the rational demands. It hasn't enough large and functionally good public spaces. The appearance of the house is very simple. A number of defects can be found in the execution.

2.2 Necessity of modernization

The modernization of the primary school in Budaörs is enforced by a complex process as it is usual. The reasons of modernization can be classify into two groups: one reason is the physical ageing, which appears in the degradation of structures, the other reason is the moral ageing, which occurs from the changing of the requirements connected to the building. According to the call for competition the main reasons of the modernization belongs to the second group because the house is in a quite good condition *(Csík, 2009)*.

The most important new demands connected to the school are the followings:

- The capacity of the school is not enough.
- In the last years the number of children arriving by car is increased therefore a new entrance is needed.
- The building is not accessible for disabled people.
- The public spaces are small.
- The school doesn't have an entrance hall.
- The area per pupil is low, only 5.21 square meters per person in contrast with the ideal 10 square meters per person.
- Important special classrooms are missing.
- The facade isn't aesthetic.
- There are lots of defects on the prefabricated panels.
- The joints of the frontal panels need revision.
- Windows are outdated.
- The energetic features of the building are disadvantageous.
- The heat insulation was made according to the standards of the 1970's.
- The structural details have medium-strong thermal bridges (Szabó and Nyíri, 1999).

2.3 Concept of modernization

The goal of the architectural competition was to expand the educational building in such a way that the modernization of the whole building would be solved as well. During the designing process of the school for the competition several different aspects were considered, for example: to support of the educational program of the school, to create a harmony between the natural and the built environment, to design a house having low consumption, to meet the sustainability, to design an ergonomic building, to consider the interest of the children, the teachers and the owner. The design thinks over the space organisation, the mass forming and the face-work of the existing building *(Figure 4)*.

Figure 4: Modernized Hermann Otto Primary School

To reach a better functional operation the public spaces are converted: new main entrance is designed on the south end of the building where a new entrance hall is situated having visual connections to the schoolyard and the library as well. The spaces opposite to the staircases get back their original function as lounge, in this way the illumination of the corridors get better. Now some matching functions are located in different places of the building. This situation is eliminated by the reorganization of the functions. The toilets get new place at the north end of the building. In this way valuable places can be used as new classrooms and new up-to-date toilets can be built. The mass of the designed building can be separated into three units. The south one contains the entrance and the important public spaces. The middle one contains the classrooms. And the north one operates as a vertical block with the toilets and the elevator.

The suggested facade modernization has three main goals.

- The design does not suggest removing the frontal panels, but significantly improving the heat insulation of the face-work. In this way no building waste is generated, the heat capacity of the frontal wall is maintained; the execution of the facelift is easier. The existing windows should be replaced to new three-ply ones. In order to reduce the ventilation heat loss artificial ventilation should be provided.

- The main goals of the structural design were to make the solar profit maximal in winter and to reduce the heat admission minimal in summer. Therefore on the external side of the glassing shading structures are installed to regulate the incoming light.

- One of these shading structures is a green facade, which lives in front of the classrooms on a steel framework. This vegetation can solve the shading in a natural way. The green facade and the wood covering with its natural colour on the south and north parts of the building are predestined to create harmony between the building and the natural environment.

The building expanded significantly due to the redesign. But the careful structural and mechanical design can reach that the energy consumption of the new house is less than the existing one as the preliminary dates show.

3. Modernization of Széchenyi István University

3.1 Building description

The other examined building is the main building of the Széchenyi István University in Győr beside the river Mosoni-Danube, which was designed in 1969-74 and built in 1971-77 *(Figure 5)*. The building complex of the former college was the biggest educational investment of the decade in the country. One of the major Hungarian architectural and engineering consulting companies, KÖZTI (Public Building Designer Company) was commissioned to design this project (leading architect: Miklós Hofer, structural engineer: Kálmán Z. Horváth) *(Hofer et al, 1975)*.

Figure 5: Main building of Széchenyi István University

The building has a very strong concept and order expressing strictly the spirit of the architectural and historical age in which it was made. Miklós Hofer preparing the design process made a scholarly program analysis in which he considered the communications and telecommunications as the most intensive developing technical sciences. Therefore the possibility of the expansion and the flexibility became his main goals, as he considered the college as a permanently developing and changing organization where buildings were the spatial frames of the changing function *(Hofer et al, 1978)*. In addition to this elevated aim the designs had to fit the building-trade of the socialist period, which preferred prefabricated large-sized elements in construction.

According to these principles Miklós Hofer created a functional and (mega)structural composition in which high dual towers were made for non variable, vertical functions and 18 m spread slabs were made between the towers for variable spaces: seminar rooms and offices. The house was formed with four similar units. In each unit the different functions are separated into different levels resulting a terraced cross-section where auditoriums are on the first floor, seminar rooms are on the second and third floors and offices on the other ones. Structures are strongly emphasized in the visual image of the house. Movements of masses and structural units give a deep plasticity of the facades on which the concrete elements appeared with several different surfaces *(Hofer et al, 1975)*.

This building is classifiable as a masterpiece of the movement of New Brutalism. This style emerged mainly based on Le Corbusier's life-work in England in the years of 1950s and 1960s. Later Le Corbusier's principles returned in England, where Alison and Peter Smithson became the leading advocates of the new movement (McKinstry, 2008). In 1966 the architectural critic Reyner Banham described the purposes of the new style as follows (Banham, 1966):

- the building was a unified, clear and memorable visual image;
- the building exhibited its structures clearly;
- raw, untreated materials got high valuation at the design.

Other architects can also be associated with Brutalism as Ernő Goldfinger, Denys Lasdun, Louis Kahn, John Andrews, Ralph Rapson and Paul Rudolph. Miklós Hofer could get first hand experiences about the principles of New Brutalism in 1962-63 working in London in the architect studio of Ernő Goldfinger *(Marosán, 2000)*. Hofer most important architectural design intent for the educational building was to introduce the enormous structure openly, almost brutally *(Hofer et al, 1975)*. The intent became truth and the concrete structures expressed this brutal aesthetics well. Therefore people usually find the university buildings unfriendly but the profession acknowledged the worth of this design and Miklós Hofer was awarded with the most significant Hungarian architectural tribute, Ybl Prize in 1978 *(Schéry, 1995)*.

3.2 Necessity of modernization

The possibility of the expansion and the flexibility were the main elements of the concept from the beginning so changing of the building was an accepted necessity by designers *(Hofer et al, 1980)*. They thought about the college building as a complex of structures ordered in a hierarchy, which had three levels according to the moral lifetime of elements. By now the university building is almost 40 years old so the revision of the structures and the modernization is surely needed at least related to the secondary and the tertiary categories.

Management commissioned a preparing study, which examined the condition of the building and its service systems *(Galambos et al, 2008)*. According to this study the service systems are considerably outdated. Therefore the study suggested changing almost all service networks. But to reduce the maintenance cost the energy wasting structures of the house should be also converted because the way of energy saving is dual: the new service systems will use less primary energy with better efficiency and the produced fewer secondary energy will be saved by the improved thermal shell of the building.

Based on the recommendations of the comprehensive study including chapters about functionality, building constructions *(Zádor, 2008) (Somfai and Molnárka, 2001)*, mechanical and electrical engineering *(Galambos et al, 2008)* and fire protection *(Szűcs, 2008)* university management ordered the architectural plans of frontal modernization. Architectural design should react to several different practical problems caused by the radically changed requirements and degradation. The original solutions of the building structures are equal to the standard of the 1970s and the quality of the execution was almost average. These circumstances and the destructive impact of decades resulted to the actual problematic condition of the building.

Main problems of the building in a short list:

- Several damages of the concrete structures are observable on the facades.
- The designed terrace roofs are still not walkable.
- Flat and terrace roofs often leaked.
- Whole facade shows almost homogeneously significant heat losing.
- Structures have strong thermal bridges.
- Complete external heat insulation is strongly recommended.
- Heat insulation of the window structures is poor, glasses are blurred.
- Steel windows have not sealing between the window frame and the casement.
- Steel frames of windows started corroding.
- Windows of rooms are designed with a special unpractical vertical section.
- Southern windows should be designed with external shadowing.
- Acoustic problems make difficult the education in the seminar rooms.
- Building is not able to fulfil the recent fire protecting requirements.

- Building has to be divided into four fire-sections.

- Conditions of the safe escape at an emergency should be improved.

3.3 Concept of modernization

The architectural design job focused on the frontal modernization of the educational building reacting all aforementioned practical aspects which were related to this part of the conversion (leading architect: Attila Bodrossy, Tamás Czigány). Architectural design had to find out solutions of the existing problems so that the architectural quality of the building would not be changed significantly. Therefore the main goal of the architectural redesign was to save the spirit of the building (Ságoly, 2006), which was possible if the way of the conversion had emphasized the original concept of the house (Figure 6). Keeping the following conceptual elements was the most important objects to reach this goal in the case of this building:

- to keep the contrast between vertical and horizontal functions, which appeared in the building as double towers and floors between them;

- to keep the visibility of the heaviness of elements, which are originally made of concrete, but they will be covered with the needed external heat insulation;

- to keep the character of a building made of precast panels having gaps between the elements;

- to keep the deep plasticity of the facade, which is given from the movements of masses, from the formation of the towers and from the double breaking of the windows vertical section.

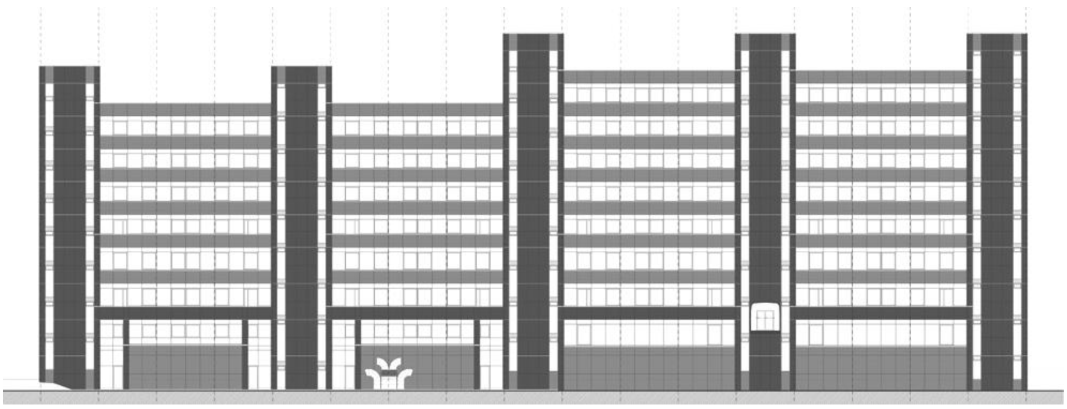

Figure 6: Modernized north elevation of Széchenyi István University

This redesign of the house planed an exterior continuous thermal shell around the building. The bounding structures of the house are redesigned to fulfil the current requirements of the Hungarian decree with a big allowance. The over-fulfilment is about 120-140%. The heat insulation is uniform on each structure, so thermal bridges are eliminated.

Unfortunately the task doesn't allow preserving the concrete of the frontal structures as visible material so such covering should be selected which can give a similar impression as the fair-face concrete. The manufacture of new prefabricated concrete covering would be an ideal, but very expensive, solution of this problem so designers have to select a kind of light, thin frontal panel system. Fibre-cement boards have good fire-resistance so the application of it seems to be the favourable. According to the architectural goals of the facelift the panels are used in two different tones of grey to keep the contrast between the vertical and horizontal functions. The tones can intensify the visibility of the heaviness of the elements as well. Fibre-cement face work is mountable with smaller panels, so the gap image of the fronts will be denser than the original was. Therefore the fronts are designed using two types of gap: a normal thin gap and a stronger one to sign the levels of the floors.

In the designed frontal modernization the window structures are completely renewed with aluminium framed windows and curtain wall structures. These up-to-date products will be able to radically reduce the heat loss of the building. The double breaking seminar room and office windows are removed in the plans, but to keep the plasticity of the facade the new window structures are mounted in a deep position over the around heat insulated parapet panels. The building has more fix windows than before because of some reasons of heat insulation and fire-protection. On the southern fronts the windows get external blinds as shading devices to protect the rooms from the heat of the summer sun.

4. Conclusion

Although both presented projects are modernization tasks, they seem to be completely different. Both modernized buildings are public buildings for education, so the connected rules and requirements are quite similar. They were made in the same age, during the socialist era of Hungary. This time using of large-sized precast reinforced concrete elements were preferred in the building trade by the government. These buildings are designed under this pressure, so the used structures show several similarities. Houses are about 30-40 years old and they are still in use despite to some functional problems, which need some modification or sometimes expansion. This continuous operation is the cause, why the idea of demolition and building of a new house was not raised as an issue, this can value up the worth of the structures. Structures have several defects, but in both cases the renovation seems to be economical. The energetic modernization of the buildings, the consequent heat-insulation and the change of service systems, hold out to save about 40% of the energy cost. Due to these reasons the execution of the modernization is expectable in the near future.

The studies illustrate well, that the decision about the modernization is a mainly financial question. Reviewed the scopes of modernization they can be ordered into three categories by their purpose. These three categories are: comfort, safety and economy. The categories are in similar relation with us as those three parts of the determination of sustainability: social, environmental and economical. Positioning the actions in this system there is no one which has only an economic aim, but it is clearly visible that the most important tasks have a strong economic impulse. If an action is reversionary that has better chance to be realized. So modernization is mostly an economical stress *(Figure 7)*.

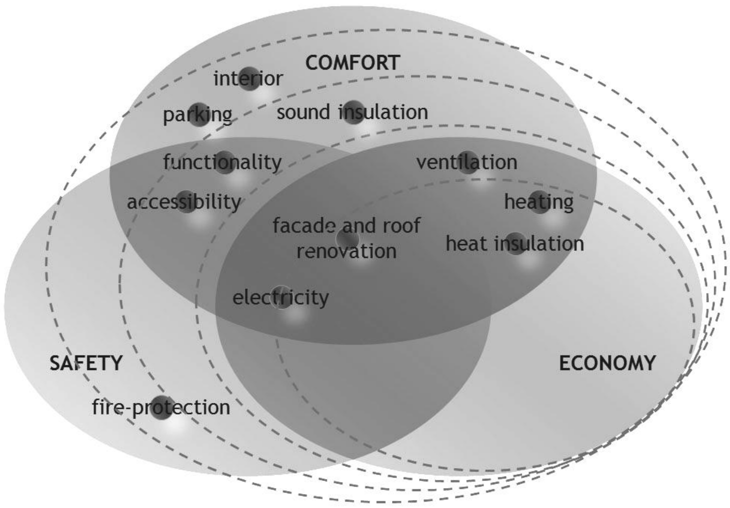

Figure 7: Scopes of modernization

The differences of the two projects are few in number, but they are significant. First the motivation of the modernization is other and other. The school has mostly moral degradation, and it needs new area for the education. The school management wants to do the frontal modernization together with expansion. In case of the university the physical degradation plays the major role. University management commissioned the design of the modernization to improve the physical condition of the building. Questions of moral degradation are in the second position in this design.

The two buildings represent different architectural values. The school is a ready-cut building in contrast with the university which is an individual design. At the modernization of the school designers could concentrate the functional problems and they could modify the building if it had been favourable. The university with its size, significance and its elevated architectural concept is an important building in the Hungarian architectural history. Recognising this situation the concept of the modernization concentrated to keep the original character of the university as it was possible.

As these case studies show nowadays the architects stand before a new and interesting job in which the buildings of the near past have to be modernized according to the recent requirements. Good solutions for this kind of problems can be found only by responsible decisions overviewed all aspects of the building waiting for modernization.

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Monitoring Useful Solar Fraction in Retrofitted Social Housing

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Abstract

Registered Social Landlords (RSLs) are responsible for 2.15 million homes in the UK (Department of Communities and Local Government, 2006) and will therefore need to be at the forefront for the drive for sustainable homes if the government's aim of reducing emissions of green house gases by 80% is to be hit by 2050. As it is estimated that 87% of currently existing properties will still be in use in 2050 (Boardman, 2007), retrofitting renewable technologies will be of vital importance if key targets are to be hit. Multiple previous studies have looked at the output of domestic solar hot water (SHW) systems in the UK. However, very few of these assess retrofitted systems in situ, being mainly laboratory based, and none assess how SHW systems perform in social housing. The paper presents a review of domestic SHW performance in-situ based on previous studies and available data sheets, assessing particularly how the in-situ results differ from those in laboratory conditions. A review of modelling techniques in order to predict performance of SHW systems will be included within the paper, as well as models to predict household demand for hot water. The paper presents a detailed methodology of proposed field monitoring of a number of domestic social properties with and without SHW systems. Within this are included details on the background to the project with Gentoo Homes, an RSL in the north east of England, and the research project's aims and objectives.

Keywords: solar hot water, retrofit, social housing, solar fraction, RSL

1. Introduction

1.1 Background and Gentoo project

The UK government is legally bound to cut total greenhouse gas emissions by 80% by the year 2050, as well as achieving a significant cut of at least 34 % by 2020 based on 1990 levels (Climate Change Act, 2008). To make such cuts in emissions it seems likely that a cut larger than the 80% figure will need to be made in the residential sector, so as to mitigate the probable increases in other areas such as aviation (Bows and Anderson, 2007). The government has begun to address the issues of carbon emissions within the housing sector by pushing forward plans to install smart meters within all properties, phase out incandescent light bulbs and running the Low Carbon Buildings Programme (Energy Saving Trust, 2007).

In the UK, the turnover of building stock is relatively slow compared to most developed countries, meaning 87% of current properties will still be in use in 2050 (Boardman, 2007). This makes the retrofitting of energy efficient measures and micro-generation technologies to existing stock essential going forward, if such a reduction in CO2 emissions is to be achieved. The government is introducing a microgeneration tariff in April 2010 for electricity, and a tariff for heat in 2011, in order to make microgeneration in domestic properties more financially viable (Bergman et al, 2009).

Of around 25 million homes in the UK, 2.15 million (around 9%) are in the ownership of registered social landlords (RSLs) (Communities and Local Government, 2006). Because of the number of houses controlled by RSLs it is important that they adopt retrofit carbon cutting measures across a large proportion of their housing stock if government targets are to be achieved. It is also useful for RSLs to be the forerunners of private landlords in retrofitting as they often have a larger skill base and funds within their organisations for the purpose of retrofit, as well as controlling around 9% of the housing stock (Communities and Local Government, 2006).

Gentoo is a RSL based in Sunderland, UK, with a stock of around 30,000 homes and is one of the largest in the country. In September 2008 Gentoo began “Retrofit Reality” a project to retrofit 140 of their homes with carbon saving measures funded in part by a grant from the Housing Corporation (which became the Tenant Services Authority in November 2008 or TSA). Combinations of technologies are being used within the project including A-rated boilers, external cladding, argon-filled double glazing and mains fed showers. 17 of the houses are to be fitted with solar hot water (SHW) systems. It is these retrofitted solar properties which will be the main focus of this paper.

1.2 Previous studies

Domestic hot water accounts for 24.6% of the total primary energy consumption by housing in the UK (BERR, 2008). Yao and Steemers (2005) find that energy usage for domestic hot water depends on many factors, such as the required water temperature, the volume requirement per person and the household size. CIBSE (2007) estimate hot water use to be typically between 30-55 litres per day in the UK at a temperature of 55oc.

Herring et al (2007) state that in 2005 there already existed 82,200 domestic microgeneration systems of which more than 95% were SHW systems. However uptake was largely found to be specific to households with similar age and economic profiles and uptake of the systems was relatively slow due to the cost time and effort associated with their planning, installation and use. Despite this, those who had installed the systems were overwhelmingly happy with the technologies based on consumer research carried out by the Herring et al (2007) study.

Martin and Watson (2002) and Knudsen and Furbo (2004) have undertaken laboratory based studies into the performance of SHW systems. Others, such as Lloyd and Kerr (2008), have carried out research concerning the addition of these low and zero carbon (LZC) systems to houses, both in new build and retrofit scenarios.

Although there have been many studies designed to monitor the output of SHW both in commercial and domestic conditions, Knudsen (2002) and Lloyd and Kerr (2008) found that few tests have been done with the systems in-situ or in what could be considered a "real life" scenario. This meant that few of the vagaries of consumer behaviour and weather impacts had been taken into account and it is these which Knudsen (2002) and Lloyd and Kerr (2008) looked particularly to assess. Jordan and Furbo (2005) and Lloyd and Kerr (2008) perceived many of the influencing factors in the performance of domestic SHW to be attributable to the performance of the storage system.

Andersen (1998) and Lloyd and Kerr (2008) found that the in-situ monitoring of energy output of domestic SHW showed output to be lower than in laboratory conditions, as well as being far more variable. Degelman (2006) used monitoring on a domestic SHW system to show that the system became significantly degraded in performance over time.

Many studies use models to predict solar output from domestic systems (Jordan and Vajen, (2001); Kalogirou and Tripanagnostopoulos, (2006); Lima et al, (2006); Souliotis et al, (2009)). Hobbi and Siddiqui (2009) use a TRNSYS model to advise the design of a domestic hot water system in a cold climate, showing the solar fraction produced. Meir et al (2002) use a TRNSYS model to predict the performance of solar systems before comparing the predicted solar output with actual results from monitoring.

The simulation model used in the predictive element of the study is the Transient Energy System Simulation Tool or TRNSYS. This modelling tool was chosen after careful review of the appropriate literature. The TRNSYS model is used widely in the modelling of solar processes in the academic literature Many studies use models to predict solar output from domestic systems, with the TRNSYS model being the most widely used within the academic literature (Jordan and Vajen, 2001; Kalogirou and Tripanagnostopoulos, 2006; Lima et al, 2006; Souliotis et al, 2009).

Duffie and Beckman (1991) use TRNSYS models for almost all of their workings on solar thermal systems and see it as the most suitable tool for modelling solar output in varying levels of complexity. The TRNSYS software is seen as a powerful tool for research and development, for understanding systems' function and for design. TRNSYS can also be used flexibly with the user's own data for parameters such as weather, which made it an appropriate choice for use in this study. Kalogirou

(2009b) finds TRNSYS models can be validated to an accuracy of 4.7% when modelling a thermosyphon system. Kalogirou uses TRNSYS more than any other system for modelling solar output and cites the flexibility and user-friendly nature of what is a complex tool. Kalogirou frequently uses TRNSYS in his many studies on solar thermal.

1.3 Research project

The aim of the research project is to use an industry standard domestic energy model to predict the performance of solar collectors added to social houses as part of the RSL's retrofit programme. The model will look at domestic hot water energy demand in short time steps, to give hot water daily demand profiles. The model will also predict SHW output from a simulation designed to imitate the "real" retrofitted SHW systems added as part of the RSL's retrofit programme. To do this it can use imported daily demand profiles and imported weather data.

A number of dwellings fitted with SHW will be monitored to determine the performance of the collectors and the solar fraction used by the household. The research project will compare the in-situ results from the monitored domestic SHW systems with the predictions made by the solar collector model and comment on the differences seen between the two sets of results.

Objectives:

- To monitor the performance of in-situ, retrofitted renewable energy sources on domestic housing stock over a minimum of 12 months

- To predict the performance of the retrofitted SHW systems using an industry standard model, TRNSYS, in short time steps

- To analyse the differences between projected and actual performance

- To compare the modelled data with that from the monitored properties, identifying the model accuracy and suggesting amendments to model in order to incorporate observed performance differences

2. Methodology

The methodology essentially takes the form of two streams of work; the monitoring and the modelling aspects, which will ultimately combine so that the in-situ results may be compared to the outputs predicted by the modelling work.

2.1 Monitoring in-situ solar hot water systems

In order to assess the performance and useful solar fraction provided by the SHW collectors, a monitoring system was installed in six retrofitted houses, and in a further two non-retrofitted houses in order to provide baseline data.

The houses were chosen to be as alike as possible (by using relevant data) to ensure that the results from the monitoring was influenced as little as possible by factors not relevant to the study. The building and construction type was taken into account to find similar sized and designed properties. Information from RSL's customer surveys was then used to find households with the same number of occupants, of the same age and occupation patterns. This sample was to represent an "average" household for the size of the properties and the estate in which they were situated.

Within the six solar properties identical monitoring systems were set up. Each system had three heat meters to measure energy supply and demand of the solar collector, the auxiliary boiler and the hot water outflow from the hot water tank. Although sufficient data could be obtained from using just two heat meters, a third was installed as this allowed any system losses to be accurately recorded. The heat meters give a measurement of total energy in the hot water by measuring water flow with a turbine and water temperature with platinum resistance thermometers (PRTs) to give kWh output ($Q=mCp\Delta t$). The heat meters were set up for the domestic scenario, being able to take account of low flow rates, and would pulse a signal to the data logger for each kWh of energy registered through them, periods of hot water usage could then be seen when the information displayed.

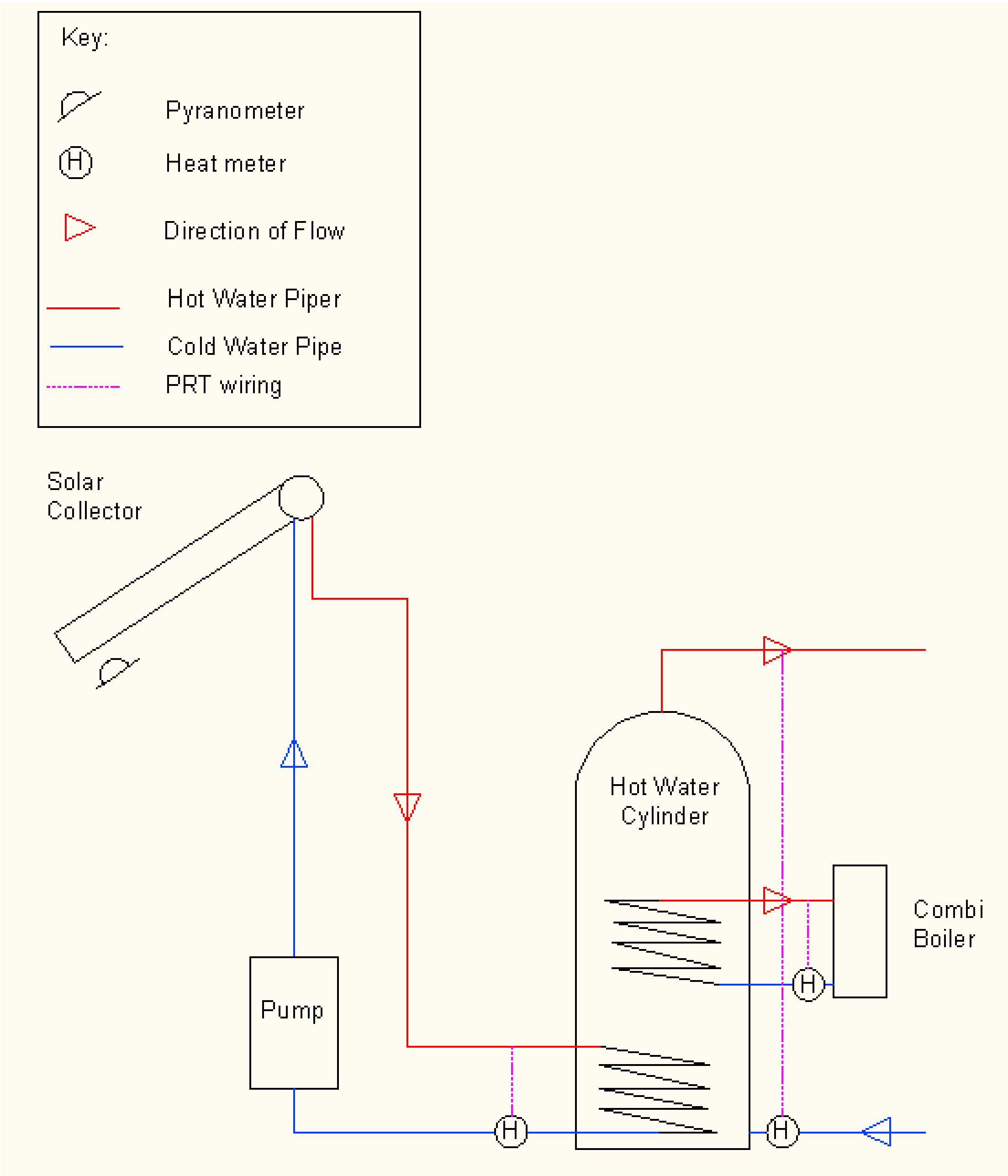
A pyranometer was fitted to the roof of each property at the same mounting angle as the solar collector to measure in plane solar irradiance. As well as this measurement, there was also a weather station set up within half a mile of the properties in order to record local weather patterns in detail. The pyranometers would give details of solar irradiation in half hourly averages, at the angle at which the panel was fitted. The weather station was equipped with a temperature probe for ambient air temperature, a humidity probe for air humidity, two pyranometers to the same specification as those in the properties with one to measure diffuse solar radiation and one to measure horizontal solar irradiance.

All of the measurements were logged to data acquisition units which included GSM modems in order that the data could be transferred remotely without any disturbance to the tenants of the monitored properties.

Alongside the six SHW retrofitted houses, two houses of similar design and occupation were monitored as control properties. These properties had a reduced monitoring system installed with only one heat meter being situated on the boiler outflow to measure hot water consumption.

2.2 Schematic diagram of monitoring system set up

Schematic of monitoring kit for solar hot water properties:



2.3 Modelled data

A model was built in TRNSYS to act as a "base case" from which the various parameters can be tested to see how they affect SHW output. The base case was built from a worked example from CIBSE's Solar Heating: design and installation guide which allowed a typical SHW system to be built and validated (CIBSE, 2007). The worked example was done using the information in the table below:

Example Energy load	*Energy annum kWh*
DHW usage 120 litres per day	*2267*
Solar pipe losses	*232*
Solar store losses	*295*
Store losses from tappings	*50*
Total DHW load annum	*2844*
Solar fraction at 60^{o}c	*40%*
Solar energy target to collect if optimum	*1138*

Using this worked example and other scenarios from the literature, the model was validated by observing output from the model to be within 5% accuracy of these case studies. The base case model was then used as the basis against which a change in parameters such as collector area, tank size or daily demand profiles, could be measured and the output expressed in terms of a "percentage shift from base case". In order to further validate the model, scenarios were run based on previously conducted studies and the modelled results compared to these, to confirm that the sensitivity of the model was correct.

The weather data used initially in the model comes from the Meteonorm database which provides average weather files based on previously recorded data. As in-situ weather is recorded using the on-site weather station, this data can be added to the TRNSYS simulation.

Once validated, key scenarios are run on the TRNSYS software to imitate likely scenarios in the monitored sample of properties, based on different hot water demand profiles, total daily draw-offs of hot water etc. A system can be designed to be identical to the in-situ system in the sample properties in terms of the sizing of the different components of the SHW system.

2.4 Other data collected

For this project a number of factors about the tenants themselves were recorded. These were; age, work patterns, gender and number of occupants in household, and were taken from the housing association's "customer survey" for 2008.

3. Future work

The ultimate aim of the research project is to use the in-situ results from the monitoring to compare with the modelled data from TRNSYS. The in-situ will be compared with the modelled output and the differences observed and investigated. The source of these potential differences will be considered and investigated and will help form recommendations of improvements to the model. Finally, these improvements will be implemented to the model and an assessment of how close the match between in-situ and modelled is will be made.

In order to do this an exact replica system of the “real” SHW systems must be built within TRNSYS and a number of different scenarios run to give a range of modelled results. Once data is monitored from the in-situ SHW, and a full data set produced for a 12 month period, this data will be input into the model to create hot water demand profiles for each household.

In-situ weather station data will allow real weather data to be added to the model, monitored hot water profiles and loads from the sample 8 households can be added also and thus the accuracy of the modelled output can be improved for a retrofit scenario.

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Effects of Tall Office Building Envelope Technologies and Design Strategies on Comfort and Energy Consumption in Hot, Arid Climate

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Abstract

In the Middle East 40% of energy is used in buildings, more than in industry or transport, and the absolute figure is rising fast, because of the recent construction boom. In hot arid climate, the energy consumption in office building for cooling and lighting is enormous due to problems of overheating and high solar gain. Since the building envelope functions as an environmental filter, and controls the influence of the outdoor on the indoor environment, appropriate design strategies and technologies are necessary to create a climate responsive envelope. This paper is directed to optimizing thermal, visual comfort and energy efficiency through the application of different technologies and design strategies for office building envelope in hot arid climate. The study analysed the outdoor and indoor climatic conditions, to understand the problems of overheating, discomfort, and the energy needed to achieve the indoor environment quality. Building simulation programs were used to evaluate the effects of different technologies and design strategies on the comfort and energy consumption. The technologies included: glazing performance, shading and solar control, insulation, thermal mass, and daylight systems. In addition, the design strategies included: opaque to transparent ratio, orientation, and natural day and night ventilation. The results show the potential for a significant decrease in energy consumption for cooling and lighting. On the other hand, thermal and visual comfort can be increased. Reducing the energy consumption for cooling and lighting as well as improving the indoor comfort are of great importance towards sustainable and climate responsive buildings.

Keywords: hot arid climate, comfort, energy efficiency, intelligent envelope, design strategies

1. Introduction

The building envelope functions as an environmental filter; it forms a skin around the building and controls the influence of the outdoor on the indoor environment. In tall buildings, walls cover more than 90% of the shell and highly influence the indoor environment. Moreover, the annual solar energy received at the envelope surfaces of the building is in the same order as the energy needed to operate it as suggested by Andresen et al. (2005). Much interest has recently been focused on building envelope, which by adaptive or responsive actions will make it possible to utilize more of this energy for building purposes, and reducing the energy use. In line with a sustainable development approach, it is critical for practitioners to create healthy, sustainable office building envelopes especially in climates where the energy consumption for air conditioning is very high. Furthermore, we are in front of global challenges: currently around the world, 40% of the energy is consumed in buildings. The construction sector uses 30% of our resources and 20% of our water, producing up to 40% of the world greenhouse gases and generating 40% of the world solid waste (World sustainable building conference 2008). According to Hass and Amato (2006) building facades are responsible for around one third of buildings energy bill. Yeang (1999) suggested that tall buildings present in cities around the world will continue to extend and to develop with increasing intensity.

The analyses of the outdoor conditions in hot arid climates underline the problems of overheating and discomfort due to high temperature and solar radiation. The main problems in arid climate are the dry air with a large diurnal temperature variation, low relative humidity, and high solar radiation: this leads to a high risk of overheating. The analysis of the outdoor air temperature for five cities in hot arid climate (Basra in Iraq, Kuwait city in Kuwait, Dubai in UAE, Doha in Qatar, and Riyadh in Saudi Arabia) showed the extreme high temperature especially in summer time, when the average highs arrive at around 40-43°C. In addition, the difference between the average low and average high temperature is relatively high and it could reach between 10-23°C. On the other hand, the analysis of the outdoor solar radiation (monthly average) on the horizontal and vertical planes for the five cities mentioned above shows very high values, as can be seen in table (1). This means that special attention should be taken in designing the south, east, and west facades.

Table 1: Average solar radiation, air temperature, and relative humidity for the five locations

City	*Dubai*	*Doha*	*Riyadh*	*Kuwait*	*Basra*
Monthly average solar radiation, Wh/m²	*6292*	*3470*	*6206*	*4926*	*5540*
Min. average air temperature, Cº	*17*	*21.5*	*15.5*	*14.6*	*19*
Max. average air temperature, Cº	*39*	*33*	*37*	*38*	*31.5*
Average relative humidity, %	*43.8*	*46.7*	*23*	*29.7*	*33*

The humidity average for the major part of the year ranges from 20 to 50%. For such an arid climate, special consideration should then be taken in the design phase to avoid discomfort due to high temperatures. The analysis of the precipitation shows the low amount of falling. For this reason special consideration should be taken at the design phase to minimize the water consumed in building construction and operation.

Thermal comfort is very difficult to define because of the need to take into account a range of environmental and personal factors when deciding what will make people feel comfortable. Thermal comfort is defined in British Standard EN ISO 7730 as "that condition of mind which expresses satisfaction with the thermal environment". The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) proposed a definition of the suitable quality level for an indoor environment, as stated in Table (2). The most commonly used indicator of thermal comfort is air temperature. However, air temperature alone is not an accurate indicator of thermal comfort. Air temperature should always be considered in relation to other environmental (radiant temperature ,air velocity ,and humidity) and personal (clothing insulation ,metabolic heat) factors. Daylight, on the other hand, is one of the most important requirements for natural, healthy and productive working environment. Good natural lighting and unimpeded views out of a building belong to the minimum standards required by guidelines for workplaces in many countries.

Table 2: indoor environment quality level according to ASHRAE

Season	*Comfort temperature*	*Comfort temperature range*	*Relative humidity*	*Air velocity*
Summer	*24.5 °C*	*23~26 °C*	*30~65%*	*0.25 m/s*
Winter	*22 °C*	*20~23.5 °C*		*0.15 m/s*

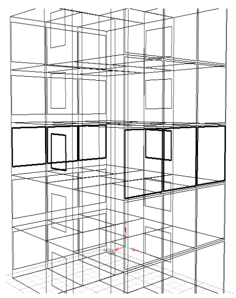
Until recent years, energy efficiency has been a relatively low priority to building owners and investors. However, with the dramatic increase and awareness of energy use concerns, energy efficiency is fast becoming part of real estate management, design, and operations strategy (Omer 2008). Economic and industrial development in countries with hot, dry climate led to an increasing demand for electricity for air conditioning and lighting to overcome the discomfort during the harsh summer. Al-Hadhrami & Ahmad (2009) found that air conditioning requires about 73% of total electricity consumed in residential buildings in Saudi Arabia, for the cooling loads season extends over more than 7 months of the year. In most Gulf States, 40% of energy use is consumed in buildings, more than by industry or transport. The absolute figure is rising fast, as construction booms, especially in countries such as UAE. AboulNaga & Eisheshtawy (2001) found that the annual total energy use in buildings varies from 120-312 Kwh/m², while the average annual energy consumption for contemporary buildings is 268 Kwh/m².

2. Methodology

The study used two simulation programs in order to evaluate the effects of different building envelope technologies and design strategies on comfort and energy efficiency. ECOTECT and TRNSYS dynamic simulation programs were used for these evaluations. The building simulation model used and other inputs are stated in table (3). The simulation model is selected to represent a typical tall office building in which each floor is divided into 9 thermal zones; each thermal zone has

4m width, 6m depth and 3.5m height. The simulations were performed for five cities in hot climate: Riyadh (Saudi Arabia), Abu Dhabi (UAE), Doha (Qatar), Kuwait city (Kuwait), and Basra (Iraq). Meteonorm climate data files were used. The study evaluated different technologies to be applied in tall building envelope in hot arid climate including: glazing performance, shading and solar control, insulation, thermal mass, and daylight systems, as well as design strategies including: opaque to transparent ratio, orientation, and natural day and night ventilation. Thermal, visual comfort and energy consumption were used as performance parameters.

Table 3: building simulation model and input data

Comfort temperature: 20-26 °C *Thermal zone: 4mx6m = 24 m², height 3.5m* *Cooling operation: 7 AM to 9 PM week days* *Occupancy: 1 person per 10 m^2* *Internal wall: brick temper frame, 19 cm thick, U value 1.77 W/m²K, solar absorption 0.7*	*Internal gains* *Persons: 14 W/m², Computer: 50 W, Lighting: 5 W/m²* *Luminance level: 500 lux* *Relative Humidity: 50%* *Ventilation rate: 5 l/s occupied, 1 l/s unoccupied.*	

This paper presents the first results of an on-going study aimed at finding design guidelines to evaluate the performance of different envelope technologies and the related design alternatives during the early design stage. Although the study was conducted for the five cities mentioned above, this paper presents a sample for selected cities as the results are close for some of the design alternatives considered.

3. Results and discussion

3.1 Effects of window wall ratio and orientation

Minimizing the effect of solar radiation within the hot urban environment may often be a desirable design criterion, the effect of building orientation and window to wall ratio being crucial factors on cooling loads and discomfort in that context. The control of indoor air temperature can be achieved by the correct orientation of the building and by a balanced ratio of opaque to transparent areas, while ensuring adequate sky view in order to moderate the harshness of the climate.

The simulations were done for different windows to walls ratio (30%, 50%, 70% and 90%), and orientations: (south, north, east, west, 30º from N to E, 30 º from S to W, 60 º from N to E, 60 º from S to W, 30 º from N to W, 30 º from S to E, 60 º from N to W, and 60 º from S to E). The simulation was performed using ECOTECT software for Riyadh city in Saudi Arabia. Figure (1) shows the results in terms of cooling loads, and discomfort hours. For 30% glazing size, the difference in cooling loads for different orientations remains small; this can reach maximum 20 Kwh/m² yr. This percentage can then be used for east and west orientation. For 50% glazing size, the orientation effect starts to appear and the cooling loads difference can reach more than 35 Kwh/m² yr. For 70% glazing size, the cooling loads difference by changing the orientation is clear and can reach up to 45 Kwh/m² yr., so this glazing ratio could be used in certain orientations, such as north. For 90% glazing size, the cooling loads difference due to orientation is even more evident and can reach 60 Kwh/m² yr.

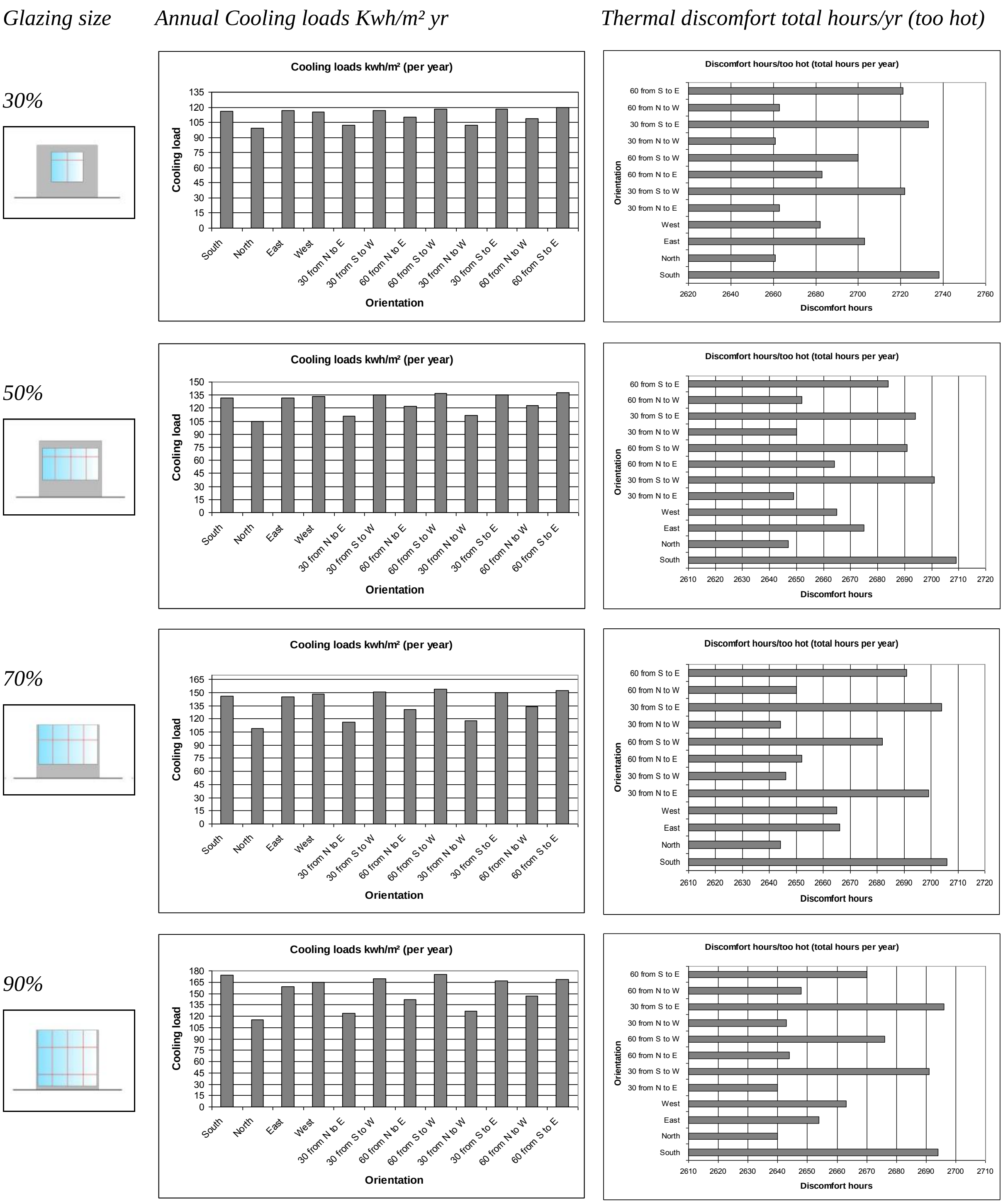


Fig. 1: the effect of window to wall ratio and orientation on the cooling load and thermal comfort

It can be concluded from the simulations, that the minimum cooling load was for the north and south orientations and it can be seen that variation of the transparent to opaque ratio causes only a small difference in the cooling load in the north orientations and a large difference for other orientations.

3.2 Effects of natural day and night ventilation

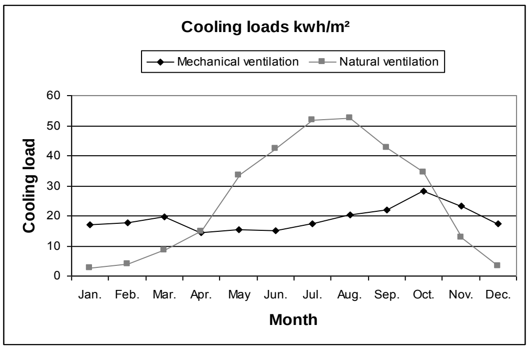
Natural ventilation has two different functions: to supply fresh air and, potentially, to provide cooling in summer. Haase & Amato (2009) examined the potential for natural ventilation to achieve thermal comfort in hot and humid climate and found that the improvement in comfort by natural ventilation ranges between 9-41% in tropical climate, between 3-14% in subtropical climate and between 8-56% in temperate climate. On the other hand, night ventilation may contribute to reducing cooling loads and improving thermal comfort. This technique uses the outdoor cool air to decrease the indoor air temperature and the temperature of building structure, especially for buildings with high thermal mass. In certain climates with large variation in diurnal outdoor temperatures (as in our case) night time ventilation can be used to cool down the thermal mass of the buildings and reduce the cooling loads.

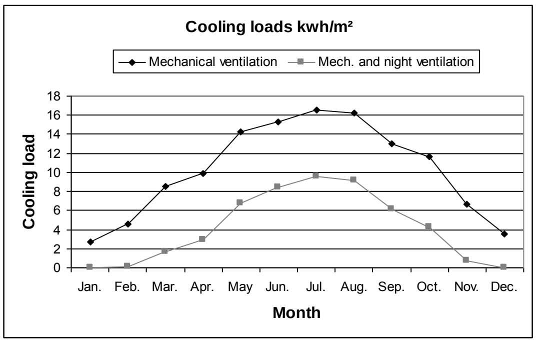
The simulations about the use of all day natural ventilation were done for five different cities using TRNSYS software. Figure (2) shows the evaluation of cooling loads and discomfort hours for 30% glazing to the west orientation zone and 70% glazing to the south orientation zone for three cities. The results showed a dramatic increase in cooling loads and discomfort hours using the daytime ventilation strategy except for a few months (January, February, and December). This can be justified by the high outdoor air temperature during the day for the rest of the year. For this reason, natural daytime ventilation can be used in a limited period of the year. Moreover, the effects of night ventilation, used for 3 hours in the early morning between 2:00 AM - 5:00 AM, were evaluated. The evaluation of cooling loads and discomfort hours for 30% glazing to the west orientation zone, and 70% glazing to the south orientation zone shows a significant decrease in cooling loads and discomfort hours using the night ventilation strategy around the year.

Daytime ventilation, 70% glazing to south orientation/ Monthly Cooling loads

Night ventilation, 30% glazing to west orientation/ Monthly Cooling loads

Basra, Iraq





Dubai, UAE

Doha, Qatar

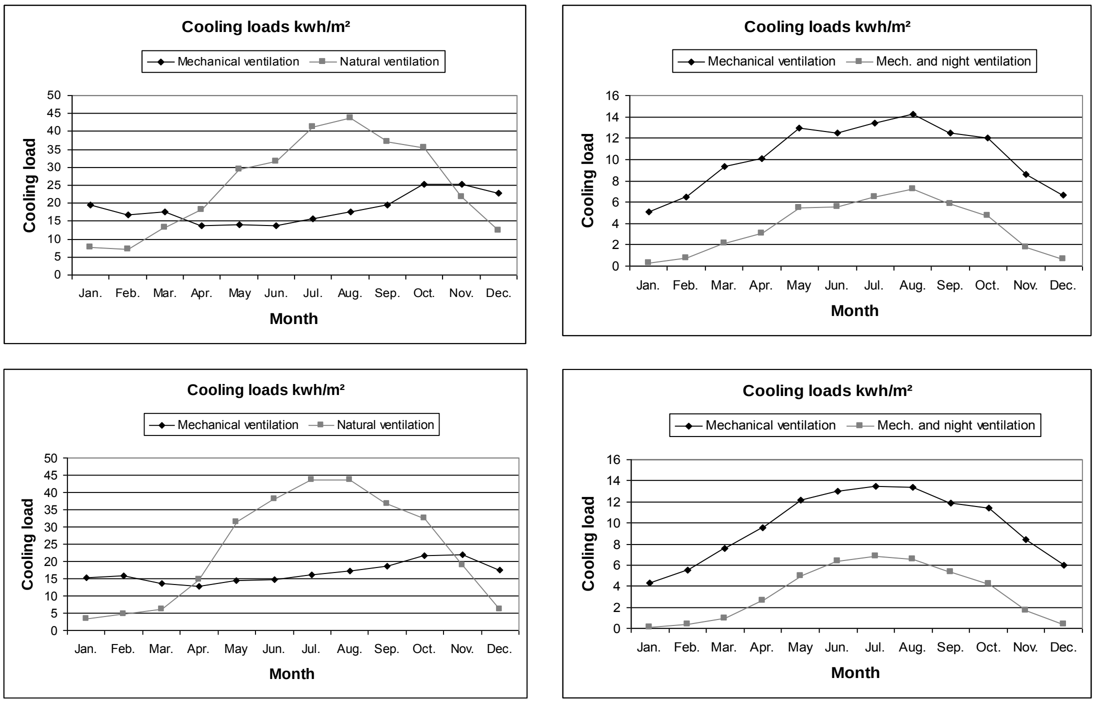


Fig. 2: the effect of natural day-time and night-time ventilation on the cooling loads

3.3 Effects of glazing performance

There is a growing interest in the use of transparent facades in commercial buildings, even in hot climates, with relatively high transmittance glazing systems. In Europe there is an earnest attempt to achieve high performance using advanced façade concepts. In the Gulf region, architects and engineers are further behind but remain interested in pursuing the environmental and performance goals. It is often dangerous to take a design solution from one climate and location and transport it to a new one without a good understanding to how the systems work. A study in the UAE by AboulNaga (2006) examined the impact of glazing on daylight and energy consumption for commercial buildings and found that the glazing properties – especially the shading coefficient – have a large influence on daylight and energy consumption.

The simulations in this work were done for different glazing types: single, double, double argon filled, and tinted glazing. The simulations considered the cooling load for 30% glazing to the west orientation zone, and 70% glazing to south orientation zone, as of the optimization presented in 3.1. The simulations were done for the five cities in hot arid climates Abu Dhabi in UAE, Basra in Iraq, Doha in Qatar, Kuwait city in Kuwait and Riyadh in Saudi Arabia. TRNSYS simulation software and Meteonorm climate data files were used. For the zone with 30% glazing to the west, the effect of glazing types on cooling loads is significant and the difference can reach more than 60 Kwh/m² yr. between single clear and double tinted glazing in all tested cities. For the zone with 70% glazing to the south, the effect of glazing types on cooling loads is also important and the difference can reach more than 70 Kwh/m² yr. between single clear and double tinted glazing in all tested cities. Figure (3) shows the annual cooling loads and solar gain for three cities. For this region, with high solar radiation and high outdoor temperature around the year, the use of solar control glazing either body tinted (absorbing) or coated (reflective) is crucial to reduce unwanted solar gain. Moreover, using advanced glazing and shading elements may help to reduce cooling loads and discomfort hours.

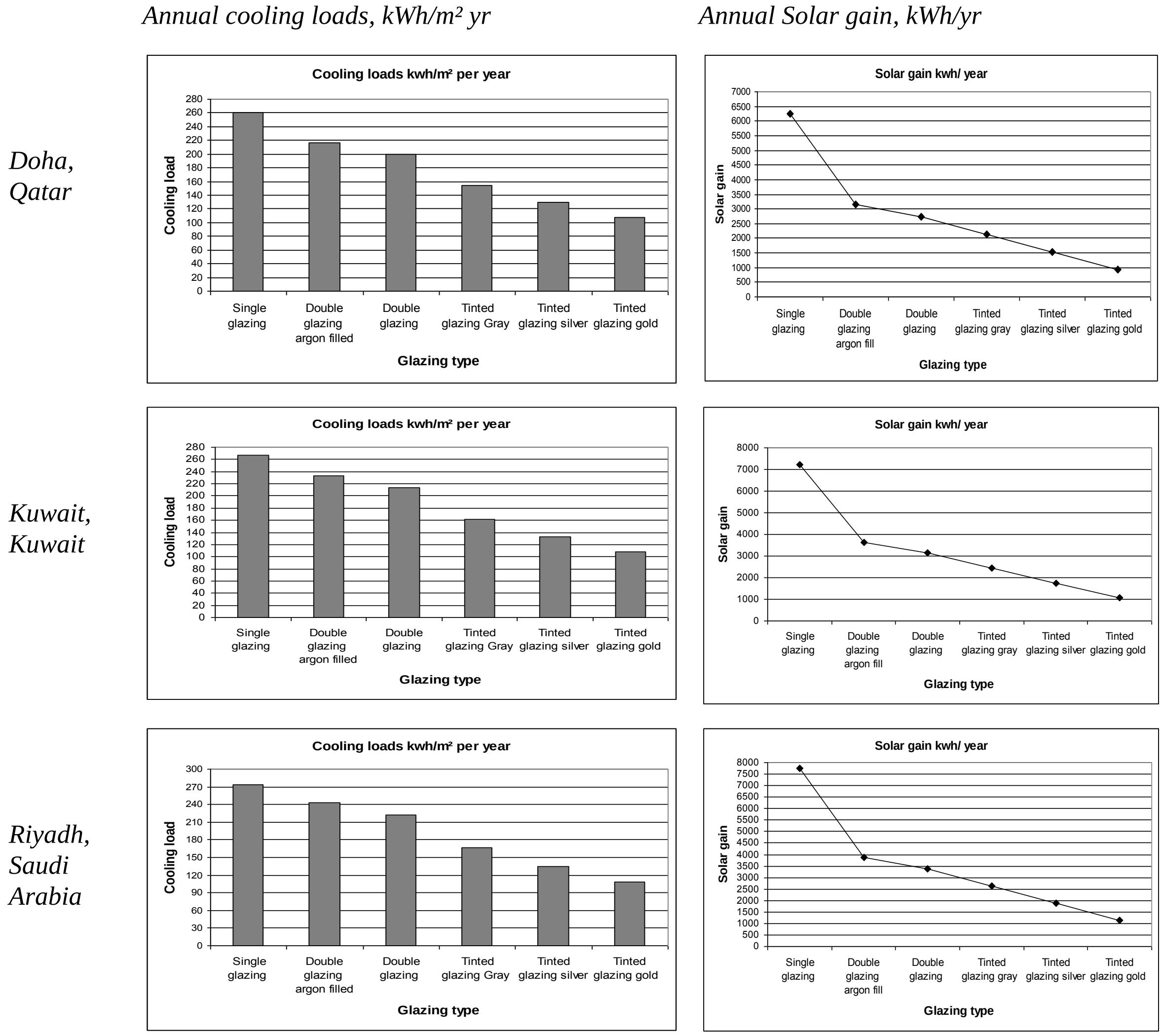


Fig. 3: the effects of changing glazing types on the cooling loads and solar gain in hot climates

3.4 Effects of fixed and movable shading

The simulations were done for the use of fixed shading and its effect on the cooling loads and comfort. The conditions were set at 30% clear double glazing to the west, and 70% to the south orientation thermal zones. TRNSYS simulation software was used. Horizontal overhangs were used for the south orientation and vertical ones for the west orientation. The results showed a significant decrease in the cooling loads of up to 60 Kwh/m² yr., when shading was applied. The same simulations were also done for the use of movable shading and its effect on the cooling loads and comforts. Again, horizontal louvers were used for the south orientation and vertical ones for the west orientation. The shading is closed when the total solar radiation on the façade surface higher than 400 W/m² and open when it is lower than 380 W/m². The results show a significant decrease in the cooling loads up to 70 Kwh/m² yr. Figure (4) shows the effect of shading on the monthly cooling loads for three cities.

Fixed shading, 70% glazing and south orientation/ Monthly cooling loads | *Movable shading, 30% glazing and west orientation/ Monthly cooling loads*

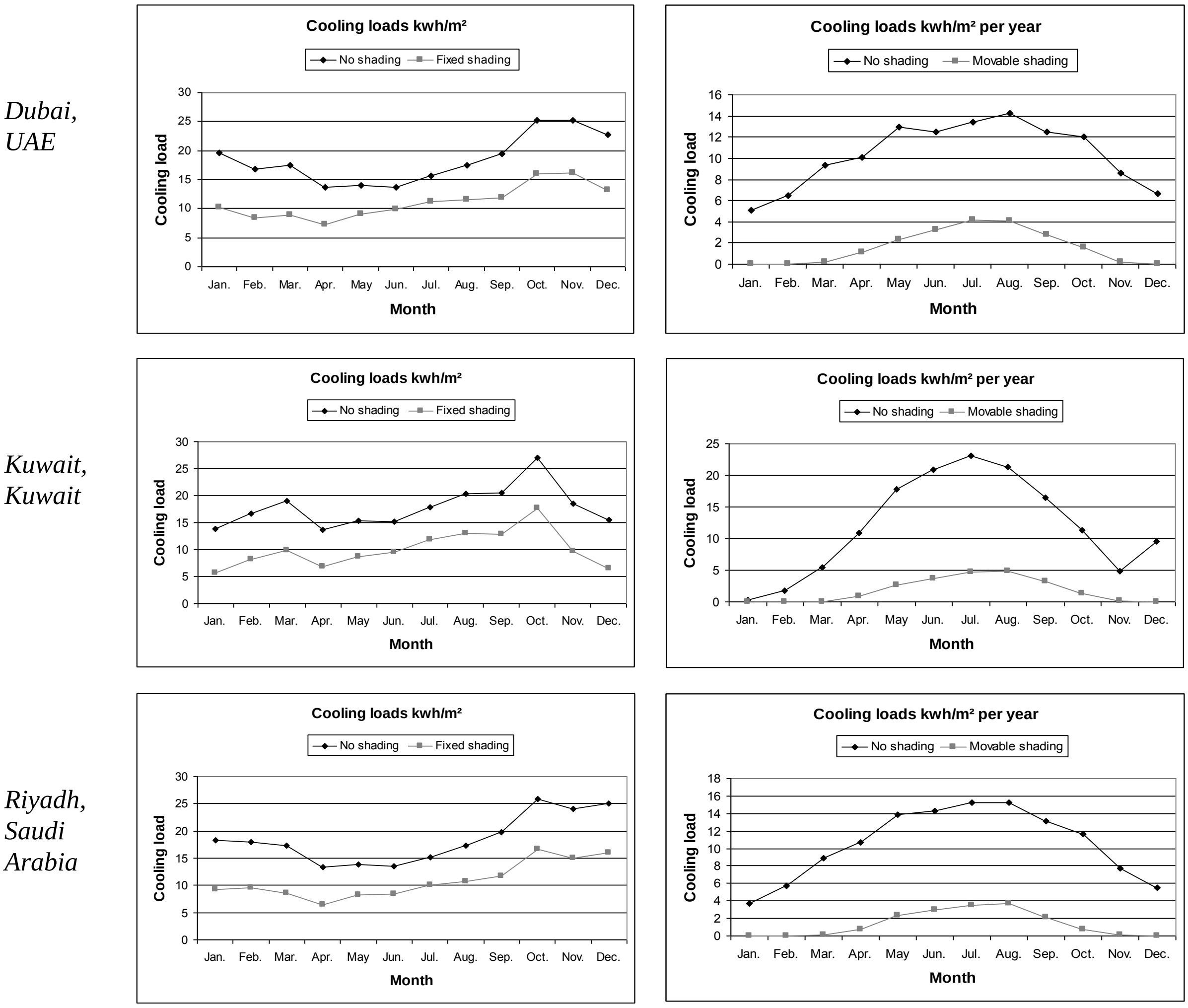
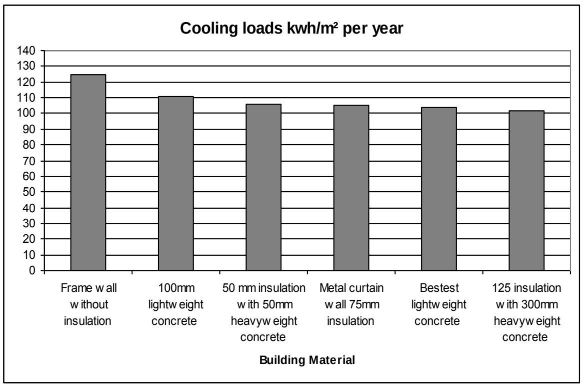


Fig. 4: effect of fixed and movable shading on the monthly cooling loads for different locations

3.5 Effects of insulation and thermal mass

The simulations were done for different materials and U-values, using TRNSYS simulation software. Conditions were set at 30% clear double glazing to the east and 50% glazing to the west. The simulations used the climate data file for the city of Riyadh, Saudi Arabia. The results show that increasing insulation for traditional opaque materials types has a limited effect on the comfort and cooling loads in hot arid climates. It can be concluded from the simulations, that changing the U-values for opaque materials has a limited effect on the cooling load – up to 20 Kwh/m² yr. The discomfort hours remain high in all passive cases due to the high air temperature and high solar radiation. The difference in discomfort hours due to changing U-values may reach at maximum 25 hours per year, and in some cases the discomfort may increase by decreasing the U-value (higher thermal resistance). The results indicate that the impact of the U-value of envelope components in office buildings is not significant if the glazed surface is significant (50% at least). It was found that adding more wall insulation does not always reduce annual energy consumption and in some cases adding thermal insulation directly increases annual energy consumption. That can be justified by the internal gains from equipment, lighting and occupants. Therefore, reducing thermal insulation and using relatively high U-values encourage heat losses and reduce the total cooling loads. On the other hand, using high thermal mass materials combined with night-time natural ventilation may have a positive effect on reducing the cooling loads and discomfort hours.

30% glazing to the east orientation



50% glazing to the west orientation

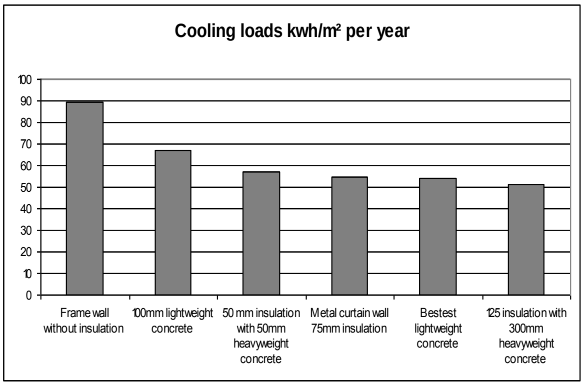


Fig. 5: effects of changing U-value and building materials on the cooling loads

3.6 Effects on daylight and visual comfort

In locations with clear skies and high levels of solar radiation, natural light can be used for energy saving and visual comfort. Providing the building interior with daylight can contribute to the reduction in the energy used for artificial lighting, and helps improve visual comfort. In order to achieve visual comfort and in the same time reduce heat gain, sunlight must be controlled and daylight redirected into the space. Lighting quality and daylight play an important role in architecture and building envelope design. For these reasons, care should be taken to apply building envelope technologies and design strategies to enhance daylight and visual comfort while controlling overheating.

The simulations were done using ECOTECT software for Riyadh, Saudi Arabia to evaluate the influence of building envelope technologies and design strategies on daylight use. The results show that the daylight factor is influenced by the following: opening size, orientation, glazing types and shading, as shown in figure (6). For these reasons, attention for daylight use should be taken when applying the technologies and design strategies mentioned before.

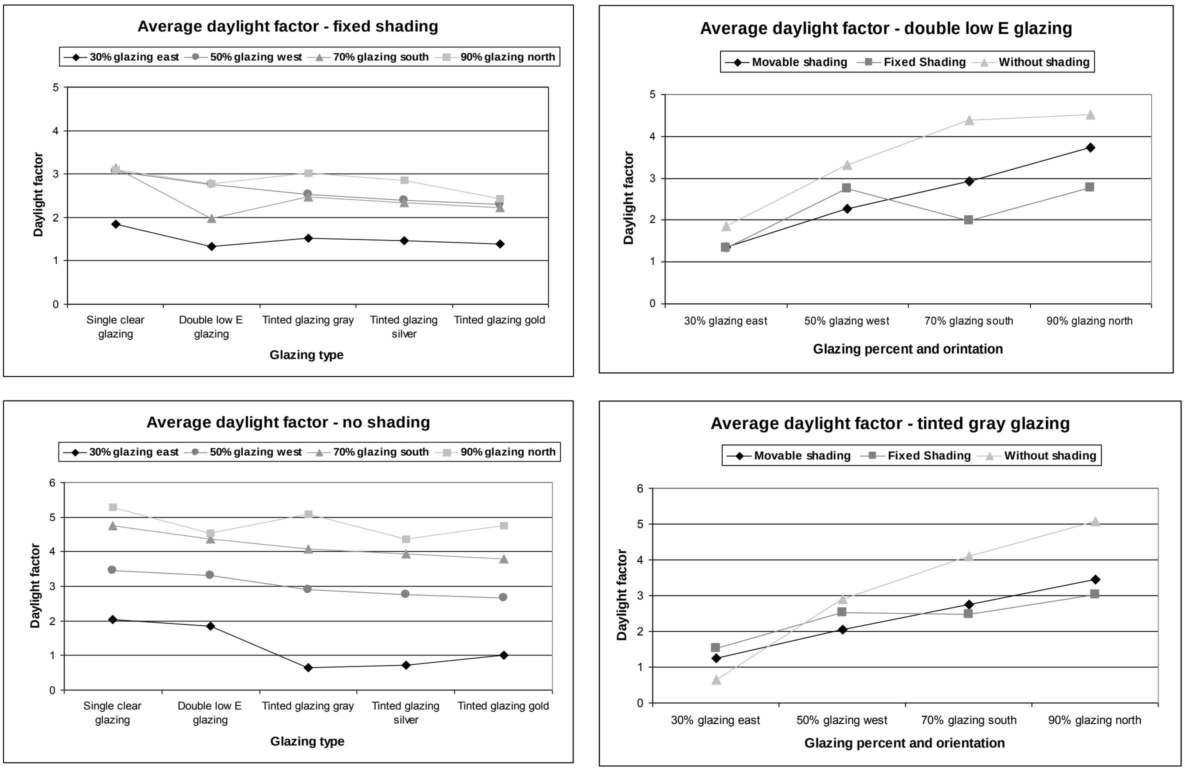


Fig. 6: Effect of shading and glazing type on daylight factor

4. Conclusions

This paper presents the first results of an on-going study aimed at finding design guidelines for tall office building envelope in hot arid climates. In addition, it aims to find guidance for the envelope performance evaluation in the early design stage. These guidelines will provide designers with preliminary indications about the potential effects of different technologies and design strategies. This evaluation is important to ensure thermal, visual comfort and energy efficiency, and increasing the awareness of designers about climate responsive design. The main findings, at this stage of the research work, are the following:

- windows to wall ratio has an effect on cooling loads and comfort and should be decided according to the orientation;

- using the daytime natural ventilation in winter and night ventilation in summer will improve comfort and energy efficiency (dynamic envelope);

- tinted and reflective glazing types have a significant effect on comfort and cooling loads in office buildings in hot climates;
- fixed and movable shading should be used according to the orientation (adaptive envelope);
- decreasing U-values may have a negative effect on comfort and cooling loads in hot climate, while the use of materials with high thermal capacity can help improve comfort and energy efficiency;
- finally, for the previous technologies and design strategies care should be taken to daylight efficiency and visual comfort.

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- Quality and Safety on Construction Sites (W099)
- Construction in Developing Countries (W107)
- Sustainable Buildings regional and global triennial conference series (CIB, iiSBE & UNEP)
- Revaluing Construction
- International Construction Client's Forum

CIB Commissions (August 2010)

TG58	Clients and Construction Innovation
TG59	People in Construction
TG62	Built Environment Complexity
TG63	Disasters and the Built Environment
TG64	Leadership in Construction
TG65	Small Firms in Construction
TG66	Energy and the Built Environment
TG67	Statutory Adjudication in Construction
TG68	Construction Mediation
TG69	Green Buildings and the Law
TG71	Research and Innovation Transfer
TG72	Public Private Partnership
TG73	R&D Programs in Construction
TG74	New Production and Business Models in Construction
TG75	Engineering Studies on Traditional Constructions
TG76	Recognising Innovation in Construction
TG77	Health and the Built Environment
TG78	Informality and Emergence in Construction
TG79	Building Regulations and Control in the Face of Climate Change
TG80	Legal and Regulatory Aspects of BIM
TG81	Global Construction Data
W014	Fire
W018	Timber Structures
W023	Wall Structures
W040	Heat and Moisture Transfer in Buildings
W051	Acoustics
W055	Construction Industry Economics
W056	Sandwich Panels
W062	Water Supply and Drainage
W065	Organisation and Management of Construction
W069	Housing Sociology
W070	Facilities Management and Maintenance
W077	Indoor Climate
W078	Information Technology for Construction
W080	Prediction of Service Life of Building Materials and Components
W083	Roofing Materials and Systems
W084	Building Comfortable Environments for All
W086	Building Pathology
W089	Building Research and Education
W092	Procurement Systems
W096	Architectural Management
W098	Intelligent & Responsive Buildings
W099	Safety and Health on Construction Sites
W101	Spatial Planning and infrastructure Development
W102	Information and Knowledge Management in Building
W104	Open Building Implementation
W107	Construction in Developing Countries
W108	Climate Change and the Built Environment
W110	Informal Settlements and Affordable Housing
W111	Usability of Workplaces
W112	Culture in Construction
W113	Law and Dispute Resolution
W114	Earthquake Engineering and Buildings
W115	Construction Materials Stewardship
W116	Smart and Sustainable Built Environments
W117	Performance Measurement in Construction

International Council for Research and Innovation in Building and Construction

Publications: The CIB produces a wide range of special publications, conference proceedings, etc., most of which are available to CIB Members via the CIB home pages. The CIB network also provides access to the publications of its more than 400 Members.

Recent CIB publications include:

- Guide and Bibliography to Service Life and Durability Research for Buildings and Components (CIB 295)
- Performance Based Methods for Service Life Prediction (CIB 294)
- Performance Criteria of Buildings for Health and Comfort (CIB 292)
- Performance Based Building 1st International State-of-the-Art Report (CIB 291)
- Proceedings of the CIB-CTBUH Conference on Tall Buildings: Strategies for Performance in the Aftermath of the World Trade Centre (CIB 290)
- Condition Assessment of Roofs (CIB 289)
- Proceedings from the 3rd International Postgraduate Research Conference in the Built and Human Environment
- Proceedings of the 5th International Conference on Performance-Based Codes and Fire Safety Design Methods
- Proceedings of the 29th International Symposium on Water Supply and Drainage for Buildings
- Agenda 21 for Sustainable Development in Developing Countries

R&D Collaboration: The CIB provides an active platform for international collaborative R&D between academia, R&D organisations and industry.

Publications arising from recent collaborative R&D activities include:

- Agenda 21 for Sustainable Construction
- Agenda 21 for Sustainable Construction in Developing Countries
- The Construction Sector System Approach: An International Framework (CIB 293)
- Red Man, Green Man: A Review of the Use of Performance Indicators for Urban Sustainability (CIB 286a)
- Benchmarking of Labour-Intensive Construction Activities: Lean Construction and Fundamental Principles of Working Management (CIB 276)
- Guide and Bibliography to Service Life and Durability Research for Buildings and Components (CIB 295)
- Performance-Based Building Regulatory Systems (CIB 299)
- Design for Deconstruction and Materials Reuse (CIB 272)
- Value Through Design (CIB 280)

Themes: The main thrust of CIB activities takes place through a network of around 50 Working Commissions and Task Groups, organised around four CIB Priority Themes:

- Sustainable Construction
- Clients and Users
- Revaluing Construction
- Integrated Design and Delivery Solutions

CIB Annual Membership Fee 2010 – 2013

Membership will be automatically renewed each calendar year in January, unless cancelled in writing 3 months before the year end

Fee Category		**2010**	**2011**	**2012**	**2013**
FM1	Fee level	11837	12015	12195	12378
FM2	Fee level	7892	8010	8131	8252
FM3	Fee level	2715	2756	2797	2839
AM1	Fee level	1364	1384	1405	1426
AM2	Fee level	1133	1246	1371	1426
IM	Fee level	271	275	279	283

All amounts in EURO

The lowest Fee Category an organisation can be in depends on the organisation's profile:

FM1 Full Member Fee Category **1** | Multi disciplinary building research institutes of national standing having a broad field of research

FM2 Full Member Fee Category **2** | Medium size research Institutes; Public agencies with major research interest; Companies with major research interest

FM3 Full Member Fee Category **3** | Information centres of national standing; Organisations normally in Category 4 or 5 which prefer to be a Full Member

AM1 Associate Member Fee Category **4** | Sectoral research & documentation institutes; Institutes for standardisation; Companies, consultants, contractors etc.; Professional associations

AM2 Associate Member Fee Category **5** | Departments, faculties, schools or colleges of universities or technical Institutes of higher education (Universities as a whole can not be Member)

IM Individual Member Fee Category **6** | Individuals having an interest in the activities of CIB (not representing an organisation)

Fee Reduction:
A reduction is offered to all fee levels in the magnitude of 50% for Members in countries with a GNIpc less than USD 1000 and a reduction to all fee levels in the magnitude of 25% for Members in countries with a GNIpc between USD 1000 – 7000, as defined by the Worldbank. (see http://siteresources.worldbank.org/DATASTATISTICS/Resources/GNIPC.pdf)

Reward for Prompt Payment:
All above indicated fee amounts will be increased by 10%. Members will subsequently be rewarded a 10% reduction in case of actual payment received within 3 months after the invoice date.

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CIB Publication 355