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Evaluating the Feasibility of 'Zero Carbon' Compact Dwellings in Urban Areas

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EVALUATING THE FEASIBILITY OF 'ZERO CARBON' COMPACT DWELLINGS IN URBAN AREAS

By

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A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

May 2013

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ABSTRACT

Reducing the carbon footprint of domestic properties is, due to global warming and social impact of increased energy costs, an ever increasing priority. Although the compulsive building standards are set by the building regulation part L1, The Code for Sustainable Homes have set more stringent requirements above the requirements of Building Regulations to achieve zero carbon emissions during occupation. This Code for Sustainable Homes (CSH) requires all new homes to be zero carbon by 2016. Land scarcity and lower number of people per household forces developers to develop compact apartment-based dwellings on brown field sites, constraining the design.

The aim of this research is to understand the effect of practical constraints on real building design and technology on achieving zero carbon performance in compact urban dwellings in a maritime northern European climate.

In this work, currently commercially implementable renewable generation technologies are evaluated for their suitability in a compact urban setting. A model-based approach is developed to evaluate the energy consumption (both regulated and unregulated) and energy balance under the specific constraints of compact urban buildings. Graphical representation enables the introduction of a demand envelope, which shows the boundaries of the minimum and maximum expected thermal and electrical energy consumption over one year period.

The research has three key findings:

1. Due to variations in energy consumption by the occupants, mainly by the unregulated energy consumption, multiple renewable energy technologies would have to be implemented to achieve the lowest possible carbon emission.
2. Although the combination of PV, CHP and HP is the generation option with the lowest carbon emissions, it is not completely carbon free when producing the required electrical and thermal energy. This suggests that there is a high likelihood that zero-carbon energy generation can not be achieved in this case study of a compact urban dwelling with the currently available technology.
3. The simulations show that with highly insulated dwellings the amount of space heating required is less than 10% of the overall energy consumption, as opposed to the 60% generally achieved in the building industry. Subsequent on-site measurements showed an estimation of just under 30% of the total energy consumption was used in space heating, which is higher than the simulated value, but still less than half that of a conventional dwelling.

The main academic recommendation resulting from this research is a requirement for further ongoing research into new generation technologies as they become mature.

Recommendations for the sponsoring company include continuation of measurements at the case study building to enable confirmation of energy consumption/generation findings so far.

KEYWORDS

zero carbon, renewable energy systems, system integration, compact urban dwellings, Code for Sustainable Homes

ACKNOWLEDGEMENTS

First and foremost I must mention Vincent Smedley, of PS Sustainability Ltd., in the role of friend and industrial supervisor, for without his tireless support and encouragement, and still keeping his wit together, this doctorate would never have been started or completed.

I also wish to thank my academic supervisors, Dr. P. Rowley, Dr. R. Buswell and Dr. S.K. Firth for their guidance and encouragement.

A special word of thanks goes to my partner, Monique Steijger, for her continuing believe in me and this project and her exceptionally skill to pull me out of rabbit holes.

PREFACE

Most great ideas start over a beer…. How the yeast in the sweet wort competes out all other bacteria, eventually having access to all the resources. But once the resources are depleted, they succumb in their own waste product. At least that product is palatable. And yeast cells are not known for their intelligence.

By living all over Europe, you get the gist of what is really important. Living in the UK made me wonder, why do people put up with living in low housing standards, comparing with Sweden or Switzerland? Why is there so much energy wasted in a country that is never cold like Sweden or hot like Greece? There are always alternatives, according to Spock.

My first challenge was my own home building project, in 2002. It was a nearly (and now really is) a zero carbon home. The concept was so novel, that even the architect asked if we wanted to live in a mud hut…. But it has been a great living experience, and even better that we effectively live without any energy costs. Fortunately things are changing for the better, the UK the Code For Sustainable Homes is pointing at the right direction, raising the building standard so zero carbon living can be achieved.

Then, by chance, an even tougher challenge came to light. My friend and colleague, Vince Smedley, asked me if we could design true zero carbon homes for renting out on a small infill site in Derby. Here the journey of true sustainability continued. This thesis is a result of this part of the journey. Even here I would like to thank him for the trust in me to walk with me on this journey.

USED ACRONYMS / ABBREVIATIONS

ACH	Air changes per hour
BREDEM	Building Research Establishment Domestic Energy Model
CHP	Combined Heat and Power plant
COP	Coefficient of Performance
CSH	Code for Sustainable Homes
DHW	Domestic hot water
EPS	Expanded Poly Styrene
HP	Heat Pump
ICF	Insulating Concrete Form
MVHR	Mechanical Ventilation with Heat Recovery
PV	Photo Voltaic
SHINE-ZC	Sustainable Housing Innovation Network of Excellence – Zero Carbon
SPF	Seasonal Performance Factor
ST(C)	Solar thermal (Collector)
VO	Vegetable Oil

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PAPERS

The following papers, included in the appendices, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research.

PAPER 1 (SEE APPENDIX A)

Steijger L.A., Buswell R., Smedley V., Firth S.K. and Rowley P., 2010. An air source heat pump model for operation in cold humid environments. *8th International conference on system simulation in buildings*, 13-15 December 2010, Liege

PAPER 2 (SEE APPENDIX B)

Steijger L.A., Buswell R., Smedley V., Firth S.K. and Rowley P., 2013. Establishing the zero-carbon performance of compact urban dwellings, *Journal of building performance simulation, , DOI:10.1080/19401493.2012.724086*

PAPER 3 (SEE APPENDIX C)

Steijger L.A., Buswell R., Smedley V., Firth S.K. and Rowley P., 2012. An approach to visualising the operational mix of renewable generation technologies needed to achieve zero-carbon emissions from compact urban dwellings. *1st IBPSA-England conference on building performance simulation*, 10-11 September 2012, Loughborough

1 INTRODUCTION

1.1 THE GENERAL SUBJECT DOMAIN

It is widely accepted that climate change is a serious and urgent issue that needs to be addressed by reducing the level of Green House Gas (GHG) production globally (Stern 2007). The Intergovernmental Panel on Climate Change (IPCC)'s Fourth Assessment Report (2007) confirms that the primary concern is that greenhouse gas emissions from human activity have risen by 70% between 1970 and 2004. Following the Royal Commission on Environmental Pollution (RCEP) report (2000) the UK government committed to an 80% reduction in CO_2 emissions by 2050, enforcing changes through legislation and these goals can only be achieved through setting and achieving strict targets in all energy-consuming sectors (McManus et al. 2010). Over 27% of UK's CO_2 emissions come from the energy used to heat, light and run homes (Department for Communities and Local Government 2007), and it is therefore vital to ensure that higher sustainability performance standards are integrated within the design of new homes (Banfill and Peacock, 2007).

The minimum building standards in the UK are defined in the Building Regulations for Carbon emissions in Part L (Office of the deputy Prime Minister). To indicate the direction of these building standards, the UK government has introduced the Code for Sustainable Homes (CSH) to drive a step-change in sustainable home building practice (Department for Communities and Local Government 2006, updated version 2010). The CSH is an environmental assessment method for rating and certifying the performance of new homes and to obtain the highest level of the code, level 6, net emissions of CO_2 must be zero during occupation. By 2016 all new homes built in the UK are intended to meet these criteria of the CSH (Department for Communities and Local Government 2006), requiring them to be "zero carbon" (Energy Saving Trust 2008). To meet the zero carbon criteria, all the energy consumed within the building (including unregulated energy like cooking, white goods and entertainment) must be generated in or near the site to offset any fossil or fossil-generated fuels imported into the home, so that over a year, the net CO_2 emissions are zero.

The UK housing market is under pressure from a rising population and there is a shift towards the construction of smaller dwellings (McManus et al. 2010). The Office of National Statistics projects that the UK population is to increase by 4.9 million from an estimated 62.3 million in 2010 to 67.2 million over the ten year period to 2020. Given the projected growth in the population, the number of households in England is projected to grow to 27.8 million in 2031, an increase of 6.3 million (29 %) over the 2006 estimate. Nearly two-thirds of this increase is accounted for by one person households who are projected to rise by 4 million from 2006 to 2031. The Housing and Planning statistics in 2010 shows that in the ten years between 1999 and 2009 the proportion of new dwellings built on previously developed land has increased steadily from 59 per cent to 80 per cent of dwellings. The density of new dwellings built in England has nearly doubled between 2000 and 2009. Dwelling density is higher on brown field sites than green field sites, which could indicate that on redeveloped land, flats are likely to be built (DCLC, 2010). Banfill and Peacock (2007) concluded that the trend towards inward migration is resulting in new homes being built on brown field sites in towns and cities, where space is limited. The lack of space for buildings on such sites tends to produce workable designs of smaller, apartment based dwellings.

New development with higher building quality has its influence on the energy consumption. The largest end-use of energy in dwellings in the UK is said to be space heating (Department for Trade and Industry, 2007). Historically this is due to the low insulation value and high air permeability of the building envelope. Low carbon housing has been shown to be possible by reducing the space heating demand by improving the characteristics of the building envelope and increasing the air tightness, with controlled ventilation (Lowe, 2007). In new developments, with a largely reduced space heating demand, electricity and domestic hot water (DHW) are likely to be the highest energy consumption factors in domestic buildings. Whilst space heating is primarily weather driven, DHW and electricity are occupant driven, i.e. the behaviour of the occupant has a large influence over the energy consumption. As an overall result, in new developed dwellings, it can be expected that the energy requirement is not only lower but also spread more evenly over a whole year and driven by the lifestyle of the occupants.

To cover the consumption, on site generation of zero carbon energy is required to achieve CSH level 6. The combination of renewable generation systems to cover the complete energy demand requires a detailed analysis to establish which combination of energy carriers (solar, wind, ambient thermal energy and biomass) and available converters (solar thermal, PV, wind turbines, heat pumps and biomass boilers/CHP) results in the lowest possible CO_2 emissions. Off site energy generation is allowed as long as there is a dedicated supply line to the generation plant (CSH technical guide, 2010)

Kapsalaki et al. (2009) looked into near zero energy buildings from a holistic point of view and developed a methodology for designing these types of building in various climates. Optimum orientation and layout of the building are an essential part of the method. But building on a given brown field site can result in specific limitations; non-optimal orientation, close proximity to other buildings and space restrictions constrain the usability of the available solar energy, and space constraint limits storage, either for bio-fuel or thermal energy. Literature about these constraints is limited and tools for visualisation and optimisation of generation sources that are in balance with the consumption were not found, so decisions on how to strike the correct balance between consumption and generation, and which renewable energy system to implement, are difficult to make during the design stage. Simulation of the whole building does give some clarity; however it does not define the boundary of feasibility of zero carbon of a given solution. Therefore, research in helping in this decision making (e.g. a new tool to aid the decision making process) process is required.

The research reported in this thesis is focussed on modelling of energy generation and consumption for compact urban domestic buildings at the design stage in order to minimise the CO_2 emissions during occupation. A key factor for the industrial sponsor was to develop an approach that could be practically applied using currently available information to generate a method for selecting the appropriate mix of low carbon generation technologies and to calculate an estimate of the likely variation of the demand and supply in-use. This is important because this relates directly to the likelihood of achieving CSH level 6 status and, in addition where properties are rented with inclusive energy bills, the generation can provide a revenue stream. Hence understanding the risk associated with the in-use performance can affect the financing of a project.

Although there is a requirement to achieve level 6 in the CSH, economic factors will decide eventually if a solution is viable or not. To omit the economic factors in this study was a conscious decision, however, because of the volatility of some of the renewable energy carriers and/or converters. For example, PV panels have dropped 90% in price from 1980 and

50% from 2008 comparing with the price paid in 2010 (NREL, 2011). Feed in Tariffs in the UK started (superseding the Renewable Obligation Certificates) in 2010 with 43.3 p/kWh and dropping subsequently to 14.9 p/kWh in 2013 for new installations (Ofgem, 2013), a drop of approximately 60%. A new tariff, promoting the use of renewable heat (the so called Renewable Heat Incentive) has been talked of for a long time, but apart from a £7 mln. field trial, no actual subsidies are paid out as yet (DECC, 2013). Also the price of bio fuel is highly volatile; the Food and Agricultural Organisation of the United Nations concluded in a report that "*Food price volatility may increase because of stronger linkages between agricultural and energy markets, as well as an increased frequency of weather shocks*" (FAO, 2011). Therefore, including solid economic factors in this thesis is almost impossible in such a volatile market.

1.2 THE INDUSTRIAL SPONSOR

The industrial sponsor is PS Sustainability Ltd. a small to medium enterprise, located in Derby, East Midlands UK PS Sustainability Ltd. is a company with a turnover of £500k per year, and was established in 2008. It has centred its focus on the renewable sector, undertaking collaboration with a local property developer to work on greener living.

The first major project for this company was the development of low cost residential housing on a brown field site in Derby, Sustainable Housing Innovation Network of Excellence – Zero Carbon, in short SHINE-ZC. The overall project aim was to investigate the possibility and viability of zero carbon housing, CSH level 6. It comprises of six terraced houses and three flats in the private rented housing sector. SHINE-ZC's objective is to tackle all of the most complex technical issues that arise when trying to achieve CSH level 6 in a real-world constrained urban brown field site. The installed renewable generation technologies are designed to meet the rigorous requirements of CSH level 6, whilst demonstrating viability from a commercial perspective in this difficult environment. The key principle of this demonstration project is one of integration of the various components of the building, from the building fabric and ventilation regime to the integration of all the available renewable technologies into one working system.

This type of rented housing by its nature has a low profit margin. To make the project more viable, an additional source of revenue is the on-site generation of electrical and thermal energy. PS Sustainability Ltd is operating as an Energy Service Company (ESCO), providing low carbon thermal and electrical energy to the occupants of the dwellings. In this approach PS Sustainability Ltd is unique, however, it also has an unique design question: how much and of what type (thermal or electrical) energy is required for these dwellings, not only from a cost perspective, but also from an energy balance perspective and what generation equipment and usage is required. To find the optimum generation type and capacity is vital for the success of this project.

1.3 THE CONTEXT OF THE RESEARCH

Although not specifically focussed on the CO_2 emission aspect, studies into the design of low carbon dwellings are in abundance. Already, in 1981, Pfalz and Steemers dedicated a book describing 31 projects of solar houses in Europe (Pfalz and Steemers, 1981). A couple of years before that, in 1979, De Boon described 50 projects in the Netherlands regarding building with solar energy (De Boon, 1979). The conclusions out of these books are still valid today: reduce the space heating demand through good insulation and ventilation with heat recovery; good workmanship during build has a large effect on achieving the required air movement through the build; and minimise heat loss in the thermal system through good insulation of the domestic hot water system. Although heat pumps are mentioned in these books there was no data available as a performance indicator and PV was still part of the future, so the focus was solely on thermal energy provision. Peippo et al. (1998) looked into multivariate optimisation of design trade-offs for solar low energy buildings. Their findings give insight into some of the design routes. They recommend firstly utilizing all the potential from energy efficiency measures, which costs are substantially lower than any generation options, and then, using the remaining of the budget, to add renewable energy generation equipment. The main focus of this study was on economic feasibility, whilst coping with the technical limitations, and some interdependencies (e.g. the utilisation of electrical energy to generate useful thermal energy using heat pumps) were not considered. Another limitation of this study is the neglect of shading of close proximity buildings, which limits the solar gain and variable building shapes, which for an infill site have to be considered.

After around 2000, there is a shift in literature from solar design (i.e. thermal orientated) to reducing CO_2 (i.e. low emission orientated). Before 2000, the main focus was on the thermal aspect of the building, with (reducing the requirement for) space heating the most important aspect. With PV becoming commercially available around 2000, roof mounted renewable electrical generation became viable, thus a slight shift in focus from thermal only to the inclusion of electrical energy. Although the objectives are similar, there are differences in the details of the design, including the (electrical) generation side and occupant behaviour. Banfill and Peacock in 2007 showed a way to achieve zero carbon for new development in the UK, however without any practical design rules. They reiterate the influence of occupant behaviour to enable achieving of zero-carbon homes. Also higher comfort temperatures are to be expected, and found comfortable, in low carbon homes. This might lead to a higher space heating demand. More recently, Berggren et al., (2011) published a design for a zero-carbon dwelling in a non-urban area in Sweden.

Gill et al. in 2010 compared the energy consumption of 25 aspiring low carbon dwellings in the UK. His conclusions are remarkable in a sense that he identified occupant behaviour as the most important factor in more than one sense:

- occupants undermine overall performance and compliance with standards and design expectations,
- the estimated energy use outside scope of UK regulations was the most important cause of CO_2 emissions, due to estimated high use of electricity consumed by small goods.

Pilkington et al. (2010) come to an even more challenging conclusion: “If occupants in low energy dwellings don’t start to think and work in a sustainable matter, no matter how good the dwellings are, it won’t achieve the required zero-carbon”. Completely sustainable buildings would be buildings made from recyclable material. Ip and Miller (2009) looked into a building strategy called earthships. Although the build cost for earth ships is very low, it is shown that the UK climate is not suitable for these type of buildings, a “bedroom” (called hut) temperature of less than 14 ºC is not comfortable according to the CIBSE guide.(CIBSE, 2005).

Chicco and Mancarella’s (2009) review of the literature also shows that reaching “zero carbon” requires an integrated approach for building design and that this may lead to significant benefits in terms of higher energy efficiency, reduced CO_2 emissions and enhanced economy. They suggest that coupling of controllable CHP plants to volatile resources such as wind power could greatly enhance the overall energy and economic performance of an integrated energy system, and even more so if PV systems and electrical heat pumps are added. However, no coupling into the urban settings is studied in the review and no calculation/design considerations are given. For these design considerations, a tool is required to determine the optimum utilisation of the installed equipment.

One concept of an integrated approach is showed by Chen et al. (2010) for a near zero energy house in the continental Canadian climate. Highly insulated build, airtight and ventilation with heat recovery reduce the space heating requirement. An optimised south facing roof with roof integrated PV and solar thermal collectors combined (with air as a transfer medium) provides electrical and thermal energy for space heat. A heat exchanger provides some preheating for DHW, a resistive electric heater can boost both the space heating and DHW. It was concluded that the prioritising of the energy flows determine the success of the project.

Lowe (2007) shows the possibilities of decarbonising the UK housing stock, by super insulation, controlled ventilation and heat recovery. He also looks into ways for on site generation capacity but, again, no calculation and design considerations are given for compact urban designs. A study in the USA by Parker (2008) concluded that investment in building envelope and energy conservation should be favoured above the generation options. The same conclusion came out of a study by Leckner and Zmeureanu (2008). As a general rule it can be concluded that the first big step to achieve zero carbon is a high quality building, well insulated, airtight and using ventilation with heat recovery. The main impact the building envelope has is on space heating, although it also reduces (by less heat transfer into the building) the need for cooling in summer.

Occupancy patterns and dwelling characteristics have a significant impact on the electricity consumption. Several extended studies highlight the importance of the energy consciousness of the occupants. A recent research report found the presence and use of solar technologies did indicate changes in behaviour especially in passively adopting households (Dobby and Thomas, 2005). But this was not conclusive and other research found contradictory results (Keirstead, 2008). Monahan and Powell (2010) looked into 14 newly constructed low energy affordable homes. Four different technologies, ground source heat pumps, passive and active solar and mechanical ventilation with heat recovery were implemented. Their conclusion was that homes with active solar generated the lowest CO_2 emission. Another conclusion was that ventilation with heat recovery only works efficiently in air tight buildings. From this study it was evident that with building design only the space heating requirement can be targeted, the DHW and electricity use were similar to the UK average. Yohanis et al. (2008) found that smaller terraced dwellings with few occupants use less electrical energy than larger dwellings. A relationship was found between floor area and annual energy consumption similar to Anderson’s BREDEM model, albeit with different electrical energy consumption parameters (BREDEM 677 + 24 TFA vs. Yohanis et al. 233 + 49 TFA, consumption in kWh/year, with TFA the total floor area in m^2). The measurements were taken from a representative sample from Northern Ireland dwellings, not dissimilar from the Midlands in the UK. Firth et al. (2008) measured the electrical consumption in an urban setting in the Midlands, and Richardson et al. (2010) confirmed these findings. These studies gives an insight into how much electrical energy need to be generated, but not by what means to achieve the lowest possible CO_2 emissions. The overall trend is an increase in electricity consumption.

Modelling techniques to simulate the energy use and generation are also commonly used. The models range from a technical simulation as described by Banfill and Peacock (2007) to the socio-economic aspects in Agent Based Modelling as described by Natarajan (2011). Natarajan claims a consumption prediction with a maximum error of 5%, however, the actual values for the agents were not mentioned in the paper. His method could well be developed to improve prediction of the variance in thermal and electrical consumption. What is missing in these studies is the feasibility, the limitations and the sizing/yield of the proposed renewable generation options to fulfil the expected energy consumption especially in a compact urban setting.

Abel (1994) already split up the energy requirements in electrical and thermal and acknowledged the interdependences between these types of energies. From his viewpoint there is a split between “low energy buildings” and “energy efficient buildings”; the main difference is the higher economic focus in an energy efficient building. One of his conclusions is that the focus needs to be on decreasing the need for space heating and DHW, without increasing the need for electrical consumption. The possible generation options are a second step in the process.

It was concluded that most of the studies that are showing complete dwellings and/or projects ignore the limitations set by the trend in the building industry in the UK. Restrictions to build on green field sites force developers to redevelop (urban) brown field sites, where planning limitations, site orientation and layout restrict the design parameters of the building. A lower person count per household eliminates the requirement for multiple bedrooms, and combined with the land issue, results in smaller “compact urban” dwellings. As a result, the variation in building type, size and layout is limited. For this study, compact urban is defined as when the living space of this type of dwellings is limited to 50 m^2, height restrictions limit the building to either apartments or two storey building with a flat roof, in an urban setting with close approximation to other buildings. Low person count per dwelling and a small footprint reduce the requirement for space heating. Lower energy requirements allow a centralised generation in an on site (small) plant room, eliminating the space required for heating equipment in each individual dwelling. But, as space comes at a premium, this still limits the possibilities of the installed renewable technology, in particular the roof space required for harvesting solar energy.

This research, by using a “compact urban” case study building, establishes the energy demand and investigates the possible generation options in and for a compact urban setting.

2 AIM AND OBJECTIVES

From the introduction it was concluded that the direction of the building industry in the UK is heading for small apartment based dwellings. The Code for Sustainable Homes defines the direction of the legislative framework to which new resident building needs to adhere. One of the key factors of this direction is that the dwellings must be “zero carbon” during occupation. No research has taken place into the feasibility of zero carbon for this type of dwelling. For developers it is therefore difficult to establish which and how much of the available renewable energy generation is required for this type of dwelling. PS Sustainability Ltd. is at the forefront of zero carbon design and needed an approach of development for these types of dwellings. As this approach is not generally available, the goal of this research is to find an answer to this question.

So the overall aim can be defined as:

To understand the effect of practical constraints on real building design and technology on achieving zero or low carbon performance in compact urban dwellings in a maritime northern European climate.

Specific objectives are:

- To critically review the renewable generation technologies that are currently commercially implementable and appropriate in compact urban dwellings;
- To develop a model based approach to evaluate the energy consumption and energy balance in these type of buildings;
- To critically review the available information for parameter selection to drive the simulation and to model the case study building on which to base further analysis, validating the predicted energy consumption with measured data;
- To develop methods of visualising the combined occupant, building and energy system generation and consumption characteristics to support better design; and,
- To utilize the visualisation methods, combined with simulations of the case study building to investigate the performance of different combinations of renewable generation technology to establish the combination best suited to achieve zero or low carbon performance in practice.

3 ADOPTED METHODOLOGY

As the overall aim is to study the feasibility of compact urban zero carbon dwellings, the consumption of energy vs. the low carbon generation capabilities of systems in an urban setting are compared, i.e. the main focus is the total energy balance to achieve zero carbon compact urban dwellings. The research plan undertaken is shown in Figure 1. An initial literature review showed limited knowledge on the design limitations for, and implementation of, low carbon energy strategies in compact urban dwellings. A further literature research was carried out on the usability of renewable resources in an urban setting and the energy requirements for this type of dwelling.

To achieve no CO_2 emissions during occupation, the complete energy balance, consumption and generation, need to be studied. One part of this energy balance is the energy consumption. Literature and UK specific models like BREDEM (Anderson et al., 2002) contain the parameters for this part of the study. The other part of the balance is the energy generation. The reviewed literature contained the feasibility of each specific renewable energy option and the expected limitations. These consumptions and limitations are used to determine the boundary parameters.

With these parameters found in literature, these findings then needed to be combined to study the feasibility of zero carbon. One approach to combine and investigate the results is by computer simulation. From these findings, a computer model using a building simulation tool (TRNSYS) was generated. Outputs of the simulations are the energy consumption and the interdependencies between key system parameters. This computer model, generated from the observed parameters in literature and the results of simulations, can identify limitations and generate solutions in the problem space without the need for study of a real-world building with the installed systems.

As any model of simulation it is only an abstraction from reality and therefore inherent with limitations (it is not possible to simulate every aspect of the building) and discrepancies from reality. One of the main advantages of computer simulation is the allowable flexibility. Location, geometry, materials and shading can be easily changed. To limit the scope of the research, the location, geometry, building design and materials of the building are fixed, adapted from a design of a case study building. The studied variation existed in the amount of energy the occupants consume and the energy generation options. As the occupational energy consumption varies, the renewable energy generation systems must be capable of adjusting their output to accommodate this variation. It is useful to generate a tool to visualise how and if the plants are capable to cope with this variation.

The Code for Sustainable Homes states that the net energy balance over one whole year period must be net zero carbon. This implies that the simulation must at least cover one year. However, a surplus generated during a certain interval (e.g. in case of electrical energy, PV. in summer or a CHP during daytime) may be consumed at a later time.

The study and simulated outputs were verified with the data from a real world case study building. Data from the case study building is available and has been compared with the computer model generated data. Data gathering over several years will be required to allow an indication of whether the consumption is within the set parameters and/or the yield data from the individual sub systems, e.g. the amount of kWh generated by the P.V., is comparable with the model for that subsystem. Without this verification, the presented tool is based only on general assumptions.

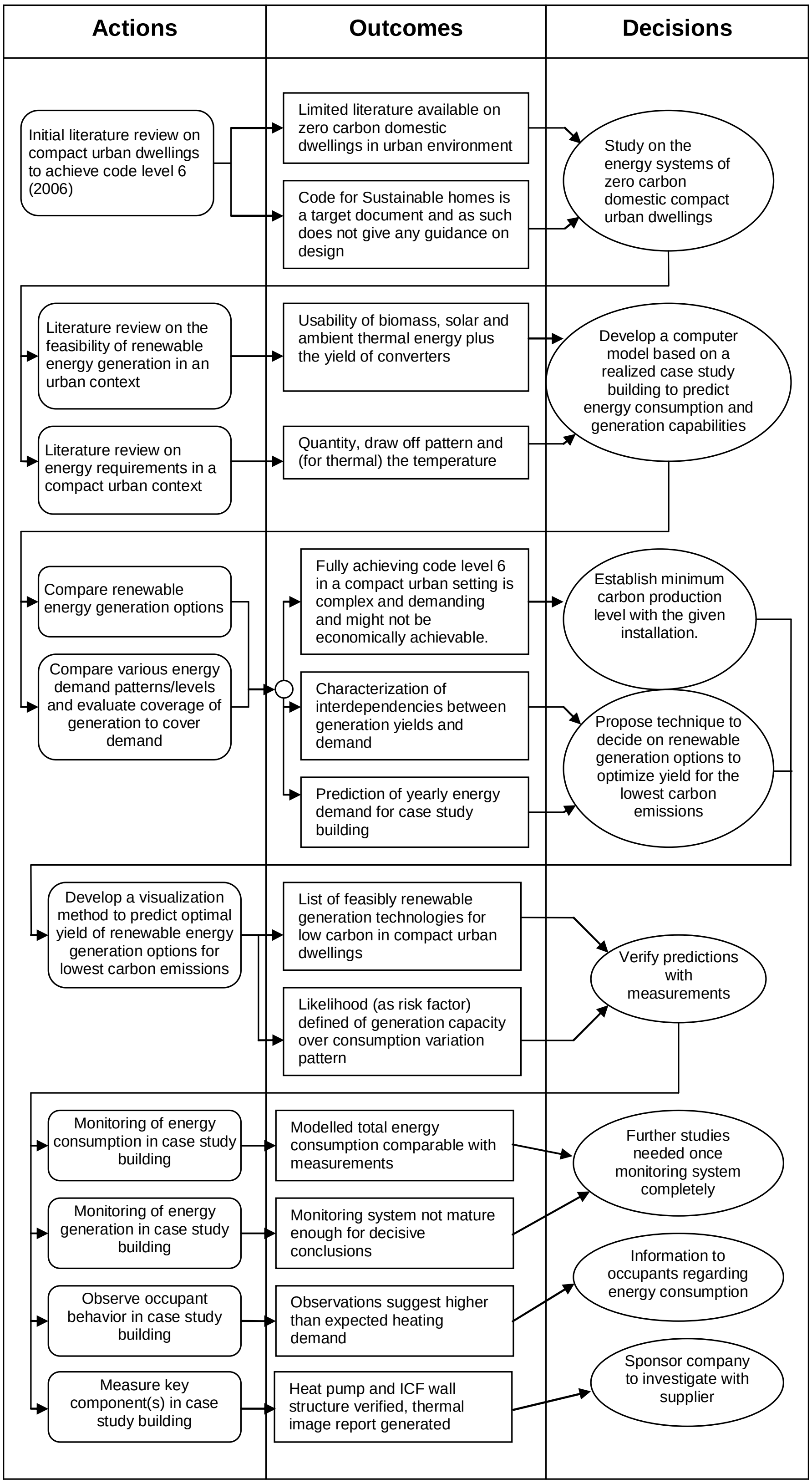

Figure 1 Work flow diagram research undertaken

3.1 SIMULATION TOOLS/MODEL

Although the main object of the study is a building, the focus is on the energy flows within the building. Therefore a simulation package must be selected that can incorporate these energy flows. Most building simulation tools focus on the building materials, temperatures and lighting, but have limited access/capability of integration of renewable energy systems. Crawley et al.. (2005) compared the capabilities of a variety of building simulation tools, which resulted in the selection of TRNSYS 16.0 as the preferred simulation program for this research. The capability of this tool to integrate complex external models and controls made this tool preferable over other options.

Apart from the method, setting the scope is as important. Limited research is done on redevelopment of inner city brown field sites, with their own set of limitations. The trend in the building industry is towards smaller apartment based dwellings. Limited study was available in literature on the feasibility of zero carbon for this type of building, with factors that have not been considered such as:

- apartment based compact urban;
- non optimal orientation;
- shading due to other buildings;
- occupation driven instead of weather driven energy consumption; and
- lack of energy storage space (for all forms of energy e.g. bio fuel, thermal energy etc.).

These factors have a substantial influence on the performance of the installed low carbon technologies. A computer model can show the limitations in design to achieve zero-carbon and demonstrate the effect of these building constraints.

Simulation was considered the best option to provide the answers to the developer’s questions on implementation of the renewable technology with a given building design. The simulation can be verified once real life data is available.

3.2 METHODOLOGY DEVELOPMENT/REFINEMENT

Most simulation tool software packages come with a standard library of validated models to build the complete simulation. TRNSYS is no exception to this. However, some of the parts in this library need adequate parameter setting to enable correct simulation of the equipment. This allows the user to integrate adequately his/her own equipment into the model. As an example, the heat pump model in TRNSYS requires the COP curve and research was required to establish the parameter setting in a real environment for this part of the simulation. Out of this research, an updated heat pump model was generated to be included into the overall simulation. The paper resulted from this research is attached in Appendix A.

3.3 ANALYSIS AND VISUALISATION

Developing a model does not give the required answers; parameter variation and rerunning the model generate a variation in outcomes, which can be analysed. Generated graphs will help visualise the findings from the simulations and can be used as an aid during the design process to determine the possible renewable generation options. The result of the analysis resulted in two papers, attached in Appendix B and C.

3.4 VERIFICATION AND VALIDATION OF THE APPROACH

Computer simulations are only an abstract of the real world. To validate the computer model and the assumptions behind it, real world data is required. Thus a Building Management System needs to be included into the building to measure the key parameters of the energy consumption and generation, enabling the validation of the model approach. The findings are used to validate the calculation of the U-value of the walls. The results of these measurements are attached in appendix D. A qualitative verification of the build quality with a thermal image camera report is attached in Appendix E.

4 THE RESEARCH UNDERTAKEN

The aim of this work is to understand the effect of practical constraints on real building design and technology on achieving zero or low carbon performance in compact urban dwellings in a maritime northern European climate. The goal is to determine a complete energy balance, with on one side the consumption and on the opposite side the feasibility of the possible generation plants. From the literature review a model needs to be generated and from the outcome of the model, verified with real word data, an approach to estimate the feasibility of the various generation options and their CO_2 emissions can be calculated.

Publications extracted out of this research are shown in the appendices. This chapter contains an expansion on the published work.

4.1 UNDERSTANDING THE DRIVING INPUTS FOR LOW ENERGY COMPACT URBAN BUILDINGS

The requirements for a comfortable living space go back to when human kind started to live in caves. Sheltering from the elements and using foraged wood to increase the temperature of the cave, preparing the kill and providing some light in the dark days fulfilled the earliest energy requirements. Modern living is basically the same, although the requirements for comfort are better specified and buildings have replaced the caves. The occasional dive in the local river is replaced by a warm morning shower.

The wood that provided the light, space heating and cooking has been replaced by other (mostly non-renewable) sources. As discussed in Chapter 1, the amount of people now living on this planet and the high CO_2 emission of the resources used are likely to have a rapid changing climate effect on this planet. To reduce these CO_2 emissions whilst still creating the required comfort in the living space a more integrated approach with renewable energy sources needs to be taken. Such an approach is depicted in Figure 2.

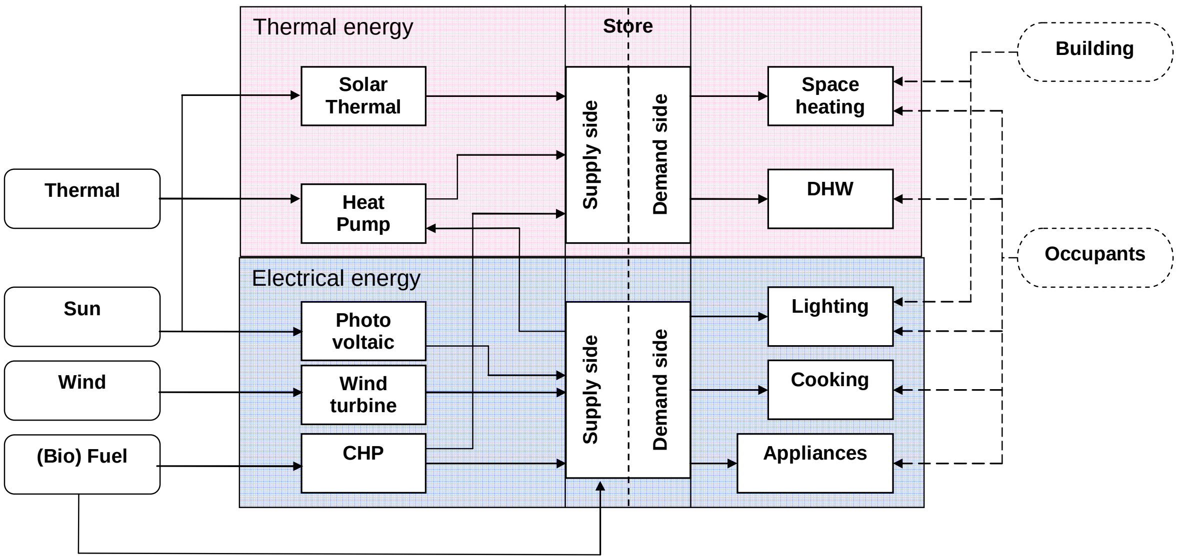

Figure 2 Block diagram showing integrated generic renewable energy approach.

On the right hand side is the demand requirement. Most of the energy demand requirements are determined mainly by the occupant, although the design of the building has a large influence on the requirement for space heating and lighting. To generate this energy, four principal energy carriers, wind, sun, thermal and (bio) fuel are available, as shown on the left hand side. Sun and wind as energy sources are well known, as is (bio) fuel, in the form of gas (e.g. methane), liquid (e.g. oil) or solid (e.g. wood). Thermal energy is the energy that results of matter having a temperature above 0 K, or as Encyclopaedia Britannia states: *Thermal energy is the part of the total potential energy and kinetic energy of matter that results in the system temperature* (Encyclopaedia Brittania, 2013). This energy can be extracted from a fluid (mainly air or water) using a heat pump.

As the generation and consumption might not happen simultaneously, a store needs to be provided. To estimate how much energy needs to be generated and when, and what the storage capacity needs to be, the energy consumption needs to be estimated first.

4.1.1 ESTIMATION OF ENERGY CONSUMPTION

With a given building design, estimations can be generated for the total energy consumption. As stated in the Code for Sustainable Homes (2006), all energy needs to be generated from renewable resources. The consumption side of the energy balance can be split in two parts:

1. Thermal demand
2. Electrical energy demand

Thermal demand can be split up further in energy required for space heating and domestic hot water. Electrical energy demand includes lighting, cooking, energy for white goods and ventilation with heat recovery and small power.

4.1.1.1 Thermal demand: Space heating

The largest energy use in dwellings in the UK is said to be space heating. Historically this is due to the low insulation value and high air permeability of the building envelope. The UK housing energy fact file (Palmer and Cooper, 2012) shows that space heating takes up around 60% of the total energy consumption. Low carbon housing has been shown to be possible by reducing the space heating demand by improving the characteristics of the building envelope and increasing the air tightness, with controlled ventilation (Lowe, 2007).

Mahdavi and Doppelbauer (2010) provide information on passive house design and the influence of high insulation and low ventilation losses on the indoor environment. They conclude that space heating requirements can be reduced to $10W/m^2$ by using effective insulation and ventilation loss reduction. The low heat loss might even require cooling during the warmer parts of the year, due to the larger impact of the internal gains.

Neither the Code for Sustainable Homes nor the passive house standard state any temperature settings and/or heating requirements in the dwelling. To obtain the required heating settings, guidelines for these requirements need to be given. The CIBSE guide defines comfort levels with set temperatures between 18 and 24 ºC, however, without occupational profiles. The BREDEM model (Anderson et al., 2002) defines a zone and weekly pattern. The temperatures are set to 21 ºC in zone 1 and 18 ºC in zone 2 when active (occupied and people not asleep) and no heating outside these periods. What type of room(s) the zones are in is not defined in the BREDEM model. Yao et al. (2005) identified five different occupational patterns and resulting heating load profiles. One of these profiles scenarios matches occupation times of the BREDEM set points, however, the temperature is set to 15 ºC when not active. For the temperature setting parameter in the model, the set points for BREDEM are used, with zone 1 the upstairs living area and zone 2 the downstairs bedrooms. For the flats all rooms are assumed to be in zone 1.

As the internal temperature and therefore the space heating requirement has multiple dependencies (weather, occupancy and internal gains) the energy calculation requires a dynamic simulation.

4.1.1.2 Thermal demand: Domestic hot water

The other main thermal energy demand is the demand for domestic hot water. Currently the average household in the UK, according to the UK housing energy fact file (Palmer and Cooper, 2012), spends 18% of the total energy consumption on hot water. This report identified a trend in reduction in DHW consumption; one of the reasons for this reduction is given to be a shift to electrical (power) showers and dishwashers, which both result in an increase in electrical consumption, but a reduction in generally centrally generated DHW.

The quantity of Domestic Hot Water (DHW) to supply is not specified in the CSH, although a limit of 80 litres/person/day of potable water is required for the application of code level 6. This is achieved by a combination of water saving faucets, smaller baths, and the use of grey water for flushing toilets etc. However, the CSH does not state the amount and temperature setting for domestic hot water to achieve level 6. Hence other data is required to estimate this demand.

Different sources of data specify different volumes and temperatures of daily domestic hot water resulting in different energy requirements. Volume and energy requirement can be calculated using the equation in the BREDEM model (Anderson et al., 2001). The volume in this model is 38 + 25 N, with N the number of people in the household. With one person this equates to 63 litres/day, approx. 20% below the limit for the CSH level 6. The Energy Savings Trust (EST) Measurement of Domestic Hot Water Consumption in Dwellings report (2008) estimated a higher volume to be 46 + 26 N. With one person, this equates to 72 litres, 10 % less than the CSH limit. For two people this equates to 98 litres. If we assume the maximum spread as the consumption limits from the EST report, the minimum estimated consumption is 37 litres/day to a maximum consumption of 99 litres per day for single person households. This is lower than the average hot water consumption of 122 litres/day per household, according to the same report.

The EST report (2008) also measured the monthly average water inlet temperature, and showed that the inlet temperature varied between 10 and 20 ºC. The average inlet temperature of this profile is approximately 5 ºC higher than the assumption in Yao et al. (2005) of 10 ºC. A larger variance was found on the outlet temperature of the DHW. Widén et al. (2009) assume an outlet temperature of 55 ºC, others (Yao et al., 2005) define an output temperature profile depending on usage patterns, and the BREDEM model assumes an output temperature rise of 50 ºC and a 15% heat loss between the hot water cylinder and the tap point. Using Yao et al. their profile results in an average temperature of the DHW draw of 47 ºC. With an assumed inlet temperature of 10 ºC, a temperature rise of 50 ºC and a loss of 15%, the effective average output temperature using the BREDEM model (Anderson et al., 2001) is 52.5 ºC. The DEFRA report (2008) showed a larger variance in outlet temperature; however, the mean delivery temperature for regular boilers was measured at 52.9°C with 95%

confidence interval at ±1.5°C, corresponding with the BREDEM values. The DEFRA estimated the energy requirement for hot water to be 126 kJ or 0.035 kWh per litre hot water consumed. With an occupation of two people this equates to 3.25 kWh/day, or a continuous load of 125 W. The BREDEM does not define a draw off pattern; the DEFRA measured an average draw off pattern per hour, with a peak of 40 litres in the morning and a smaller peak of 20 litres in the evening. If this thermal energy is taken from a temperature dependent resource, like solar thermal panels or a heat pump, the draw off pattern has an influence on the inlet temperature to this resource. Therefore, to capture/generate the required output temperature, the energy yield needs to be calculated dynamically.

Temperature is an important factor, however health and safety of drinking water provision also needs consideration. The major threat in domestic hot water is the Legionella bacteria (Legionella Pneumophila) causing Legionnaires Disease. According to the Health and Safety Executive (2009), to avoid Legionella, hot water should be stored above 60 ºC and transported above 50 ºC.

As an assumption for the volume of DHW for the model, it varies from the lower limit of 37 litres per day to a maximum of 122 litres per day. This equates to approximately half and one and a half the CSH level 6 requirement and the lower limit corresponds with the lower limit of the DEFRA report. The higher limit corresponds with the UK household average. This setting was chosen as it was expected that the number of occupants in these dwelling is expected to be less than average. As the profile for the inlet temperature is not known, the same assumption has been used as Yao et al. (2005), 10ºC. The outlet temperature is set to 50ºC. This is the median between the outlet temperatures of the BREDEM model and DEFRA model and the temperature of the profile Yao et al. derived in 2005. The draw off pattern is set to the DEFRA measurements and adjusted for the total volume of water per day.

4.1.1.3 Electrical energy requirement

As the Code for Sustainable Homes does not provide any guidelines on the amount of electricity used, other sources for this information must be found. For code level 5, the next performance level down the scale, the energy performance is stated to be 100% better than the 2006 Building regulations Part L (Department for Communities and Local Government), which is '*…zero emissions in relation to Building Regulations issues (i.e. zero emissions from heating, hot water, ventilation and lighting)…*'. From this, it can be inferred that in order to comply with code level 6, all energy used for space heating, ventilation, water heating, lighting, small power (i.e. non regulated) and ancillary loads such as pumps and controls must be generated through the use of zero-carbon technologies. The CSH also states "*The carbon benefit of energy generated by low or zero carbon technology can only be allocated to dwellings that are directly supplied by the installation via dedicated supplies*" (CSH, 2010). This makes remote generation in an urban environment impractical. As currently there are no options allowed under the CSH code level 6 to purchase zero-carbon energy from the market, an implication of this is that all electricity used by the occupant must be generated on site. It is interesting to note that the allowable solutions for tomorrow's new homes report by the Zero Carbon Hub (2011) is proposing to exclude the unregulated use (more than 50% of the electricity consumption) from the definition of zero-carbon. In effect this is dropping the energy requirement for CSH level 6 back to level 5.

The challenge for the designer is that there is no reference to the electricity consumption from non-regulated loads (such as appliances) that should be attained. Therefore other ways of estimating electrical consumption requirements must be found. DECC studied in 2012 the electrical consumption patterns in the UK This Powering the Nation survey found that, on average, 2.83 MWh of electrical energy is consumed in flats and 2.89 MWh of electrical energy is consumed in small terraced houses in their study, for which 50% or more of the electricity used in homes surveyed was used for appliances. This survey suggested that 16% of household electricity powers cold appliances (fridges/freezers), 14% is used for wet appliances (washing machines and dishwashers), 14% for consumer electronics, and 6% for information and communication technology. The BREDEM model (Anderson et al., 2001) estimates the annual electrical energy consumption with 50 m^2 of living space and an occupation with 1 person to be 2.88 MWh (all low energy lighting and cooking on electric). This seems to correlate with the DECC study for this type of apartment.

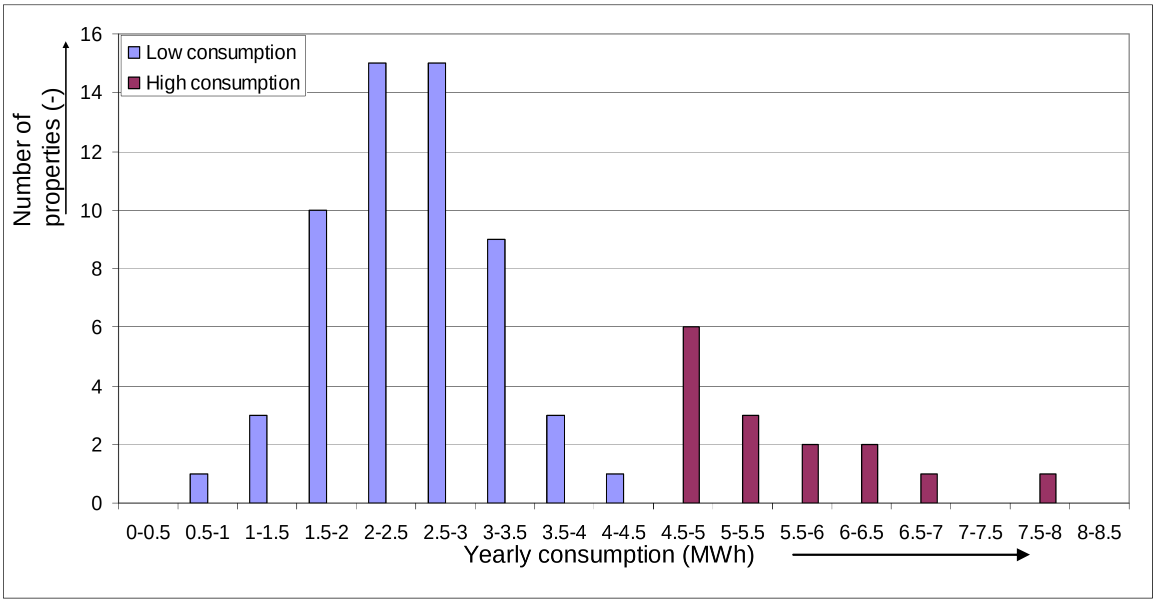

Figure 3 Electrical consumption distribution using Firth et al. (2008) dataset

One of the factors that fluctuates the electricity consumption is the occupant behaviour. Richardson et al.. (2010) confirmed the findings of Firth et al.. (2008) of a 10-fold difference in electricity use of similar type of dwellings. The lowest consumption found was one dwelling with an annual consumption of 0.8 MWh, the highest of 7.86 MWh, as shown in Figure 3. Firth et al.. also showed a large difference between similar dwellings for cold generation (i.e. for fridges and freezers) and stand-by electricity consumption, from below 50 W to over 500 W, again a 10-fold difference in consumption. However, both studies omit the floor area of the dwellings researched and the amount of occupants in the building. Firth et al.. (2008) split the dataset in three groups; a low, medium and high energy group. However, if the dataset is binned in 16 bins with a bin size of 500 kWh/year electricity consumption, the distribution curve emerges as shown in Figure 3. The total dataset is split between 0 to 4.5 MWh/year and 4.5 to 8.5 MWh/year. From this curve, it can be derived that 80% of the data in the dataset is part of the low consumption curve. This curve seems to indicate a normal distribution, with an average electricity consumption of 2.5 MWh per year and a standard distribution of 750 kWh. As no mention was made of the type of dwellings, apart from the spread, no other assumption can be made from this study. Two standard deviations will cover 95% of the consumptions, so a lower limit of 1 MWh and an upper limit of 4 MWh per annum per dwelling are used for the simulation.

If the BREDEM model (Anderson et al. 2001) is used to estimate the yearly consumption a value of 2.29 MWh per dwelling is calculated, based on a floor area of 50 m^2, 100% low energy lighting, 2 people occupying the dwelling and electrical cooking. This approach gives a point to which a comparison of systems can be based. A base load of 75 W was estimated for the MVHR unit and electricity required for the fridge-freezer. Working backwards from the target of 2.29 MWh, subtracting the base load of 75W running 24 hours, 365 days of the year, leaves a load of 496 W during occupied hours, taken to be 07:00 until 09:00 and 16:00 until 23:00. 75% of the load is assumed to be consumed in the living area (first floor), where the cooking takes place. The base load is 25% lower than the base load as established by Yao et al. (2005) and the assumption was made due to the higher efficiency of the appliances and lighting. Seasonal variations are not considered as stated in the BREDEM model and apart from the energy consumed in extract fans, internal heat gain to each apartment is equal to the electricity used for appliances and lighting together with 90% of the energy required for cooking (Anderson et al., 2001). More elaborate load profiles are available, e.g. from Richardson et al., (2010) but the influence of these on the space heating, due to the time constants involved, are limited. Hence a simple load profile was adequate in this situation. As the Code for Sustainable Homes requires a net annual zero CO_2 emission, the fluctuation of the electricity is not relevant to achieve the code level 6.

4.1.2 GENERATION OPTIONS

To achieve the highest level in the Code for Sustainable Homes, all energy must come from renewable sources. The CSH states that code level 6 can be achieved by *'…Using low and zero carbon technologies such as solar thermal panels, biomass boilers, wind turbines, and combined heat and power systems (CHP). It would mean for example that energy taken from the national grid would have to be replaced by low or zero carbon generated energy, so that over a year the net emissions were zero. …'* Only very recently (2012) has Good Energy entered the national utilities market, claiming to provide only zero carbon energy, although this option is not applicable under the CSH, as occupants are free to choose their energy supplier. The CSH also states that *"The carbon benefit of energy generated by low or zero carbon technologies can only be allocated to the dwellings that are directly supplied by the installation via dedicated supplies"*. For rural communities, a remote zero-carbon electricity generator, e.g. a wind turbine, can comply with this requirement; however, remote generation in an urban situation requires dedicated cables to the site, which is impracticable. Therefore the above statement implies that all the required energy must be generated on site.

In principle there are only four renewable energy carriers:

1. Solar (either for electrical or thermal energy)
2. Wind (mainly electrical energy)
3. Thermal energy from ambient (either from soil and/or air)
4. Biomass (depending on fuel, thermal and/or electrical energy)

4.1.2.1 Solar

Solar energy capture can be split in three major categories:

1. Passive solar capture
2. Solar thermal capture
3. Solar electric capture

Passive solar capture has the longest history, however, it is only utilised for space heating. It mainly relies on (south facing) glazing, since this admits, but prevents re-emission of the solar energy. Mahdavi and Doppelbauer (2010), Kachadorian (1997) and Berggren et al. (2012) show the principles of passive solar design. These designs include optimised orientation for solar gains, inclusion of the use of solar spaces, low U-value walls and windows and ventilation with heat recovery. An urban setting with a site dependent orientation and in close proximity to other buildings limits the available solar gain in winter when required, and summer solar gain is to be avoided to prevent overheating. Limiting the environmental influence due to well insulated walls and roofs, combined with controlled ventilation with heat recovery will aid towards a lower heating energy requirement.

Solar thermal collectors are used for active solar thermal capture. Solar thermal collectors come in various shapes and sizes, from concentrating mirrors generating steam for turbines, the possibility of including photovoltaics (Norton et al., 2011) to almost passive hot air collectors. The most common system on domestic properties in the UK are flat plate solar hot water systems. A solar thermal system's performance is optimized by positioning the collectors in direct sunlight and locating them on a sloped roof with a southerly orientation. Practical field tests show an annual yield in the UK of 250 to 400 kWh/m^{2}year (Martin and Watson, 2001) on a 30º pitched roof due south, if sufficient storage is provided. Lower pitched roofs will show a lower yield, especially in winter; CIBSE shows 8% reduction in yearly total irradiation incident but 30% less in January comparing a horizontal surface with a surface at a 30º pitch. For direct irradiation, these values are 22% reduction on a yearly basis and 65% reduction in January (CIBSE, 2005). The total solar radiation is around 1000 kWh/m^{2}year (Energy Savings Trust, 2012). If a reduction of 22% is assumed due to the non-optimised pitch the minimum total yield is 200 kWh/m^{2}year. A conservative yield is therefore estimated to be around 20% of the solar energy available for solar thermal.

Generating electricity via photovoltaic (PV) is the latest form of solar energy capture. PV panels convert energy from the sun into electricity through semi-conductor cells (Energy Saving Trust, 2004). PV technology is mature (Wiginton et al., 2010) and its performance can be easily predicted (Jardine et al., 2003). The installed cost of a typical photovoltaic array for a dwelling used to be relatively high (Energy Saving Trust (2004), Ramanathan and Ganesh (1994)) with payback times measured in several decades (Watson et al., 2008). Ren et al. (2010) questioned the technology's cost efficiency. However, prices for PV installations are decreasing; wholesale prices for PV modules dropped by 70% between May 2009 and June 2012 according to sologico.com. Feed In Tariffs introduced in 2010 have accelerate payback times, which is encouraging deployment, as expected (Williams, 2010). Pay-back times within a few years have now been quoted by installers, due to the lower cost price of the installation.

Photovoltaics have been shown to provide net reductions in both CO_2 emissions (Allen and Hammond, 2010; Ren et al., 2010; James et al., 2010) and significant contributions towards the annual electrical demand (Bahaj and James, 2007). The approximate percentage of an average household's electricity demand provided by a typical solar PV installation ranges between 27-57% (Allen et al., 2008; Allen and Hammond, 2010) with claims for export levels as high as 70% in some cases (Allen and Hammond, 2010; Bahaj and James, 2010). The actual output of a PV module is a function of orientation, solar radiation, wind speed, air temperature, soiling and various system-related losses (Tian et al., 2007). Typical yields in the UK are given of around 750 to 800 kWh per year output for each kW_p installed (Huld et al., 2008). This yield might cover the net electricity demand for a compact urban home (the only feasible space to fit solar panels is on the roof, around 25 m^2 of roof space will allow around 2-3 kW_p PV array fitted).

Norton et al. (2011) stated that there are several combined solar thermal with integrated PV on the market. The disadvantages stated are the detrimental effect if the thermal part of the panels becomes stagnated due to system failure, the more complex installation and increased cost. As the PV system voltage increase for an increased system performance, an increased risk of electrical fault due to leakage must be also mitigated if the thermal transfer medium is conductive (e.g. water with glycol). Therefore, at the moment the preferred option is to keep both systems, PV and ST, separate. As a result the PV will be competing for space with the solar thermal energy collection, either the electrical demand or heat demand might not be covered by solar on its own.

4.1.2.2 Wind

Wind turbines harness the energy in wind to produce electricity (Energy Saving Trust, 2008). Only small scale wind turbines installed within the built environment are classified as micro generation technology (James, 2010). The power output of a wind turbine is proportional to the cube of the wind speed; therefore, to be cost effective, turbines must be placed in windy locations (Bahaj et al. 2007), i.e. with an average yearly wind speed higher than 5 m/s

Many studies claim that roof-mounted turbine technology has the potential to reduce CO_2 emissions (Allen and Hammond, 2010; Bahaj et al., 2007; James et al., 2010) and reduce consumers' dependence on conventional electricity resource (Allen and Hammond, 2010; Bahaj et al., 2007). The payback time is expected to be beyond the typical lifetime of a turbine (James et al., 2010; Peacock et al., 2008). It is unclear how usable any of these claims are, as yield estimates are complex (James et al., 2010, Peacock et al., 2008), manufacturer's performance claims are unverified (Dayan, 2006) and wind resource appears to be overestimated (Bahaj et al., 2007; James et al., 2010; Peacock et al., 2008) and unsuitable for urban application (Peacock et al., 2008). It is also not clear yet how payback time is being influenced by the Feed in Tariff.

Building mounted wind turbines experience poor performance in urban locations (Heath et al., 2007; Bahaj et al., 2007; Energy Saving Trust, 2004; James et al., 2010; Mithraratne, 2009; Watson et al, 2008). Trials cited by James et al. (2010) and Bahaj et al. (2007) show that the wind resource in urban locations in the UK is not sufficient and annual generation is far less than predicted. Turbines in the urban environment generally experience an increased level of turbulence, which can reduce output and increase stress on turbines (Dayan, 2006). Allen and Hammond (2010) show that the average urban wind turbine provides only 2-5% of a typical household's electricity usage. Turbines mounted on taller buildings in the urban environment may experience fewer issues with wind resource and turbulence (Bahaj et al., 2007; Dayan, 2006). Urban wind generation has also been shown to cause noise problems to the surrounding area (Watson et al., 2008).

Off-site wind turbines can be considered under the allowable solutions, however the CSH stipulated a dedicated supply. Therefore it will not be feasible in an urban setting.

It is uncertain whether sufficiently efficient performing turbines will become commercially viable for use in urban locations by 2016. Community wind turbines in a non-urban setting are allowed under the CSH rules, as long as the supply is connected to the dwelling(s) via dedicated cables. Therefore, for all of the above reasons, wind is not considered an option as a source of energy in compact urban development in this study.

4.1.2.3 Thermal energy

Thermal energy is available in the air, water or soil, and although abundant, it is not normally at the right temperature level in the UK to be used directly. Air temperature is weather and season dependent, but the average soil temperature in the Midlands UK is around 10 ºC (Met Office, 2012). Low temperature space heating requires at least a temperature of 40 ºC and DHW at least a temperature of 50 to 55 ºC (Knoll and Wagenaar, 1994). One method to extract the thermal energy and increase the temperature to a useful level is by using heat pumps. A heat pump transfers heat from a lower to a higher temperature by consuming (electrical) energy. Cabrol and Rowley (2011) showed that heat pumps can be effective in low carbon dwellings; hence heat pumps can be used as an alternative way to provide the required thermal energy. The thermal yield of a heat pump is expressed in the Coefficient Of Performance (COP), which is the quotient of the delivered thermal energy and the required energy input to deliver the output energy. Heat pumps require, depending on their operation point, 25 to over 75% (in most installations electrical) energy input, and upper limit temperatures vary between 55 ºC and 65ºC (Sparn et al., 2011, Kingspan Datasheet, 2009). In a compact urban setting, however, the surface area for horizontal ground source heat pumps is likely to be too small (Baxi, 2006), and for vertical ground source heat pumps the costs are prohibitive. Therefore only air sourced heat pumps are considered in this study. The Energy Saving Trust (2012) found that the yearly Seasonal Performance Factor (SPF) of air source heat pumps was 1.89, however, no precise data is available about the system conditions that generated this data. To determine the electrical requirement for the given thermal output over a longer period of time, a dynamic model is required as a large parameter set to determine the overall system performance.

4.1.2.4 Biomass

Lam et al. (2010) state that biomass is one of the key renewable energy sources. The most important biomass fuels are solid, sawdust, wood chips, bark, straw, cereals, grass (Obernberger, 1998) and fuel wood (Ramanathan and Ganesh, 1994), each with different combustion behaviour and potential (Obernberger, 1998). Vegetable Oil (VO) is an available liquid renewable fuel, which can be easily converted into bio-diesel by transesterification (Pennsylvania State University, 2008). They can all be easily stored and transported (Hall and Scrase, 1998). Anaerobic digestion of solid and liquid bio mass could generate bio-gas; however, this bio fuel is not readily available at the moment.

The payback period for biomass systems depends on fuel type, as well as the fossil fuel that is displaced (Energy Saving Trust, 2004). Fuels like woodchip and logs still compare favourably with coal, oil and LPG, although pellet fuel cannot compete with current gas prices (Energy Saving Trust, 2004). Generally speaking, systems pay for themselves over their lifetime (Energy Saving Trust, 2004). The Energy Saving Trust (2008) claim biomass is a low carbon fuel and Gomes and Muylaert de Araújo (2009) also claim reductions in CO_2 emissions (as compared to fossil fuels).

However, most of these claims often don't take account of the environmental impacts of bio fuel production (Hall and Scrase, 1998), such as high specific land use (Lam et al., 2010) that strain agricultural resources also needed to satisfy food demands (Lam et al., 2010; Pękala et al., 2010), water consumption and pollutant emissions (Paula Gomes and Muylaert de Araújo, 2009), deforestation (Lam et al., 2010) and the resultant loss of biodiversity (Lam et al., 2010). Especially the use of palm oil as a renewable energy source has come under scrutiny because of the vast expansion of palm oil fields replacing tropical rain forests (Stichnothe and Schuchardt, 2011) that could lead to an increase in global warming. (Bala et al., 2007)

Demirbas (2005) stated that the cost of bio-diesel, a refined version of vegetable oil, varies, depending on the base stock, geographic area, variability of crop production, the price of crude petroleum and other factors. He stated that the price for vegetable oil is approx. twice the price of fossil fuel, mainly due to the high price of the raw material. Zhang et al. (2013) studied the carbon emission balance of different feedstock and concluded that some production methods to produce vegetable oil for combustion are even carbon negative. However, if electrical energy is required to achieve the required CSH level, and can not be generated by solar, vegetable oil is the only option for small scale generation, although at twice the expense of fossil diesel oil.

Combined heat and power (CHP) plants can also be run on biomass (Energy Saving Trust, 2008). Micro-CHP allows individual homes to generate a proportion of their own electrical supply, whilst also supplying heat and hot water (Energy Saving Trust, 2004). The Energy Saving Trust (2004) refer to it as a technology for the future, whilst Obernberger (1998) claims it is of growing importance for small-scale applications. Once the technology is fully established and commercially available, micro-CHP systems can provide enough heat for domestic heating and hot water and have the potential to make substantial savings in CO_2 emissions from the home, according to the Energy Saving Trust (2004). Watson (2004) estimates a payback time of well over a decade. Feed-In Tariff is available for micro CHP installations smaller than 2kW; however, this is limited to 30,000 installations, with a review after 12,000 installations planned (DEFRA 2011). Unfortunately, oil fed CHP's are not eligible under this scheme. Larger installations using energy from waste can take advantage of Renewable Obligation Certificates. (DEFRA 2011).

McManus et al. (2010) found a number of disadvantages of this technology by stating that micro CHP systems do not perform as well under real-life working conditions as claimed by manufacturers and that output is significantly biased towards heat, which would be wasted in well insulated houses, especially in summer when the system must still be operated to produce electricity. They also reference a study by the Carbon Trust (2007), stating that carbon savings as a result of micro-CHP in smaller and newer houses are likely to be insignificant. To mitigate against (a part of) this waste, Haeseldonckx et al. (2007) propose the use of a thermal storage not to waste the heat generated by a micro-CHP.

Table 1 Carbon intensity factors (φ) for electricity and heat generation.

Source	Carbon intensity factors ϕ (kg CO_2/kWh)
Natural Gas	0.18
Grid Electricity	0.52
Vegetable Oil/Biodiesel	0.14

The release of CO_2 from the fuel must also be considered if low carbon generation devices are used such as CHP or biomass boilers,. The conversion factors for grid electricity, gas conversion and vegetable oil are taken from the Department for Environment, Food and Rural Affairs (2011) and given in Table 1. SAP 2009 (Building Research Establishment, 2009) estimates the carbon intensity factor for vegetable oil only at 0.04 kg CO_2/kWh. This conversion factor corresponds with the direct emission of the combustion of fuel as stated in the DEFRA report, not including the indirect emissions associated with the productions and transport of the fuel. Although the CO_2 emissions are zero for bio fuels, the DEFRA emission calculation is including the NO_x emissions as CO_2 equivalent. As more than 60% of VO is derived from tropical locations (US Department of Agriculture, 2013) with long transport routes, the higher value (Scope 3, biodiesel) of the DEFRA is assumed in this thesis.

Burning biofuel therefore generates also CO_2 equivalents. In order to achieve zero carbon performance, over production of electricity and subsequent net export to the grid is required in order to offset the emissions. The combustion of vegetable oil with low CO_2 emissions can replace grid generated electricity with relatively higher emissions. It is still possible to generate electricity with biofuel with a negative CO_2 emission, if the electrical output of the generator fed by VO is higher than 27% of the total energy input and net fed back into the grid. This surplus offsets the CO_2 emission generated by the grid electricity, albeit marginally. In an urban area, air pollution as a result of biomass combustion (Paula Gomes and de Araújo, 2009) is a disadvantage for using biomass. Clean burning fuel is therefore required to mitigate the risk of air pollution.

4.1.3 STORAGE

Supply and demand are usually not in balance. During the day and in summer there is a larger likelihood of a surplus in solar energy, this in contrast to cold winter nights. This supply and demand mismatch can be offset through the use of energy storage.

Electrical energy can be stored in various ways, e.g. chemical (batteries), electric (capacitors) or magnetic fields (superconducting inductors). As a dynamic store, electrical energy can be “stored” in the grid, whereby a surplus of electrical energy is fed into the grid and a deficiency of electrical energy is taken from the grid. Westra and Tossijn (1980) concluded already in 1980 that grid connection is the most cost efficient and low carbon way of storing electricity if a large proportion of the electricity generation is generated with non-renewable carbon intensive energy sources.

Thermal storage has to be considered on site. Two types of storage need to be considered, one to buffer the variation of day and night (diurnal storage) and one to buffer the variation of the seasons. Garg et al. (1985) described in depth various methods of thermal storage. They state that sensible heat storage in water is only economical for a few days. Although Ampatzi et al. (2012) assumed a 70 ºC temperature difference in a water based system is feasible, they acknowledge the fact that this might undersize the store and 35 ºC temperature difference would be more pragmatic.

Instead of high temperature storage, low temperature storage in rock (packed bed) is an alternative for larger stores; the lower temperature and lower risk of boiling/freezing and leakage makes this option an economical alternative for seasonal storage. Size and insulation values for the diurnal and seasonal store for compact urban dwellings are likely limited by the available storage space. Heat pumps then could lift the temperature to a required level. A review of papers by Pinel et al. (2011) concluded that fulfilment of the requirement for seasonal storage of thermal energy is difficult to achieve with the current set-up due to long term self discharge.

The capacity and configuration of the thermal store has a significant impact on the performance and operational characteristics of the generation equipment (Haeseldonckx et al., 2007). Heat pumps have a start up time constant of around 2 minutes (Steijger et al., 2010) and CHP require a longer time to reach the optimum performance point, so a prolonged running period is preferred. Thermal storage buffers the demand and supply side, resulting in a longer running time of the generation equipment compared with energy delivery on demand. A higher energy storage loss needs to be taken into account with this solution.

For diurnal stores, the choice between a single large store or smaller distributed thermal stores is complicated (Grondzik et al., 2010; Knoll and Wagenaar, 1994). One large central store has lower losses per volume of storage than distributed stores with the same thermal characteristics. Distributed stores have a larger surface to volume ratio and therefore incur higher losses. The benefits of distributed systems are the shorter pipe runs to the final consumption and the lack of circulation pump required to avoid long time lags between opening the hot water tap and achieving the required tap temperature or facing this time lag that might occur. This has been shown to be an issue with centralised systems (Knoll and Wagenaar, 1994).

Biomass storage space can also be a major issue for a domestic application in an urban area (Energy Saving Trust, 2004). A high density energy source is required. Solid fuels such as wood have an energy density of 2500 kWh/m^3, liquid (bio-) gas such as LPG 7000 kWh/m^3 and liquid bio fuel (diesel and/or VO) approximately 10000 kWh/m^3 (BINAS, 1998). For cogeneration purposes, bio gas is currently in limited supply with an immature distribution network. If in future sufficient biogas becomes available with a well established distribution network, this might become an option for generation of zero-carbon thermal and electrical energy. Solid bio fuels are currently widely available on the market; however, small commercially available solid bio fuel plant can only convert this energy into thermal energy, leaving out the flexibility to generate electrical energy. For these reasons, notwithstanding the aforementioned constraints, liquid bio fuel in the form of vegetable oil is the chosen option for this study; it has the highest energy density per volume, the lowest risk (no pressurized gas), a mature distribution network and the conversion to electricity and heat is well established using a standard diesel micro CHP.

4.1.4 CONCLUSION ON ENERGY BALANCE

Compact urban dwellings in the Midlands UK show their own specific set of limitations to achieve zero carbon.

On the consumption side, space heating used to be the highest energy consumer. Although the average space heating requirement is at the moment 60% of the total energy requirements, higher insulation standards, lower uncontrolled air infiltration and ventilation with heat recovery reduce this requirement. Occupancy patterns and set temperature are defined by Anderson et al. (2001) in the BREDEM model. CIBSE states that comfortable temperatures range from 18 to 24 ºC. An accurate estimation of the required energy for space heating and internal temperatures is dependent on a large parameter set, like the internal temperature settings and occupation, weather patterns, solar and other gains. Hence it is likely that a dynamic model is required to estimate the required space heating energy.

Domestic hot water energy requirement is split in two key parameters. From the DEFRA study, the hot water consumption for a single occupant dwelling is estimated to be 72 litres per day with a maximum variation between 37 and 122 litres per day. As no data was available on the water inlet temperature, this temperature is set to 10 ºC, the delivery temperature to 50 ºC. The draw off pattern is the same as measured by the DEFRA, adjusted for the total volume. As heat pumps and solar collectors have a performance that varies with the inlet temperature, the energy captured/generated needs to be simulated dynamically.

From the Code for Sustainable Homes (2006) it can be inferred that all (regulated and unregulated) electricity needs to be generated on site using zero carbon technologies. The CSH itself does not state a limitation or demand profile to the electricity consumption, so a demand profile has to be generated. The BREDEM model predicts a yearly consumption of 2.29 MWh per dwelling with an assumed base load of approx. 75 W during non active hours, resulting in 496 W during active hours.

On the generation side the limits are more stringent. The CSH states that code level 6 can be achieved by *'…Using low and zero carbon technologies such as solar thermal panels, biomass boilers, wind turbines, and combined heat and power systems (CHP). It would mean for example that energy taken from the national grid would have to be replaced by low or zero carbon generated energy, so that over a year the net emissions were zero. …'* The above statement implies that all the required energy must be generated on site. From the four energy carriers (solar, wind, biomass and ambient thermal) wind is not feasible. Field tests have shown this. Passive solar is limited due to shading of adjacent buildings; place for active solar capture is only available on the roof of the building. Orientation and pitch are given by the limitations of the design; hence the orientation might be sub-optimal. As combined thermal and electrical generation panels are not readily available, PV and solar thermal compete for the same roof space.

Biomass can come in three forms, solid (wood pellets, elephants grass etc), liquid (in the form of vegetable oil or bio diesel) and biogas. From these three forms, the liquid form has the highest energy density per volume and is the easiest to convert into thermal and electrical energy. To generate electrical energy in a small generation plant, (micro CHP) the only viable feedstock is vegetable oil, although with a high cost and a questionable overall CO_2 balance.

Thermal energy can be harvested using heat pumps, these require electrical energy as an input. As this is an energy resource, the energy for the heat pump(s) must be generated on site to be considered for the energy balance.

Buffering is required to timely match the generation and consumption. The grid is used as an infinite buffer for electrical energy. Two types of thermal energy buffers are required, a diurnal one to level out the day/night generation/demand pattern and a seasonal buffer to level the summer/winter generation/demand pattern. Diurnal thermal storage can be realised in decentralised hot water storage, seasonal stores can be utilised in sensible heat store in a packed bed. The capacity of these stores needs to be determined.

As there are a few interdependencies (roof space for solar thermal and PV, electrical energy consumption vs. space heating requirements and flow of thermal/electrical energy with CHP and/or heat pump) a static calculation is not suitable. Therefore a dynamic model is required.

4.2 CASE STUDY BUILDING, MODEL DESCRIPTION AND SIMULATION RESULTS

Building simulation can be used as a tool to accurately estimate the behaviour of a building and the corresponding energy consumption. The actual system that needs to be modelled is shown in Figure 4. The left hand side is the generation side, comprising of thermal energy generation via solar thermal panels, heat pump and a CHP, and electricity generation via the PV system and the CHP. Wind power is omitted. The right hand side is the consumption side, with the influence of the building itself (building materials, orientation, shading etc.) and the occupants inhabiting the building. As the demand and the consumption might not occur simultaneously, storage is required. Electrical energy is “stored” in the grid, whereas thermal energy is stored in water for diurnal storage. Seasonal storage was considered but not implemented at this stage.

To generate a model of a building, the characteristics of the building need to be established. In this thesis a case study building is used.

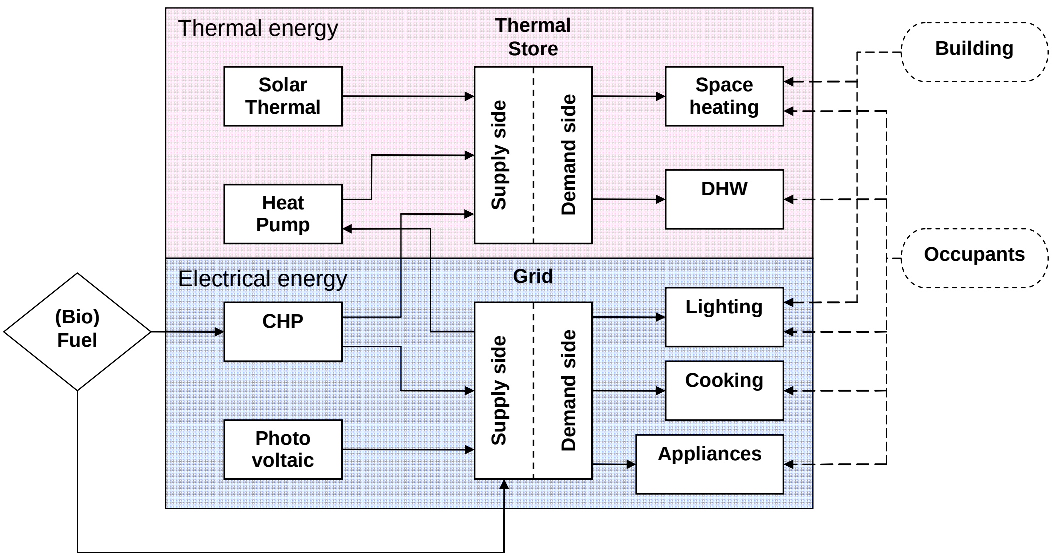

Figure 4 Block diagram of the total system with the available low carbon generation options.

4.2.1 THE CASE STUDY BUILDING

The compact urban dwelling used as case study in this research is a newly developed building under the project name of SHINE-ZC. The SHINE-ZC building in Derby (UK) comprises of 9 adjacent compact urban dwellings; six 2-storey houses and a 3-storey block containing three flats and a shared staircase. Each dwelling has a living space of approximately 50 m^2. The total internal volume is 1326 m^3. The dwellings are adjoined as shown in Figure 5 and Figure 6. A photo of the finished building is shown in Figure 7.

The front of the building faces approximately north, which is dictated by the shape of the site. This, in conjunction with the close proximity of surrounding buildings (the distance to the adjacent building on the North side is less than 10 meters, the distance on the south side is less than 5 meters) limits the winter solar gain. The roof area is split in two levels; around 160 m^2 on the houses and 70 m^2 on top of the flats. Due to planning height restrictions the 230 m^2 roof faces south with a 6 degree slope, rather than the 40º south facing slope that is deemed ideal in terms of solar collector yield for this latitude (Energy Saving Trust 2004). Due to the close proximity of other buildings, the roof space is the only space available for solar energy collection.

The wall is constructed with Insulating Concrete wall Form (ICF), a layered and highly insulating construction comprising of 150mm of Expanded Poly Styrene (EPS), 150mm structural concrete, another 75mm of EPS and the internal surface is plasterboard with a skim coat to a total of 15mm thick. The external surface has either 10mm thick wooden cladding or 10mm render, depending on the location on the building (see Figure 5 and Figure 7). The resultant U-value is calculated to be 0.123 W/m^2K. The construction quality was closely managed and on-site air permeability tests showed permeability 1.88 $m^3/(hr.m^2)$. This results in a less than 0.35 air exchanges per hour for each dwelling in occupation. The windows are triple glazed, with a certified U-value of 0.8 W/m^2K. The g-factor is specified to be 0.31. Special sealing around the window openings prevents heat loss through draught, the effective air leakage is 0 (Sheerframe, 2009). The solar gain in winter is minimal (<50 W) due to the shading of adjacent buildings, practical experience living in low energy dwellings show that the solar gain needs to be limited to prevent overheating in the summer as the internal gains are expected to provide enough heat to maintain the desired space conditions for all but the coldest parts of the year (Den Boon, 1979). The solar gain is limited by placing the majority of the windows on the north side of the building, whilst south facing windows are shaded in summer by an overhanging roof ridge and adjacent buildings. The north facing windows are large enough to provide enough light during daytime; the artificial lighting in the building is generated by low energy lights.

Figure 5 Render of the development (Simon Foote Architects 2008).

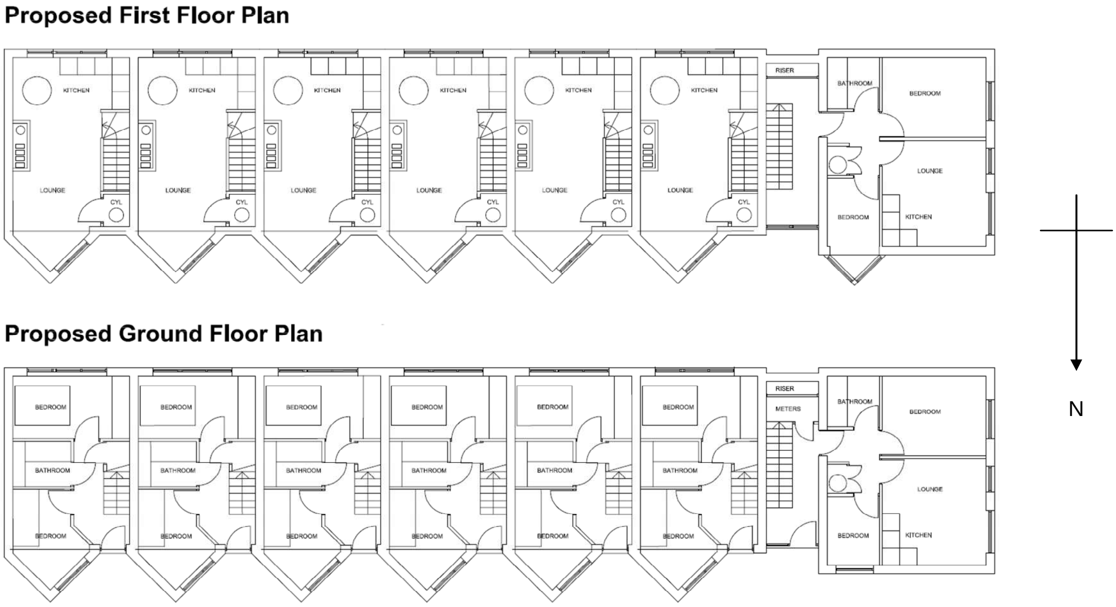

Figure 6 Floor plans of the dwellings (Simon Foote Architects 2008).

Figure 7 Photo of the front (North side) of the building, the six two story terraced houses at the back, three apartments on top of each other at the front.

The building is designed to have warmer living spaces and cooler bedrooms by placing the living space on the first floor and the bedrooms and bathrooms on the ground floor in the houses. The apartments occupy just one floor each. A plant room is built at the back of the plot to house the control equipment, HP and CHP. An overview of the key design parameters for the building is given in Table 2.

Table 2: Key parameters of the building.

	End house	*Middle houses*	*Bottom flat*	*Middle flat*	*Top flat*
Number of units	1	5	1	1	1
Floor area (m^2)	55	55	42	44	46
Volume (m^3)	140	140	105	110	115
External wall area (m^2)	75	45	47.5	50	52.5
Window area (m^2)	8.5	8.5	5.5	6.5	6.5
Roof area (m^2)	25	25	-	-	70
Ventilation rate (ACH)	0.88	0.88	1.28	1.28	1.28
Heat loss fabric (W/K)	21	18	13	11	15
Ventilation heat loss (W/K)	17	17	17	17	17

Infiltration was estimated to be small. The leakage measured during blow door tests of 1.88 $m^3/h.m^2$ with an envelope area of 140 m^2, then adjusted for the normalised pressure according to CIBSE (2005), resulted in an estimated air exchange during occupation of 0.35 Air Changes per Hour (ACH).Ventilation is provided by a mechanical ventilation and heat recovery (MVHR) unit. The domestic ventilation rate is set as required by the UK building regulations (Part F), which is 17 litres/second/dwelling (Department for Communities and Local Government, 2006). As the MVHR is a centralised system, the kitchen and bathroom fans are balanced using local shutters in the ducting. The heat recovery rate is specified to be 90 % (Segen, 2006). In summer the MHVR will run to provide ventilation without heat recovery. When the room air temperature is above 24ºC (maximum acceptable temperature according to the CIBSE guide (2005)), the extract air bypasses the heat exchanger. It switches the heat recovery on again when the temperature drops below 22 ºC. With the set ventilation rate and heat recovery rate the ventilation loss can be calculated.

With a finished design as described above, the TRNSYS model can be implemented using the in built program TRNBUILD. As common with these types of simulation tools, the building is modelled in zones. For each of the houses two zones are allocated, the upper and lower floor. For the flats and the common staircase one zone per entity is allocated. This results in a total of 16 zones. Parameters to define the properties of the individual elements (walls, windows, roofs, etc.) are set according to the material properties (e.g. thermal resistance of the Expanded Polystyrene (EPS) in the ICF structure) and/or manufacturer specification (e.g. doors and windows).

On top of the flats a 4 kW PV system was installed, on the roof of the houses, 6 fields of 9 panels, each with an area of 2 m^2, spectral selective flat plate solar thermal collectors were installed. A 22 kW diesel motor and generator set was converted to a micro CHP. The size of the CHP was chosen so that its thermal capacity could provide twice the amount of required thermal energy at 99% of the days. Heat pumps are planned to be installed, but were not installed during the original build phase.

A central BMS system, measuring and logging temperatures in the dwelling, the storage tanks and the solar thermal array, controls the complete installation. Once the installation is finished, the complete system will be as shown in Figure 8. Weekly energy measurements combined with the data obtained from the BMS will indicate the state of the energy balance.

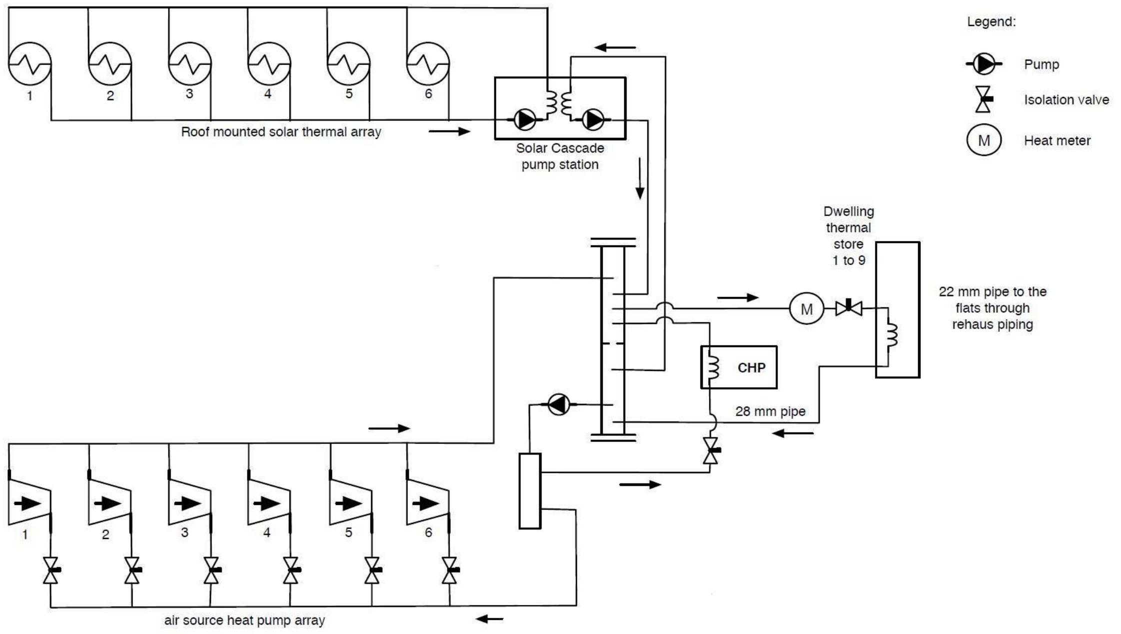

Figure 8 Schematics of the thermal energy distribution

4.2.2 SIMULATION TO AID THE DESIGN OPTIMISATION

Simulation is just a tool to predetermine answers to some of the design questions. As the main focus is the optimised generation mix with the lowest CO_2 emissions, the first answer required is the energy requirement. The thermal energy has two parts to it, the space heating and domestic hot water. Space heating is dependent on the internal gains and as the space heating requirement is expected to be low, a variation in the electrical consumption is likely to have an influence on this requirement.

Domestic hot water is the other energy requirement. This requirement has limited influence on the space heating and/or electrical demand.

Other simulations are required to determine the interdependencies between various generation and demand parameters. With a relative small diurnal thermal store, the yield for solar thermal is dependent on the water consumption. Also solar thermal is competing with PV on roof space. Simulation is required to determine the characteristics of these interdependencies.

Heat pumps show a yield dependency based on temperature difference between evaporator and condenser coil. As the chosen source of thermal energy is ambient air, simulation is required to determine the seasonal performance factor, varying on which part of the year the heat pump is required to run.

With these parameters established, the feasibility of a carbon neutral home can be determined.

4.2.3 DEMAND PARAMETERS

As described in section 4.1.1, the energy consumption depends on the occupation and shows a large variation.

4.2.3.1 Occupational profile

The BREDEM model parameters have been used in TRNSYS to generate an occupational profile for weekdays and weekends. Figure 9 shows the schedules for Zone 1, and Zone 2 during weekdays and weekends. The heat gain for two people seated at rest is added to the living area of the dwelling (the top floor in the houses).

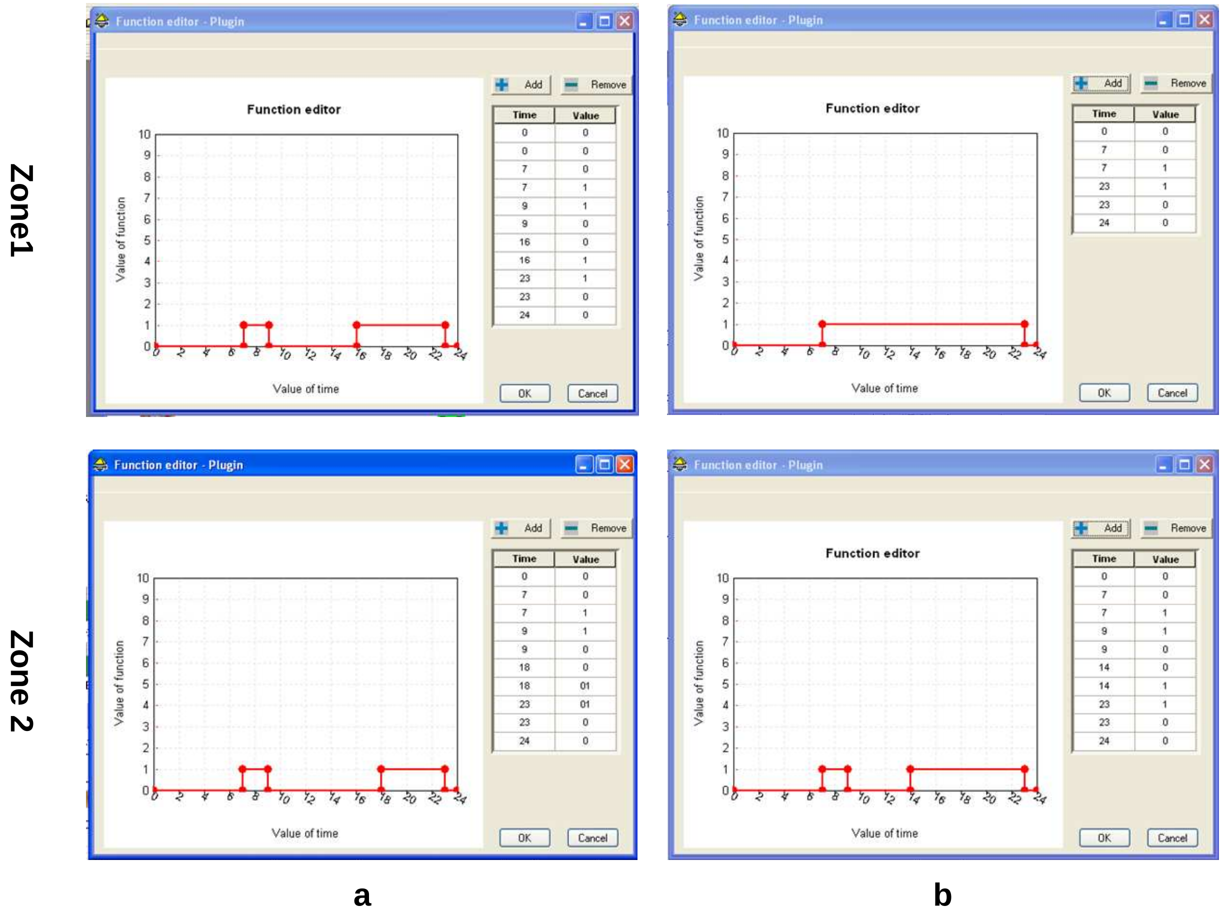

Figure 9 Occupation schedules for zone 1 and 2 during weekdays (a) and weekends (b)

During the night (23:00 till 7:00) the internal heat gain is calculated as two peoples' heat gain (seated at rest, 115 W per person (CIBSE, 2005)) added to Zone 2 (the bottom floor in the houses).

4.2.3.2 Infiltration, ventilation and air movement

Ventilation is provided by a mechanical ventilation and heat recovery (MVHR) unit. No air movement is modelled between the different zones, except the ventilation air through the heat recovery unit. The uncontrolled air exchange rate of 0.35 ACH is included in the simulation. For the purpose of assessing the heat losses by the MVHR, the ventilation rate is reduced by the efficiency using the manufacturer's performance benchmark data as described by Taylor et al. (2010) "*the thermal effects of ventilation heat recovery can be simulated precisely by reducing the ventilation rate by the proportion of heat recovered*". The heat exchanger in the heat recovery unit is bypassed if the temperature is higher than 24 ºC and heat recovery resumes when the temperature drops below 22 ºC. A lower temperature is not possible as the reference temperature for heating is set to 21 ºC according to the BREDEM method (Anderson et al., 2001). The electrical power used to drive the fan and the heat electrically generated by the heat recovery unit is added to the internal gains according to the BREDEM method.

4.2.3.3 Electricity demand and internal gains

Since the CSH does not specify the electrical demands and the CO_2 emmission is based on a net-annual value, the BREDEM model (Anderson et al., 2001) is used to estimate the yearly consumption; calculated to be 2288 kWh per dwelling. This value represents the total energy requirement including cooking, electrical lighting, white goods and portable equipment for the whole building. A base load of 75 W was estimated for the MHVR unit and electricity required for the fridge-freezer. Working backwards from the target of 2,288 kWh, subtracting the base load of 75W running 24 hours, 365 days of the year, leaves a load of 496 W during occupied hours, taken to be 07:00 until 09:00 and 16:00 until 23:00. 75% of the load is assumed to be consumed in the living area (first floor). The base load is 25% lower than the base load as established by Yao and Steemers (2005) and the assumption was made due to the higher efficiency of the appliances and lighting. Cooking is assumed to be done using electrical energy, it requires the lowest energy demand (according to Andersen et al., 2001) and as it does not release moisture into the air as part of the combustion process, the ventilation requirements are lower comparing to cooking on gas. Seasonal variations were not considered as stated in the BREDEM model and apart from the energy consumed in extract fans, internal heat gain to each apartment is equal to the electricity used for appliances and lighting together with 90% of the energy required for cooking (Anderson et al., 2001). More elaborate load profiles are available, e.g. from Firth et al. (2008) or Richardson et al. (2010), but the influence of these on the space heating, due to the time constants involved, are limited; the time constant of the building is much larger than the fluctuation of the electricity in the building, therefore an average consumption over the period is adequate.

The total electricity over a year has an impact on the required space heating; due to the low heat loss parameter, an increase in electrical consumption will have a large effect in reducing the requirement for space heating. Firth et al. (2008) showed a ten-fold difference in electricity consumption. This variance needs to be taken into account to establish the robustness of the chosen generation solution. As the requirement for space heating is small, high internal electrical gains might be sufficient to fulfil the space heating requirement completely.

4.2.3.4 Heating set points, control and scheduling

The Code for Sustainable Homes does not define the internal comfort settings for the dwellings. Therefore the BREDEM temperature settings have been used (Anderson et al., 2001). The set-back space heating setting is 15 ºC during the night (23:00 until 7:00 hours) and non-occupied hours and 21ºC during the occupied hours (see Figure 9).

Standard radiators fed from a storage tank provide the space heating; a coil in the tank provides hot water. The reason for this decision were the robustness that the occupants were expected to be familiar with the system, and should be able to operate the heating system. A central thermostat controls the circulation of the hot water and radiator thermostats control the individual room temperatures. The space heating input to the living spaces is calculated from the radiator models described by Knoll and Wagenaar (1994):

$$P_{out} = P_n\, f_0\, f_n\, (\Delta T/50)^{\,n\beta}$$

P_{out} is the output power, (kW),
P_n the nominal output power of the radiator, (kW)
f_0 and f_m correction factors for radiator type and flow, nβ is determined by the way the radiator is connected, (top/bottom, one both side connection).

With the input temperature and flow rate given, the output power and therefore the return temperature to the tank can be calculated. Due to the low water content in modern radiators and the high output power, the time constants for a radiator are low, heating up less than 1 minute, but cooling down typically 7-10 minutes, due to the capacitance of the radiator. Therefore the radiator control time constants determine the time step for the simulation, which is set at 1 minute. The water is drawn from and returned to the tank. The capacitance of the radiator represented in the model results in a first order system cooling down with a time constant of 9 minutes.

4.2.3.5 DHW storage, draw off and scheduling

The thermal storage is provided by a water tank in each dwelling. These have to be large enough to provide one day of energy for space heating and DHW and small enough to fit in the limited dwelling space. Practical limitations on the size of the thermal energy storage require a larger temperature difference in the tank to enable sufficient diurnal thermal energy storage. Each dwelling therefore has a tank assumed to be fully mixed (worst case) containing 315 litres of water. Stratification might occur, this will enhance the performance of solar collector and HP, therefore a fully mixed tank is the worst case. The CHP and flat plate solar thermal collectors can provide high temperature thermal energy (albeit for the solar thermal collectors with a dramatic efficiency drop); up to 95 ºC to prevent boiling of the water, so to store this energy this temperature is the upper limit. No more thermal energy can be stored if this temperature is reached, and therefore the thermal energy provided by the CHP or solar thermal is wasted. Given that the UK DHW supply temperatures are typically 48 ºC or above, the thermal stores are taken to be able to supply no useful heat if the bulk water temperature drops below 50ºC.

The CSH requires that for a level 6 dwelling the potable water consumption must be less than 80litres/day/person. The assumption has been made here that the majority of this water is going to be used for personal hygiene, as the toilets will use gray water. The dwellings are considered here to be single occupancy and since the DHW system uses potable water it is assumed for the sake of capacity sizing and heat supply that the whole 80 litres is drawn off as hot water each day. The energy requirement is calculated, with a fixed inlet temperature of 10 ºC and an outlet temperature of 40ºC.

As an assumption for the volume of water for the model, a variation is simulated from the lower limit of 37 litres per day to a maximum of 122 litres per day. This equates to approximately half and one and a half the CSH level 6 requirement; with the lower limit corresponds with the lower limit of the DEFRA report and the higher limit the average household hot water consumption with an occupancy of 4 people.

The BREDEM calculations use the same water volume, but it does not suggest a water draw-off pattern. It is, therefore assumed that half of the domestic hot water is used in the morning (between 7:00 and 8:00) and half in the evening (between 18:00 and 19:00).

4.2.4 MODELLING THE GENERATION OPTIONS

Solar thermal collectors, photovoltaic panels, air-source heat pumps and a bio-fuelled, micro-CHP where considered in this analysis. Wind generation, ground source heat pumps and biomass boilers were not considered in this case for reasons explained in section 4.1.4.

The only place available for solar collection is the roof. Solar thermal and PV are competing for this space, as there are no combined thermal/PV panels readily available on the market.

Heat can be harvested by the solar thermal array. The parameters required for this model are taken from the datasheet (Dimplex, 2011) The zero heat loss efficiency is stated to be 74.8% with a heat loss coefficient of 3.93 W/m^{2}K. The solar thermal panels are modelled using the theoretical flat plate collectors, type 73 based on a Hottel-Whiller quasi-steady state model. This is allowed, as the solar radiation steps are available in one hour steps only and the time constant of the solar collector are much smaller than this time step. One of the main parameters affecting the yield of the Solar Thermal Collectors (STCs) is the temperature of the fluid entering the collector, coming from the bottom of the tank with the lowest temperature. A rise of the inlet temperature has a negative influence on the yield of the solar collector due to the higher thermal losses in the collector. Solar thermal energy is transferred from the collector into the tank if at least one of the tanks has a sufficiently low temperature, measured at the bottom of each tank. No heat is added to the tanks if the tanks are completely charged.

If the most common type of PV array (crystalline silicon) is used, Bayod-Rújula et al. (2010) show that around 9m^2 of roof space is required to install 1kWp of PV panels. With 230m^2 of roof space, a maximum installation of approximately 25kWp can be installed. TRNSYS standard library type 194b with inverter is used, based on models developed by de Soto et al. (2005), to determine the yield of the PV array.

To convert biomass into useful energy the biofuel needs combustion. A boiler would only provide thermal energy whereas a CHP can provide electrical and thermal energy. Hence only a CHP is considered in this simulation, however, bio fuelled boilers could be used in cases where only thermal energy is required. There is a range of heat to power ratios for CHPs from 10:1 (Whispergen, 2010) to 2:1 (Baxi Dachs mini CHP, 2010). A small diesel CHP, however, can reach a 1.5:1 heat to electricity ratio (Tipkoetter BioGenio, 2010). Additional thermal losses with the operation and transport of thermal energy of these small CHP can be high (30% is not uncommon). The total efficiency of the CHP is assumed to be 35% electrical output, 35% effective thermal output, 30 % thermal losses and hence a limiting case of 1:1 heat to electricity has been taken here. The micro-CHP is modelled as a constant power output with an electrical power estimated at 10kW. With a typical thermal time constant of a CHP of ten minutes and if the CHP is started once a day and usually runs un-modulated for longer than two hours to deliver the heat to the 9 thermal stores (2.8 m^3 water), the run time is much larger (>10 times) than the start-up time and so the start-up and shut down time constants have been neglected. If the thermal stores are at the maximum temperature the CHP switches off. Integration over the CHP running time determines the amount of electrical energy generated. As we do not have the exact losses in relation to the running temperature and the complexity of the control and accurate modelling of all the pipe work in the dwelling, we assumed a relatively high initial thermal loss (30%) to accommodate this variation i.e. a worst case scenario.

Heat pumps are used to harvest the thermal energy from ambient. From experiments described in Appendix A, a computational model was created by implementing the equations generated from the experiments. The resulting model calculates the Coefficient Of Performance (COP) as a function of air humidity, air temperature on the evaporator side and water temperature on the condenser side. The power consumption and the COP was integrated into the TRNSYS model for this standard heat pump with a rated COP of 3.5 and a high performance heat pump with a rated COP of 4.3 under standard conditions (T_{in} = 15 ºC, T_{out} = 35 ºC) (see Appendix B and Sparn et al. 2011). Under real conditions, it can be expected that the COP is lower than under these set test conditions, as the input temperature is lower and the output temperature is higher than the temperatures during the specification tests. The maximum temperature the heat pump can deliver is 55 ºC; hence the heat pump switches off when the bottom nodes in each of the storage tanks reach this temperature. The electrical power consumed by the heat pumps needs to be offset by either the PV array or micro-CHP. The start up time constant for an air source heat pump is approximately 40 seconds and since the time to charge the thermal stores is very much larger (larger than 2000 seconds) typically the unit would be expected to run for 30 minutes or more and hence the start up dynamics can be neglected in this analysis. The electrical load to the heat pumps is assumed constant; however, as stated, the heat output is dependent on the operating conditions.

Superposition, where possible, is used to determine the operational parameters of the installed renewable energy generation options. The generation options are season dependent, e.g. it is beneficial to run the heat pump in summer (also providing DHW with a temperature of at least 50 ºC) and the CHP in winter. The store in each dwelling is sized to supply at least one day of thermal energy, and therefore each day can be viewed as an independent “generation” day from the day before. Because of the size of the store, resistive top-up is not considered in the simulation.

4.2.5 SIMULATION RESULTS

The model is run with different scenarios to obtain an estimation of the energy balance parameters for the real building. The following characteristics have been investigated:

1) The overall energy consumption of the dwelling, split up between space heating, domestic hot water and electricity.

2) The relationship between space heating and electricity consumption. It can be expected that if the electricity consumption increases, the requirement for space heating in low energy dwellings is reduced.

3) The effect of variation of the thermal and electrical energy consumption utilising the mix of installed renewable generation options on the emission of CO_2.

4) The relationship on the division of roof space occupied by solar thermal and PV with a third parameter the DHW consumption. It can be expected that with a higher DHW the yield of solar thermal increases (Martin and Watson, 2001), however, a balance needs to be struck between electrical generation of the PV and the thermal generation of the thermal panels.

5) The change in seasonal performance of a heat pump over the various periods of the year. As the performance of a heat pump changes with the temperature difference, it can be expected that the seasonal performance of a heat pump is lower if used throughout the year, instead of using it for (topping up) DHW during the summer period.

4.2.6 ENERGY CONSUMPTION

One of the main questions for compact urban zero carbon dwellings is if the chosen mix of renewable energy systems can deliver the required energy requirement. The TRNSYS model can generate the required energy balance by simulation of different scenarios. An initial simulation, using the BREDEM model as input, already shows some interesting conclusions as shown in Figure 10. Thermal energy for space heating is only required from November until March, and only counts for less than 10% of the total energy requirements in this simulation. DHW requires about 40% of the energy required and the electricity requirement is approximately 50% of the total energy demand. The total electrical energy demand for the whole building (9 dwellings) is 20.6 MWh. The simulated thermal energy is demand 19.2 MWh, for which 3.8 MWh is used for space heating.

The total modelled energy consumption can be validated by the electrical meter readings. As in 2012 no renewable energy source (apart from the PV) was operational, this measurement gives an accurate reading of the actual total energy consumption. The energy consumption was read weekly from the electricity meters from 01/01/2012 to 31/12/2012.

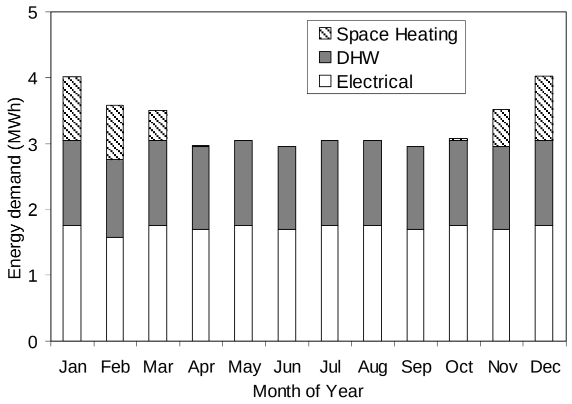

Figure 10 Estimated energy demand for the whole building (9 dwellings) using the TRNSYS model with the BREDEM parameter setting.

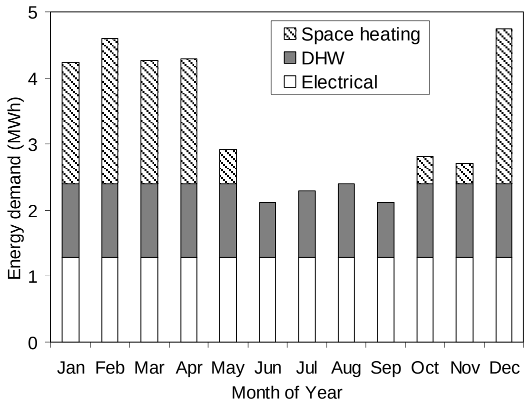

Figure 11 Indication of energy consumption of the whole building (9 dwellings) based on measured meter readings

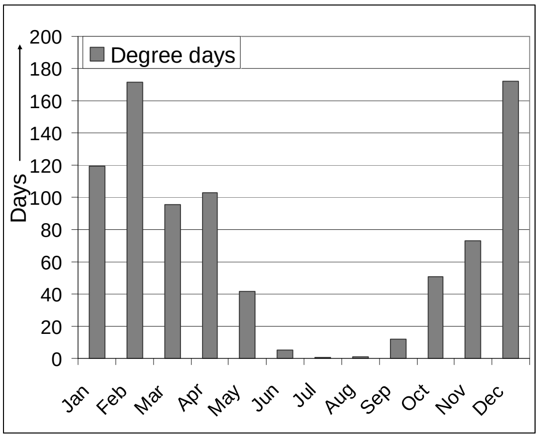

Figure 12 Heating degree days of 2012 measured at the dwelling, the reference temperature was set to 10 ºC

Although the measured energy demand can not be split up precisely, an estimation of the split can be made. The first assumption is that in August no heating is required and August shows to have the highest energy consumption without heating. If this energy requirement was subtracted from all other months, the surplus of the other months could be assumed to be for space heating, as low energy lighting is used throughout the whole dwelling. This assumption has more validity as the months October and November were exceptionally warm in 2012, in contrast to the much colder December, reflected in the degree days graph shown in Figure 12. Apart from the month November, the thermal energy required for space heating correlates with the measured degree-days. The resulting annual space heating energy requirement estimation was 11.4 MWh nearly three times as much as the model predicted. Another assumption is that the electrical demand is equal for each month, and only the DHW varied throughout the year. This was based on the permanent base load, which is assumed independent of the season. Potable water was monitored on a less regular basis (readings at the beginning and end of the year) and since potable water was used for toilet flushing, it was assumed that 35% (WaterWise.org 2012) is used as cold water and constant throughout the year, a total of 12.6 MWh is used for DHW. A total of 24 MWh. of thermal energy was estimated to be consumed during 2012. The results of these assumptions are shown in Figure 11. Electrical use is estimated to be 15.5 MWh. The model predicted an electrical energy use of 20.6 MWh.

As the electrical demand is estimated to be lower than the model predicted, the space heating requirement increases as shown in Figure 13. There is also some anecdotal evidence resulting in higher space heating requirement, some occupants switched off the ventilation and heat recovery unit, and used opening windows as a primary source of ventilation. Also it was observed that occupants smoked cigarettes outside with the front door completely opened (during heating season). Wall flux measurements also indicate a higher U-value for the wall than predicted (see Appendix D).

The total amount of energy is measured to be 39.5 MWh. The TRNSYS model estimated a total yearly energy use of 39.8 MWh.

4.3 CHALLENGE OF THE COMBINATORIAL NATURE OF THE DESIGN PROBLEM

Using the above results from simulations, the results are now graphically presented to enable analysis of the design problem. Each generation capability has its own characteristics and limitations. The challenge here is to find the optimum solution for the lowest possible CO_2 emissions.

4.3.1 UNDERSTANDING THE MODEL INTERDEPENDENCIES

The interdependencies between the different parts of the model need to be understood, to enable proper design decisions. The following sections contain the studies into the most pronounced interdependencies in the model.

4.3.1.1 Relationship between electricity consumption and space heating

As the space heating requirement is low, the influence of the electrical consumption on the space heating is relatively high, as, according to BREDEM, most of the electricity consumed is added to the internal gains, therefore lowering the requirement for space heating. Firth et al.. (2008) and Richardson et al. (2010) showed a tenfold difference in electrical consumption.

If this variation is applied to the space heating requirement, it is clear that the space heating requirement is reduced, as shown in Figure 13. With an electrical consumption of 33% of the BREDEM value, (6.8 MWh for the 9 dwellings) an annual space heating is required of 5.7 MWh. With an electrical consumption of twice the BREDEM value, (41 MWh for the 9 dwellings), the space heating requirement has dropped to 1.7 MWh for the 9 dwellings. Although Firth at al. found a variation of 10, for the purposes of this thesis, it was judged that this would be closer to a variation of 4 by averaging over 9 dwellings, but further work is required to generate a more robust limit. This results in a lower limit of approx. 10 MWh. and an upper limit of 40 MWh for the whole building for the annual electrical demand.

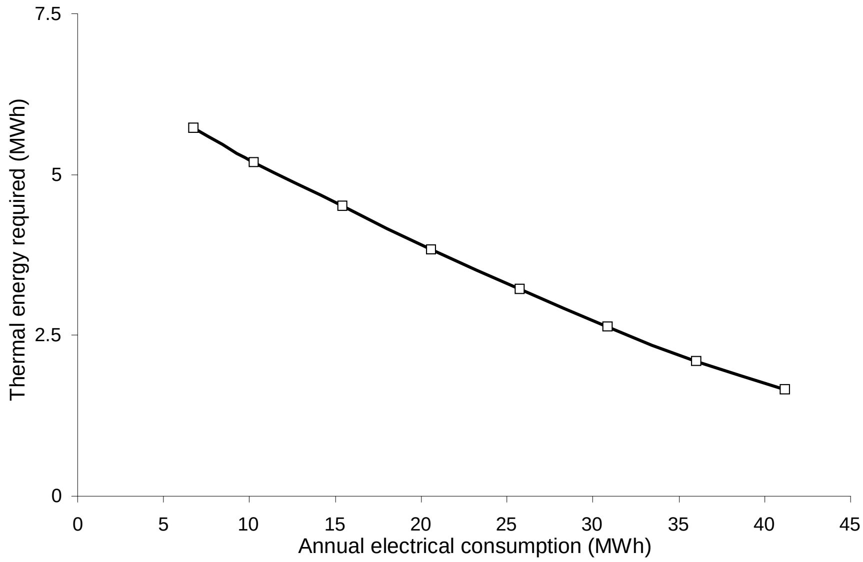

Figure 13 Simulated annual thermal energy requirement for space heating vs. annual electrical consumption for the whole building.

4.3.1.2 Effect of variation of DHW consumption on the thermal energy consumption

Apart from varying the electrical consumption, the DHW is also occupant driven and therefore variable. As an assumption for the volume of water for the model, it varies from the lower limit of 37 litres per day to a maximum of 122 litres per day with a median of 80 litres/day. This results in a thermal demand of 7.0 MWh to 23.4 MWh per year for the whole building for DHW. These values are a thermal demand and they need to be added to the space heating demand over the complete graph, as shown in Figure 13

4.3.1.3 Visualisation of the "Demand Envelope"

With the electrical generation boundaries and the thermal boundaries, the amount of energy that has to be generated is now defined. Adjusting the boundaries with the thermal demand for heating, an area with these limitations (Electrical demand, thermal demand): (10, 12.3) to (40,25.0) This area, henceforward called the demand envelope, defines the boundaries of the energy requirements for the whole building. This demand envelope is the area shown in Figure 14. The BREDEM value is shown as the black triangle in this figure.

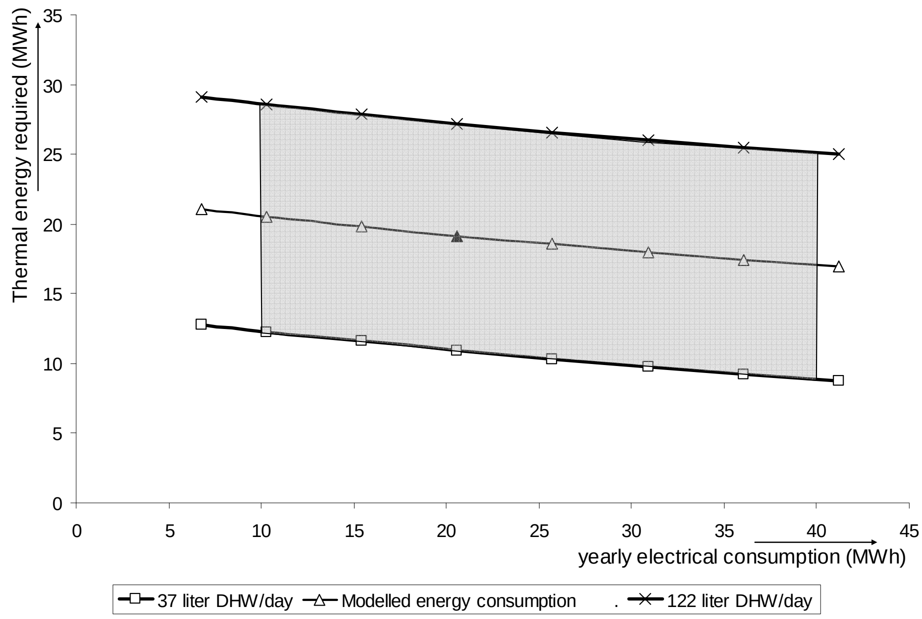

Figure 14 Variation on thermal and electrical consumption.
The grey area, the demand envelope, defines the expected variation of the thermal and electrical energy consumption due to the variation in electrical and DHW consumption.

4.3.1.4 Relationship of solar thermal and PV on roof occupancy

Since both electrical and heating energy can be generated on the roof, albeit only one system can occupy a given space, it is useful to look at the trade off characteristics between STC and PV. Instead of looking at the systems separately, a term “roof yield” could be defined as being the energy collected from the roof. A variation in technology (PV or STC) defines the type and amount of energy harvested from the roof.

The electrical generation of the PV is taken to be proportional to the array area and the simulation confirms the findings of the literature, in that each kWp installed on the roof generates around 750-850 kWh per year for this location. With the set parameters of the solar panels and the inverter 806 kWh per year is generated for every kWp installed.

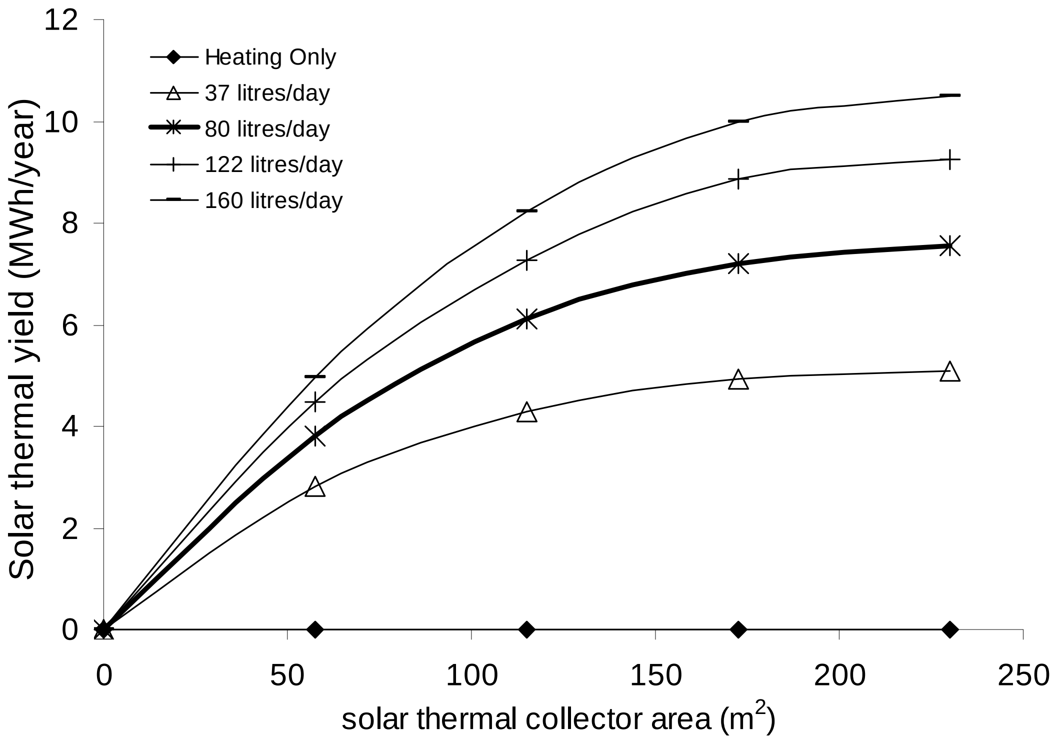

Figure 15 Solar thermal yield as function of roof area and DHW draw

The variation of the heat output of the STC is a function of roof area and the collector inlet temperature, which is dependent on the temperature coming from the bottom node of the thermal stores. The relationships are similar to those published by Brinkworth (2001) who derived a set of plots using the storage capacity and the collector area as variables. The plot in Figure 15 depicts the results of 16 simulations with varying STC area and DHW draw-off, since the volume of water draw has an impact on the energy stored. As thermal storage capacity is limited, due to space constraints, to a total of 2835 litres and a total solar thermal collector area of approximately 110 m^2, the store capacity is the limiting yield factor. The higher use of DHW empties the diurnal thermal store allowing the heat to be replenished, hence increasing the yield from the STC. It is to be noted that the solar thermal yield is much lower than the yield estimated in the literature (Martin and Watson, 2001), due to the limited thermal storage. Also, due to the low pitched roof, no yield is generated if only space heating was required (i.e. no DHW thermal energy demand).

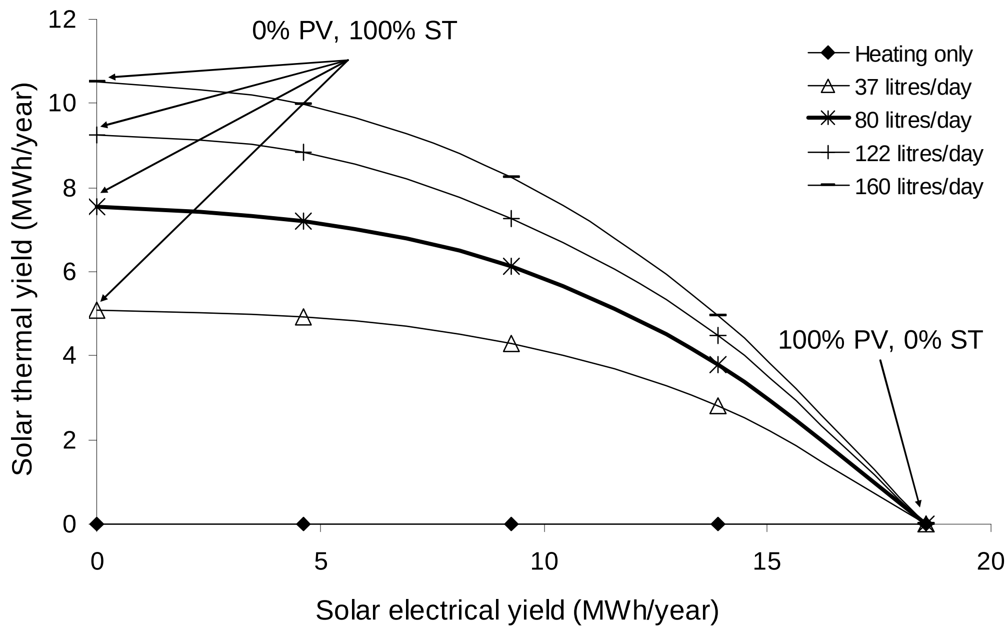

Figure 16 PV/Solar thermal trade off electricity vs. thermal energy yield

Figure 16 depicts the electricity to heat collection area trade-off characteristic generated for this building. Note from section 4.2.6 that the annual BREDEM estimates of electricity and heat consumption are 20.6 MWh and 19.1 MWh respectively. If the whole roof were covered with PV, the yield would be around 18.5 MWh, or ~90% of the electrical demand of the building, as shown in Figure 16.

On the case study building a 3.78 kW_p PV system, consisting of 3 x 6 Yinli 210 W PV panels, is installed on the roof above the flats. The total surface area of these panels is 27 m^2, just under 40% of the available roof space of the flats. The reason for this limitation is the maximum return on the feed in tariffs; systems over 4 kWp have a lower pence per kWh feed in tariff rate. Every week the yield of the PV system was recorded. The simulation estimates a yield of 3.04 MWh per year. The measured yield was 3.2 MWh 5% higher than the simulation. If the feasible roof would have been fully covered with PV (excluding partially shaded and 1 meter from the roof ledge), a total yield of 19.4 MWh or 95% of the total electricity consumption could be generated. Although in this case the electrical demand might completely be covered, no room would have been left for solar thermal collection.

The main observation is that neither PV nor ST can supply 100% of the electricity and heat demand, even when 100% of the roof is covered with one or the other technology and so additional low-carbon heat and/or electricity generation is required. Another observation is that the yield of PV is higher than the yield of solar thermal energy. The reasons for this are the limited storage capacity and the low pitch of the roof. In summer, the diurnal store is at the maximum temperature and therefore limits the yield from the solar thermal array. In winter, the low pitch of the roof, along with the lower temperatures and limited radiation reduces the collected energy.

It must be noted that space heating has a minimal effect (less than 0.5 kWh per year for the whole building) due to the lower pitch of the solar thermal collectors. There is hardly any collection during winter so the solar power collected is only during the time that no space heating is required and it is therefore used for DHW. As the capacity and time constant of the storage tank(s) is laid out for diurnal storage, solar energy collected in summer can not be used in winter.

4.3.1.5 Variation of seasonal performance of heatpumps

To utilize the ambient thermal energy, heat pumps can be used. A heat pump transfers thermal energy from a lower to a higher temperature by consuming a second source of energy. For domestic application this is generally electrical energy. The COP gives the performance of the heat pump at a set point; however, to estimate the yield of a heat pump, the seasonal performance factor (SPF) needs to be calculated out of the simulation. It is custom to specify heat pump at temperatures that result in a high COP, but generally non general conditions, e.g. 15 ºC in and 35 ºC out. As a result the seasonal performance can be expected to be less than the COP, as the average input temperature is lower and the output temperature is higher than the temperatures set in the tests. Therefore, this seasonal performance over a given period must be calculated from results from the simulation by:

$$SPF = \frac{\sum E_{thermal}}{T_{running} P_{in}} \qquad (11)$$

Where:

SPF	Seasonal performance factor	( )
$E_{thermal}$	Generated thermal energy	(kWh)
$T_{running}$	Time that the heat pump is running	(hrs)
P_{in}	Electrical input power	(kW)

Two heat pump models were simulated, a “standard” heat pump as tested in appendix A, and a high performance heat pump from the NREL test report by Sparn et al.. (2011). One way to model a heat pump is by its COP function:

$$\begin{aligned} COP = \; & \{A\, T_{w,out}^2 + B\, T_{w,out} + C\}\, T_{wet\,bulb}^2 \\ & + \{D\, T_{w,out} + E\}\, T_{wet\,bulb} \\ & + \{F\, T_{w,out}^2 + G\, T_{w,out} + H\} \end{aligned} \qquad (10)$$

with:

COP	Coefficient of performance (-)
$T_{wet\,bulb}$	Wet bulb temperature (ºC)
$T_{w,out}$	Water outlet temperature (ºC)

The coefficients of the two heat pumps are shown in Table 3. For the high performance heat pump the coefficients A and B are 0, generating a standard bilinear equation, as described in appendix A.

Table 3 Coefficients of the COP equations for the standard and high performance heat pump.

Heatpump	Coefficients of the COP equation							
	A	B	C	D	E	F	G	H
Standard	$-1.2.10^{-5}$	$9.6.10^{-4}$	0.017	0.0003	0.057	-0.0043	- 0.46	13.3
High performance	--	--	$1.1.10^{-4}$	0.0007	0.059	$-3.5.10^{-6}$	-0.11	12.9

Table 4 SPF for a standard and high performance heat pump
and two water flow temperature set points

Running period Restricted to:	Seasonal performance of the heat pumps			
	Standard 65ºC	Standard 55ºC	High Perform. 65ºC	High Perform. 55ºC
Whole year	1.64	2.33	1.89	2.66
Mar – Nov	1.68	2.58	2.09	3.01
Apr – Oct	1.72	2.78	2.28	3.33
Jun – Aug	2.10	3.15	2.59	3.82

The simulations confirmed the anecdotal evidence of low performing heat pumps. Although the COP in the datasheet stated a value of 3.5, simulated seasonal performance in TRNSYS, using the dataset obtained as shown in appendix A, with a 315-liter storage tank and a switch off temperature of the maximum temperature of 65 ºC showed a seasonal performance of 1.64 for a whole year of operation, a 50% reduction in performance. A simulated high performance heat pump increased this value to 1.89. The highest SPF was 3.82, using a high performance heat pump, running during the summer and a water supply temperature control set point of 55 ºC. Table 4 shows that the difference in performance is more dependent on the switch point setting (55ºC vs. 65ºC) than on the stated performance (3.5 vs. 4.3). The whole year values are similar as found in the heat pump field trial report from DEFRA (2012)

4.3.1.6 Conclusions from the modelling

The energy balance shows a total energy requirement of around 40 MWh for the whole dwelling. Just over half (20.6 MWh) is required for electrical energy, 19.2 MWh thermal energy is required for which only 10% of the total energy requirement (3.8 MWh) is required for space heating. Including the variation due to occupant behaviour, the likely variation boundaries are minimum 9 MWh electrical and 12.2 MWh thermal energy to a maximum of 36 MWh electrical and 25.2 MWh thermal energy.

Limitations due to roof space on the PV and/or STC yield (with 100% available roof coverage, the yield estimated to be 18.5 MWh) supports the conclusion that solar energy on its own can not provide all the electrical and/or thermal energy required.

Limitations on available thermal storage limits the yield on solar thermal. With a 315 litre water store in each dwelling, the total yield of solar thermal is only 7.5 MWh. Higher water consumption increases the yield; with a consumption of 160 litres the yield is 10.5 MWh, about half the yield of PV.

The performance of heat pumps depends on the temperature difference between the cold and hot side. Running the heat pumps therefore during summer (provision of hot water) will result in a higher seasonal performance. Lowering the switching temperature from 65 ºC to 55 ºC also improves the seasonal performance, even more than the difference between a standard and a high performance air source heat pump. The variation on performance ranges from 1.64 (standard heat pump, providing all thermal energy throughout the whole year and a switching off temperature of 65 ºC) to 3.82 (high performance heat pump, providing hot water during the summer and switch of point set at 55 ºC).

4.3.2 MAKING DESIGN DECISIONS BASED ON ANALYSIS OF THE RESULTS

The previous chapters described the consumption and possible generation options. This chapter investigates which combination of generation options will lead to the lowest carbon generation what effect the variation in consumption has on the generation option.

Figure 14 in section 4.3.1.2 depicts the demand envelope, and a similar picture for each of the generation options is also required.

4.3.2.1 Graphical representation of the generation options

From the previous studies it was concluded that PV, ST, HP and CHP were the only suitable candidates to generate on site low carbon energy. These generators are visualised in a thermal/electrical grid, the results are shown in Figure 17. On the vertical axis the thermal energy generation is depicted, and the horizontal axis depicts the electrical generation.

A heat pump with a seasonal performance of 1.64 would require 1 kWh of electricity to generate 1.64 kWh of thermal energy. As a result, the slope of that vector is negative with a factor -1.64. A heat pump with a higher performance requires less electrical energy to generate the same amount of heat, therefore the slope increases.

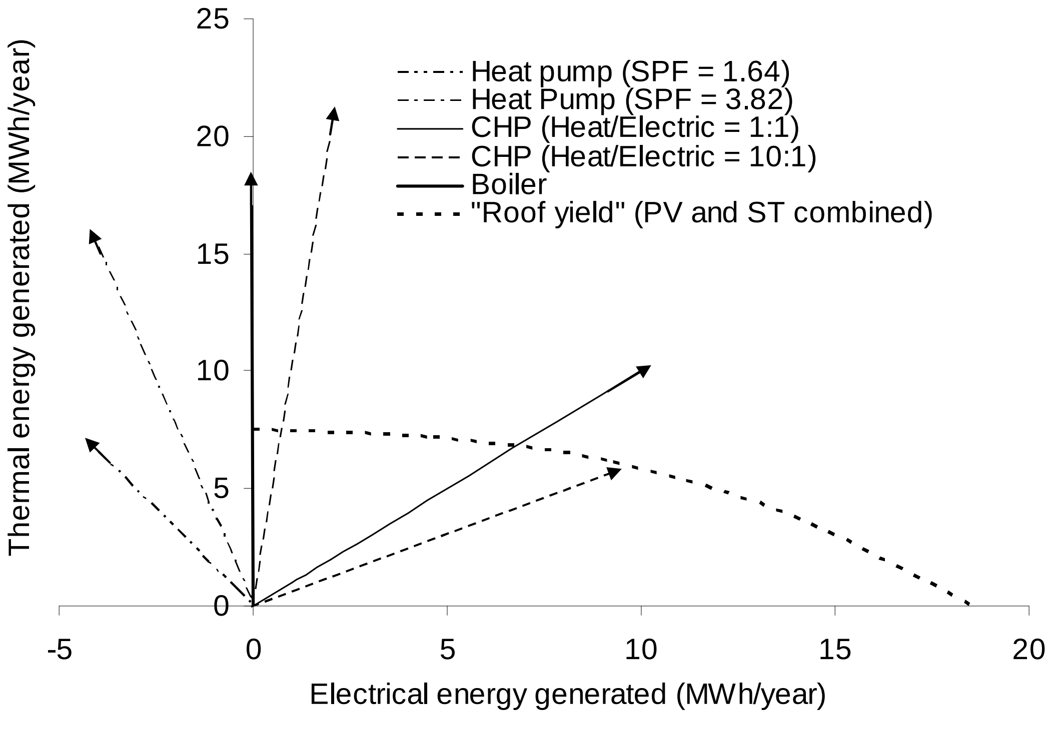

Figure 17 Vector diagram of the generation options

On the right hand side of Figure 17 similar electricity/heat characteristics for two different types of micro-CHP are also plotted. The CHP converts (in this case) vegetable oil into both thermal and electrical energy, the ratio of which is determined by the plant. The limiting cases here are taken to be 1:1 to 10:1 (heat to electricity). Again, the length of the vector is proportional to the number of running hours and is also proportional to the amount of fuel (in this case) vegetable oil used. Note that since a gas boiler, biomass boiler or ST do not generate any electricity, they would be represented by a vertical line extending upwards along $x = 0$ from the origin of the plot to the appropriate value of annual heat generation: PV extends horizontally rightwards along $y = 0$, to the appropriate value of annual electricity generation since it does not produce heat.

PV and ST share, however, another limitation; the roof space. If “roof space” is considered as the generator, the vector could generate thermal and electrical energy, similar to the CHP, but only limited to the “roof yield limit” line. Although combined PV/ST are in production, they are not commonly available. If they become commercial available, the electricity generated by the PV would be a (fixed) horizontal line, and the thermal collector yield a vertical line, depending on the storage and the consumption.

4.4 FINDING THE LOWEST CARBON GENERATION MIX

4.4.1 GENERATION COMBINATIONS FOR LOW CO_2 EMISSIONS WITH A SINGLE CONSUMPTION POINT

The heat/electricity generation characteristics depicted for the generation equipment in Figure 17 can be used in isolation, or in combination to determine the annual total building CO_2 emissions (tonnes CO_2/year), ϕ,

$$\phi = \Delta\varepsilon\phi_{grid} + \frac{\Delta\theta\phi_{gas}}{\eta_{boiler}} + \frac{\tau_{chp}\mu_{chp}\phi_{veg\_oil}}{\eta_{chp}} \quad (2)$$

where $\Delta\varepsilon = \varepsilon_{gen} - \varepsilon_{dem}$, the difference between the annual generation of electricity and the annual electricity demand (MWh/year) and ϕ_{grid} is the carbon intensity factor for grid electricity (kg CO_2/kWh). If the installed generation equipment does not produce the electricity required, grid electricity is used to make up the difference. Conversely if there is a surplus of electricity generated, the CO_2 emissions from the buildings will be negative, indicating an offsetting of CO_2 emissions released by electricity generated by the grid. $\Delta\theta = \theta_{gen} - \theta_{dem}$ is the difference between the annual generation of and demand for heat (MWh/year) and ϕ_{gas} is the carbon intensity factor for natural gas. Only CHP has been considered in the analysis and hence τ_{chp} and μ_{chp} give the run time (hrs) and the fuel consumption (m^3/hr) and again factored by the efficiency (η_{chp}) and the carbon intensity factor ϕ_{veg_oil}. If surplus heat generated, this is dumped and hence complete energy balance can not be achieved, resulting in a waste of thermal energy (1.3 MWh in the simulated

BREDEM case). If the generation equipment does not produce sufficient heat it is assumed that this is achieved by burning natural gas in a conventional boiler plant.

The deficit in thermal energy demand supplied by the boiler is factored by the boiler efficiency, η_{boiler}. $\Delta\varepsilon$ and $\Delta\theta$ are derived from characteristic plots that depict the annual generation characteristics of the renewable energy generation equipment. These have been derived from the simulation and hence implicitly represent any operational characteristics that are due to control set-points, strategies and capacities. Figure 18 shows two plots: the left with the high performance heat pump, running all year with a water flow temperature of 55°C (SPF equals 2.66); and the CHP characteristic lines for the 1:1 heat to power generation plotted. The right plot details the STC/PV trade-off curve from Figure 18 for the BREDEM case of 80litres/day DHW draw-off. On both plots the target (BREDEM) heat/electricity demand is indicated by the large black dot: this is the target value, if the generation line crosses through the demand point there is no over or under generation and the demand is satisfied. The CHP in the first plot demonstrates that the CHP alone when run for 2350 hrs can satisfy the electrical demand, but with around 1.4 MWh/year over production of heat. The HP uses electricity to generate heat and requires around 8.2 MWh/year in addition to the 20.6 MWh/year required to satisfy the electrical demand from appliances. The right hand plot demonstrates that on this building the limited roof space means that the target demand for electricity and heat cannot be met with either PV or ST.

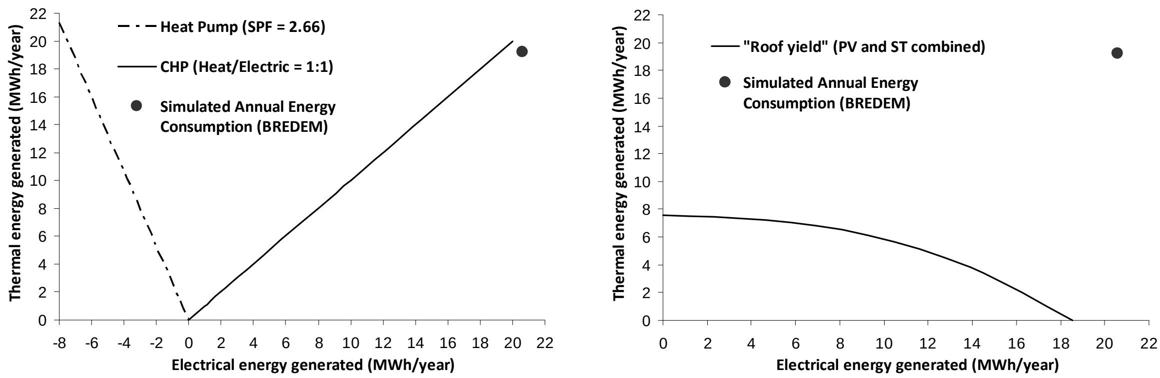

Figure 18 Single and "roof" system generation capabilities and the required energy generation target.

This way of representing the analysis can be extended to include multiple generation devices. Figure 19 depicts the characteristics of a number of combinations of equipment and the resultant generation demand deficit, note that the grid acts as an "infinite" electrical store and that in the simulations each dwelling was equipped with a 315 litre hot water store.

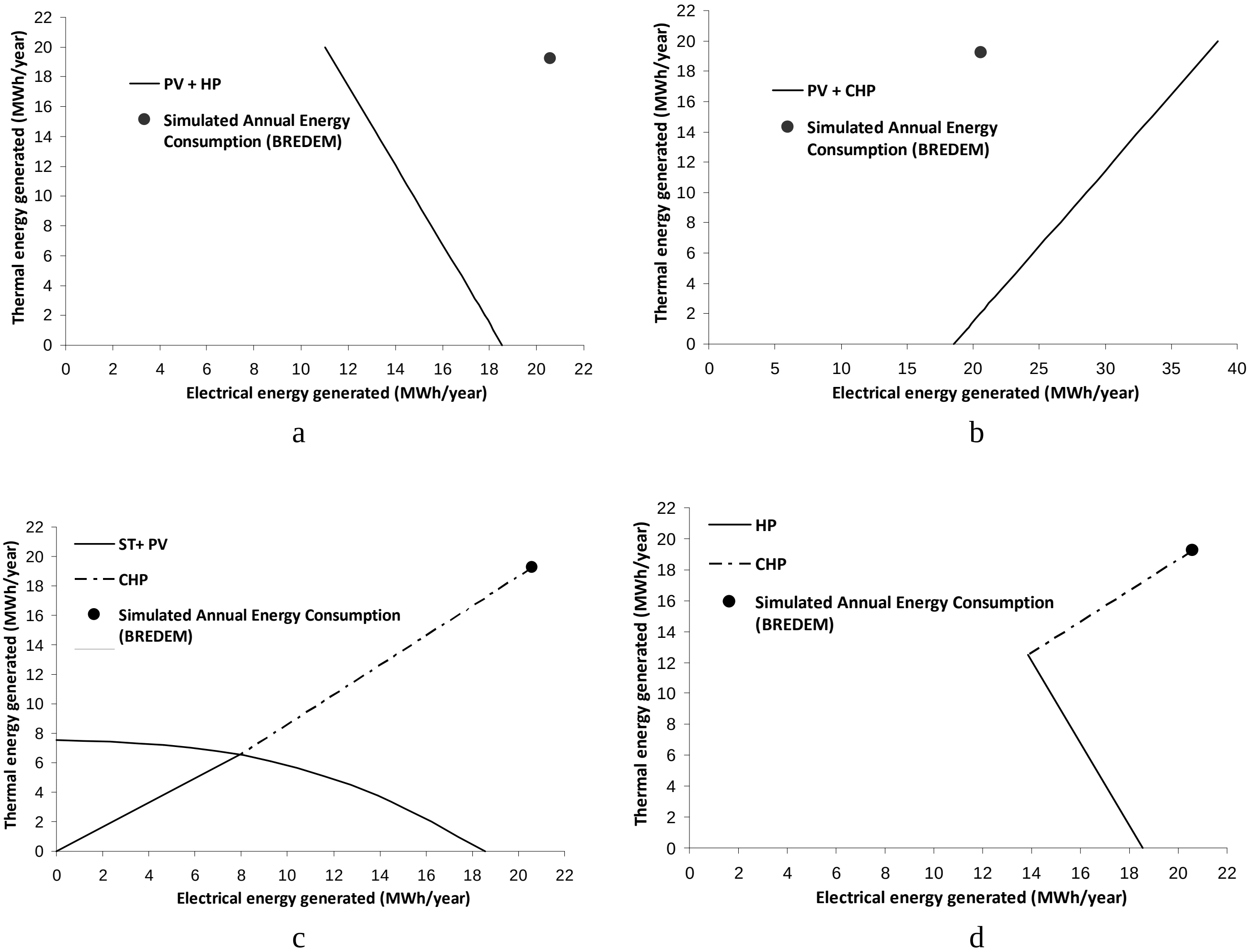

Figure 19 multiple generation capabilities and the required energy generation target

Figure 19 depicts four plant combinations. The top two plots (a, b) show two, two-technology options, PV and HP (a) and PV and CHP (b) and both configurations utilise a 100% of the roof area covered with PV. The former option has a generation deficit $\Delta\varepsilon = 13.7$ MWh/year, while the latter option has a heat generation deficit $\Delta\theta = 17.1$ MWh/year, although the CHP can be run for longer to deliver the required heat and provide a surplus of $\Delta\varepsilon = -27.1$ MWh/year electrical energy, which may be desirable, depending on feed in tariffs.

The bottom two plots (c, d) in Figure 19 depict three-technology options. The option on the left uses a combination of PV and ST on the roof, the balance of which is determined by the selection of the CHP. In the plot the dotted line mirrors the relationship between PV and ST yield in Figure 16. The solid line represents the combined heat/electricity generation from the roof-installed technologies. The dashed line depicts the CHP generation. Here a CHP with a heat to power ratio of 1:1 has been selected, which determines the gradient of the dashed line. Following this line down from the target intersects the PV/STC characteristic line, determining the appropriate balance of roof generation technologies to be 44% PV and 56% STC. The length of the dashed line represents the CHP running time and hence the quantity of fuel used: this line is shorter than the CHP lines in the top right plot and in the bottom left plot, reflecting the reduction in vegetable oil used.

The last plot in Figure 19 shows the second of the three-technology options. The additional PV on the roof, a 100% in this option, is used to offset the power required for the heat pumps shown by the solid line. The dashed line shows the additional heat and electricity generation provided by the CHP, producing 5.6 MWh/year of heat and the same of electricity. The reduction of the CHP run time between this option and the former option is due to the additional heat generated by the HP and this significantly reduces the vegetable oil required and hence the CO_2 produced. Option d depicted in Figure 19 is the configuration with the lowest possible CO_2 emissions for this building.

Table 5 Summary of onsite thermal and electricity generation options for the SHINE-ZC building

	Solution code	Onsite energy system	Capacity	Operational time	Percentage of base-case building energy demand supplied by onsite energy systems		Annual total building CO_2 emissions (tonnes CO_2/year)
					Thermal	Electrical	
Single option	Base-case	Gas boiler	20 kW	Jan – Dec	100%	0%	14.32
	HP*	Heat pump	20 kW	Jan – Dec	100%	-35%	14.58
	CHP	CHP	22 kW	Jan – Dec	107%	100%	8.05
	STC	Solar thermal	230 m^2	Jan – Dec	47%	0%	12.67
	PV	PV	25 kW_p	Jan – Dec	0%	90%	4.59
Two options	HP*-STC	Heat pump	20 kW	Jan – Dec	53%	-18%	12.80
		Solar thermal	230 m^2	Jan – Dec	47%	0%	
		Total	-	-	100%	-18%	
	HP*-PV	Heat pump	20 kW	Jan – Dec	100%	-35%	4.85
		PV	25 kW_p	Jan – Dec	0%	90%	
		Total	-	-	100%	55%	
	CHP-STC	CHP	22 kW	Jan – Dec	61%	56%	9.25
		Solar thermal	230 m^2	Jan – Dec	39%	0%	
		Total	-	-	100%	56%	
	CHP-PV	CHP	22 kW	Jan – Dec	11%	10%	3.94
		PV	25 kW_p	Jan – Dec	0%	90%	
		Total	-	-	11%	100%	
Three options	CHP-STC-PV	CHP	22 kW	Jan – Dec	66%	61%	4.92
		Solar thermal	130 m^2	Jan – Dec	34%	0%	
		PV	10.75 kW_p	Jan – Dec	0%	39%	
		Total	-	-	100%	100%	
	HP*-CHP-PV	CHP	22 kW	Dec – Feb	29%	27%	2.19
		HP	20 kW	Mar – Nov	71%	-17%	
		PV	25 kW_p	Jan – Dec	0%	90%	
		Total	-	-	100%	100%	
	HP*-STC-PV	HP	20 kW	Jan – Dec	50%	-18%	6.94
		Solar thermal	130 m^2	Jan – Dec	50%	0%	
		PV	10.75 kW_p	Jan – Dec	0%	53%	
		Total	-	-	100%	36%	

Note: * if a heat pump is used whole year round, a standard heat pump with 65 ºC switch off temperature is used (SPF = 1.64) For the March/November period, the SPF of 1.68 is used.

Expanding the generation equipment combination options, Table 5 details the balance of heat and electricity generation and demand for each of these and gives the annual CO_2 produced in each case. A value of 100% shows that all of the thermal or electrical demand is met by the onsite energy system, a value of 0% shows that none of the thermal or electrical demand is met. A negative value shows that the configuration increased the electricity demand required (i.e. to power a HP). A value greater than 100% shows a surplus generated: Electricity is exported to the grid, but heat is assumed to be dumped to atmosphere, the CO_2 emissions, however, are added to the total. Overruns of plant to achieve the production of electricity while dumping heat or vice-versa is not considered in this analysis, although is a viable option. Using the model and the BREDEM energy consumption values, the amount of CO_2 emitted is 2.19 tonnes. The measurements and assumptions of the first year during occupation shows an estimated electricity consumption of 15.5 MWh and thermal consumption of 24 MWh. Using these values, the emission of CO_2 decreased to 1.34 tonnes.

4.4.2 Generation options covering the demand envelope

Section 4.4 looked into the lowest CO_2 emission possible to achieve one fixed simulation point. However, as shown in Figure 14, due to the variation in occupant behaviour it is not one point that needs to be covered, but the demand envelope. The same technique can be used to determine the feasibility of fulfilling the energy demand through the on site generation equipment.

In this instance, it is assumed that the roof is covered with PV, the simulation show a higher yield from PV than from ST. The combination of generation plant is therefore similar to option d of Figure 19, PV is generating the electricity and a combination of running hours of the CHP and HP to match the balance in electrical and thermal demand.

The result is shown in Figure 20. The demand envelope is shown as the greyed area 1-8. PV generates up to 18.4 MWh per year, and this point is indicated by point A. The CHP and HP will be required to generate the energy that the PV cannot, hence these generator’s characteristic line is rooted at point A. As stated before, the heat pump requires electricity to transfer heat, therefore the resulting line A-B has a negative slope, defined by the seasonal performance. To the left of the line the PV will be able to satisfy the electrical demand and the power required to run the heat pump to satisfy the heat demand. To the right of the line additional electricity generation is required hence more PV or where that is not possible, the use of CHP.

A CHP generates electricity and heat, therefore its slope is positive, the slope defined by the heat/power quotation. The resulting CHP characteristic is line A-C. To the left of the line the CHP will produce a surplus of electricity, which can be either used for the heat pump to generate additional thermal energy, or fed back into the grid. To the right of this line, the electrical demand can not be satisfied without producing a surplus of thermal energy and thermal energy is wasted in this case.

As a result, the demand envelope is split in three sections, area 1-3-4-5-6-8-1, 1-2-3-1 and 6-7-8-6. In area 1-3-4-5-6-8-1 a total energy balance can be struck by a combination of running hours of the heat pump and the CHP. Both the simulated energy demand (dark triangle) and the measured demand (grey diamond) shown in Figure 20 are in this area. On the left hand side of line A-B there is a surplus of energy generation; line A-B is the “zero-carbon line”. In area 1-2-3-1 a surplus of electrical energy is generated by the PV, which can be sold back to the grid, in this situation the dwellings are true carbon negative and the CHP is not required. In area 6-7-8-6 more electrical energy is required with a surplus of thermal energy. In this case thermal energy must be wasted if 100% on site energy generation is required.

The zero-emission line is line A-B. On this line, the electrical energy generated by the PV is sufficient to cover the electrical energy demand and the electrical energy required to run the heat pump, to generate the required thermal energy. The CHP has a fixed ratio of electrical to thermal energy, independent of the amount of running hours, the angle is fixed, but the length is determined by the amount of energy required, and therefore linked to the emission of CO_2. This results in a parallel line to the line AB on the amount of emitted CO_2.

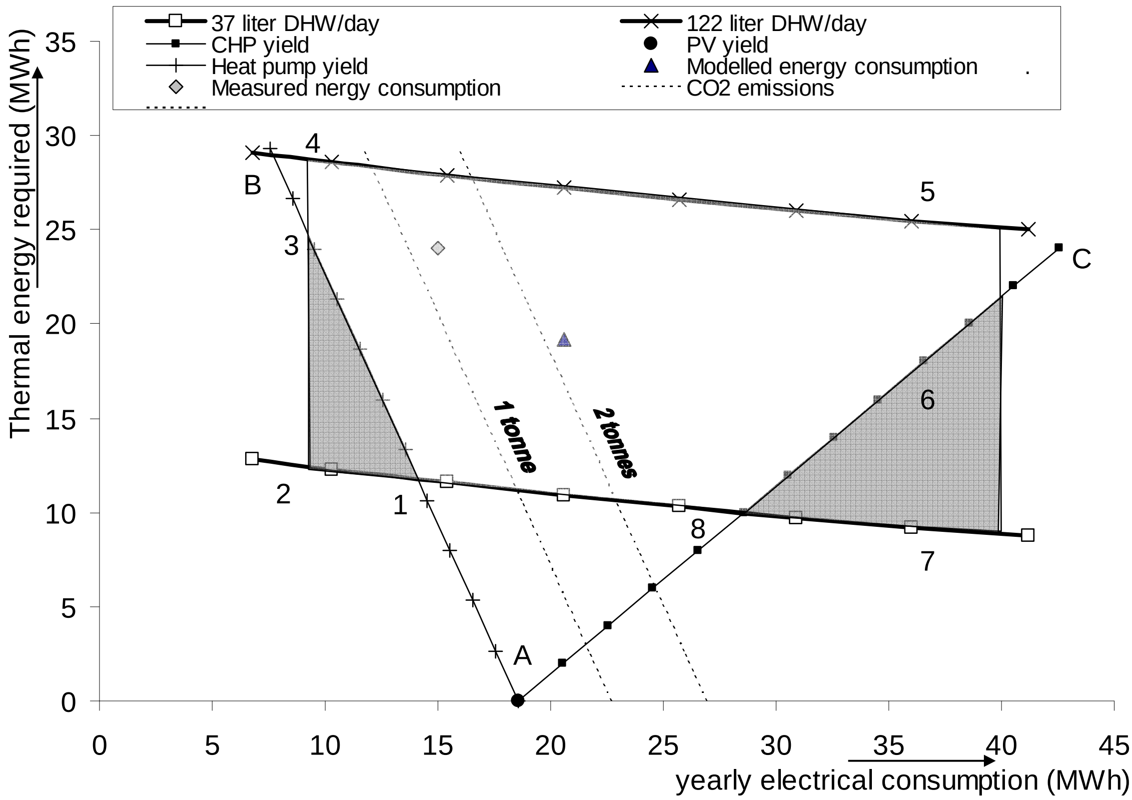

Figure 20 Coverage of the demand envelope by the generation options of PV, HP and CHP.

In respect of CO_2 emissions, the emissions increase linearly with the running time of the CHP. This is shown in Figure 20 with the emission lines parallel to the heat pump yield line. The highest CO_2 emission is at point 5, which requires the largest amount of operating hours of the CHP. At this point the CO_2 emissions are estimated to be 6.5 tonnes.

The PV, CHP and HP are all needed to have a good chance of achieving a complete energy balance with a minimum of waste heat generation. The coverage risk indicator, i_r, can be calculated by,

$$i_r = a_{hpp}/a_{lde}, \quad (2)$$

where a_{hpp} and a_{lde} are the heat/power possible provision area (1-6,8) and likely demand envelope area (1-8) respectively. For this building $i_r > 80\%$. Especially high electrical demand combined with low thermal demand might result in waste of thermal energy. If the CHP heat/electricity production ratio increases from 1:1, the value of *r* will go down indicating an increased likelihood of the building not performing with a complete energy balance as waste heat is generated.

Another area of interest is the area with low electrical use, 1-2-3-1. In this area the PV array on the roof is producing more electricity than required to generate the thermal energy with the heat pump, i.e. the building is carbon negative. The coverage carbon negative indicator, i_{cn} can be calculated by a similar formula dividing the area of 1-2-3-1 with the total area of the demand envelope, as in (2), and in this case $i_{cn} < 10\%$.

With the first year measurement and estimation of the energy consumption, a larger thermal but less electrical energy than modelled was required. The total energy requirement is the same. As a result the CHP has to run fewer hours and the heat pump running hours are increased. The net effect is a lower CO_2 emission with the measured energy consumption values than the simulated values. With the measured energy consumption and an optimum energy generation, the CO_2 emissions are reduced with 40% from the 2.19 tonnes predicted by the TRNSYS model to the 1.33 tonnes with the measured data.

5 FINDINGS & IMPLICATIONS

As with any study, the findings and implications are only valid within the set assumptions. Different types of building, (with regard to orientation and/or envelope), plot size and/or location and of course economic factors determine if a given solution is valid and economical. In this case study, the limitations of a flat roof, very limited storage capacity, limited plot size, commercially available systems and the focus on the emissions of CO_2, rather than cost, resulted in these key finding. These key findings and their implications are detailed in the next sections.

5.1 REQUIREMENTS FOR MULTIPLE RESOURCES

Due to variations in energy consumption by the occupants, multiple renewable energy sources have to be implemented to achieve the lowest possible CO_2 emission.

Table 5 showed the possible energy generation configurations and their corresponding CO_2 emissions. Of the single source options (either solar, biomass or ambient thermal), installing PV to cover the roof has the lowest CO_2 emission with 4.6 tonnes CO_2. This is due to the high CO_2 intensity of the national grid. Biofuelled CHP emits nearly double the emissions compared to PV, (8.1 tonnes CO_2) followed by solar thermal (12.7 tonnes CO_2). An air source heat pump with a SPF < 2.4, used year round with grid electricity, emits more than a conventional gas boiler. If limited (diurnal) storage is available, the yield from PV is higher than the yield of solar thermal.

With dual resources, the lowest emissions are estimated to be achieved by the combination of bio-fuel CHP and PV, where the CHP only runs in the coldest months, December/January. During the rest of the year the CO_2 emissions of a condensing gas boiler are assumed. The total CO_2 emission from this option is 3.9 tonnes CO_2 per year. The next preferable option is PV/Heat pump. As 90% of the electricity consumption is provided by the PV, the CO_2 emissions from the electricity used by the heat pump are reduced to 4.9 tonnes CO_2 per year, again the emissions of a condensing boiler are assumed to provide the required thermal energy. Using triple resources, a combination of PV, CHP and HP results in the lowest CO_2 emission, 2.2 tonnes CO_2 per year. First year on site measurements show a higher thermal consumption combined with a lower electrical consumption compared with the modelling assumptions. In this case the emissions are 1.3 tonnes of CO_2 per year.

5.2 FEASIBILITY OF ZERO CARBON IN COMPACT URBAN DWELLINGS

Although the combination of PV, CHP and HP is the lowest generation option, it is not completely carbon free when producing the required electrical and thermal energy, with a simulated emission of 2.2 tonnes CO_2 per year for this case study building. If it is assumed that the case study is typical of new urban dwellings, this suggests that there is a high likelihood that zero-carbon energy generation can not be achieved in compact urban settings with the currently available technology and carbon intense grid electricity when including the in-home appliances (unregulated) as stated in the CSH. Due to the possible variation in energy consumption across dwellings, a demand envelope is defined. With the given energy generation options, 90% of this demand area can be covered without a surplus of electrical and/or thermal energy over a period of one year so a complete balance of thermal and electrical energy can be achieved by selecting the correct mix of renewable energy generation systems, PV, CHP and HP. In approximately 10% of the demand envelope, zero carbon can be achieved using PV and HP. The building can be even carbon negative, i.e. the surplus of electrical energy produced offsetting the carbon intense grid electricity will effectively reduce the CO_2 emission.

5.3 SHIFT OF ENERGY DEMAND

As expected, the sum of electrical energy and thermal energy for DHW outstrip the demand for heating in low carbon dwellings. This is a confirmation of previous studies (Gill et al., 2011).

In the building industry there is a perception that the largest energy consumption in a dwelling is thermal energy required for winter heating. Increasing the building standard with better insulation, lower air leakage and ventilation with heat recovery reduces this energy requirement. Historically, space heating accounted for over 60% of the energy consumption, however, the simulations show that with highly insulated dwellings the amount of space heating required could be less than 10% of the overall energy consumption. Electricity (including cooking, lighting and appliances) requires approx. 50% of the energy demand according to the model and DHW requires 40% of the total energy demand.

The on-site measurements showed that the actual required space heating of the case study building in 2012 was much lower than the UK average of 60% of the overall energy requirement, but not as low as the 10% achieved in the simulations. It is estimated that just under 30% of the energy was required for space heating. Lower electricity consumption of 15.5 MWh instead of 20.9 MWh per year resulted in a higher space heating demand as the actual internal electrical gains are lower than simulated electrical gains. The 2012 summer was exceptionally wet and dull and there is anecdotal evidence of switched off MVHR units (instead ventilating by opening windows) and observations in low energy conscious occupant behaviour, e.g. people leaving the doors open whilst smoking at the front door. These factors will increase the requirement for space heating. Although higher than the simulated 10% of the total energy consumption, it is still less than half that of a conventional dwelling. Further measurements and information to encourage energy conscious behaviour to the occupants are required to confirm this finding, or if this is an exception mainly due to occupant behaviour.

5.4 CONTRIBUTION TO EXISTING THEORY AND PRACTICE

5.4.1 REVIEW OF THE ENERGY CONSUMPTION AND GENERATION TECHNOLOGIES

In the literature there are numerous articles available on the design of zero-carbon homes. Generally speaking the generation side of these papers focuses on either the electrical side or on the thermal side of the energy required. However, to be used as design criteria both aspects are equally important.

For most simulation studies in the literature, simulation parameters are not optimised for a compact urban situation. Although the building fabric parameters are similar as for most studies, the rest of the parameters used in this study (apartment buildings with limited roof and storage space, in an urban location with shading by neighbouring buildings, suboptimal orientation and roof angle and low wind yield) provide a much more likely scenario for homes built now and going forward in the UK, due to urbanisation and the trend towards smaller households.

Available space puts a limitation on storage. For the storage of electrical energy, the grid is used. However, for thermal storage, the maximise size of 315 litre water tanks could provide thermal storage only for one day of thermal heat. This volume was set as the lowest limit. Each property has its own thermal store, so a total volume of 2835 litres thermal store is available. A larger thermal store would increase the yield of solar thermal, but this benefit is of limited benefit due to the low pitched roof.

Energy reduction is mainly focussed on the space heating requirement, standard to be over 60% of the total energy demand. Well insulated building fabric, in combination with ventilation with heat recovery, reduces this demand to 10% of the overall energy requirements in the simulation. The from the energy meter readings estimated space heating energy use in the case study building was 30% of the total, three times higher as the simulated space heating requirement, potentially due to a lower electrical use, fabric (higher U-value of the wall) and occupational (switching off heat recovery unit and opening windows etc.) factors. DHW and electrical consumption (i.e. the unregulated consumption) can not be reduced by modifying the building, but only by educating the occupants on desired behaviour. The values generated by the BREDEM model generate a good starting point for the simulation; the measured total energy required matched the simulated value, although a smaller amount of electricity was used. The demand envelope, the limit of the minimum and maximum of the thermal and electrical demand has shown to be valid for this research; however, more research is required to finalise the precise boundary and shape of this area.

Solar energy can be harnessed in the form of thermal and/or electrical energy. However, limited storage space (in this case around 25 litre per m^2 of solar collector) and a low pitched roof (higher fluctuation in solar irradiance over the year) limits the yield of solar thermal and although, as described in most literature, generally PV has a lower yield in kWh per year, PV is favourable in these circumstances when grid connected (the most efficient way of "storing" the electricity) no local storage is required. As a result the net yield of PV is higher than STC per m^2 roof space. Certainly, because of the recent drop in PV prices, the cost per kWh installed becomes more favourable for PV.

Thermal energy can be recaptured from ambient utilising heat pumps. Ground source heat pumps (vertical and horizontal) are under normal circumstances not suitable for compact urban dwellings, either for cost reasons or geological dependencies and space limitations. This restricts the solution to be mainly air source heat pumps although other options might be possible, depending on the circumstances. A new simulations model for an air source heat pump, as described in appendix A, has been used in the simulation, taking into account the high air humidity often occurring in a cool maritime climate.

A small CHP plant can generate electrical as well as thermal energy. To obtain the smallest footprint and the ability to generate electrical energy, the preferred option is vegetable oil (VO) or bio diesel. Solid bio fuels have a lower energy density and currently there is no combustion plant available for these fuels that generate electrical energy on this small scale. Bio-gas is currently not readily available. Liquid bio fuels are expressed as a low carbon fuel, these still emit CO_2 equivalent green house gasses. As vegetable oil emits CO_2, costing are estimated to be twice the cost of standard diesel, a CHP is approx. 5-10 times more expensive than a condensing boiler, the economic viability of this solution is questionable.

Literature review shows that wind energy is not recommended in an urban setting due to low yield, high turbulence and noise.

5.4.2 VISUALISATION AID FOR DESIGN

During the design stage, the implementation concept for renewable technology is a key factor in the feasibility of low carbon dwellings. A contributing aspect of this study is the introduction of a visualisation technique to aid decision making at design stage on the lowest carbon combination of generation options, along with introduction of a coverage risk indicator, which indicates the percentage likelihood of a particular generation configuration in achieving a zero carbon building. Within the graphics a demand envelope has been introduced, the boundaries of which are the minimum and maximum expected thermal and electrical energy over one year.

5.4.3 ANALYSIS OF THE GENERATION OPTIONS

On site renewable energy sources, as dedicated supply connections to remote generators, and as required by CSH level 6, are not feasible in an urban situation. With limited storage facilities on-site, resulting in only diurnal storage and low pitched roof, the yield of PV is higher than solar thermal. Thermal energy can be generated by either using a heat pump or CHP. For the lowest CO_2 emission a combination of PV, heat pump and CHP is required, emitting 2.2 tonnes of CO_2 per annum simulated with the demand parameters set by the BREDEM method. This combination would only emit 1.3 tonnes if the energy consumption, using the measured data from the first year energy consumption, was optimised using these generators.

To achieve a complete energy balance, the demand envelope must be covered by the energy generation options. In this case study, approx. 80% of the demand envelope, the combination of PV, CHP and HP can cover the required combination of thermal and electrical demand. As the CHP is emitting CO_2, only the combination PV/HP can achieve zero carbon, this is the case in approx. 10% of the demand envelope. Therefore in around 90% of the demand envelope the case study building will emit net carbon over the course of a year.

5.4.4 HEAT PUMP PERFORMANCE VARIATION

The simulation also shows that heat pumps experience a variation in seasonal performance, depending on at which time(s) of year they are used and the outlet temperature set point of the heat pump has a large influence on the performance (see Table 4). Comparing a standard heat pump with a high performance one, this switching point even had a larger influence than the performance difference, running the pump to 55 ºC instead of 65 ºC had a higher impact than the difference between a standard heat pump and a high performance heat pump. It would be recommended to run the heat pump with as low a feed temperature as possible, although a high performance heat pump will decrease the electrical generation demand.

5.5 IMPLICATIONS/IMPACT ON THE SPONSOR

The visualisation technique and coverage risk indicator introduced in this study enable PS Sustainability Ltd to decide on the most optimal combination of generation options for future compact urban building projects at design stage, from the perspectives of energy demand coverage, cost and CO_2 emissions. It also enables them to calculate the likely level of on going revenue in their capacity of Energy Service Company (ESCO).

On-site measurements and observations have indicated that further communications are necessary at the SHINE-ZC project to influence occupant behaviour and achieve a demand pattern that is more aligned with the sponsor’s goal of zero carbon housing.

The space heating demand was higher than the values simulated. One of the factors could be the higher U-values; the wall measurements indicate that actual U-values of the ICF are higher than those claimed by the manufacturers. It is likely that the sponsor will want to investigate this further.

5.6 IMPLICATIONS/IMPACT ON WIDER INDUSTRY

The results of this research show a number of interesting facts that will have an impact on the way low carbon dwellings will be designed and built going forward. Code Level 6 in the Code for Sustainable Homes as it was declared in 2006 is difficult to achieve in compact urban dwellings. As the 2010 standard requires dedicated supply lines for remote generators, the latter statement still holds true. Excluding the unregulated electricity consumption effectively eliminates CSH level 6, as the main difference between level 5 and level 6 on the CO_2 emission site is the unregulated electricity consumption. Net import from external energy sources (renewable or not) is required. The techniques introduced in this study can be used by the industry at design stage to define the combination of energy generation equipment to achieve the lowest possible CO_2 emissions for the site's parameters.

The implication of smaller apartment based, highly sealed dwellings with high levels of insulation and resulting low energy loss, shifts the energy demand from heating and weather driven to electrical and DHW, and therefore occupant driven. Another effect is that, in combination with a predicted increase in ambient temperature due to global warming and higher electrical consumption (due to more efficient but increased number of electrical consumer goods), maintaining an acceptable comfort temperature level is more difficult to achieve in summer. The focus on energy generation, therefore, needs to shift from heating provision to electricity and DHW provision.

Economic factors will decide in the end if a solution is viable or not. However, due to the high volatility of some of the energy carriers and/or converters, an economic view can only be taken on a project by project basis, depending on the cost/benefit analysis of that particular project at that particular time. It is almost impossible with ongoing change in legislation and tariffs, and the development in the PV market to give an adequate indication of the most economical generic solution. In this respect, multiple generation options, although they might give the lowest possible CO_2 emissions, might not be feasible due to the economic restraints.

5.7 RECOMMENDATIONS FOR INDUSTRY/FURTHER RESEARCH

The findings of this study indicate that Code Level 6 in the Code for Sustainable Homes as it was declared in 2006 is difficult to achieve in compact urban dwellings, which are the most likely types of homes built now and going forward, due to urbanisation and the trend towards smaller households. In 2010 the requirements for Code Level 6 were relaxed, so that import of renewable energy would be allowed. However, the requirement that dictates dedicated supply lines negates the feasibility of remote generation options. Although this is not a requirement of“ Allowable generation options” but the “Allowable generation option” is effectively a step back, exempting the unregulated electricity consumption from the energy balance.

The lowest CO_2 emissions are generated with PV in combination with a heat pump. If a gas connection is on site, thermal energy can be generated using a standard condensing boiler, otherwise, with larger emissions, provide thermal energy through the heat pump throughout the whole year. Due to the lack of (thermal) storage capacity, in a compact urban setting and with a flat roof, solar thermal is likely to have a lower yield than P.V. per installed kW. Due to the price recent drop of PV, this might also be the cheaper option.

Building simulation methods using heat pumps in a maritime climate should consider using the heat pump model introduced as part of this study to calculate COP as a function of air humidity, air temperature on the evaporator side and water temperature on the condenser side.

Further research is needed into new generation and storage technologies as they become mature, such as combined photovoltaic and thermal panels for example. These would need to be included for consideration into the techniques proposed in this study, to find the optimal combination of generation options for a particular building.

It is recommended that further studies are performed at the SHINE-ZC building, using actual monitoring data once systems have been completely installed. This will enable further investigation into actual demand patterns against different weather patterns.

5.8 CRITICAL EVALUATION OF THE RESEARCH

One of the key factors of the Code for Sustainable Homes is that new residential dwellings in the UK must be “zero carbon” during occupation. Although the direction of the building industry in the UK is heading for small apartment based dwellings, limited research has taken place into the feasibility of zero carbon for this type of dwelling. For developers it is therefore difficult to establish at design stage which and how much of the available renewable energy generation is required for this type of dwelling. The aim of this research was, therefore, to understand the effect of practical constraints on real building design and technology on achieving zero or low carbon performance in compact urban dwellings in a northern European maritime climate.

Current commercially implementable renewable generation technologies were evaluated for their suitability in a compact urban setting. PV and STC compete for roof space, the only available space for solar collection; air source heat pumps were deemed the only commercially available and therefore viable electrical to thermal energy converter and a micro CHP running on VO the only bio fuel micro generation plant capable of generating electrical and thermal energy. As vegetable oil emits CO_2, costing estimated to be twice the cost of standard diesel, the economic viability of this solution is questionable. Similarly, ground source heat pumps, horizontal, vertical (bore holes) or integrated in the building fabric are possible, but not readily commercially available and likely to be cost prohibitive in a compact urban setting.

A model based approach was developed to evaluate the energy consumption and energy balance under the specific constraints of compact urban buildings, i.e. limited roof and storage space, shading by neighbouring buildings, suboptimal orientation and roof angle, and low wind yield. Most other low carbon home simulation designs in the literature use favourable parameters to meet the objective of low carbon emissions, however, these do not satisfy the much more likely scenario of compact urban buildings, due to urbanisation and the trend towards smaller households. This study further provided a review of the available information for parameter selection to drive the simulation and to model the case study building on which to base further analysis, validating the estimated energy consumption with measured data. The simulation based analysis of the renewable system combinations enabled investigation of the influence and interdependencies of heat and electricity demands on the on-site zero-carbon generation performance, for which there is limited information in other studies.

Another contributing aspect of this study is the introduction of a method of visualising the combined occupant, building and equipment generation and consumption characteristics to support better design and enable decision making at design stage on the combination of generation options with the lowest CO_2 emissions during occupation. A coverage risk indicator was introduced, which indicates the percentage likelihood of a particular generation configuration of achieving a zero carbon building. Graphical representation enabled introduction of a demand envelope, the boundaries of which are the minimum and maximum expected thermal and electrical energy over one year. The visualisation methods and simulation of the case study building were implemented to investigate the performance of different mixes of renewable generation technology to establish the combination most likely to achieve zero or low carbon performance in practice.

It can, therefore, be concluded that this study has satisfied its aim of developing an approach that can be used to establish the most appropriate mix of low carbon generation technologies to satisfy the net yearly demand for low energy compact urban dwellings in a maritime Northern European climate at design stage.

Having a real compact urban building as a case study has helped set realistic parameters in the simulation model, and on-site measurements are helping to corroborate the findings in this study.

The main academic recommendation as a result of this research is on going research into emerging generation technologies (e.g. the combination of PV and solar thermal) as they become mature for consideration into the techniques proposed in this study, to enable identification of a future combination of renewable generation technologies capable of establishing true zero carbon compact urban dwellings.

A further academic recommendation is the use of the heat pump model introduced in this study in building simulations for a maritime climate. If the COP curves or equations are known, this model has and can be adapted for other models of heat pump.

Recommendations for the sponsoring company include continuation of measurements at the case study building to enable confirmation of energy consumption findings so far, further education of occupants of the case study building to achieve a demand pattern that is more aligned with the sponsor’s goal of zero carbon housing, and investigation of measured wall u-values against ICF manufacturer performance claims.

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APPENDIX A An Air Source Heat Pump Model For Operation in Cold Humid Environments

Steijger L.A., Buswell R., Smedley V., Firth S.K. and Rowley P., 2010. An air source heat pump model for operation in cold humid environments. *8th International conference on system simulation in buildings*, 13-15 December 2010 Liege

Abstract

There is considerable interest in the use of heat pumps as a potential low-carbon alternative to fossil fuel-based domestic space heating and hot water systems. In many cases, heat pumps are combined with other energy sources such as solar thermal and/or electric resistive heating, to ensure that building thermal loads can be met, and in order to minimise carbon emissions from such integrated systems. Whilst meeting the comfort demands in the occupied space, relatively complex control strategies are required in comparison to simple thermostatic control typically implemented to control gas fired heating systems in domestic buildings. Well characterised models of the principal components of these systems are required to explore and identify the most appropriate strategies in simulation. However, models of air source heat pumps (ASHPs) operating in humid climates, such as the UK, are limited. This paper presents an experimental setup designed to capture the operation of the ASHP in conditions similar to those found throughout a typical heating season in the UK. Results from a number of tests on a 10kW ASHP are presented in terms of the coefficient of performance (COP) and the steady-state operation are used to develop a model using empirical curve fitting. The overall maximum time constant is also established. The resulting model calculates COP as a function of air humidity, air temperature on the evaporator side and water temperature on the condenser side.

Keywords – Air source heat pumps, empirical model …

Paper type – Conference paper

Corrigendum: Equation (2) on page 67 is not correct and therefore the sentence:

The heat transfer on the refrigerant side is given by equation 2.

$$Q = \rho \, V \, \Delta h_{vap} \qquad (2)$$

can be ignored.

1 INTRODUCTION

Simulations can be used to study the performance of various physical system or component configurations in order to identify suitable values for control parameters that aim to reduce running time, reduce energy consumption and minimise operating costs (Fu et al, 2003). The identification of appropriate control strategies is increasingly important for domestic systems that have two or more sources of heat generation. Well defined and realistic models of the key components, of which ASHP's are one, is essential. ASHP's offer great advantages in terms of cost and a reduction in installation time, but a disadvantage is that by using external air as the heat source, makes them sensitive to the prevailing air condition. In humid climates such as the UK it is common to observe close to saturation conditions for significant periods during the heating season, which results in partially or fully wet coil operating conditions. In colder periods this can lead to frost formation on the evaporation coil, to prevent excessive frost build up the ASHP must run from time to time in reverse, to free the air-side coil of ice. The identification of these characteristics has been the focus of the work described in the paper, this work was carried out in order to develop a model that more correctly reflects the likely operating conditions for an ASHP in a cold humid environment.

The paper presents the test set up, data from a series of tests performed on a 10kW domestic packaged ASHP unit. A model is developed that describes the ASHP operation for approximately 70% of typical heating seasons in the midlands of the UK.

2 MODELLING HEAT PUMPS

Existing literature describes approaches for the development of heat pump performance models. One such approach for heat pump performance simulation involves characterising the operation in terms of the underlying physics of the processes in each of the individual components, i.e. the compressor, condenser, expansion valve and evaporator. The simultaneous solution of the equations describing mass, momentum and heat-balance equations, thermodynamic and thermo-physical property relationships and heat or work transfer relationships needs to be executed to generate an output from the model (Welsby et al, 1988). The governing equations take the form of ordinary differential equations in dynamic models, compared with algebraic equations used in steady-state modelling (Ahrens et al, 1983). System variables such as refrigeration mixture, compressor efficiency and the refrigerant flow through the heat exchangers, however, have a great influence on the overall performance of a heat pump and are difficult to model. The result is that first-principle based modelling of heat pumps is complex, error prone and of limited practical use (Heap et al, 1979).

Another approach is to treat the heat pump as a 'black box', modelling the internal thermodynamic and heat transfer processes implicitly in the relationship (Morrison et al. 2004). Taking the empirical data and fitting a mathematical curve to this is one such approach, and has been proven effective for modelling heat pumps. A key parameter for assessing heat pump operation in heating mode is the COP. This is defined as the ratio of the amount of heat output (in this case heating of water) to the energy input, in this case the electrical energy used to drive the refrigerant pump. In an ASHP the heat source is the ambient air, the driving power is electricity and the heat is transferred to water in the heat distribution circuit. The variables of each of these components are listed in Table 1. Not all of these variables need to be explicitly modelled since many have little impact on the COP and therefore can be neglected, simplifying the resulting solution.

Table 1: Required variables for ASHP modelling.

Air inlet properties	**Electrical properties**	**Water outlet properties**	**Time constants**
Inlet temperature of the air	Voltage	Inlet temperature	Starting up time constant
Outlet temperature of the inlet air	Current	Outlet temperature	De-freezing time constant
Air Humidity of the inlet air	Frequency	Flow rate	Heat transfer time constant
Air Humidity of the outlet air	Power factor	Density	
Flow rate through the evaporator		Specific heat capacity	
Wind regime over the heat pump (angle and speed)			

2.1 SELECTION OF INLET AIR PARAMETERS

The air inlet temperature is a key parameter used for the characterisation of ASHP. A simple model as used by Andre et al (2008) that models the temperature difference between the cold air inlet and the hot water output. According to Heap et al (1979) air humidity has an influence on the performance of an air source heat pump; if the temperature on the evaporator is above freezing, the latent heat from the condensing air moisture will increase the performance. However, if the temperature of the evaporator coil is below freezing, ice will collect eventually closing off the flow around the evaporator fins. Chen et al (2009) studied the influence of the air humidity and recorded a 10% fluctuation in COP with an air humidity variation of 65 to 90%: Freezing of the evaporator coil was stated as the main reduction in performance. The inclusion of air humidity as an input parameter is therefore critical when modeling ASHP performance in locations with a high prevalence of excessive humidity at low ambient temperatures.

If we assume that the air is not re-circulated, the air leaving the heat pump has no influence on the heat pump anymore and hence has no bearing on the performance of the heat pump. Exhaust air parameters like the temperature and humidity are assumed to have no influence on the performance. In practical operation, in confined spaces this might not be the case, but installation recommendations should limit this type of circulation.

The flow rate through the evaporator coil, is considered to be constant. In a real installation the evaporator coil will experience the collection of, dust, pollen, leaves, etc on the air-side coil surface (Pak et al, 2003), which could have a detrimental effect on the performance. The effects of variable wind velocity (Yao et al, 2004) can also influence performance, but these issues are beyond the scope of the work reported here.

2.2 ELECTRICAL PARAMETERS

The heat pump is controlled through on/off switching of the compressor, and as such is representative of the most commonly installed ASHP units used for domestic applications. ASHP’s are electrically driven and the input electrical supply is assumed here to be a nominal 230V at 50Hz. It is recognised that to accurately calculate the COP of the heat pump, the time varying characteristics of the input power need to be determined precisely, this necessitates an accurate power factor measurement. As partial loading of heat pumps using frequency inverters for the compressor becomes more common, the voltage frequency and/or the partial load factor will need to be included (Bettanini et al, 2003).

2.3 WATER OUTLET PARAMETERS

The heat on the condenser side of the heat pump is transferred into a fluid (typically water) via a heat exchanger. Here the water is not mixed with antifreeze or other liquids, and so the relevant properties are taken to be: density, 998 kg/m^3, expansion coefficient, 0.21 x10^{-3}/ºC and specific heat c_p = 4.1855 kJ/kg°C @ 25°C. The heat transferred to the waterside can be evaluated using equation 1:

$$Q = \rho\ V\ c_p\ \Delta T \quad (1)$$

Where ρ is the density, V is the volume, c_p is the specific heat capacity and ΔT the temperature difference between the water inlet and water outlet temperature. Variations in density and specific heat are considered to be negligible over the range of temperatures experienced during normal operation. The heat transferred into the water on the condensing side is determined by the heat exchanger configuration and operating conditions. The heat transfer on the refrigerant side is given by equation 2.

$$Q = \rho\ V\ \Delta h_{vap} \qquad (2)$$

with Δh_{vap} the specific latent heat of evaporation. From (1) with a given heat output Q, a set flow rate V and a constant density and specific heat, either the heat distribution loop outlet or inlet temperatures are required to determine the temperature difference over the evaporator coil.

Water mass flow rate through the heat exchanger is also important, particularly if the flow rate is sufficiently low such that it is laminar, this will have a significant impact on heat transfer coefficient.

2.4 SYSTEM TIME CONSTANTS

The aspects discussed above are the static parameters of a heat pump. To generate optimised control, the time constants within the system also need to be known, especially the start-up time constant. This is the time between starting the heat pump and the output power reaching 63% of its end value with all other parameters fixed.

Another performance related time constant is the duration between defrost cycles. This time constant is dependent on the temperature and the air humidity. As stated previously, Chen et al (2009) recorded the time between defrost cycles as a function of the air humidity and temperature.

The third time constant relates to the heat capacity of the heat pump coils. If the flow is varied within the coil, there could be a delay in temperature variation due to the heat capacity of the heat exchanger within the ASHP.

From the above discussion the focus of the simulation will be on the temperature and humidity on the evaporator coil/air inlet side of the ASHP, the water in, outlet temperature and the flow rate of the water in the condenser side of the heat pump. Time constants, especially the starting up time, also need to be established.

3 EXPERIMENTAL SET-UP

The test rig as shown in Figure 21 was built up in an environmental chamber. Water was connected to the ASHP via a three way valve (Valve1) and a water mass flow controlling two way valve (Valve2). A pump provided the necessary flow for circulation. The water outlet temperature ($T_{w,out}$)at the condenser is controlled by adjusting the water mass flow rate (Valve2). The condenser water inlet temperature ($T_{w,in}$) can be controlled by mixing the warm water from the outlet with the cold external feed (Valve1). A bypass valve placed in parallel with Valve2 ensures a minimum flow rate. The flow is measured with a calibrated oval gear flow meter, with an accuracy of ±0.5 % of the maximum flow.

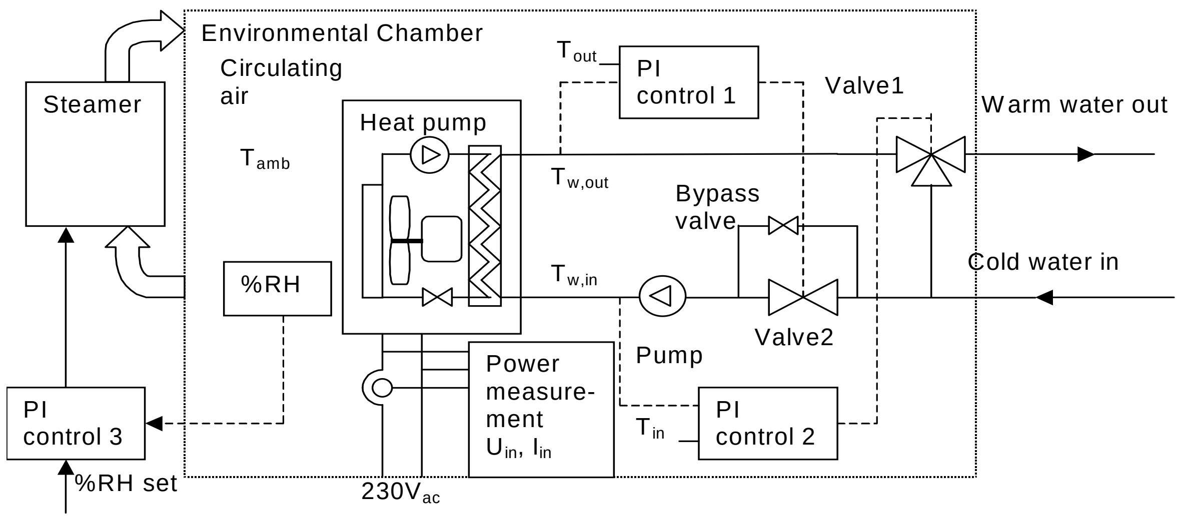

Figure 21: Schematic model of the Test rig.

The principle of the test is based on defining a starting temperature and air humidity, within the chamber, and then letting the ASHP run cooling the chamber down and thus varying the inlet air temperature on the evaporator side. The tests are started at an air temperature of 15ºC and tests verified that the rate of change in air temperature was slow compared to the time constants of the ASHP, and so the test measurements can be considered to be made at, or close to, steady-state. Air humidity is maintained at the desired value by adding steam via a steam humidifier in the supply air duct to the chamber.

Temperatures are measured using PT1000 elements to DIN EN 60751 Class Y. The maximum error on the temperature measurements is calculated at ±0.2 ºC. Humidity is measured to ±3% and the power measurements (voltage, current and power) to an error of ±0.5%. The nominal electrical power taken up by the heat pump was approximately 3 kVA with a cos(φ) of 0.85.

3.1 TEST SERIES

The range of each of the driving environmental input variables on the air-side needs to be determined. For the U.K., CIBSE gives guidance on average temperature and air humidity, but not in correlation to each other over a heating season. If a heating hour is defined as when the ambient temperature is less than 15ºC, an estimate of the heating season can be made using weather data from the nearest geographically located weather station. Weather data from Sutton Bonnington airfield was obtained, applying above 15ºC limit it can be calculated that for 72.2% of the heating season period, the air temperature is between 2ºC and 15ºC with a humidity of higher than 75%.

Since the heat pump COP decreases with increasing temperature difference between ambient air temperature and the hot water set point, the heating flow temperature ($T_{w,\ out}$) in the dwelling should be as low as possible: A flow temperature ($T_{w,\ out}$) of 35 ºC to 50ºC has been assumed. The return flow into the heat pump ($T_{w,\ in}$) will under normal operating conditions be approximately 10ºC – 20ºC lower than the feed temperature. The volumetric flow rate in domestic water based heating system is normally between 0.05 and 0.5 litres/second.

A series of tests were developed to characterise this region of operation. Each of the following test were run for ambient air temperatures through the range 15ºC down to 2ºC:

COP as a function of the air humidity: The air humidity was controlled at 85% RH, 90% RH and 100% RH. The water outlet temperature ($T_{w,\ out}$) at the condenser is set at 40ºC and the water inlet temperature ($T_{w,\ in}$) to the condenser heat exchanger was held constant at 20ºC. The data was used to generate the curves for the dependency on the air humidity.

COP as a function of the condenser outlet water temperature: The outlet water temperature ($T_{w,\ out}$) after the condenser heat exchanger is controlled at 40ºC, 45ºC and 50ºC. The air humidity is kept constant at 90% RH and the inlet temperature (Tw, in) to the condenser heat exchanger is set at 20ºC. This data has been used to generate the standard COP curves of the heat pump.

COP as a function of the inlet water temperature ($T_{w,\ in}$): The inlet water temperature was controlled at 20ºC, 25ºC and 30ºC, the air humidity was set at 90%RH and the outlet temperature was set at 45ºC. From this set of measurements the dependency on the inlet temperature has been determined.

3.2 MEASURED DATA

Data was collected every 10 seconds and each test was approximately 5 hours in duration (the time it takes to cool the room from 15ºC to 2ºC). Figure 22 depicts data from one test: The ambient air can be seen to change at a rate of approximately 1 degree every 20 minutes. The plot shows noise on the calculated COP that can be attributed to the condenser water inlet flow regulation in order to maintain the inlet and outlet temperature settings. The fluctuation in the air humidity is a result of the used steamer, once the internal overflow was full, a drain and a following automatic refill sequence resulted in a slight fluctuation of the air humidity.

As the two control loops interact with each other, to obtain stability, the output temperature control was set within a time constant of 1 minute control, the control for the inlet temperature was set at 10 minutes. As extra heat was added to the test chamber at start to maintain a slow decrease in temperature, as the test series continued, this heat was switched off manually if the temperature did not decrease for more than 0.1 ºC in 10 minutes. As a result, some step changes in the temperature and COP are visible in the curves. (around 11:30 and 13:00)

The COP has been calculated for each of the test series. To do this using the quasi-steady data, the ambient air temperature was used to calculate bin samples that fell into sequential bins of 1ºC, from 15ºC down to 2ºC. The data for each variable was averaged according to the samples that fell into each bin, and these were used in the analysis to represent the steady-state performance characteristics of the ASHP.

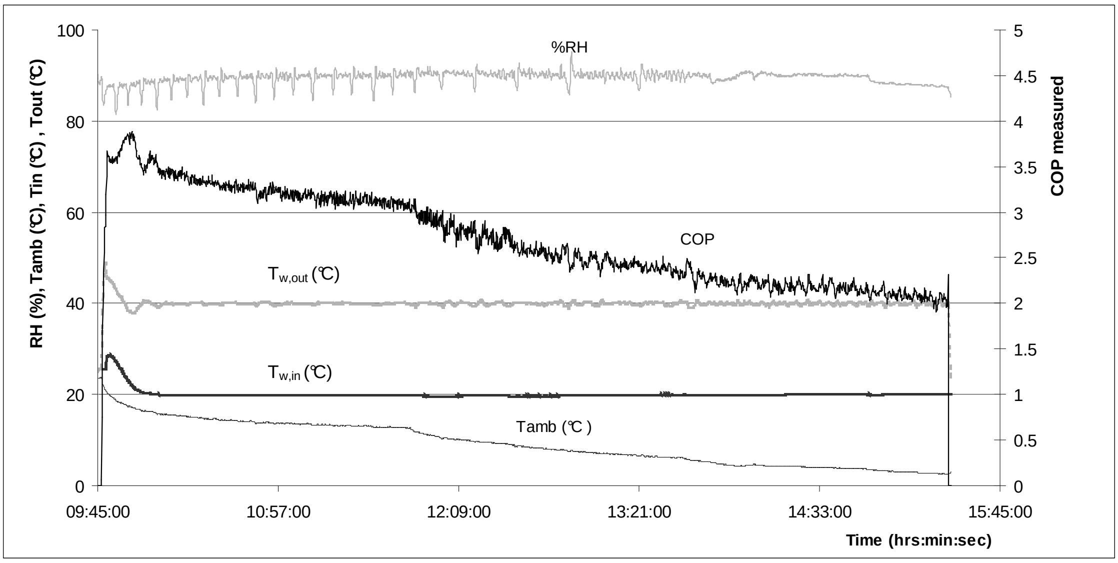

Figure 22: data from one of the test series. On the left axis from top to bottom the %RH, outlet water temperature, inlet water temperature and the ambient air temperature. On the right axis the calculated COP of the heat pump.

4 RESULTS

For each of the test series the results are presented and discussed. Appropriate models from the literature are then identified and applied to sequentially build up a new model for ASHP operation in cool, humid environments.

4.1 COP AS FUNCTION OF THE AIR HUMIDITY

Three test series were conducted and the results plotted in Figure 4. Note that the limitations of the environmental test chamber resulted in the 100% humidity test series ceasing at 6ºC: The steam humidifier, prevented a further reduction in temperature while maintaining 100% saturation.

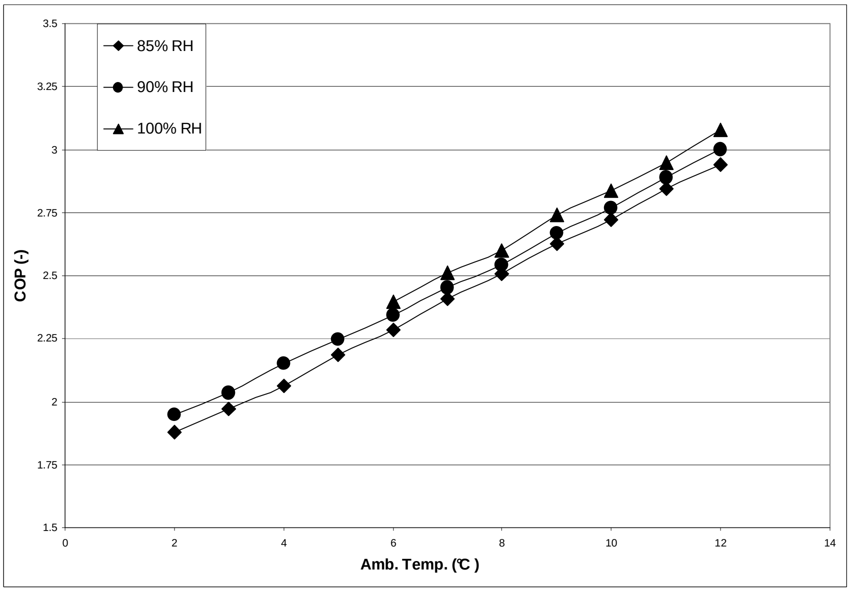

Figure 23: COP as a function of the air humidity. The outlet water temperature was controlled to 40 ºC, the inlet water temperature controlled at 20 ºC, The ambient temperature varied between 14 and 2 ºC.

Figure 23 shows the dependence of COP on ambient air temperature, and a weaker, but not insignificant dependence on air humidity. The coil was operating in at least partially wet conditions during the test, and so further tests are required to determine dry coil operation. It was noted during the test that the exhaust air was measured to be close to saturation throughout most of the test period.

4.1.1 MODEL DEVELOPMENT

The model used by Morrison et al (2004) (Equation 3) uses input variables air inlet temperature and humidity, and a formula to link the two. It uses a linear equation to link the ambient air T_{amb} with the outlet water temperature $T_{w,out}$. It does not, however, give values of the system parameters a_1 to a_3:

$$COP = (a_1 + a_2(T_{w,out} - T_{amb}))\ (1 - a_3\ (T_{amb} - T_{wetbulb})/(T_{amb} - T_{dewpoint})\ ) \qquad (3)$$

When calculating a value for constant a_3 for the relationships shown in Figure 23 it was found that the solution for a3 varies between 2.2 < a3 < 4, with an ambient air temperature range of between 2°C and 14 °C. Therefore this approach was rejected due to the large variation.

Another approach is to take the viewpoint from an evaporation dynamics point of view. It was noted that the exhaust air was saturated. We hence could assume that the evaporator coil was covered in moisture and air was blowing over it. As such the evaporator coil is operating in a similar state as the wick in the wet bulb measurement, i.e. the balance between the condensation and evaporation on a wet surface. So if the input for the model is not the dry bulb, but the wet bulb temperature, not only the ambient (dry bulb) temperature, but also the air humidity is automatically incorporated into the model.

Lawrence (2005) derived a simple approximation for a correlation of the dew point and the air humidity for air humidity's higher than 50%:

$$T_d = T_{amb} – (100 - \%RH) / 5 \quad \text{or } T_{amb} – T_d = (100 - \%RH)/5 \quad (4)$$

In the measurement range of 2°C and 14 °C and air humidity higher than 80%, the factor between the wet bulb depression and the dew point depression ranges from approximately 1.5 to 2.5. Assuming the average of 2, the depression is:

$$T_{amb} – T_{wetbulb} = \Delta T_{rh} = - (100 - \%RH) / 10 \quad (5)$$

With the air humidity changing from 85% to 100 %, the temperature difference caused by the air humidity ΔT_{rh} caused an effective ambient air temperature increase of 1.5 °C. This is confirmed by our measurement results. So the measurements confirm that instead of using the dry bulb temperature for calculating the COP, for high air humidity's, the wet bulb temperature is more appropriate as input value for the model. If only the relative humidity is known, the wet bulb temperature can be calculated using equation (5).

So at high air humidifies (>85%), using the wet bulb temperature instead of the dry bulb temperature as input to the model compensates for the air humidity in this experiment.

4.2 COP AS FUNCTION OF THE CONDENSOR OUTPUT WATER TEMPERATURE

The results are shown in Figure 24. There is a significant dependency on the temperature difference between the air temperature and the condenser water output temperature. As the temperature difference between the air temperature T_{air} and the water outlet $T_{w,out}$ increases, the COP decreases, confirming the characteristics observed in most of the relevant literature.

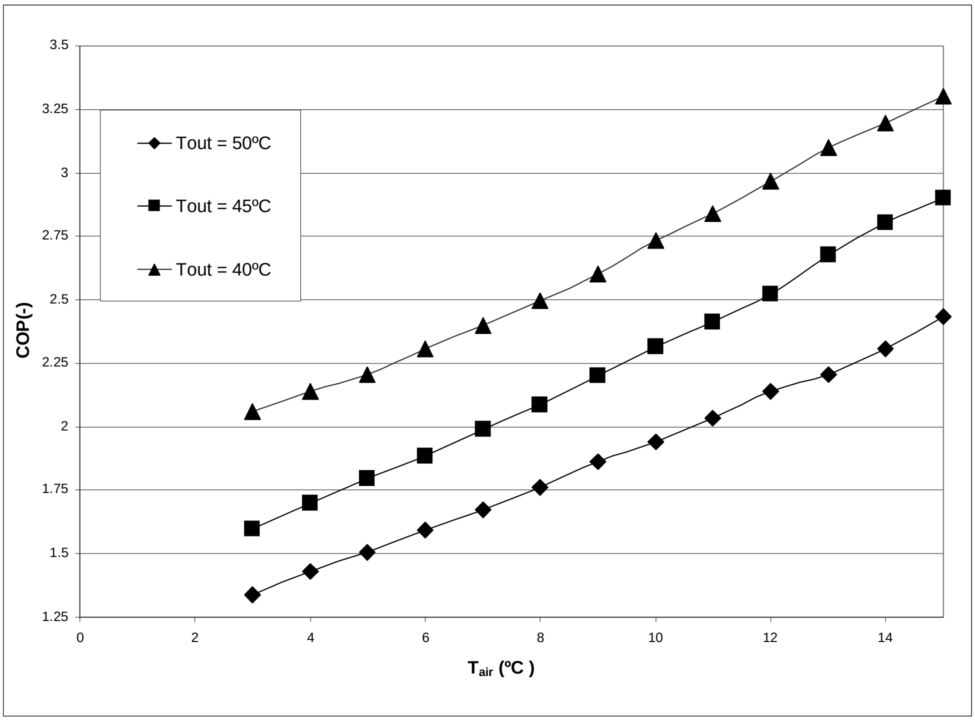

Figure 24: COP as function of the ambient temperature and condenser water outlet temperature.

Baek et al (2005) already formulated an equation with the temperature dependencies (using the wet bulb and outlet water temperature as the effective temperatures):

$$COP = a_0 + a_1T_{wet\ bulb} + a_2T_{wet\ bulb}^2 + a_3T_{w,out}^2 + a_4T_{w,out} + a_5T_{wet\ bulb}T_{w,out} \quad (6)$$

with a_0 to a_5 system constants, depending on the heat pump.

Using these graphs and equation 5, a numerical solution generates the relationship between the COP on one side and the wet bulb temperature $T_{wet\ bulb}$ and the water temperature $T_{w,out}$ on the other side of the equation. As the polynomial equation used by Baek et al (2005) is quadratic the highest term has been assumed quadratic for the equations. With a $T_{w,out}$ of 40ºC the polynomial describing the curve is:

$$COP = 0.0021T_{wet\ bulb}^2 + 0.069T_{wet\ bulb} + 1.82 \quad (7)$$

Similar for $T_{w,out}$ = 45ºC and 50ºC:

$$COP = 0.0018\ T_{wet\ bulb}^2 + 0.072T_{wet\ bulb} + 1.36 \quad (8)$$

$$COP = 0.0009T_{wet\ bulb}^2 + 0.073T_{wet\ bulb} + 1.12 \quad (9)$$

With these three equations we have a relationship between the coefficients with the only variable the output temperature. An equation can be established for the quadratic term, the linear term and the constants. If we use the three points to fit a curve for the output temperature, we can determine the coefficients for this heat pump:

$$
\begin{aligned}
COP = \; & \left\{ -1.2.10^{-5}\, T_{w,out}^{2} + 9.6.10^{-4}\, T_{w,out} - 0.017 \right\} T_{wet\ bulb}^{2} \\
& + \left\{ 0.0003\, T_{w,out} + 0.057 \right\} T_{wet\ bulb} \\
& + \left\{ 0.0043\, T_{w,out}^{2} - 0.46\, T_{w,out} + 13.3 \right\}
\end{aligned} \quad (10)
$$

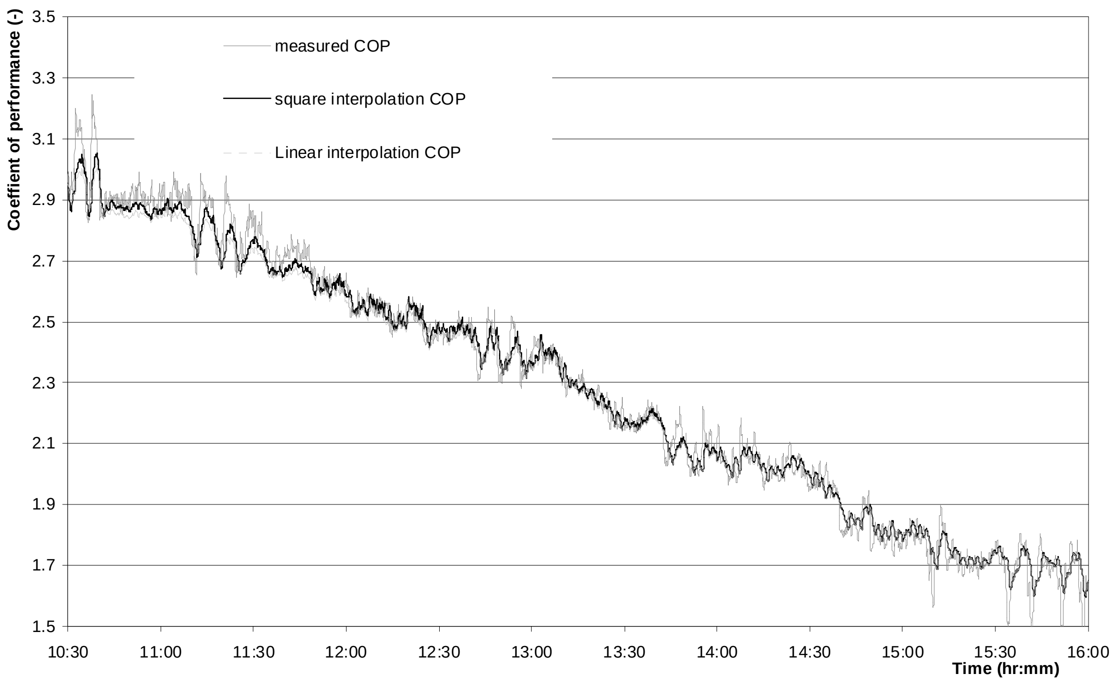

Figure 25 The difference of a square polynomial interpolation and a linear interpolation for the quadratic term is negligible for this heat pump. The quadratic interpolation is slightly better with higher $T_{wet\ bulb}$ and $T_{w,out}$

It has two extra terms comparing with Baek et al (2005). These extra terms are the result of a polynomial interpolation on the quadratic term of the equation. A constant would have resulted in the same formula as Baek et al (2005) and the differences between the two methods is negligible as shown in Figure 25.

Combining (4) and (9) it is possible to check the measured data against the computed model. The result is shown in Figure 26. Although the instantaneous error peaks at 10%, the moving average over 60 periods (10 minutes) after start-up is below 2.5 %. This is due to the fast control of the flow for the instantaneous value, whereas the model is based on the temperatures only, which have a time lag as shown in the next paragraph.

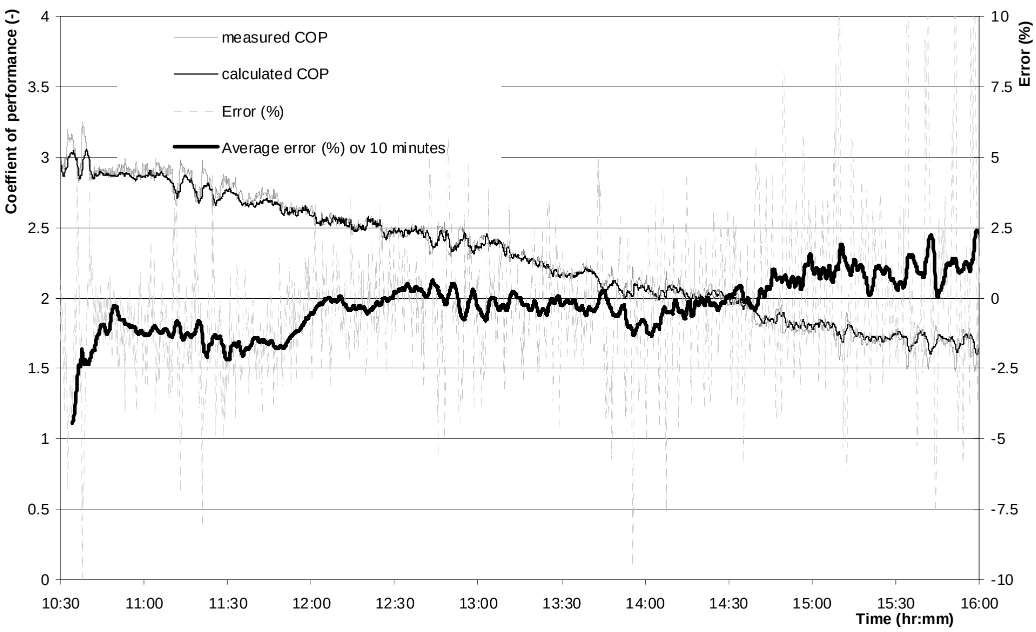

Figure 26 Comparison of the model with the real values. As the instantaneous error is peaking at 10% due to the fast control of the flow rate, the rolling average error averaged over 60 samples is less than 2.5 % after start-up.

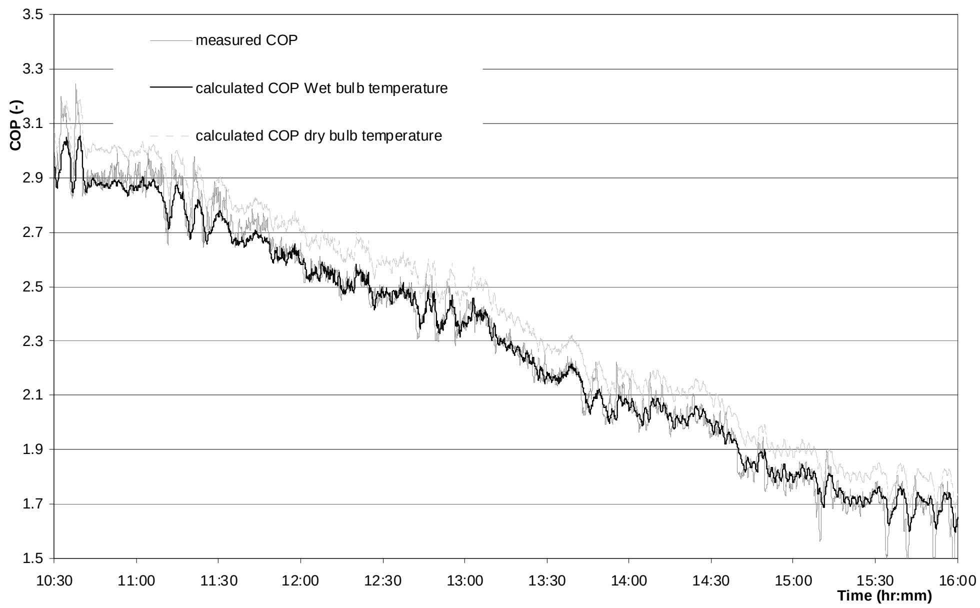

Figure 27 Comparison of the model with the difference in using the dry and wet bulb temperature. Using the dry bulb temperature creates an offset between the real measured COP and the calculated COP in the model.

Figure 27 shows the influence of the air humidity. If the normal ambient temperature is used, the COP follows a curve just above the more accurate curve using the wet bulb temperature.

The advantage of the new model is that it combines the findings of Baek with a compensation for the influence of the air humidity. This results in an error less than 2.5 % in an average over 60 samples.

4.3 COP AS FUNCTION OF CONDENSOR WATER INLET TMPERATURE

Figure 28 shows no major influence of the condenser inlet temperature on the performance on the COP. However, the plot demonstrates that the flow rate through the water heat exchanger is fully turbulent. The flow rate changes from 0.14 l/s with an inlet temperature of 30ºC and ambient temperature of 15ºC to 0.04 l/s with an ambient temperature of 2ºC and an inlet temperature of 20ºC. The outlet temperature was controlled to 45 ºC. If there was an influence from the flow rate, the graphs would not overlay each other and disperse at a low flow rate if the flow was to change from turbulent to laminar. It was observed that there was a drop in heat transfer as the flow rate dropped below 0.01 l/s, which was attributed to the onset of laminar flow in the water side of the condenser heat-exchanger.

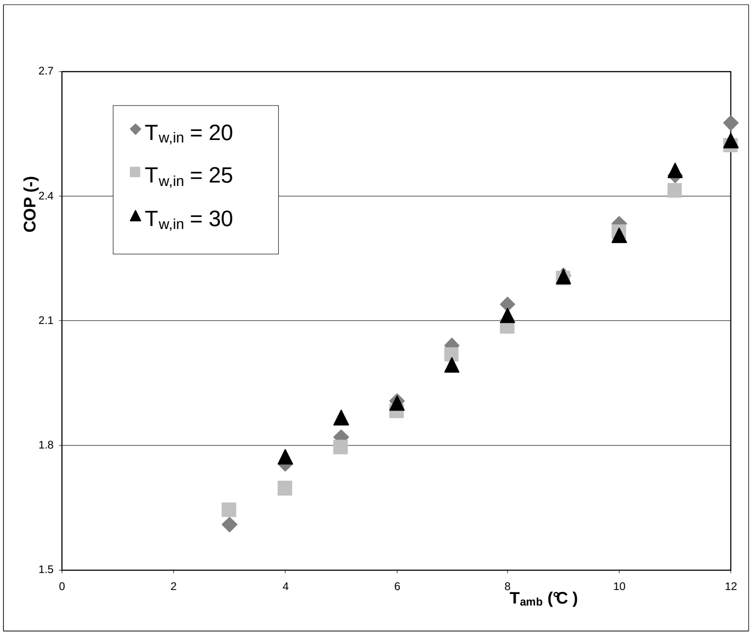

Figure 28: COP as function of the condenser water inlet temperature. Outlet temperature was held constant at 45, flow rate of the water was modulated, inlet temperature between 12 and 3 ºC.

4.4 TIME CONSTANT OF THE HEAT PUMP

To determine if the heat pump should be modelled with a steady-state simulation or a dynamic one, the time constants of the heat pump need to be established. If the time constants are much less (<100 times) than the steady-state running time of the heat pump, the error will be less than 1 %, and can be ignored. If the time constants are >100 times the steady state of the heat pump, the error cause by this will be larger, and has to be taken into consideration. As the heat pump under test has a constant compressor speed, the time constant of switching the unit on and the heat output needs to be established.

Figure 29 shows the input current and the output temperature during switch on. The heat output shows similarity with a first order system with a time constant between approx. 30 to 40 seconds.

If the running time of this heat pump is much larger than the time constant of the heat pump (assume time step of simulation >100 times the time constants of the heat pump i.e. between 3000 and 4000 seconds). The error due to the start up time can be neglected as the start-up time is 40 seconds and is therefore negligible when compared with the heat pump running time.

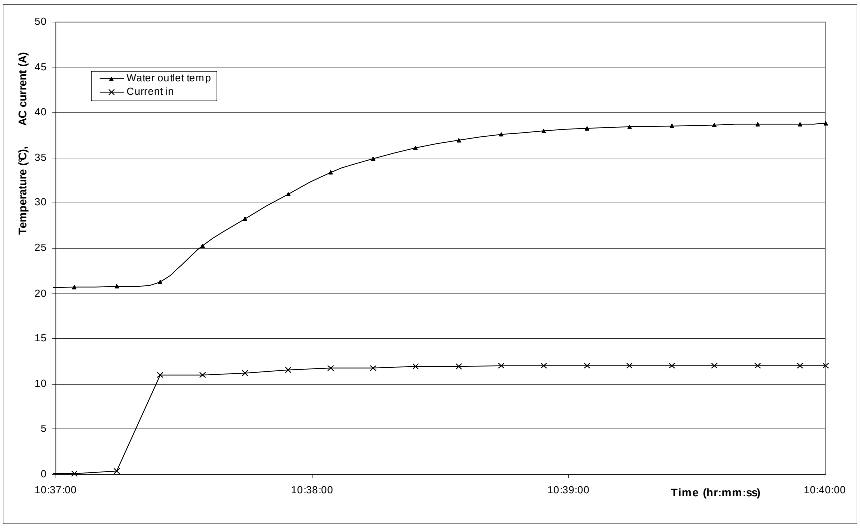

Figure 29 Switching on time constant of the heat pump. The time constant between switching on the heat pump and generating heat out is approximately 40 seconds.

The control for the flow rate is run on a 10 second cycle, well within the time constant of the heat pump. This is the reason for the relative large instantaneous error between the model and the measurements.

5 CONCLUSION

To develop control strategies and parameters settings, modelling is a useful tool. However, the results of the simulation are as good as the models used. This paper looked into all the relevant parameters and confirmed, albeit with different equations, the previous studies. A new empirical model, combining the findings of Baek et all (2005) and Morrision et all (2004) and time constants have been established for one heat pump, and the error over a rolling average of 60 samples (which equates 10 minutes) is less than 2.5% of the measured values. This model, in its present form, needs to be refined. More empirical data comparisons need to be made, particularly with different types of heat pumps and lower air humidity's. The model may then be used to conduct a full parametric implementation of heat pumps for developing control and optimisation strategies. In addition, expansion of the model is to consider inverter driven heat pumps, the effect of clogging up the evaporator coil and/or defrosting need to be researched, and for a more accurate dynamic model, transients and start-up influences needs to be developed. More research is hence necessary to obtain an universal air source heat pump model.

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APPENDIX B ESTABLISING THE ZERO-CARBON PERFORMANCE OF COMPACT URBAN DWELLINGS

Steijger L.A., Buswell R., Smedley V., Firth S.K. and Rowley P., 2013. Establishing the zero-carbon performance of compact urban dwellings, Journal of building performance simulation, DOI:10.1080/19401493.2012.724086

Abstract:

This paper presents an analysis of the zero-carbon performance of a case-study building which is representative of a growing number of new buildings that are being built on redevelopment sites in inner-city areas in the UK. Compact urban dwellings are apartment style buildings with a floor area of 50 m^2 per dwelling, often based over two floors. The constraints of this type of building on achieving zero-carbon performance in the context of the Code for Sustainable Homes is discussed and the shortcomings of the code are demonstrated in terms of the target heat and electricity demand targets for the design of the building systems. A graphical representation of the simulation results is used to present the findings. It has been demonstrated that in specific urban contexts, zero-carbon performance as defined within the current UK compliance framework may be very difficult to achieve in practice given the assumptions used in the simulation here. Therefore, it is very likely that zero-carbon compact urban dwellings may require a net off-site import of electrical and/or thermal energy.

Keywords: zero-carbon; energy generation systems; CHP; solar; compact urban dwelling; system integration

Paper type: Journal paper

Corrigendum: Equation 2 on page 95 the efficiency of the CHP is incorrect, the formula should read:

$$\phi = \Delta\varepsilon\phi_{grid} + \frac{\Delta\theta\phi_{gas}}{\eta_{boiler}} + \frac{\tau_{chp}\mu_{chp}\phi_{veg\_oil}}{\eta_{chp}} \qquad (2)$$

1 INTRODUCTION

It is widely accepted that climate change is a serious and urgent issue that needs to be addressed by reducing the level of GreenHouse Gas (GHG) production globally (Stern 2007). The Intergovernmental Panel on Climate Change (IPCC)'s Fourth Assessment Report (2007) confirms that the primary concern is that greenhouse gas emissions from human activity have risen "by 70% between 1970 and 2004". Following the Royal Commission on Environmental Pollution (RCEP) report (2000) the UK government committed to an 80% reduction in CO_2 emissions by 2050, enforcing changes through legislation. Meeting this emissions goal of the UK can only be achieved through setting and achieving strict targets in all energy-consuming sectors (McManus et al. 2010), and as over 27% of UK's CO_2 emissions come from the energy used to heat, light and run homes (Department for Communities and Local Government 2007), it is vital to ensure that higher sustainability performance standards are integrated within the design of new homes.

The UK government has introduced the Code for Sustainable Homes (CSH) to drive a step-change in sustainable home building practice (Department for Communities and Local Government 2006). The CSH is an environmental assessment method for rating and certifying the performance of new homes and is a UK government owned, national standard. The CSH covers nine categories of sustainable design, of which 6 are mandatory (energy and CO_2 emissions, water, materials, surface water run-off, waste and health and well-being) and 3 are flexible (pollution, management during build and occupation and ecology). To obtain the highest level of the code, level 6, net emissions of CO_2 must be zero. With the exception of water consumption, the objectives are flexible and are rated to a point scheme, where points are accumulated in each category and summed to calculate a percentage of the target value. The required percentage to achieve level 6 is 90%.

By 2016 all new homes built in the UK must meet these criteria of the CSH (Department for Communities and Local Government 2008), requiring them to be "zero carbon" (Energy Saving Trust 2008). As a result, to meet the energy demand, zero carbon energy (used for space heating, hot water and power for lighting and electrical appliances) must be generated in or near the building to offset any fossil or fossil-generated fuels imported into the home, so that over a year, the net carbon emissions are zero (McManus et al. 2010).

To compound the challenges of compliance with these requirements, the UK housing market is under pressure from a rising population and there is a shift towards the construction of smaller dwellings (McManus et al. 2010). It is projected that between 2004 and 2016 there will also be an extra 1.85 million single person households in England alone, with these figures contributing to a total increase of 2.8 million new households by this date (Department for Communities and Local Government 2007). Banfill and Peacock (2007) state that the trend towards inward migration is resulting in new homes being built on brown field sites in towns and cities, where space is limited. The lack of space for buildings on such sites tends to produce workable designs of smaller, apartment based dwellings, which is different from single property living in a house on its own land which is common throughout much of the UK. These new built homes, or compact urban dwellings, often have a living space of around 50 m^2 in either one or two stories with a likely occupation of either one or two people. The CSH stipulates that all energy must be generated on-site and hence the limited space for the installation of energy generation plant, heat storage equipment and bio-fuel storage presents a major challenge.

The shape of the site and planning restrictions often constrain the orientation of the building and the roof height, which has a direct impact on the available solar energy received by the building. The availability of solar radiation in winter in particular, can be severely restricted due to close proximity of existing structures that can cause shading on the roof, which in most cases is the only surface available for collecting solar energy. In compact urban dwellings, this problem is exacerbated because a living space of ~50 m^2 over two stories results in a maximum roof area of 25m^2 per dwelling; multi-storey flats have less than this.

This paper investigates the implications of the practical constraints of delivering a real building to code level 6 performance standards. The paper focuses on the selection and evaluation of suitable building energy generation system options under engineering and installation constraints for a case study building. A number of workable generation options for the building are established and the performance of each option compared in terms of the net annual CO_2 production.

2 CSH LEVEL 6 BUILDING AND SYSTEM DESIGN: PRACTICAL CONSTRAINTS

In the CSH (Department for Communities and Local Government 2006) the highest rating is level 6 and the code states that for this status to be awarded to a building it needs to be '*…a completely zero carbon home (i.e. zero net emissions of carbon dioxide (CO2) from all energy use in the home)...*'.

For code level 5, the next performance level down the scale, the energy performance is stated to be 100% better than the 2006 Building regulations Part L (Office of the deputy Prime Minister), which is '*…zero emissions in relation to Building Regulations issues (i.e. zero emissions from heating, hot water, ventilation and lighting)…*'. From this, it can be inferred that in order to comply with code level 6, apart from the requirements for code level 5 for energy used for space heating, ventilation, water heating, and lighting, occupant consumption of small power and ancillary loads such as pumps and controls must be also generated through the use of zero-carbon technologies. As the standard refers to a net emission rate, generation of the energy does not have to occur simultaneously to the consumption, e.g. if zero-carbon electricity is generated and fed into the grid, and consumed at a later stage from the grid, it is still accepted to be zero-carbon. The challenge for the designer is that there is no reference to the electricity consumption from non-regulated loads (such as appliances) that should be attained. Therefore, designing systems to deliver zero carbon performance in use in order to achieve this standard is challenging and represents a significant omission in the document.

Zero carbon housing has been shown to be possible by reducing the demand for energy in combination with micro generation (Keirstead 2007). The largest energy use in dwellings in the UK is said to be space heating. Mahdavi and Doppelbauer (2010) provide information on passive house design and the influence of high insulation and low ventilation losses on the indoor environment. They conclude that space heating requirements can be reduced to 10W/m^2 by using effective insulation, low ventilation losses through air tight building and ventilation with heat recovery and by maximising winter solar gain. Wall constructions with a U-value of less than 0.15W/m^2K and windows with a U-value of less than 1.0W/m^2K are becoming viable options in the building industry and hence designing to the highest thermal insulation standards is a significant step towards achieving a zero-carbon building.

Minimising infiltration losses by assuring high standards of construction and using systems such as Insulated Concrete Form (ICF) is important coupled with heat recovery in the ventilation system which can reduce typical ventilation losses by up to 90% (Segen 2006). The inclusion of the mechanical ventilation and the subsequent reduction in heat demand is a necessary trade-off with additional electricity demand.

The quantity of Domestic Hot Water (DHW) to supply is not specified in the CSH, although a limit of 80litres/person/day of (the sum of hot and cold) potable water is applied for the application of code level 6. This is achieved by a combination of water saving faucets, smaller baths, etc. and the use of grey water.

The combustion of biomass in boilers or combined heat and power (CHP) plant is a low-carbon alternative to the preferred zero-carbon heat that can be generated either by the application of solar photovoltaic arrays (PV) or wind turbines used to generate electricity to drive heat pumps (HP), or by solar thermal collectors (STC). The only space available for solar collection is the roof where approximately 25m^2 is available for solar collection per home. Practical field tests for an optimised system with sufficient thermal storage show an annual yield in the UK of 1000 to 1500 MJ/m^{2}year (Martin and Watson 2001) on a 30º pitched roof due south. Lower pitched roofs combined with limited storage will show a lower yield, especially in winter. With a DHW requirement of approximately 5500 MJ/year (1528 kWh/year) 20% of the roof space should be sufficient to cover the demand for DHW.

To fulfil the electrical energy requirement for zero carbon dwellings, all the electricity consumed by the building has to be generated without carbon emissions. Allen and Hammond (2010) found in their analysis that the combination of a micro-wind turbine and a solar PV system can completely displace the need for electricity from the grid. Wind generation, however, has also been shown to cause noise problems and have a low yield in urban locations (Watson et al. 2008). Numerous papers have been published on the yield of PV, for example: Allen and Hammond (2010), Ren et al. (2010), James et al. (2010), Bahaj and James (2007); and with a specific focus on urban environments by Steemers (2003), Tian et al. (2007) and Compagnon (2004). Huld et al. (2008) show that a typical yield of a PV system in the UK is around 750-800 kWh/year per kWp-installed power. This yield may meet the electricity demand for a compact urban home, but it competes for roof space with the solar thermal energy collection and so practically the demand for heat and power is unlikely to be met from solar collection from the roof alone.

The CSH states that code level 6 can be achieved by '…Using low and zero carbon technologies such as solar thermal panels, biomass boilers, wind turbines, and combined heat and power systems (CHP). It would mean for example that energy taken from the national grid would have to be replaced by low or zero carbon generated energy, so that over a year the net emissions were zero. …'. The conversion factors paper from the Department for Environment, Food and Rural Affairs (2011), however, states that all bio-fuels generate a certain amount of carbon emissions and are therefore not strictly speaking carbon neutral, but have lower CO_2 emissions than fossil fuels. To comply with the code level 6 standards, any CO_2 produced by the combustion of bio-fuels would still need to be offset such that the net emissions are zero over a year.

Biomass fuels can be obtained in (liquefied) biogas, liquid (waste vegetable oil) or solid (wood, elephant grass) forms. Space is at a premium in the urban environment, so the fuel with highest energy density is likely to be favoured. Solid fuels such as wood have an energy density of 2.5MWh/m^3, liquid gas such as LPG 7.0MWh/m^3 and waste vegetable oil approximately 10.0MWh/m^3 (BINAS 1998), making this a likely candidate fuel. In addition, there is a distribution network available, no requirement for pressurised storage of vegetable oil and the conversion to heat and/or electricity through micro-CHP is well established. When considering the use of biomass feedstock as an energy source, fuel availability and price volatility are issues to be considered. For cogeneration purposes, bio gas is currently in limited supply with an immature distribution network. However, if in future sufficient biogas becomes available with a well established distribution network, this might become an option for generation of zero-carbon thermal and electrical energy. Solid bio fuels are currently widely available on the market; however, small commercially available solid bio fuel plant can only convert this energy into thermal energy, leaving out the flexibility to generate electrical energy. For these reasons, notwithstanding the aforementioned constraints, liquid bio fuel in the form of waste vegetable oil is the chosen option.

The CSH does not give any reference to the expected energy consumption of dwellings through lighting and small power, although credits are earned for the use of efficient appliances and lighting systems. A key challenge in designing a building to deliver zero-carbon performance is understanding the range of consumption that can reasonably be expected in-use and the idea of a 'performance envelope' has been proposed (Steijger et al, 2012). This is particularly important since a study by Richardson et al. (2010) showed a tenfold difference between the lowest and highest electricity usage in comparable dwellings, which has a significant impact on the determination of the balance of the generation technologies for a specific building. Achieving zero-carbon in practice can only be achieved if realistic assumptions are made with regard to the demand. Once a building and its systems are complete the only recourse for a building that doesn't operate at zero-carbon is to reduce the energy demand in-use which is challenging since this is only likely to be achieved through long term education of the occupants (Bahaj and James 2007, Keirstead 2007).

In summary, achieving the CSH level 6 in compact urban dwellings is challenging principally due to the constraints on building orientation, height, roof area and pitch and the limited space for the generation equipment, thermal and fuel storage. The problem is compounded for the designer by the lack of benchmarks and targets to indicate realistic occupant led demand. These include:

- **internal air temperature**, affecting the space heating load through variations in control and thermostat settings;
- **hot water demand and consumption profiles**, although minimised with efficient devices, this is still largely dependant on the occupant; and
- **lighting and small power**, again minimised through efficient devices, but usage still led by the occupant.

Apart from the obvious contribution to the UK government's CO_2 reduction targets, the CSH highlights the benefit of lower energy bills in rated properties and this is a key selling point property developers use to attract customers. While some degree of occupant education on effective use of the systems with in a zero-carbon property is necessary, obtaining the correct balance of the provision of electricity and heat (in particular) while placing practical limits on the supply is critical to whether the building will be judged successful by the occupants. This lack of guidance hampers the designers job of determining sensible values on which to base the analysis of the mix of zero and low carbon generation technologies.

The rest of this paper focuses on a real compact urban housing development that was constructed in 2011. The building is introduced and the assumptions in the analysis are discussed. These lead to an analysis of the CO_2 emissions performance of various mixes of generation technologies.

3 DESCRIPTION OF THE CASE STUDY BUILDING

The SHINE-ZC building in Derby (UK) comprises of 9 adjacent compact urban dwellings; six 2-storey houses and a 3-storey block containing three flats and a shared staircase. Each dwelling has a living space of approximately 50 m^2. The total internal volume is 1326 m^3. The dwellings are adjoined as shown in Figure 5 and Figure 6.

Figure 30: Render of the development (Simon Foote Architects 2008).

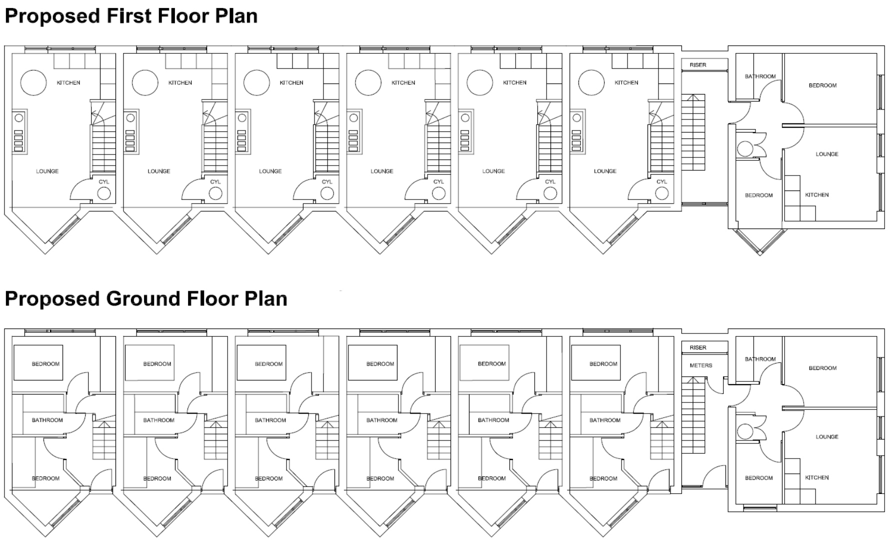

Figure 31: Floor plans of the dwellings (Simon Foote Architects 2008).

The front of the building faces approximately north, dictated by the shape of the site. The roof area is split in two levels; approx. 160 m^2 on the houses and 70 m^2 on top of the flats. Due to planning height restrictions the 230 m^2 roof faces south with a 6 degree slope, rather than the 40º south facing slope that is deemed ideal in terms of solar collector yield for this latitude (Energy Saving Trust 2004).

The wall material is constructed with Integrated Concrete wall Form (ICF), a layered and highly insulating construction comprising of 150mm of expanded polystyrene, 150mm structural concrete, another 75mm of styrene and the internal surface is plasterboard with a skim coat 15mm thick. The external surface has either 10mm thick wooden cladding or 10mm render, depending on the location on the building (see Figure 1). The resultant U-value is ~0.12W/m^{2}K. The construction quality was closely managed and on-site air permeability tests estimated air permeability less than 0.35 air exchanges per hour for each dwelling during operation. The windows are triple glazed, with a U-value of 1 W/m^{2}K. The solar gain in winter is minimal (<50 W) due to the shading of adjacent buildings, but the solar gain needs to be limited to prevent overheating in the summer as the internal gains are expected to provide enough heat to maintain the desired space conditions for all but the coldest parts of the year. The solar gain is limited by placing the majority of the windows on the north side of the building, whilst south facing windows are shaded in summer by an overhanging roof ridge and adjacent buildings.

The building is designed to have warmer living spaces and cooler bedrooms by placing the living space on the first floor and the bedrooms and bathrooms on the ground floor. An overview of the key design parameters for the building is given in Table 6.

A critical part of the building is the thermal store which is required to buffer the heat produced from the generation plant and the demand for heat. The capacity and configuration of the thermal store has a significant impact on the performance and operational characteristics of the generation equipment. The choice between a single large store and smaller distributed thermal stores is complicated (Grondzik et al, 2010, Knoll and Wagenaar, 1994). Various factors like charging regime, heat losses and control need to be considered. In this case study, a distributed system has been chosen. The decision to go for a number of separate stores over a single store was made based on the concern for electrical power required for the circulation pump and lags in the supply of hot water that has been shown to be an issue with larger centralised systems (Knoll and Wagenaar, 1994). This was a decision made early in the design since it has an impact on the provision of volume required to house it and hence on the architectural layout of the building.

In this building individual thermal stores provide the space heating and DHW capacity for each dwelling, a 315 litre water tank per apartment that is heated through circuits serving each generation device. The space heating is drawn directly from the tank and the DHW extracts heat from the tank via a coil of copper piping acting as a heat exchanger. Space heating is provided through radiators, each with a thermostatic radiator valve (TRV) for individual room air temperature control. The space heating in each dwelling is also controlled by a central thermostat located in the hallway of that dwelling which switches a circulation pump to circulate water heated by the thermal store through the radiators. Figure 32 depicts the arrangement of the heat and electricity supply for the building.

Table 6: Key parameters of the building.

	End house	*Middle houses*	*Bottom flat*	*Middle flat*	*Top flat*

Number of units	1	5	1	1	1
Floor area (m^2)	55	55	42	44	46
Volume (m^3)	140	140	105	110	115
External wall area (m^2)	75	45	47.5	50	52.5
Window area (m^2)	8.5	8.5	5.5	6.5	6.5
Roof area (m^2)	30	30	-	-	70
Ventilation rate (exch./hr)	0.53	0.53	0.93	0.93	0.93
Heat loss fabric (W/K)	21	18	13	11	15
Ventilation heat loss (W/K)	17	17	17	17	17

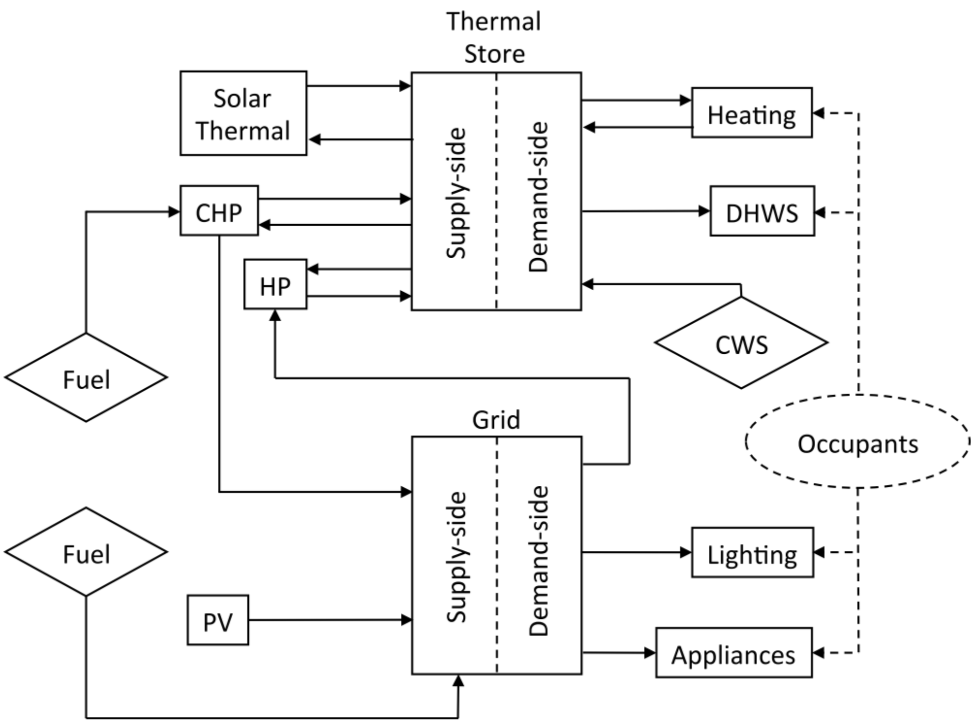

Figure 32 the arrangement of the building heat and electricity generation options.

4 MODELLING ASSUMPTIONS, ISSUES AND CONSTRAINTS

TRNSYS Version 16.01.003 (Klein et al, 2007) was used to investigate the influence of heat and electricity demands on the on-site zero carbon generation performance of a number of generation options. Each of the six houses was divided into two zones per house, one upstairs and one downstairs. Each of the flats and the staircase was modelled as a single zone. There are a number of stages to the analysis discussed in this section:

- modelling the building fabric and systems;
- selecting the appropriate capacities of the plant;

- establishing the demand profiles as inputs to the simulation; and,
- handling the interdependencies of heating and electricity generation and demand.

The detail of the characteristics of the occupancy, heating, DHW supply, lighting and small power use for each dwelling used in the analysis is important. Since the CSH does not give any limits or benchmarks to the consumption of energy, the design of the appropriate generation systems is challenging and this is a significant omission in the code. Therefore the UK BREDEM standard methodology (Anderson et al, 2001) was used to set the operating points. The analysis presented here is based on a pragmatic approach to establish the simulation input to gain insight into the problem, before applying full dynamic simulation. Using more detailed representations of these inputs and including these into the dynamic modelling of the systems and their control might generate a better estimate of the in-use performance, but is this beyond the scope of this paper.

4.1 OCCUPANCY

Anderson et al. (2001) describe occupancy during the daytime as 7:00 to 9:00 and 16:00 to 23:00 hours. The heat gain for one person seated at rest is added to the living area of the dwelling (the top floor in the houses). During the night (23:00 till 7:00) the internal heat gain is calculated as one person’s heat gain (seated at rest, (CIBSE 1986)) added to the bedroom (the bottom floor in the houses). The dwelling is not occupied from 9:00 until 16:00 hrs.

4.2 INFILTRATION, VENTILATION AND AIR MOVEMENT

Infiltration was considered to be small (0.35 ACH) during occupation. Ventilation is provided by a mechanical ventilation and heat recovery (MVHR) unit. For purpose of assessing the heat losses by the MVHR, ventilation rate is reduced by the efficiency using the manufacturer’s performance benchmark data as described by Taylor et al. (2010) “*the thermal effects of ventilation heat recovery can be simulated precisely by reducing the ventilation rate by the proportion of heat recovered*”. The ventilation rate is as required by the UK building regulations which is 17litres/second/dwelling (Office of the Deputy Prime Minister 2006). The heat recovery rate is specified to be 90 % (Segen, 2006) In summer the MHVR will run to provide ventilation. When the room air temperature is above 24ºC (maximum acceptable temperature according to the CIBSE guide 1985), the extract air bypasses the heat exchanger. It switches the heat recovery on again when the temperature drops below 22 ºC. A lower temperature is not possible as the reference temperature for heating is set to 21 ºC according to the BREDEM method (Anderson et all, 2001). The electrical power used to drive the fan and the heat generated by the heat recovery are added to the internal gains according to the BREDEM method.

4.3 ELECTRICITY DEMAND AND ELECTRICAL INTERNAL GAIN

Since the CSH does not specify the electrical demands and the CO_2 consumption is based on a net-annual value, the BREDEM model (Anderson et al. 2001) is used to estimate the yearly consumption; 2288 kWh per dwelling. This approach does not cover the full performance envelope (Steijger et al, 2012) but does give a point to which a comparison of systems can be based. This value represents the total energy requirement including cooking, electrical lighting, white goods and portable equipment for the complete building. A base load of 75 W was estimated for the MHVR unit and electricity required for the fridge-freezer. Working backwards from the target of 2288kWh, subtracting the base load of 75W running 24 hours, 365 days of the year, leaves a load of 496 W during occupied hours, taken to be 07:00 until 09:00 and 16:00 until 23:00. 75% of the load is assumed to be consumed in the living area (first floor). The base load is 25% lower than the base load as established by Yao and Steemers (2005) and the assumption was made due to the higher efficiency of the appliances and lighting. Seasonal variations were not considered as stated in the BREDEM model and apart from the energy consumed in extract fans, internal heat gain to each apartment is equal to the electricity used for appliances and lighting together with 90% of the energy required for cooking (Anderson et al, 2001). More elaborate load profiles are available, e.g. from Richardson et al, (2010) but the influence of these on the space heating, due to the time constants involved, are limited. Hence a simple load profile was adequate for this study.

4.4 HEATING SET-POINTS, CONTROL AND SCHEDULING

The code for sustainable homes does not define the internal comfort settings for the dwellings. Therefore the BREDEM temperature settings have been used (Anderson et al, 2001). The default space heating setting is 15ºC during the night (23:00 until 7:00 hours) and non-occupied hours (9:00 until 16:00 hours); and 21ºC during the occupied hours (7:00 until 9:00 and 16:00 until 23:00 hours). The space heating input to the living spaces are calculated from the radiator models described by Knoll and Wagenaar (1994). The radiator control time constants determined the time step for the simulation, which was set at 1 minute.

4.5 DHW STORAGE, DRAW OFF AND SCHEDULING

The thermal storage is provided by a water tank in each dwelling. These have to be large enough to provide one day of energy for space heating and DHW and small enough to fit in the limited dwelling space. Practical limitations on the size of the thermal energy storage require a larger temperature fluctuation in the tank to enable sufficient diurnal thermal energy storage. The CHP and flat plate solar thermal collectors can provide high temperature thermal energy (albeit for the solar thermal collectors with a dramatic efficiency drop) up to 95 ºC to prevent boiling of the water, so to store this energy this temperature is the upper limit. No more thermal energy can be stored if this temperature is reached, and therefore the thermal energy provided by the CHP or solar thermal is wasted. Given that the UK DHW supply temperatures are typically 48 ºC or above, the thermal stores are taken to be able to supply no useful heat if the bulk water temperature drops below 50ºC. A 315litre tank per dwelling can provide a full day’s heating and hot water demand in the UK Midlands 99% of the time under standard CIBSE (1986) usage levels if the bulk temperature in the tank is fluctuating with 45 ºC. The assumption is that the majority of this water is used for personal hygiene and therefore has a temperature of 40ºC at the draw-off points. The cold water supply is assumed to be 10ºC and mixed with the water from the tank to supply at 40ºC at the required flow rate. According to the health and safety executive (2009), to avoid legionella hot water should be stored above 60 ºC and transported above 50 ºC. Using a coil in the tank for heating the DHW avoids the storage problem (less than 3.2 litre is stored), and heating up the tank to at least 70 ºC once a month for sterilisation and the minimum temperature setting in the tank ensures that legionella is controlled.

The CSH requires that for a level 6 dwelling the potable water consumption must be less than 80litres/day/person. The dwellings are considered here to be single occupancy and since the

DHW system uses potable water it is assumed for the sake of capacity sizing and heat supply that the whole 80 litres is drawn off as hot water each day.

The BREDEM calculations use the same water volume, but it does not suggest a water draw-off pattern. The toilets and washing machine will use gray water. It is also assumed that half of the domestic hot water is used in the morning (between 7:00 and 8:00) and half in the evening (between 18:00 and 19:00).

4.6 HEAT AND ELECTRICITY GENERATION OPTIONS

Solar thermal collectors, photovoltaic panels, air-source heat pumps and a bio-fuelled, micro-CHP where considered in this analysis. Watson et al (2008) stated that wind generation has a very limited yield in an urban setting and bio-mass boilers were not considered in this particular case, preference being given to micro-CHP since it generates electricity as well as heat. Ground source heat pumps were also not considered because the available area for horizontal evaporator coil was limited and the commercial viability of installing vertically drilled systems was prohibitive.

If the most common type of PV array (crystalline silicon) is used, Bayod-Rújula et al (2010) show that around 9m^2 of roof space is required to install 1kWp of PV panels. With 230m^2 of roof space, a maximum installation of approximately 25kWp can be installed. TRNSYS standard library type 194b with inverter is used to determine the yield of the photo-voltaic array.

There is a range of heat to power ratios for CHP from 10:1 (Whispergen, 2010) to 2:1 (Baxi Dachs mini CHP, 2010). A small diesel CHP, however, can reach a 1.5:1 heat to electricity ratio (Tipkoetter BioGenio, 2010). Additional thermal losses with the operation of these small CHP can be high (30% is not uncommon). The total efficiency of the CHP is assumed to be 35% electrical output, 35% effective thermal output, 30 % thermal losses and hence a limiting case of 1:1 heat to electricity has been taken here. With a typical thermal time constant of a CHP of three minutes (running under full load immediately after start, reducing the warm up time) and generally if the CHP is started once a day and usually runs un-modulated for longer than two hours to deliver the heat to the 9 thermal stores (2.8 m^3 water), the run time is much larger (>50 times) than the start-up time and so the start-up and shut down time constants have been neglected. The store capacity should be sufficient to deliver the thermal energy whilst only being charged once a day; more frequent charging will have a negative effect on the overall heat delivery of the CHP. As we do not have the exact losses as relation to the running temperature, the complexity of the control and accurate modelling of all the pipe work in the dwelling, we assumed a relative high initial thermal loss to accommodate this variation i.e. a worst case scenario, which is sufficient to meet the objective of this paper.

Heat can also be generated by the solar thermal array. The solar thermal panels are modelled using the theoretical flat plate collectors, type 73 based on a Hottel-Whiller steady state model. One of the main parameters affecting the yield of the STC’s is the temperature of the fluid entering the collector, coming from the bottom of tank with the lowest temperature. The higher this inlet temperature, the lower the yield. Solar thermal energy is transferred from the collector into the tank if at least one of the tanks has a sufficiently low temperature, measured at the bottom of each tank. No heat is added to the tanks if the tanks are completely charged and the heat is wasted, resulting in a lower yield of the solar thermal system.

Cabrol and Rowley (2011) showed that heat pumps can be effective in low carbon dwellings; hence heat pumps are used as an alternative way to heat up the storage tanks. The power consumption and the Coefficient of Performance (COP) was modelled for a standard heat pump with a rated COP of 3.5 and a high performance heat pump with a rated COP of 4.3 under standard conditions described in Steijger et al, (2010) and Sparn et al. (2011). The maximum temperature the heat pump can deliver is 65ºC, hence the heat pump switches off when the bottom node in each of the storage tanks reach this temperature. The electrical power consumed by the heat pumps needs to be offset by either the PV array or micro-CHP. The start up time constant for an air source heat pump is approximately 40 seconds (Steijger et al., 2010) and since the time to charge the thermal stores is very much larger (larger than 2000 seconds) typically the unit would be expected to run for 30 minutes or more and hence the start up dynamics have been neglected in this analysis.

5 BUILDING DEMAND CHARACTERISTICS

There are a number of dependencies on the generation of heat and power: the micro-CHP generates both heat and electricity simultaneously and the ratio is a fixed characteristic of the equipment; the HP provides heat, but must be supplied with electricity; and the PV and STC compete for roof space and hence affect the ratio of zero-carbon heat and electricity production that can be achieved. Lastly the heat gain generated by the consumption of electricity in the dwellings affects the heat demand for space heating and specifying the system capacities and operational parameters is challenging. In addition, where more than one renewable option is applied, the interdependency of the demand for electricity and heat coupled with the interdependency of generation complicates the issue.

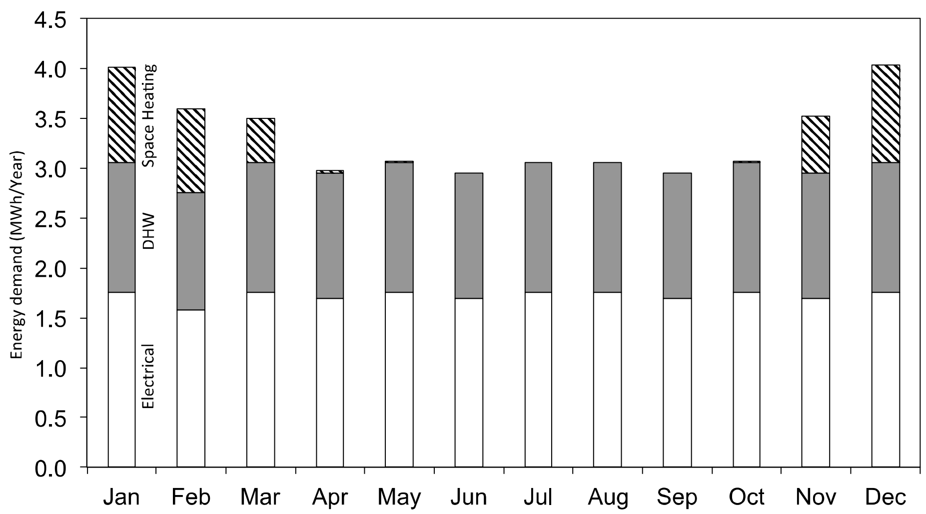

Figure 33 Estimated energy demand for the whole building.

Figure 33depicts the total electrical, DHW and space heating demand for each month for a typical year. The total annual energy demand is 19.2MWh for the whole building. Approximately one third of the electrical demand is for cooking, 15.3MWh of DHW demand and just 3.8MWh for space heating.

Highly insulated buildings such as this one require little heating and the internal gains play a significant role in maintaining the internal air temperature. The use of electrical appliances is a significant source of heat and the amount of electricity consumption can vary significantly. Richardson et al. (2010), for example, observed a tenfold difference in electricity use between the same type of properties. The results from 24 annual simulations are plotted in Figure 34. Each point in the graph is the summation of the heating demand for varying electrical loads and for four DHW draw-off cases, 0.0litres/person/day to 120.0litres/person/day. The four lines represent the different the space heating demand with the different DHW cases. The affect of the increasing electrical load on the annual heating demand can be seen as a reduction in heating. The BREDEM value of 20.6MWh electrical demand and 19.1MWh heat demand is indicated with the black dot.

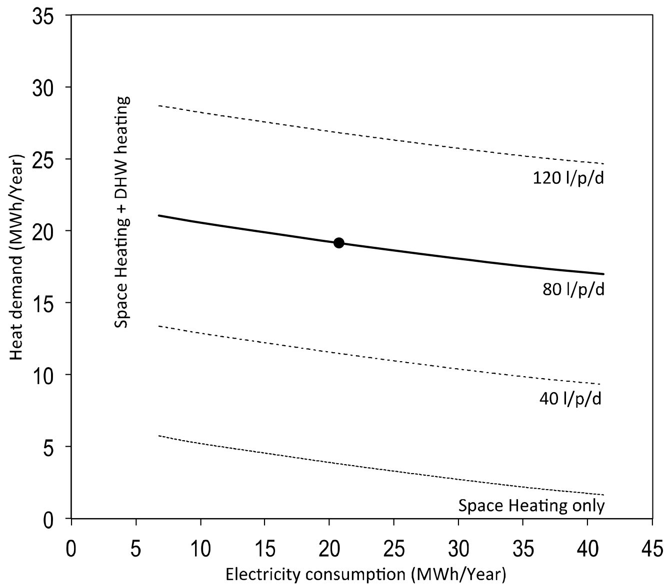

Figure 34 Annual thermal energy demand in relation to the annual electrical demand.

6 HEAT AND ELECTRICITY GENERATION CHARACTERISTICS

Since both electrical and heating energy can be generated on the roof, it is useful to look at the trade off characteristics between PV and STC. The electrical generation of the PV is taken to be proportional to the array area and the simulation confirms the findings of the literature, in that each kWp installed on the roof generates around 750-800 kWh per year for this location. The pitch of the roof is low, only 6° and hence for this building, only 741kWh is generated for every kWp installed.

The variation of the heat output of the STC is a function of roof area and the collector inlet temperature, which is dependant on the temperature coming from bottom node of the thermal stores. The relationships in Figure 6 are similar to those published by Brinkworth (2001) who derived a set of plots using the storage capacity and the collector area as variables. The left hand plot depicts the results of 12 simulations with varying STC area and DHW draw-off, since the rate of water draw has an impact on the energy stored. The higher use of DHW empties the thermal store allowing the heat to be replenished, hence increasing the yield from the STC.

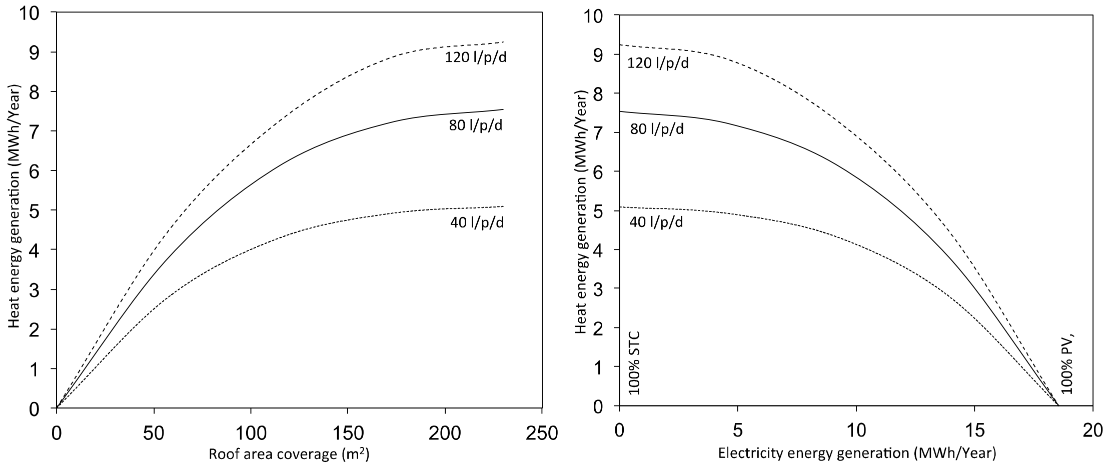

Figure 35 Yield of solar thermal as function of roof coverage and DHW draw (left) and the electricity to heat, roof generation trade-off characteristics (right).

A further 12 simulations were run varying the ratio of area covered by the PV arrays and the STCs on the roof from 0% PV, 100% STC to 100% PV, 0% STC. The right hand side of Figure 35 depicts the electricity to heat trade-off characteristic generated for this building. Note from Figure 34 that the annual BREDAM based estimates of electricity and heat consumption are 20.6MWh and 19.1MWh respectively. If the whole roof were covered with PV, the yield would be around 18.5MWh, or ~90% of the electrical demand of the building, as shown in Figure 6. The main observation is that neither PV nor STC can supply 100% of the electricity and heat demand, even when 100% of the roof is covered with one or the other technology and so additional low-carbon heat and electricity generation is required.

Simulations were run to generate the seasonal performance of the high and standard performance air source heat pump over a number of operating strategies. The seasonal performance was calculated by,

$$SPF = \frac{\sum E_{thermal}}{T_{running} P_{in}} \qquad (1)$$

where SPF is the Seasonal Performance Factor (-), $E_{thermal}$ is the heat output of the heat pump at every time step in the run period (kWh), $T_{running}$ is the time that the heat pump is running (hrs) and P_{in} is the electrical input power (kW). As part of the analysis, a number of HP scenarios were run to explore the variation in seasonal performance factors that could be expected in operation. Both standard and high performance HPs were run with the condenser water flow temperature set to 55ºC and 65ºC. The flow temperature from the condenser impacts on the heat that can be exported to the thermal store, which is dependant on the temperature of the store. Decreasing the temperature of hot water supply increases the SPF of the HP, hence reducing the electrical energy required to generate the thermal energy. In addition, if the heat pump is not needed all year for heat production, i.e. used in combination with STC or a micro-CHP, then its operation could be restricted to those times when it is at its most efficient for generating DHW; i.e. during the warmer months of the year.

The calculated seasonal performance factors are summarised in Table 2. There is a significant range of SPF from 1.64 to 3.82. Making use of the higher SPFs is only likely if the configuration of the plant does not need the HP running during the colder periods. Replacing the heat pump with a better performing type will increase the performance, however, the improvement is not as large as reducing the flow temperature set point to 55ºC. Figure 7 plots the two bounding cases from Table 2, shown with the negative gradient on the left hand side. The length of the vector defines how much energy is converted from electricity to heat and is proportional to the number of running hours. The values on the *x* axis and *y* axis are the electricity and heat generated, respectively.

Table 2. SPF for a standard and high performance heat pump with two water flow temperature set points for a range of operational strategies

Running period Restricted to:	Seasonal performance of the heat pumps Standard 65ºC	Standard 55ºC	High Perform. 65ºC	High Perform. 55ºC
Whole year	1.64	2.33	1.89	2.66
Mar – Nov	1.68	2.58	2.09	3.01
Apr – Oct	1.72	2.78	2.28	3.33
Jun – Aug	2.10	3.15	2.59	3.82

On the right hand side of Figure 36 is also plotted similar electricity/heat characteristics for two different types of micro-CHP. The CHP converts (in this case) vegetable oil into both thermal and electrical energy, the ratio of which is determined by the plant. The limiting cases here are taken to be 1:1 to 10:1 (heat to electricity). Again, the length of the vector is proportional to the number of running hours and is also proportional to the amount of vegetable oil used. Note that since a gas boiler, bio-mass boiler or STC do not generate any electricity, they would be represented by a vertical line extending upwards along $x = 0$ from the origin of the plot to the appropriate value of annual heat generation: PV extends horizontally rightwards along $y = 0$, to the appropriate value of annual electricity generation since it does not produce heat.

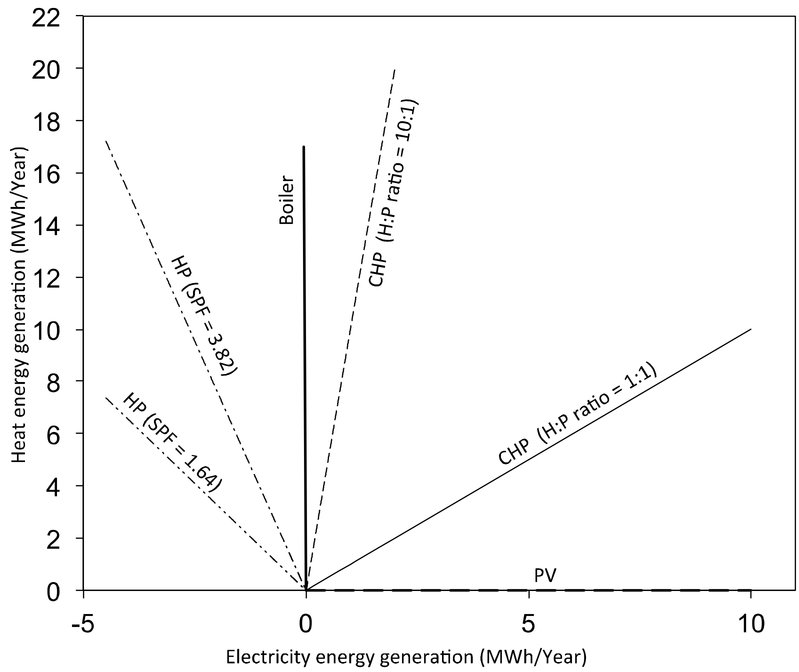

Figure 36 Thermal generation as a function of electrical power consumption/production with different type of generation plant.

7 HEAT AND ELECTRICITY GENERATION OPTIONS

The heat/electricity generation characteristics depicted for the generation equipment in Figures 6 and 7 can be used in isolation, or in combination to determine the annual total building CO_2 emissions (tonnes CO_2/year), ϕ ,

$$\phi = \Delta\varepsilon\phi_{grid} + \frac{\Delta\theta\phi_{gas}}{\eta_{boiler}} + \frac{\tau_{chp}\mu_{chp}\phi_{veg\_oil}}{\eta_{boiler}} \qquad (2)$$

where $\Delta\varepsilon = \varepsilon_{gen} - \varepsilon_{dem}$, the difference between the annual generation of electricity and the annual electricity demand (MWh/year) and ϕ_{grid} is the carbon intensity factor for grid electricity (kg CO_2/kWh). If the installed generation equipment does not produce the electricity required, grid electricity is used to make up the difference. Conversely if there is a surplus of electricity generated, the carbon emissions from the buildings will be negative, indicating an offsetting of carbon generated by the grid. $\Delta\theta = \theta_{gen} - \theta_{dem}$ is the difference between the annual generation of and demand for heat in MWh/year and ϕ_{gas} is the carbon intensity factor for natural gas. Surplus heat generated is dumped and hence a waste of energy. If the generation equipment does not produce sufficient heat it is assumed that this is achieved by burning natural gas in a conventional boiler plant. The energy demand is factored by the boiler efficiency, η_{boiler} η_{boiler}. Finally, if low carbon generation devices are used such as CHP or biomass boilers, the release of CO_2 from the fuel must also be considered. In this case only CHP has been considered in the analysis and hence τ_{chp} τ_{chp} and μ_{chp} μ_{chp} give the run time (hrs) and the fuel consumption (m^3/hr) and again factored by the efficiency (η_{chp}) and the carbon intensity factor ϕ_{chp}. In order to achieve true zero carbon performance, the over production of electricity and subsequent net export to the grid is required in order to offset the emissions from the combustion of vegetable oil with the relatively higher emissions of the grid generated electricity. The conversion factors for grid electricity, gas conversion and waste vegetable oil are taken from (Department for Environment, Food and Rural Affairs 2011) and given in Table 3.

Table 3: Carbon intensity factors (φ) for electricity and heat generation.

Source	**Carbon intensity factors ϕ (kg CO_2/kWh)**
Natural Gas	0.18
Grid Electricity	0.52
Vegetable Oil	0.14

$\Delta\varepsilon$ $\Delta\varepsilon$ and $\Delta\theta$ $\Delta\theta$ are derived from characteristic plots that depict the annual generation characteristics of the equipment. These have been derived from the simulation and hence implicitly represent any operational characteristics that are due to control set-points and strategies, capacities, etc. Figure 37 shows two plots: the left with the high performance HP, running all year with a water flow temperature of 55°C; and the CHP characteristic lines for the 1:1 heat to power generation plotted. The right plot details the STC/PV trade-off curve from Figure 6 for the BREDAM case of 80litres/person/day DHW draw-off. On both plots is plotted the target (BREDAM) heat/electricity demand indicated by the large black dot: this is the target value, if the generation line crosses through the demand point there is no over or under generation and the demand is satisfied. The CHP in the first plot demonstrates that the CHP alone when run for 2350hrs can satisfy the electrical demand, but with a ~ 1.4 MWh/year over production of heat. The HP uses electricity to generate heat and requires ~8.2MWh/year in addition to the 20.6MWh/year required to satisfy the electrical demand from appliances. The right hand plot demonstrates that on this building the limited roof space means that the target demand for electricity and heat cannot be met with either PV or STC.

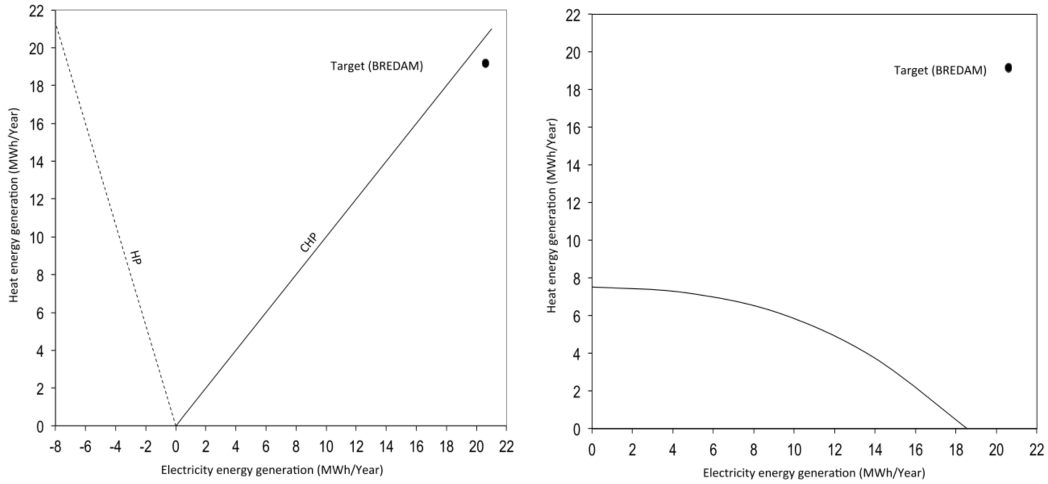

Figure 37 Single and roof generation demand deficit characteristics.

This way of representing the analysis can be extended to include multiple generation devices. Figure 38 depicts the characteristics of a number of combinations of equipment and the resultant generation demand deficit.

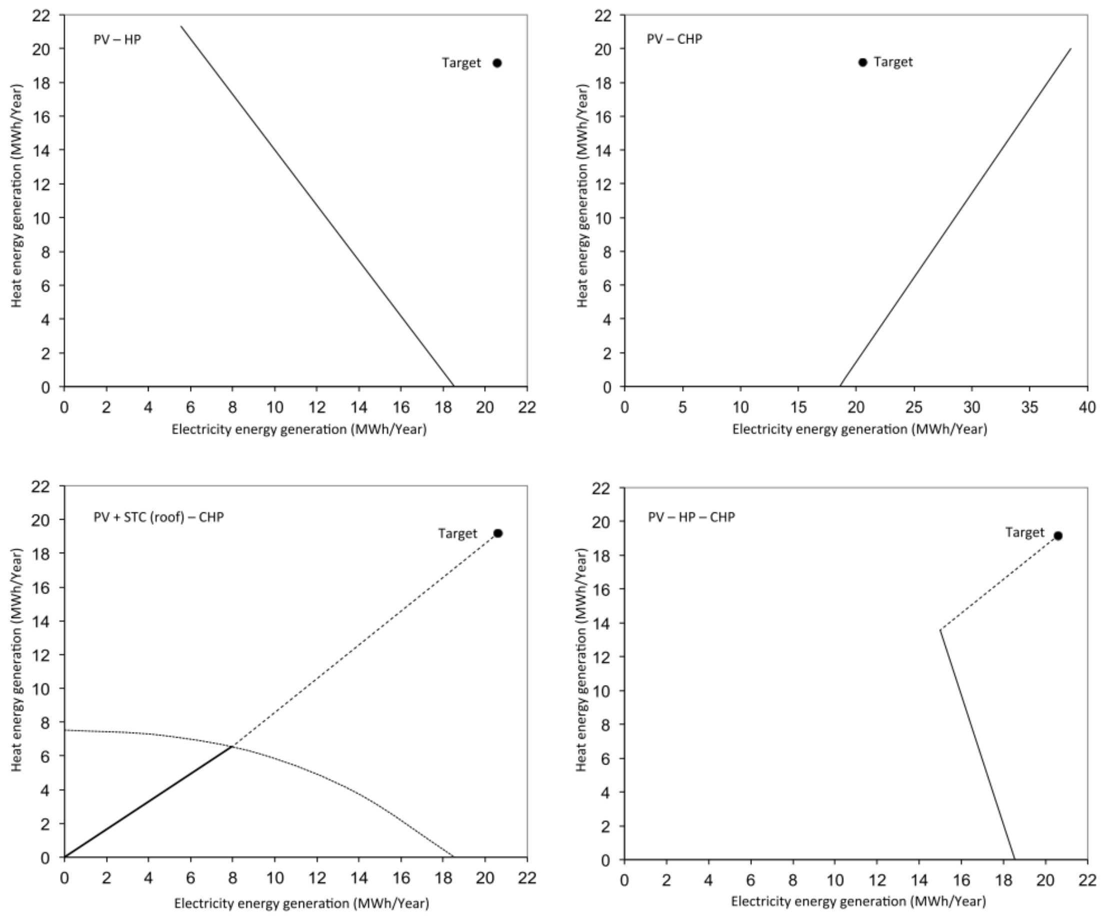

Figure 38 Multiple generation demand deficit characteristics.

Figure 38 depicts four plant combinations. The top two plots show two, two-technology options, PV and HP and PV and CHP and both configurations utilise a 100% of the roof area covered with PV. The former option has a generation deficit $\Delta\varepsilon = 13.7$ $\Delta\varepsilon = 13.7$ MWh/year, while the latter option has a heat generation deficit $\Delta\theta = 17.1$ $\Delta\theta = 17.1$ MWh/year, although the CHP can be run for longer to deliver the required heat and provide a surplus of $\Delta\varepsilon = -27.1$ $\Delta\varepsilon = -27.1$ MWh/year electrical energy, which may be desirable, depending on feed in tariffs.

The bottom two plots in Figure 38 depict three-technology options. The option on the left uses a combination of PV and STC on the roof the balance of which is determined by the selection of the CHP. In the plot the dotted line mirrors the relationship between PV and STC yield in Figure 6. The solid line represents the combined heat/electricity generation from the roof-installed technologies. The dashed line depicts the CHP generation. Here a CHP with a heat:power ratio of 1:1 has been selected, which determines the gradient of the dashed line. Following this line down from the target intersects the PV/STC characteristic line, determining the appropriate balance of roof generation technologies to be 44% PV and 56% STC. The length of the dashed line represents the CHP running time and hence the quantity of fuel used: this line is shorter than the CHP lines in the top right plot and in the bottom left plot, reflecting the reduction in vegetable oil used.

The last plot in Figure 38 shows the second of the three-technology options. The additional PV on the roof, a 100% in this option, is used to offset the power required for the heat pumps shown by the solid line. The dashed line shows the additional heat and electricity generation provided by the CHP, producing 5.6MWh/year of heat and the same of electricity. The reduction of the CHP run time between this option and the former option is due to the additional heat generated by the HP and this significantly reduces the vegetable oil required and hence the CO_2 produced. The bottom right option depicted in Figure 9 is the least carbon intense configuration possible for this building.

Expanding the generation equipment combination options, Table 4 details the balance of heat and electricity generation and demand for each of these and gives the annual CO_2 produced in each case. A value of 100% shows that all of the thermal or electrical demand is met by the onsite energy system, a value of 0% shows that none of the thermal or electrical demand is met. A negative value shows that the configuration increased the electricity demand required (i.e. to power a HP). A value greater than 100% shows a surplus generated: Electricity is exported to the Grid, but Heat is assumed to be dumped to atmosphere, the CO_2 emissions, however, are added to the total. Overruns of plant to achieve the production of electricity while dumping heat or vice-versa is not considered in this analysis, although is a viable option.

Table 4: Summary of onsite thermal and electricity generation options for the SHINE-ZC building.

	Solution code	Onsite energy system	Capacity	Operational time	Percentage of base-case building energy demand supplied by onsite energy systems[1]		Annual total building CO_2 emissions[3] (tonnes CO_2/year)
					Thermal	Electrical	
Single option	Base-case	Gas boiler	20 kW	Jan – Dec	100%	0%	14.32
	HP	Heat pump	20 kW	Jan – Dec	100%	-35%	14.58
	CHP	CHP	22 kW	Jan – Dec	107%	100%	8.05
	STC	Solar thermal	230 m^2	Jan – Dec	47%	0%	12.67
	PV	PV	25 kW_p	Jan – Dec	0%	90%	4.59
Two options	HP-STC	Heat pump	20 kW	Jan – Dec	53%	-18%	12.80
		Solar thermal	230 m^2	Jan – Dec	47%	0%	
		Total	-	-	100%	-18%	
	HP-PV	Heat pump	20 kW	Jan – Dec	100%	-35%	4.85
		PV	25 kW_p	Jan – Dec	0%	90%	
		Total	-	-	100%	55%	
	CHP-STC	CHP	22 kW	Jan – Dec	61%	56%	9.25
		Solar thermal	230 m^2	Jan – Dec	39%	0%	
		Total	-	-	100%	56%	
	CHP-PV	CHP	22 kW	Jan – Dec	11%	10%	3.94
		PV	25 kW_p	Jan – Dec	0%	90%	
		Total	-	-	11%	100%	
Three options	CHP-STC-PV	CHP	22 kW	Jan – Dec	66%	61%	4.92
		Solar thermal	130 m^2	Jan – Dec	34%	0%	
		PV	10.75 kW_p	Jan – Dec	0%	39%	
		Total	-	-	100%	100%	
	HP-CHP-PV	CHP	22 kW	Dec – Feb	29%	27%	2.19
		HP	20 kW	Mar – Nov	71%	-17%	
		PV	25 kW_p	Jan – Dec	0%	90%	
		Total	-	-	100%	100%	
	HP-STC-PV	HP	20 kW	Jan – Dec	50%	-18%	6.94
		Solar thermal	130 m^2	Jan – Dec	50%	0%	
		PV	10.75 kW_p	Jan – Dec	0%	53%	
		Total	-	-	100%	36%	

8 CONCLUSIONS

The zero-carbon performance targets set out in the CSH have been discussed in relation to compact-urban dwellings and a case study building has been presented. For the building reported here, generation options produce less than 5 tonnes of CO_2/year and the best of these produces 2.19 tonnes of CO_2/year and uses ~1600litres of vegetable oil. To put this into perspective, fulfilling the complete requirement using the electrical grid and a condensing gas boiler would emit 14.3 tonnes of CO_2/year and the additional application of PV covering the roof completely would reduce this to 4.59 tonnes/year. The focus of this research was purely on CO_2 emissions. Other criteria to be considered, such as cost, environmental factors like air quality and noise, and practicality are also important factors, but out of scope of this paper.

The nature of compact urban dwellings often results in a number of constraints, all of which hamper achieving zero-carbon energy performance:

- shading, roof pitch and orientation;
- the roof area available for the collection of solar energy;
- the space available for heat and fuel storage; and
- the space available for the generation technologies.

The limited roof area results in the need to supplement heat and electricity generation with the application of low-carbon technologies, such as micro-CHP. It has been demonstrated that in specific urban contexts, zero-carbon performance as defined within the current UK compliance framework may be very difficult to achieve in practice given the assumptions used in the simulation here. Therefore, it is very likely that zero-carbon compact urban dwellings may require a net off-site import of electrical and/or thermal energy. Also highlighted is that the CSH has a lack of guidance on the most appropriate energy consumption criteria to apply to estimating the in-use performance at the design stage, which is critical if these new developments are to contribute to the national reduction in CO_2 emissions. Incorporating into the Code for Sustainable Homes in the U.K. the set points and estimations from the BREDEM model will give approximate thermal and electrical requirements for zero-carbon dwellings.

Acknowledgements

The approach was developed as part of the systems engineering doctorate program at Loughborough University in partnership with EMRE Ltd., a small to medium sized enterprise who designed the engineering services and managed the development.

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APPENDIX C AN APPROACH TO VISUALIZING THE OPERATIONAL MIX OF RENEWABLE GENERATION TECHNOLOGIES NEEDED TO ACHIEVE ZERO-CARBON EMISSIONS FROM COMPACT URBAN DWELLINGS

Steijger L.A., Buswell R., Smedley V., Firth S.K. and Rowley P., 2012. An approach to visualising the operational mix of renewable generation technologies needed to achieve zero-carbon emissions from compact Urban dwellings. *1st IBPSA-England conference on building performance simulation*, 10-11 September 2012 Loughborough

ABSTRACT

There is an increasing demand for housing in the UK and the trend towards urban living is resulting in the redevelopment of inner city areas. Often sites are constrained by existing buildings and infrastructure and hence the choices over orientation and layout are limited, the roof area in particular. In addition, the living space is maximised to provide the greatest return on the initial investment and hence the area required for plant and equipment is at a premium. The drive towards producing dwellings that produce net zero-carbon emissions during operation places further constraints on the design of these buildings and results in a challenging web of interdependencies between the architectural layout of the building, the building fabric itself, the systems and their control, the renewable energy generation equipment and occupant demand for electricity and heat. Based on a case study, this paper presents an approach to break down these interdependencies into manageable stages and suggests a way to visualise the zero carbon performance as part of the overall design process.

Keywords: Dynamic building simulation, Zero carbon (ZC) housing, Compact urban dwelling, energy demand profiles, on-site energy generation.

1 INTRODUCTION

The trend towards inward migration is resulting in new homes being built on brown-field sites in towns and cities in the UK, where space is limited (Banfill and Peacock, 2007). In the UK, apartment based living is less common than the single family house on its own plot of land, however, to maximise the space available, these urban sites are having apartment based dwellings constructed on them. These are being termed ‘compact urban dwellings’ and often have a living space of around 50 m^2 in either one or two stories with a likely occupation of one or two people.

From 2016 all new build UK homes must meet the highest criteria of the government’s Code for Sustainable Homes (CSH) as stated in greener homes for the future. (Department for Communities and Local Government, 2006). The CSH (DCLG, 2006) states that code level 6 can be achieved by: “*using low and zero carbon technologies such as solar thermal, biomass boilers, wind turbines and combined heat and power systems (CHP). It would mean that for example energy taken from the national grid has to be replaced by low or zero carbon generated energy, so that over a year the net emissions were zero*”.

The lack of control over building orientation, building volume and roof space available in these buildings presents a major challenge to both the architect and engineer in the pursuit of an appropriate design that will deliver zero carbon operation when in service. There is little, if any, literature focused discussion of the engineering constraints, control considerations and other factors that affect the selection of the mix of renewable energy technologies during the design of these types of buildings.

The work presented here is based on a study of the design of the energy systems for a recently constructed net zero-carbon housing development in Derby, UK. This paper presents a simulation-based approach that could be applied to the design of other similar buildings, to help unpick the critical interdependences between the design of the engineering systems, system inputs and control assumptions in order to establish some confidence that a selected mix of renewables has a high chance of delivering zero-carbon performance when in use, before embarking on a more detailed analysis to determine the precise capacities, configurations and control strategies that would be developed into a working design for the real building.

2 FORMULATING THE APPROACH

The design of the energy systems for a net zero-carbon compact urban dwelling can be split into three principle components: the demand through the occupants and their influence on the consumption of electricity and heat; the building systems that deliver ventilation and heat recovery, space heating and domestic hot water (DHW) supply; and the supply/generation of heat and electricity to those systems. Ideally, it would be possible to decouple the generation systems from the building in order to explore which mix of renewables is most appropriate for a particular building.

Combined Heat and Power (CHP) plant does run largely independently of environmental conditions, and as long as there is a sufficiently large thermal store, the relatively high temperature of the heating water being produced means that it is possible to make a reasonable evaluation of performance without coupling it to a model of a building and its systems.

Although driven by the availability of solar radiation, Photovoltaic (PV) systems can also be treated in isolation to assess performance when connected to the national electricity supply grid. The Grid in this case can be treated as electrical storage with infinite capacity, where a 100% of the demand can be met and 100% of the generated power can be exported.

Systems such as Solar Thermal (ST) arrays and Heat Pumps (HP) are affected by the supply temperature of the heating water they produce and this water supply is affected by the operating conditions of the system the equipment is connected to as well as the environmental or ground conditions, depending whether you have an air sourced or ground sourced heat pump. Any intermittent generation must also be buffered by storage to maintain the supply of the demand at the appropriate time. The capacity, volume and configuration of this store are critical to the operation of the systems that might be connected to it such as CHP, HP and Solar Thermal arrays.

One of the conflicts that arise with the thermal store is the volume required. Increasing the volume of the tank increase construction costs and reduced the saleable/letable floor area of the building and hence the operation of the system is at odds with the commercial drivers. In addition, whether to have single or multiple tanks is an important consideration that can have effects on the performance (Grondzik et al. 2010).

The heat losses are minimised in these buildings in order that the demand for space heating, and hence the required onsite generation capacity, is minimised. This does mean, however, that the internal heat gains from the occupants and through the consumption of electricity through appliance use noticeably affects the heating demand in winter. Establishing the occupancy profiles and range of expected appliance use therefore becomes important to evaluate those generation systems connected to the thermal store that is part of the system used for the provision of heat.

Occupants also have control over the DHW draw-off, although principally for hygiene and food preparation is likely to dominate over the provision of heating since the high insulation levels in the fabric and MHVR minimise that required for space heating.

The dependencies between the generation and consumption of heat and electricity, the likely variation in occupation, the use of heat and electricity and the interdependencies of plant characteristics suggest that the analysis should use dynamic thermal simulation. As part of the commercial design of such buildings the challenge here is to minimise the effort expended in establishing a workable mix of renewable technologies relatively early on in the design of the engineering systems. This generates confidence that a particular scheme will produce net zero-carbon performance, before embarking on a more detailed analysis to fine tune the capacities of the each component and establish the most affective control strategy, involving further simulation work.

2.1 THE APPROACH

The approach it to establish some bounds, or an envelope of annual heat and electricity demand in which there is some confidence that the real building will operate once occupied. This can be estimated in any thermal simulation tool, or even using simple, steady-state methods. The second stage is to estimate some generation plant capacities based on conventional design-day loads for the specified building such that each generation option is able to supply 100% of the power and/or heat demand. The exceptions are the determination of the generation capacities of ST and PV which are constrained by the area available for installation. The third stage is to model the building and its systems in a dynamic simulation (TRNSYS was used here) to evaluate the overall building heat/power consumption/generation in hourly time steps and aggregating these figures over a typical year and various load conditions. The initial steps are to establish the:

1. architectural design/building dimensions;
2. available area for the collection of solar energy;
3. heating and ventilation delivery methods;
4. volume available for heat storage;
5. range of generation methods available;
6. dynamic performance estimates of the loads and generation methods;
7. principle space gain/demand characteristics; and,
8. constraints on the systems and components.

Establishing items 1 through 5 are straightforward and should be identifiable for any given project. The environmental conditions are given by historical weather data for the specified location. The principle demand characteristics describe things like the occupancy profile, space heating use, hot water consumption and use of electrical appliances. Internal gains from occupants and solar gains through the windows should be accounted for. These can be generated from rules of thumb, or by simulation which will depend on the time available for analysis and for the level of detail required. What is important is to establish the bounds for the annual heat and electricity consumption within which it can be reasonably expected the building will perform; and this is termed here, the ‘demand envelope’.

Using the architectural information, a knowledge of the heat and electricity demand and simulation results

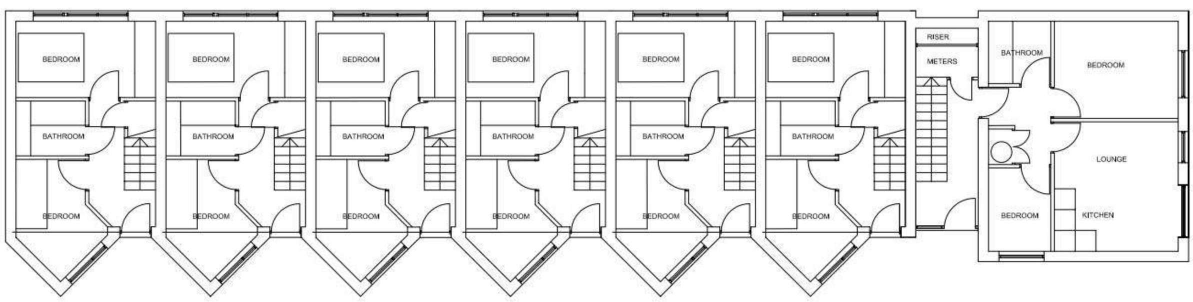

Figure 39, the ground floor plan of the building. The upper floors to the 6 identical flats are an open plan living space with kitchen. The flat to the right is the first storey of three identical units. The building dimensions are approximately 36m by 8m and 9 m at the highest point.

it is possible to estimate the size/capacity of the key components of the energy generation systems:

1. roof area for solar thermal and/or PV;
2. CHP, HP, etc. for a design heating day; and,
3. thermal store based on volume and medium.

This will allow the determination of the renewable mix required to deliver a zero-carbon evaluation energy supply together with an indicator of the risk of under/over delivery of electricity or heat, which will lead to non zero-carbon performance. To generate this indicator of risk, simulation can be used to estimate:

1. the likely annual electrical and thermal energy demand envelope, and,
2. the annual production/consumption by each of the heat and electricity generation systems.

The simulation output can be used to calculate power/heat consumption/production characteristics for each item of generation equipment. These characteristics can be overlaid on the demand envelope and used to establish the annual over/under generation for given systems combinations. The plot can be used to evaluate the in-operation balance of renewables to inform further simulation work to establish the optimum plant capacities and control strategies and set points.

The next sections of the paper introduce the case study building and work through these stages for this building, presenting the results and describing the analysis method in more detail.

3 THE CASE STUDY BUILDING

The SHINE-ZC building in Derby (Figure 39) is north facing and comprises nine dwellings; six, two-storey houses and one three-storey block containing three flats. Each dwelling has a living space of approximately 50m^2. The architectural layout of the building meant that it was challenging to make the space available for large thermal storage, which would have made solar thermal panels in particular, more effective. Instead the design was based around each dwelling having sufficient space to house a 315 litre thermal store which is large enough to supply the estimated space heating and hot water demand to each flat 99% of the time under standard conditions CIBSE (1986).

The roof area is split in two levels; usable roof area for solar collection is ~160m^2 over the 6 houses and ~70m^2 over the right hand flats. Ideally the roof would have been constructed with a 40º pitch to maximise the yield from any solar thermal or Photovoltaic (PV) systems installed (Energy Saving Trust, 2004), however, planning consent restricted the pitch to 6º, leading to an estimated loss per year of direct solar radiation in the order of 20% (CIBSE Guide 1986).

Key to minimising the heat required for space heating, is a highly insulated fabric, minimal infiltration and to employ heat recovery on the ventilation air. An Insulating Concrete Formwork (ICF) system was used for the structure in combination with triple glazed windows with U-values of 0.123W/m^{2}K and 1.0W/m^{2}K respectively. Ventilation is provided by mechanical ventilation with heat recovery (MVHR), with an air exchange rate in each dwelling of 17l/s (Building regulations part F, 2006). The heat recovery capacity of the specified system has a stated manufacturer's efficiency of 90 % (Segen, 2006).

The properties are heated with radiators with thermostatic radiator values (TRVs) for the control of individual rooms and the heating in each dwelling is controlled through a central thermostat located in the hallway of each unit.

4 ENERGY GENERATION OPTIONS

Solar thermal collectors, photovoltaic panels, air-source heat pumps and a bio-fuelled, micro combined heat and power generator where considered in this analysis. Watson et al (2008) stated that wind generation has a very limited yield in an urban setting and bio-mass boilers were not considered in this particular case. Ground source heat pumps were also not considered because the available area for horizontal evaporator coil was limited and the commercial viability of installing vertically drilled systems was prohibitive.

If the most common type of PV array (crystalline silicon) is used, Bayod-Rújula et al (2010) show that around 9m^2 of roof space is required to install 1kWp of PV panels. With 230m^2 of roof space, a maximum installation of approximately 25kW$_p$ can be installed.

The variation of the heat output of ST collector is not only dependant on area, but also on inlet temperature. Brinkworth (2001) derived a set of graphics using as parameters the storage capacity and the collector area. If the size of the panels is small compared to the storage capacity, the limiting case is the area of the collectors. If, however, the collector area is large compared to the storage capacity, the reverse is true. In this installation, the ST collectors would be mounted on the roof at 6° and hence the yield will be reduced. In addition, the capacity of the thermal storage is likely to limit their effective deployment and so they were not considered as an option in this study.

5 DEMAND CHARACTERISTICS

The demand characteristics are determined here to vary the inputs to the simulation in order to calculate the annual electrical and heat demand for the building. These figures are then used to estimate the likely demand envelope.

The level of detail used in the demand profiles are important and will affect the estimation of thermal and electrical generation. There are a number of inputs to vary:

- the occupancy profile, affecting internal heat gains, DHW use and switching of appliances;
- heating schedule, affecting the space heating demand;

The approach reported here can be easily expanded to incorporate more sophisticated models of occupancy and electrical demand (Richardson et al, 2010), DHW draw (Jordan et al, 2000) for example. The approach could be extended to include future weather scenarios also (TM36, 2005). However to demonstrate the approach, simpler models have been used and are described below.

Occupancy and Activity: Each dwelling is treated the same. The dwellings are occupied from 16:00 to 09:00 the following day. Occupants are regarded as sleeping between 23:00 and 07:00. No differentiation for weekend activity has been made in this analysis. Anderson et al, 2001)

Electrical Consumption: Three levels of electrical consumption are applied. 75W is assumed to be the unoccupied, or sleeping base load, accounting for white goods and the MHVR system. During the awake occupied hours a constant load of 496W is applied. The annual electrical consumption is therefore 2288kWh, as given in the BREDEM model (Anderson et al, 2001).

Heating Schedule: The temperature of the space is controlled to 21ºC during occupied hours in the heating season and 15ºC during unoccupied/sleeping hours. The heating season is taken to be from November until the end of March. The space heating requirement is only 20% of the total thermal requirement.

DHW draw: The CSH requires that the DHW water consumption must be less than 80 litres per day per dwelling (DCLG, 2006). There is no DHW consumption pattern given in the code and so for the purposes of this analysis it has been assumed that half of the volume is used in the morning between 07:00 and 08:00 and half in the evening between 18:00 and 19:00.

Treatment of internal heat gains: During occupancy the internal heat gains from the occupants is taken as 115 W (CIBSE, 1985). The solar heat gains are negligible as most of the windows are north facing and the south facing windows are shaded. The gain from the use of electrical appliances and lighting is assumed to heat the spaces, with the exception of the load for cooking, where only 90% of the heat generated enters the space (Anderson et al, 2001). The power used by the extract fans does not enter the space.

6 CONSTRAINTS AND ASSUMPTIONS

Thermal Stores: The thermal stores are taken to be charged to capacity when the water in the bottom of the store reaches a temperature of 90ºC; and for the purposes of control, taken to be able to supply no useful heat if the bulk water temperature drops below 50ºC. The assumption is made here that the majority of this water is used for personal hygiene and therefore has a temperature of 40ºC at the draw-off points. The cold water supply is assumed to be 10ºC and mixed with the water from the tank to supply at 40ºC at the required flow rate.

Air movement and ventilation: High construction quality is assumed and so the infiltration rate is assumed to be low. There is no air movement modelled between the different zones, except the ventilation air through the heat recovery unit. The electrical consumption and the heat generated by the heat recovery are added to the internal gains according to the BREDEM method (Anderson, 2001).

Air Source Heat Pumps: The heat pump switches on if the average store temperature is less than 50 ºC. The maximum temperature the heat pump can deliver is 65ºC, hence the control system will prevent the HP running when the water in the bottom of the thermal store reaches this temperature. The electrical load to the heat pumps is assumed constant, however the heat output is dependant on the operating conditions.

CHP: The micro-CHP is modelled as a constant power output with an electrical power estimated at 10kW. This micro-CHP plant has twice the capacity to provide all the thermal needs for all the dwellings for 99% of the days, (CIBSE, 2005). The CHP switches on once a day. If the thermal stores are at 90ºC and the electrical demand has been satisfied, the CHP switches off.

7 SIMULATION MODEL

The building and systems were simulated in TRNSYS software (Klein et al, 2007). The six houses were divided up in two zones per house, one upstairs and one downstairs. The flats and the staircase were modelled as one zone. Figure 40 details the renewable generation options, energy storage and energy inputs to the system. The occupants have some influence on the heating set points, DHW supply, lighting and appliance use. Two-way flows of heat are shown for the heating, solar thermal, HP and CHP systems. DHW is a draw-off where the heat flows from the store to the mains cold water supply. The CHP and PV both supply electricity, where as the HP consume it in exchange for heat.

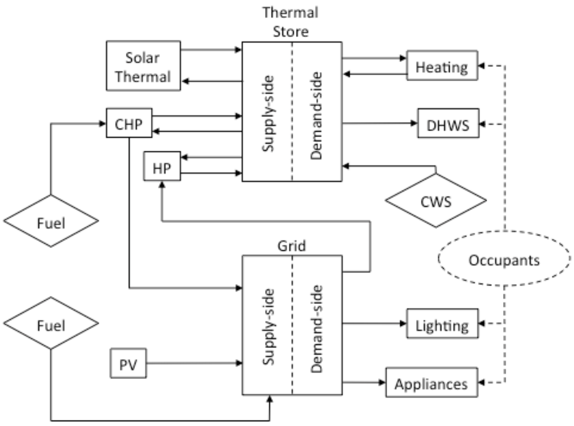

Figure 40, Block schema of the heat and electricity generation, storage and demand system.

The systems were modelled using the TRNSYS library with a few exceptions. Those to note:

- TRNSYS type 194b with inverter is used to determine the yield of the photo-voltaic array.
- TRNSYS type 4a, with 9 nodes of 0.2 meters high, which corresponds with the 1.8-meter high thermal stores in the dwellings.
- ASHP was modelled by the approach described by (Steijger et al, 2010) as the installed heat pump was completely characterized by this model.
- MHVR system was simulated using the approach described by Taylor et al (2010). This model was used because for the ease of control.
- Space heating input is calculated from the radiator models described by Knoll and Wagenaar (1994).
- There is a range of heat:power ratios for CHP from 10:1 (Whispergen 2010) to 2:1 (Baxi Dachs mini CHP, 2010). A small Diesel CHP can reach a 1.5:1 heat to electricity ratio (Tipkoetter BioGenio, 2010). Additional thermal losses with the operation of these small CHP can be high and hence a limiting case of 1:1 heat to electricity has been taken and used to illustrate the approach.

8 RESULTS AND ANALYSIS

Using the BREDAM levels of energy consumption (DHW 80 l/day/dwelling, 2.3MWh/dwelling) the simulation demonstrated electrical energy demand for the whole building is 20.6MWh/year, the DHW energy is 15.3MWh and the space heating demand is 3.8MWh/year. This gives an estimate of a central operating condition. To develop the performance envelope, a number of other simulations were carried out to vary DHW draw and electrical load. Since the space heating represented such a small proportion of the overall consumption, varying the heating schedule and internal air temperatures was neglected.

To generate the limiting cases the CSH DHW water consumption of 80 litres/day was used as a central estimate. Measured data from the Energy Saving Trust (2008) showed a mean hot water consumption of 122 litres a day with a 95% confidence interval of ±18 litres a day. The data was taken from a study of 124 homes over a year. The mean number of occupants was 2-3 and hence taken to be at the upper limit of what might be expected from these homes since the expected occupancy is 1-2. The minimum DHW usage was estimated by mirroring the difference between the upper bound and the central case, to yield a lower boundary condition 42 litres/day. Figure 41 shows the resultant annual thermal energy requirement as a function of a variation in electrical load (20.6MWh/year is approximately central on the *x* axis).

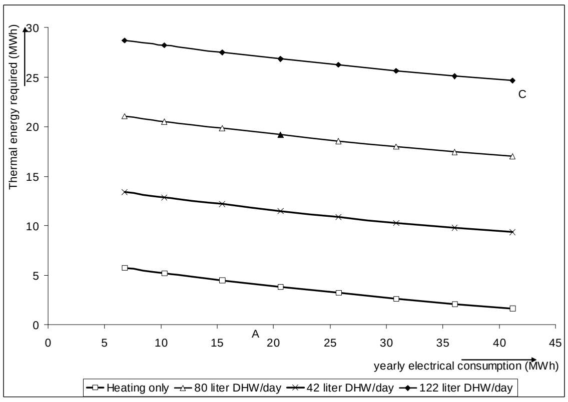

Figure 41, total thermal energy demands in relation to the average electrical use for the whole building.

The lower of the four lines represent the base heating demand. As the electrical appliance use goes up, the internal gains increase, offsetting the heat losses from the space and hence there is a reduction in the heating requirement. Second from the top is the BREDEM case for a range of electricity consumption (BREDEM electricity consumption is highlighted with a black triangle). The lines either side of that represent the upper and lower limits of the likely thermal energy consumption and as such are two sides of the likely performance envelope.

Determining the upper and lower expected levels of electrical consumption is also challenging. A recent study by Richardson et al (2010) reported a 10 fold difference in electrical consumption between similar housing with a mean consumption higher then the BREDEM value. The variation in distribution in the work was shown to be Gaussian and if the mean is multiplied by 9 to get a likely value for the consumption of the whole building, the variation in this value likely to be less than 10 fold. For the purposes of this paper, we have judged that this would be closer to a variation of 4 by averaging over 9 dwellings, but further work is needed to generate a more robust limit. The electrical consumption limits can be plotted on to Figure 3 with the limits associated with the heat demand. The building demand envelope can be shown as the grey area in Figure 4.

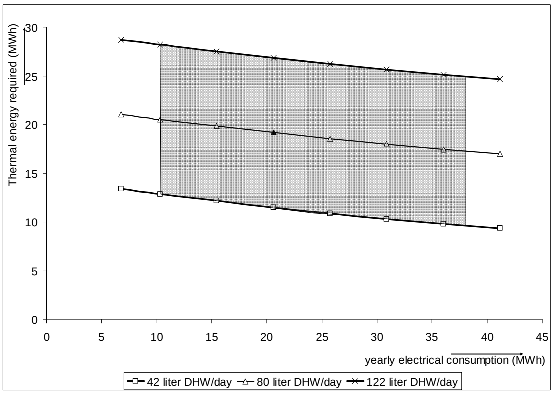

Figure 42, the likely demand envelope for the building.

The characteristics of the generation equipment can also described by their relationship between the annual electrical power and heat generated. Figure 5 depicts these characteristics, where the generation of heat/power is considered to be positive and the consumption of heat/power by the generation equipment is considered to be negative, i.e. it must be generated by another system.

For this building the ST collectors were not considered and hence the roof is covered with 100% PV. The simulation shows an annual generation of 18.5MWh. Since the PV does not interact with the building thermally, the heat/power relationship is zero. This characteristic is represented in Figure 5 by the positive horizontal line on the *x* axis, from zero to 18.5MWh.

The electricity production/consumption and heat production of the CHP and HP are not independent. The CHP generates a net positive contribution to the heat and electricity supply, whereas the HP generates heat, but uses electricity to do so, hence makes a positive contribution to the heat demand, but a negative contribution to satisfying the power demand. In more detail:

Heat pump: A heat pump transfers heat from a lower to a higher temperature by consuming electrical energy. This seasonal performance over a given period can be calculated from results from the simulation by:

$$SPF = \frac{\sum E_{thermal}}{T_{running} P_{in}} \qquad (1)$$

SPF	Seasonal performance factor	( )
$E_{thermal}$	Generated thermal energy	(kWh)
$T_{running}$	Time that the heat pump is running	(hrs)
P_{in}	Electrical input power	(kW)

As part of the analysis a number of HP scenarios were run and the lowest calculated SPF was 1.64, with a standard heat pump, running the whole year and with a water supply temperature control set point of 65 ºC. The highest SPF was 3.82, using a high performance heat pump, running during the summer and a water supply temperature control set point of 55 ºC. Figure 43 plots these two cases, shown with the negative gradient on the left hand side.

The length of the vector defines how much energy is converted from electricity to heat and is linear with the number of running hours. The value on the *x* axis in the electricity consumed and the value on the *y* axis, the amount of thermal energy generated. The limiting case is resistive heating where the heat generated to power consumed in 1:1.

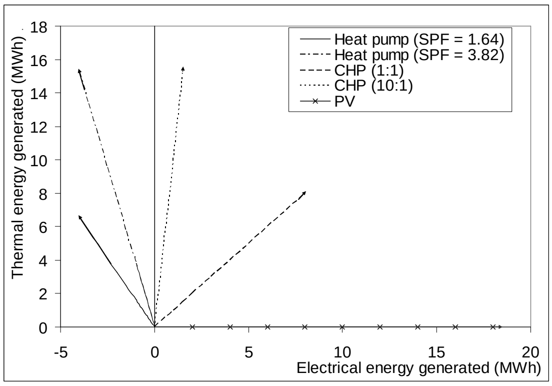

Figure 43 thermal generation as a function of electrical power consumption/production with different type of generation plant.

CHP: The CHP converts (in this case) vegetable oil into both thermal and electrical energy. The ratio of this is determined by the plant, and in this case assumed to be 1:1. Again the length of the vector is equivalent to the number of running hours. The upper case where a CHP with a 10:1 heat to electricity ratio is plotted for comparison.

Figures 4 and 5 can be overlaid to give a graphical representation of the relationship between the likely demand envelope and the heat/power characteristics of a combination of generation plant, Figure 6.

To generate the diagram, first the demand envelope in plotted. The generation from PV panels is plotted next, which establishes point A, at 18.5MWh.

The CHP will be required to generate the electricity that the PV cannot, hence the CHP characteristic line is rooted at point A. The heat generation required to cover the demand envelope is delivered when the CHP running hours are between point 5 up to point C.

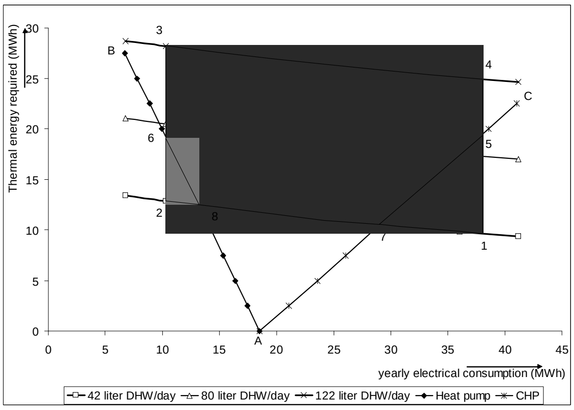

Figure 44 shows the likely demand envelope and the degree of expected coverage offered by the generation options.

The CHP is only able to operate along the linear trajectory defined by the heat-power characteristic line A-C in Figure 6. If the annual balance of heat and power consumption happens to fall anywhere to the left of that line, the CHP can only satisfy heat demand by generating a surplus of electricity, and vice-versa, to the right of the line. In order to meet combinations of heat and power requirement, a HP is needed.

If no CHP is used in the year, the HP heat/power characteristic line is also routed at point A. Because it consumes electricity, the line slopes to the left, indicating a reduction in the PV generated electricity available for consumption in the dwellings. To the left of the line the PV will be able to satisfy the electrical demand and the power required to run the heat pump to satisfy the heat demand. To the right of the line additional electricity generation is required hence more PV or where that is not possible, the use of CHP.

The light grey area shows the range of annual heat and electricity demand that can be satisfied by the combination of generation equipment. A complete energy balance can be achieved in the area 3-4-5-7-8-6. Over-production of heat will occur in the area 1-5-7 and would not require the use of the HP. Over production of electricity occurs in area 2-6-8 and the CHP is not required.

The PV, CHP and HP are all needed to have a good chance of achieving net zero-carbon emissions. The coverage risk indicator, *r*, can be calculated by,

$$r = a_{hpp} / a_{lde}, \qquad (2)$$

where a_{hpp} and a_{lde} are the heat/power provision area (3-4-5-7-8-6) and likely demand envelope area (2-3-4-1) respectively. For this building *r >85%*. Especially high electrical demand combined with low thermal demand might result in waste of thermal energy. If the CHP heat/electricity production ratio increases from 1:1, the value of *r* will go down indicating and increased likelihood of the building not performing as a zero-carbon building as waste heat is generated.

9 CONCLUSIONS

A case study building was presented and an approach to evaluating the likelihood of generating sufficient heat and power on site for the development to be zero-carbon was introduced.

The approach is a staged and utilises dynamic thermal simulation. It is intended to be used as part of the design process to gain confidence that the selected mix of renewables will deliver the required heat and electricity generation performance.

A number of findings were reported:

- there is a lack of design targets detailed in the CSH and hence values have to be found from elsewhere and their appropriateness justified;
- a ‘performance envelope’ was introduced based on annual electrical and heat demand and this was used to evaluate the selected mix of renewable technologies in the intended design;
- issues of likelihood of over and under generation were discussed and a operational coverage measure was introduced.
- It was demonstrated that a mix of PV, CHP and HP could deliver good coverage of the likely building heat/electricity demand for a compact urban dwelling development in the UK, however, an increasing CHP heat/electricity production ratio would impair the zero-carbon performance by wasting heat.

10 ACKNOWLEDGEMENTS

The approach was developed as part of the systems engineering doctorate program at Loughborough University in partnership with EMRE Ltd., a small to medium sized enterprise who designed the engineering services and managed the development.

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APPENDIX D IN-SITU U-VALUE MEASUREMENTS FOR SHINE-ZC

Abstract

The SHINE-ZC building in Derby comprises of nine adjacent, compact urban dwellings, six 2-storey houses and a 3-storey block containing three flats and a shared staircase. The buildings were designed and built by EMRE Ltd, as part of a 50/50 private and public funded demonstration project led by Loughborough University. The objective of the project was to demonstrate an ultra low energy dwelling in a compact urban environment. This report summaries the finding of on going physical in situ wall U-value measurements of the development and provides an estimate the characteristics of the ICF wall structure. The embodied thermal mass of the ICF superstructure causes the measured in situ U-value to vary with ambient internal and external environmental conditions. Therefore as part of the reports results the in situ U-value measurements have been evaluated against a theoretical mathematical model of the wall structure to aid the interpretation of the results. When comparing in situ measured flux with those from theoretical model there is a discrepancy, the flux measured is higher than the model predicted and the core temperature in the model is 0.3 ºC higher than measured. It was observed that increasing the mathematical models λ-value for the EPS (Expanded PolyStyrene) insulation material in the wall from 0.03 W/mK to 0.046 W/mK aligned the results from the model with the measurement results. With this insulation value of the EPS, it would mean that the U-value of the wall is estimated to be 0.161 W/m2K. Instrumentation at the site has been left in situ to continue measurements presenting the opportunity to evaluate results recorded over a longer time frame.

Keywords: ICF, U-value measurements, Shine-ZC

1 INTRODUCTION

This report was carried out as part of the Technology Strategy Board (TSB) Building Performance Evaluation (BPE) program 1, and evaluates in-situ U-values measurements made on the Insulated Concrete Form (ICF) super structure of the SHINE-ZC development in Derby. Buildings with some thermal mass in their superstructure will tend to exhibit some thermal inertia over time. Therefore a comparison of the in-situ material properties is made using a theoretical model and on site temperatures and heat flux measurements. The mathematical model is used as the model can be used to generate performance predictions over a year to establish if the thermal capacity of the ICF core of the wall is an aid or hindrance to the overall energy performance of the development.

2 CASE STUDY BUILDING

The dwellings are adjoined as shown in Figure 45 and Figure 46.

Figure 45. A picture of the northerly & west elevation of the development shortly after completion

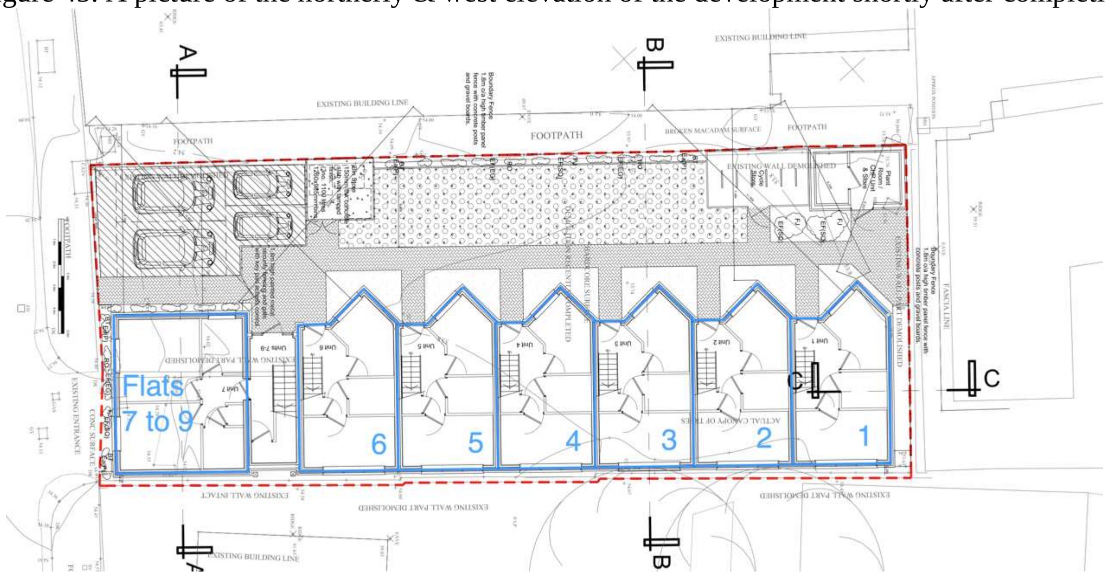


Figure 46. Floor plans of the dwellings

The inner city brown field site upon which it is built dictates the building orientation. The front of the building faces approximately north. Each dwelling has a living space of approximately 50m^2 and the total internal volume is 1326m^3. The roof area is split in two levels; approximately 160m^2 on the apartments, and 70m^2 on top of the flats. The 230 m^2 roof faces south with a 6 degree slope. The surface of the building is partially rendered with an ivory render, and partially clad with treated red cedar panelling.

Figure 46 shows a plan view of the development; the dwellings are numbered from right (1 – two storey house) to left (6 – two storey house), and bottom (7 - flat) to top (9 - flat).

ICF outside wall:	Thermal conductivity (W/mK)	Thickness (m)	Thermal resistance m^{2}K/W	Thermal Capacitance J/m^{2}K
Outside surface resistance	25.00	--	0.040	--
Rendering	0.5	0.025	0.156	32500
EPS	0.030	0.175	5.15	938
Concrete	1.400	0.150	0.06	264600
EPS	0.030	0.075	2.21	469
Plasterboard	0.160	0.013	0.081	20250
Inside surface resistance	7.690	--	0.130	--
U value Wall (Wm^{-2}K^{-1}):			0.125	

Table 7. Insulation calculation of the ICF outside wall (Source CIBSE guide A)

The wall material is Integrated Concrete Form (ICF) supplied by LOGIX UK; a highly insulating construction method that was specified with a U-value of 0.125 W/m^{2}K^1, elemental breakdown shown in Table 7. The U- value of the roof is estimated to be 0.09 W/m^{2}K^1. The concrete core represents a large thermal mass, resulting in a large time constant. The windows are triple glazed, with a U-value of 0.8 W/m^{2}K^1 and were supplied by the Litchfield Group. Insulation in the floor is estimated to be 0.059 W/m^{2}K^1. It should be noted that the ground floor insulation of the six houses serves the dual purpose of insulating from ambient ground conditions and the elevated temperatures of the under ground aggregate based thermal stores. The building has an inner city location; winter solar gain is minimal due to the shading of adjacent buildings. Summer solar gain needs to be minimised to maintain thermal comfort within the dwellings. The heat losses through the fabric are estimated around 15 W/K for the houses and 9 W/K, 11 W/K and 15 W/K for the bottom, middle and top flat respectively.

Ventilation is assisted by a mechanical ventilation heat recovery (MVHR) unit, with an air exchange rate of 17 l/s, and has 0.43 exchanges per hour in the apartments, and 0.54 in the flats. The heat recovery capacity of the installed system is stated as 90%. There is a summer bypass function in the MVHR. In this mode, the heat exchanger of the heat recovery unit is bypassed, and the air intake is not preheated. The temperature, by which the summer bypass is switched on, is 25ºC. The temperature, by which the summer bypass is switched off, is 24ºC.

Desciption	End apart.	Middle apart.	Bottom flat	Middle flat	Top flat
Number of units	1	5	1	1	1
Floor area (m^2)	55	55	42	44	46
Volume (m^3)	140	140	105	110	115
External wall area (m^2)	75	45	47.5	50	52.5
Window area (m^2)	8.5	8.5	5.5	6.5	6.5
Roof area (m^2)	30	30	--	--	70
Ventilation rate (exch./hr)	0.43	0.43	0.54	0.54	0.54
Heat loss fabric (W/K)	18	15	13	11	15
Ventilation heat loss (W/K)	8	8	8	8	8

Table 8. key parameters of the development

Of all the dwellings, the end apartment (plot 1) has the highest theoretical total losses (the combination of fabric and ventilation losses), and this loss is around 26 W/K.

Comfort levels are aided by ‘upside down living’ in the apartments i.e. the living space is on the first floor, whilst the bed/bathrooms are located on the cooler ground floor. As a result the bedrooms will stay cooler, whilst the living area will stay warmer and have more natural light.

This development uses a novel underground thermal storage solution consisting of a highly insulated aggregate bed situated under the six houses. Surplus heat from the large solar thermal array on the roof is transferred into this store over the summer months and can be extracted during the heating season using air-sourced heat pumps.

3 ICF: THEORETICAL MODEL

The wall structure is shown in Figure 47. A denotes the inside, B the plasterboard, C the internal EPS insulation, D the concrete core, E the external EPS insulation and F the external rendering, with the material properties as listed in Table 7. This wall can be modelled using a resistive/capacitive node model; each material is represented as a resistor and a capacity representing the thermal resistance and capacitance of that material as shown in Figure 49.

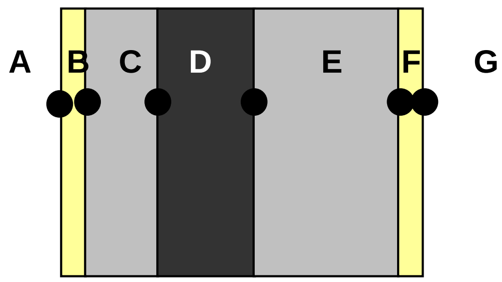


Figure 47 Cross section through the wall

The heat flux and temperatures in through the wall can be determined with the assumptions of flow and temperatures shown in Figure 48. The flux through each element is determined by the temperature difference over that element in terms of a resistance, or the temperature change over that element during a time step in terms of a capacitance. Total flux in each node must be 0.

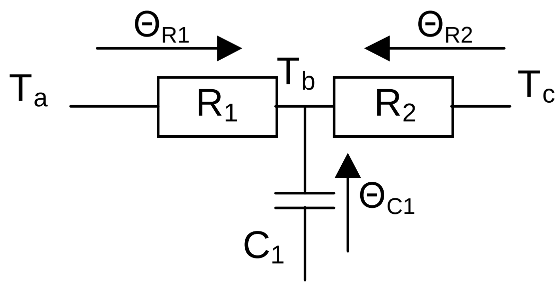


Figure 48 Calculation of one element

. In formulas: as the total heat flux in each node must be zero, i.e.

$$\Theta_{R1} + \Theta_{R2} + \Theta_{C1} = 0 \qquad (1)$$

Also:

$$\Theta_{R1} = (T_a - T_b) / R_1 \qquad (2)$$

and

$$\Theta_{C1} = C_1 \times (\Delta T_b / \Delta t) \qquad (3)$$

With ΔT_b the temperature difference in that node and Δt the time step of the iteration. For a given set of temperatures, the next set of temperatures can be calculated using the above equations:

$$T_{b@T+1} = T_{b@T} + ((T_{a@T} - T_{b@T}) / R_1 + (T_{c@T} - T_{b@T}) / R_2) \times \Delta t / C_1 \qquad (4)$$

This model is equivalent to a finite difference model, with one node in the middle of each layer of the wall structure and a calculated thermal resistance between each node depending on the material. It is an extension to the standard model (R_1 and R_2 must be equal in the standard model), as this approach can cope with different materials between the nodes (difference in R_1 and R_2).

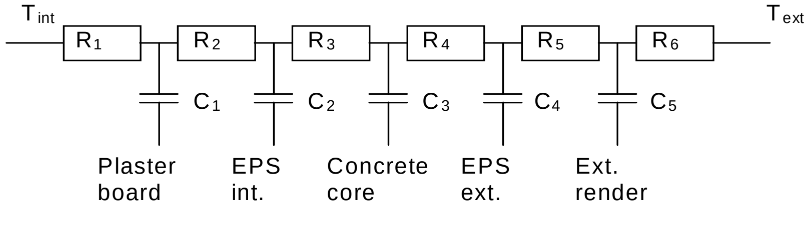


Figure 49 thermal model of the wall

The resulting model is shown in Figure 49. R1 consists of the internal surface resistance and half the resistance of the plasterboard. R2 consists of half the resistance of the plasterboard and half the resistance of the internal polystyrene, etc. It is assumed that all the heat flow is horizontal e.g. a uniformly distributed temperature on the surface of each material. The other assumption is that there is no air gap between the different materials. This is a valid assumption as the plasterboard is glued onto the polystyrene, the concrete is poured in the ICF and the render is put on wet at application.

To use the model, each capacitance and resistance has to be calculated from the values shown in Table 7. The results are shown in Table 9.

Table 9 Resistance and capacitance values through the wall.

Node	Position	R	Value (m^2K/W)	C	Value (J/m^2K)	Time constant (sec.)
1	Internal	1	0.0406			
2	Middle plasterboard	2	1.29	1	35100	1430
3	Middle EPS internal	3	1.28	2	468.75	604
4	Middle concrete	4	2.97	3	244500	313000
5	Middle EPS external	5	2.99	4	1093.75	3220
6	Middle render	6	0.428	5	32500	97300
7	External					

A time constant of 604 second or just over 10 minutes was selected for the mathematical model, as a result the highest maximum sample time is 5 minutes, less than half the lowest time constant. The time constant of the concrete core is 313000 seconds or 3.6 days. The "U-value" of the wall (ignoring the capacitance) is 0.123 W/Km^2.

The model responses to an internal and external temperature step change are shown in Figure 50. The overall time constant to an internal step change is approximately 3.5 days, the time constant as a result of an external step change is slightly larger, approx. 4 days.

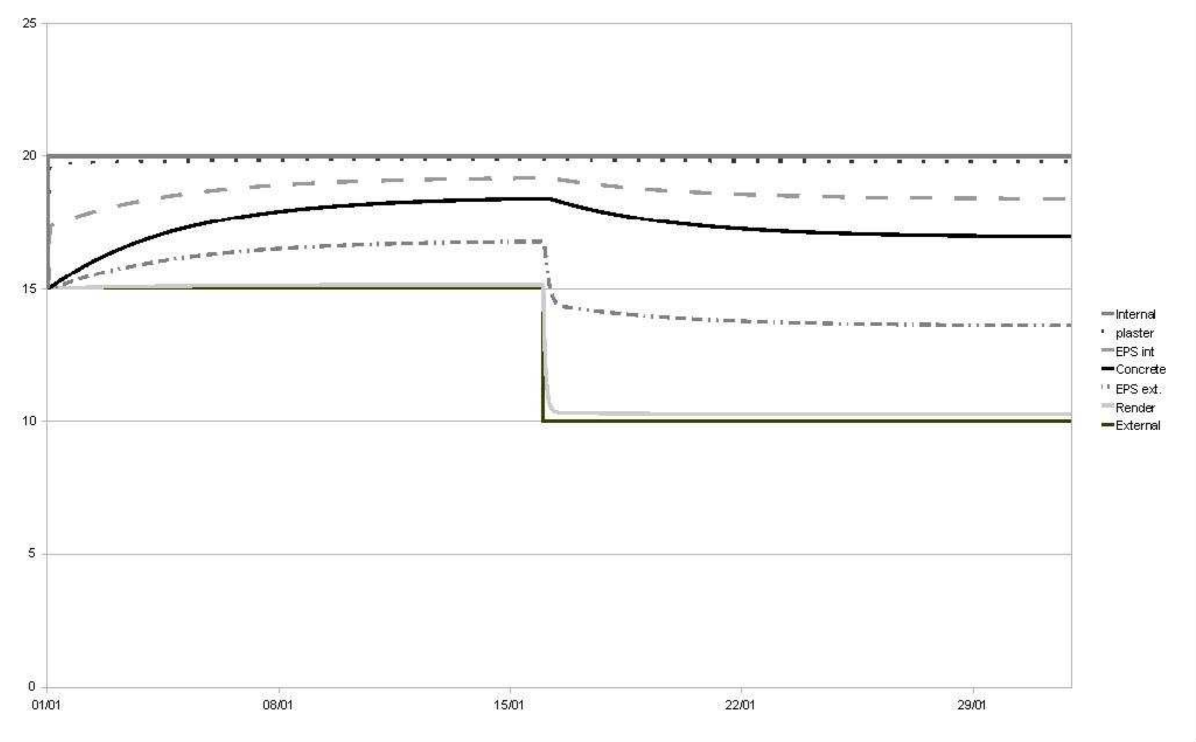


Figure 50 Step responses of internal and external wall temperatures and the response of the model to these step changes.

4 U-VALUE MEASUREMENT DATA ACQUISITION HARDWARE

Internal and external temperatures were measured using type 10K4A1 thermistors. For the internal measurement the thermistor was glued to the plasterboard on the inside. The external measurement was made by fixing the thermistor to the end of a low thermal conductivity rod past through the wall, the sensor was protected from ambient external conditions with an aluminium cap; this provided a low emissivity surface on both sides. This type of thermistor comes pre calibrated by manufacturer. A third thermistor was inserted into the concrete core to measure the core temperature.

Heat flux transducers used were circular disk heat flow sensors type HFP01 manufactured by Hukseflux Thermal Sensors BV Delft. These sensors, constructed of PVC and incorporating embedded thermocouple junctions, are designed to generate a voltage proportional to the heat flux through the disk. The heat flux sensors were used to determine the level of heat flux (in W/m^2), passing through the wall and together with the recorded temperatures enable U-values to be determined. The heat flux sensors are calibrated by Hukseflux Thermal Sensors BV. Delft. The output voltage was calibrated to be 62.9 $\mu V/Wm^{-2}$ for the sensor with series number 6985 and 63 $\mu V/Wm^{-2}$ for the sensor with series number 6986. In order to assist in providing adequate thermal contact, a circular cut-out from the plasterboard was made and the sensors were pressed into wet plaster onto the EPS of the wall. The measurements were carried out in the unheated shared stairwell of the flats, the location was an empty equipment cupboard on the first floor. The location was selected to reduce the radiative thermal energy and localized heating effects. The following photograph shows how the heat flux sensor was arranged on the wall in the cupboard. With the expected maximum heat flux (2.5 to 3 W/m^2) and two sensors in series, the output voltage is too low to be measured directly by the onsite

Building Management System (BMS). With an expected U-value of the wall of 0.123 W/m^{2}K and a maximum temperature difference of 25ºC, the maximum heat flux is expected to be 3 W/m^2. This will result in an output voltage of approx. 7.5 mV. The standard Hukseflux Thermal Sensors BV precision 200x amplifier handling the output from the flux sensors produce a signal that is too low to be accurately measured by the BMS, which has a set input voltage range of 0..10V. To overcome this problem a custom 4-20 mA converter was designed, built and tested for the installation, this converts the signal voltage into a current in the correct range to be measured by the BMS.

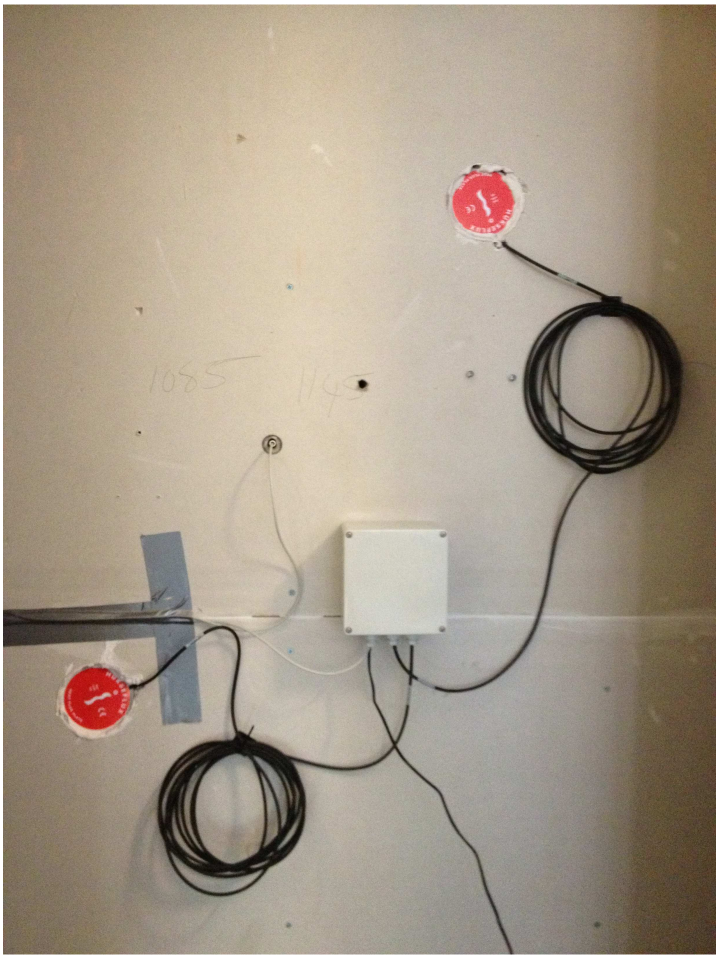
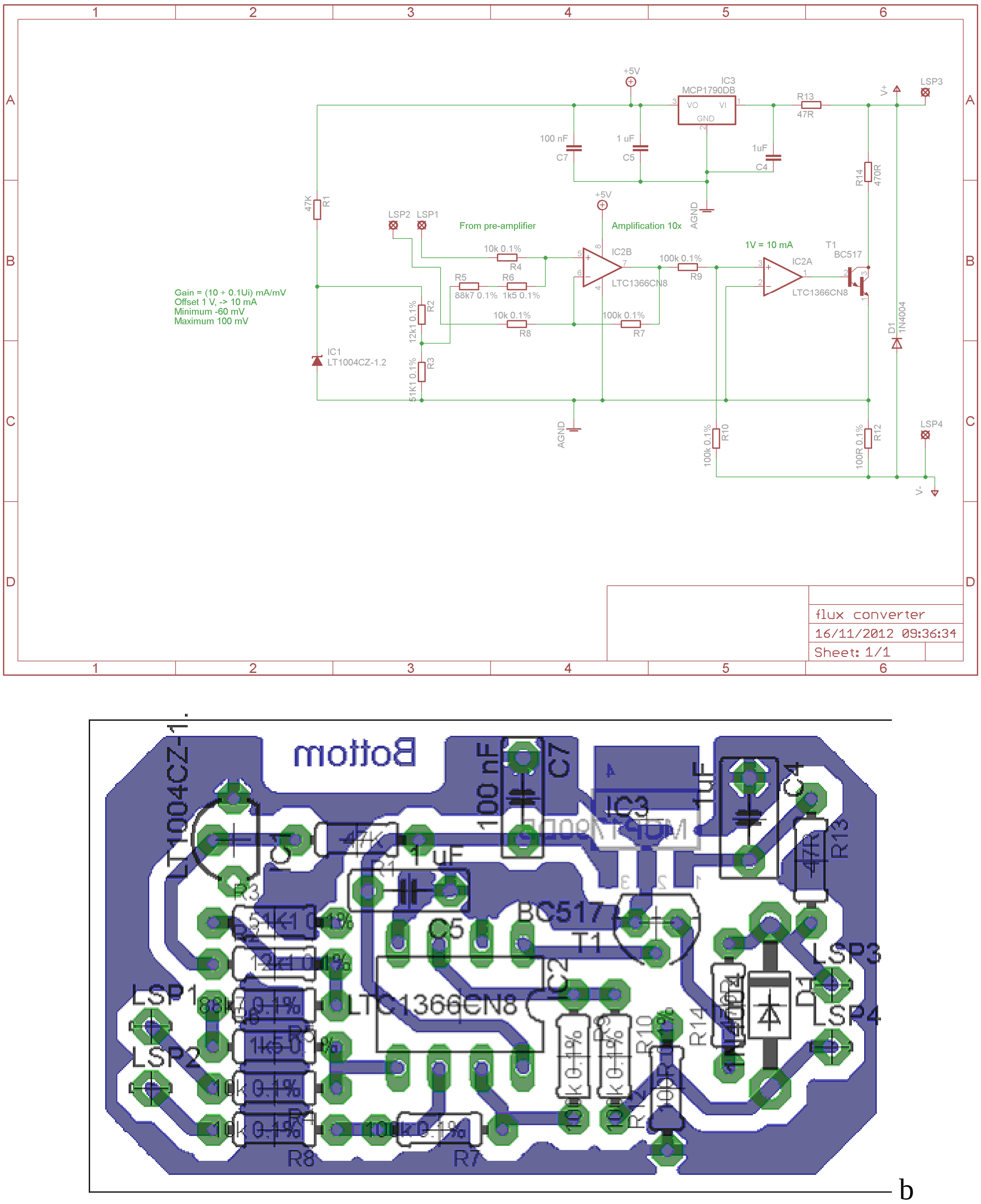


Figure 51 Arrangement of the heat flux sensors. Between the two sensors the plastic rod housing the external temperature sensor is visible. The hole above and to the right of the rod will house the concrete core temperature sensor.

The electronic schema and PCB for the 4-20 mA converter is shown in Figure 52. The DC offset for the conversion is 10.00mA, the conversion factor is 0.101 mA/mV. The schema and board layout is shown in Figure 52.



a

b

Figure 52 schematic (a) and layout (b) of the 4-20 mA converter

The conversion formula that converts the voltage reading into the flux is:

$\Theta_m = 50.0*((V_{in}/0.499)-10.0)/125.9$ (5)

Θ in W/m^2, V_{in} in Volts.

The block diagram for the complete data acquisition system is shown in Figure 53.

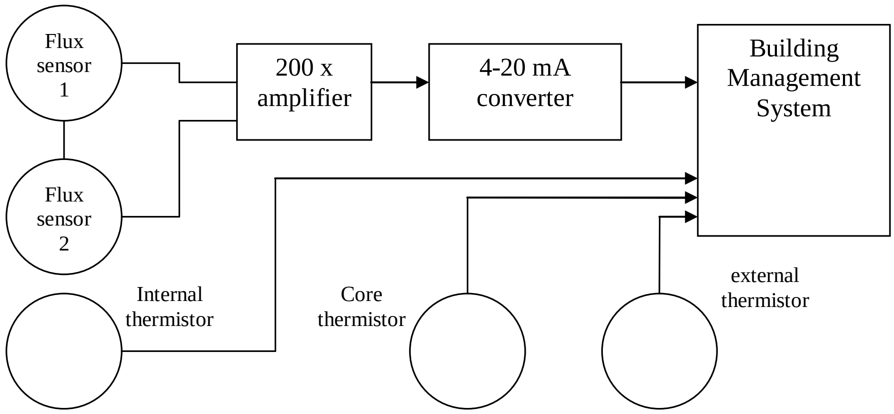


Figure 53 Block diagram of the data acquisition system.

5 MEASUREMENT DATA

Sensor data was logged every two minutes via the BMS system as per BPE guidelines. The test was run from 21 January 2013 to 6 February 2013. An extract of the data is shown in Table 10.

Table 10 Sample of the data collection

Date/Time	External Wall Temperature (ºC)	Core Temperature (ºC)	Internal Wall Temperature (ºC)	Flux Sensor (V)
21/01/2013 09:01	3.71	11.17	13.01	6.406
21/01/2013 09:03	3.73	11.17	13.01	6.409
21/01/2013 09:05	3.73	11.17	13.03	6.399
21/01/2013 09:07	3.73	11.17	12.98	6.401
21/01/2013 09:09	3.69	11.17	12.96	6.396

To determine if the flux through the wall was homogenous, a thermal image of the wall was taken. It was assumed that large difference in heat flux would show up as a temperature difference between the flux sensor and the surrounding area. As shown in Figure 54, the temperature difference between the plasterboard and the sensor is small, so a homogenous flux was assumed.

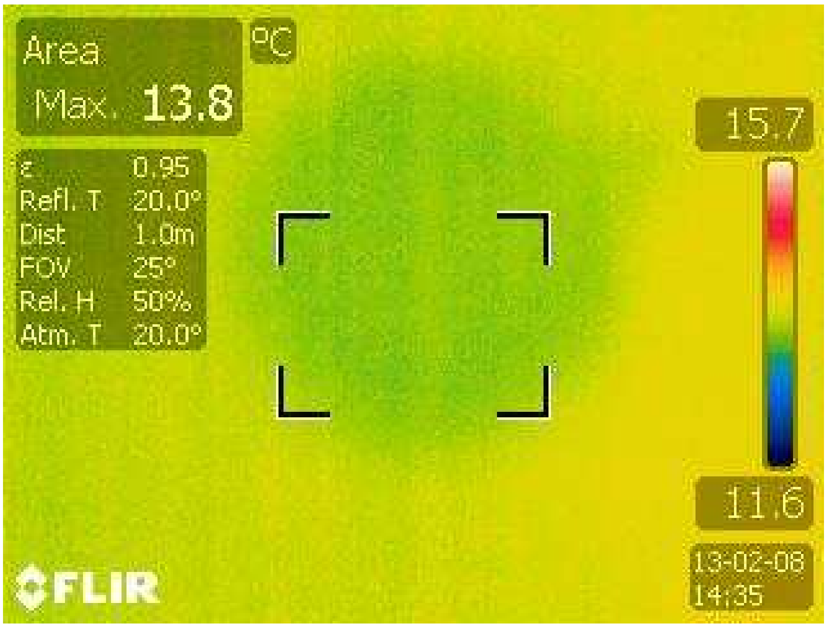


Figure 54 Infrared picture of the fitted sensor. The sensor is just visible as a slighly cooler (green) disk

6 RESULTS AND DISCUSSION

With the captured data, the theoretical model can be compared to the measured data. Two important data need to be compared:

1. the internal core temperature
2. the measured heat flux into the core.

The internal and external measured data is fed into the model and the theoretical core temperature and heat flux is compared with the measured core temperature and heat flux. The flux needs to be calculated from the voltage reading of the sensor using (5). With an input voltage of 6.046 V the flux is:

$\Theta_m = 50*((6.046/0.499)-10)/125.9 = 1.127\ W/m^2$ (6)

The model was run with the internal and external temperatures from the measurement data. The flux was calculated from the measurement as well as in the model as the flux calculated from the thermal resistance in combination with the temperature difference between the plasterboard and the internal EPS, the position where the flux sensor was located. The sample time was set to the same as the minimum run time, 2 minutes. The results were tabled. A sample of this table is shown in Table 11.

After a running period of 16 days (11250 samples) the model estimated the core temperature 0.36 ºC lower than the measured core, as shown in Figure 55. The internal temperature was relative constant between 13 and 16 ºC, whereas the external temperature fluctuated between 2 and almost 14 ºC.

Table 11 model calculation and measured values of the wall

Time (mm:ss)	Node temperatures (°C) Internal	Plaster	EPS int.	Core	EPS ext.	Render	External	Heat flux W/m^2	Measured values Flux W/m^2	Core temp (°C)
09:01	13.01	13.00	12.10	11.17	8.00	4.00	3.71	1.05	1.12	11.17
09:03	13.01	13.00	12.08	11.17	7.97	4.01	3.73	1.06	1.12	11.17
09:05	13.03	12.99	12.08	11.17	7.94	4.01	3.73	1.07	1.12	11.17
09:07	12.98	12.99	12.07	11.17	7.91	4.02	3.73	1.07	1.12	11.17
09:09	12.96	12.98	12.07	11.17	7.89	4.02	3.69	1.07	1.12	11.17
09:11	12.88	12.97	12.07	11.17	7.87	4.02	3.62	1.06	1.12	11.17
09:13	12.90	12.95	12.06	11.17	7.85	4.03	3.62	1.04	1.11	11.17
09:15	12.88	12.94	12.05	11.17	7.83	4.03	3.62	1.03	1.11	11.17
09:17	12.85	12.93	12.05	11.17	7.82	4.04	3.59	1.02	1.11	11.17
09:19	12.85	12.91	12.04	11.17	7.81	4.04	3.64	1.01	1.11	11.17
09:21	12.85	12.89	12.03	11.17	7.80	4.04	3.62	1.01	1.11	11.17
09:23	12.88	12.88	12.02	11.17	7.79	4.05	3.59	1.00	1.11	11.17
09:25	12.93	12.88	12.02	11.17	7.78	4.05	3.59	1.00	1.11	11.17
09:27	12.90	12.88	12.01	11.17	7.77	4.05	3.64	1.01	1.10	11.17
09:29	12.90	12.87	12.01	11.17	7.77	4.06	3.64	1.01	1.10	11.17
09:31	12.88	12.87	12.01	11.17	7.76	4.06	3.64	1.01	1.10	11.17

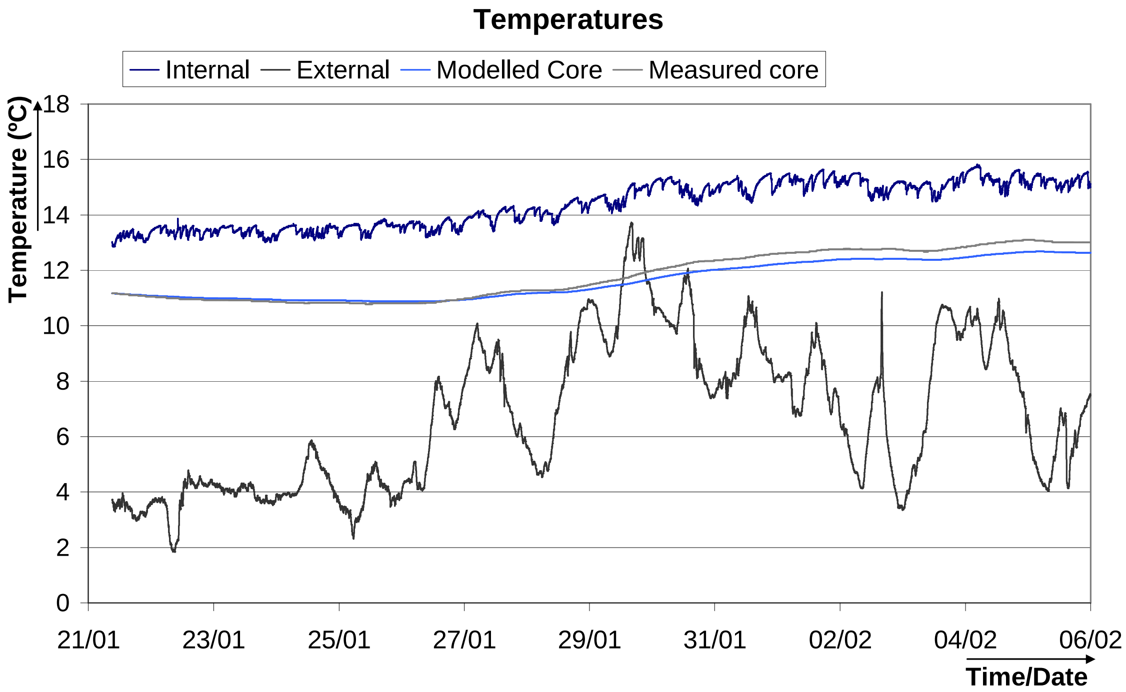


Figure 55 Measured v.s. modelled core temperature. The model calculated the core temperature 0.36 °C lower than the measured value.

The flux measurement showed a higher level of discrepancy, the flux measured was on average 1.75 times higher than the modelled flux, although there does appear to be correlation between the measured and modelled flux, as shown in Figure 56.

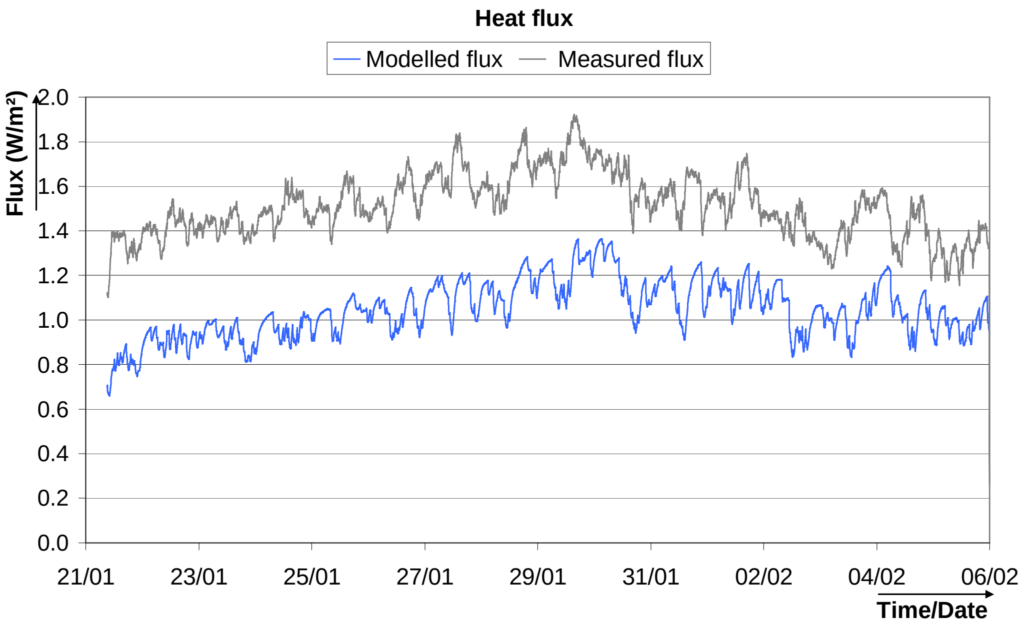


Figure 56 Measured v.s. modelled flux. The measured flux is approx. 1.75 times the modelled flux.

It was noted that varying the EPS value to 0.46, the resulting simulated flux with this K-value for EPS is shown in Figure 57. The average discrepancy between the measured and modelled flux is reduced to less than 10%.

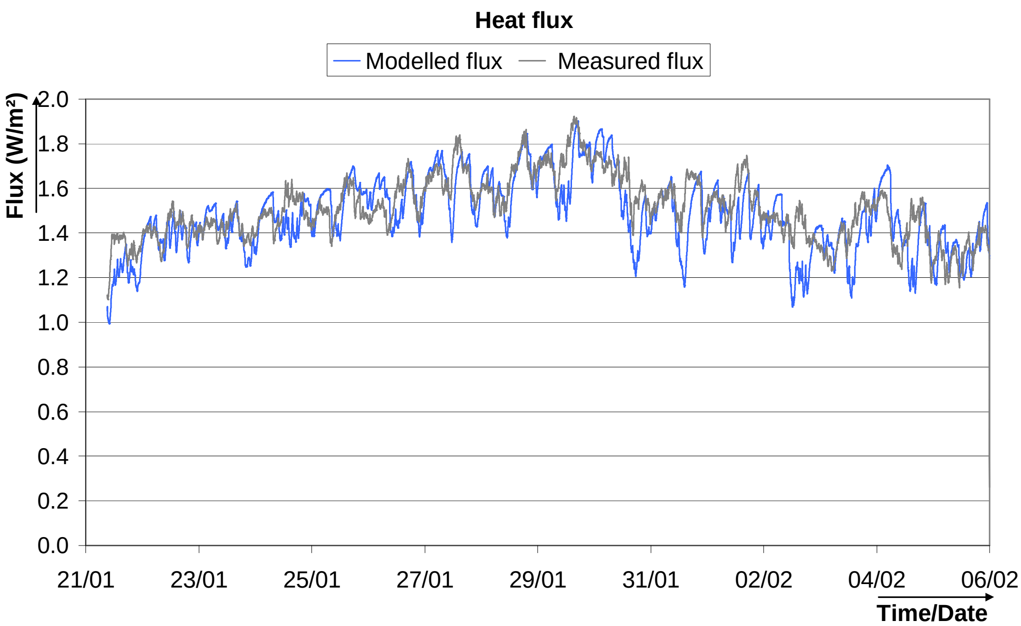


Figure 57 Measured v.s. modelled flux. If the K-value for EPS is changed to 0.046, the measured flux is approx. the same as the modelled flux.

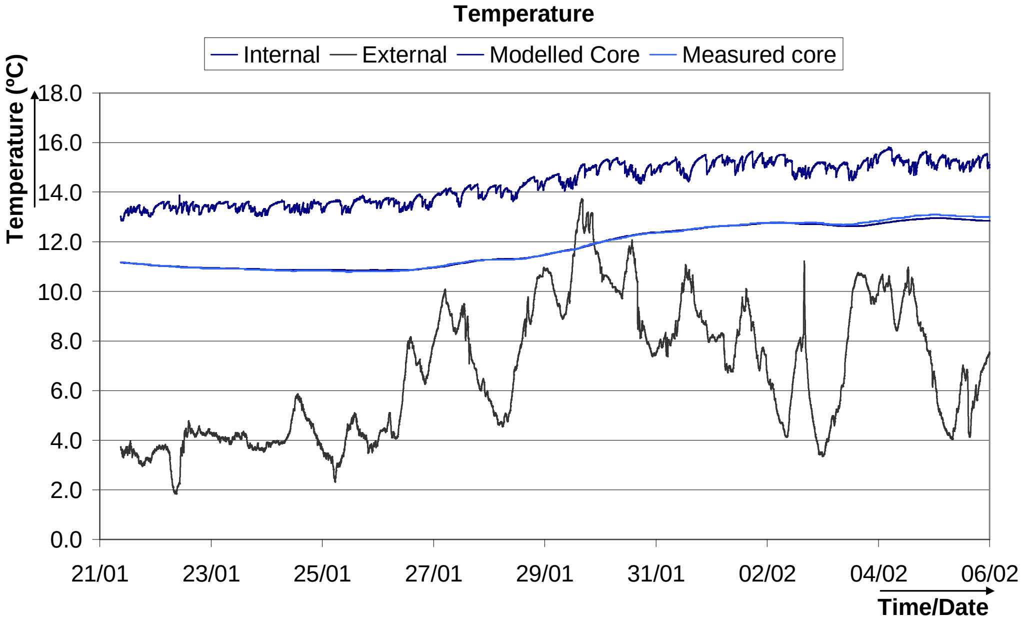


Figure 58 Modelled v.s. measured core temperature with an increased K-value of the EPS. If the K-value for EPS is changed to 0.046, the difference in core temperature between the model and measurement is less than 0.1 ºC.

When the K-value of the EPS is changed to 0.046, the difference between the measured and modelled core temperature is reduced to 0.098 ºC. Any other change in model parameters does not reduce the discrepancy between the model and the measured values. If the capacity is ignored, this means that the U-value of the wall with the increased K-value can be calculated to be 0.161 W/m^2K. The reason for this discrepancy is not known and requires further investigation.

7 CONCLUSION

The thermal mass of the ICF wall structure make a simple U-value measurement problematical. However by comparing the flux measurements with the theoretical model we were able to estimate a U-value of 0.161 W/m^2K, whilst this is higher than the calculated value of is 0.123 W/m^2K, it still represents a huge improvement on conventional wall structures.

In addition there is some evidence to show that the thermal mass of the ICF concrete core is contributing to the stability of the internal temperatures within the dwellings. For example analysis of the measured data over a longer period of time and comparison with a transient thermal model. It would also be possible to analyse the impact of different ICF core capacitance using this technique to establish an optimal configuration for internal temperature stability.

APPENDIX E THERMOGRAPHIC REPORT FOR SHINE-ZC

ABSTRACT

The SHINE-ZC building in Derby comprises of nine adjacent, compact urban dwellings, six 2-storey houses and a 3-storey block containing three flats and a shared staircase. Each dwelling has a living space of approximately $50m^2$ and the total internal volume is $1326m^3$. The buildings were designed and built by EMRE Ltd, as part of a 50/50% private and public funded demonstration project led by Loughborough University. The objective of the project was to demonstrate an ultra low energy dwelling in a compact urban environment.

1 INTRODUCTION

The dwellings are adjoined as shown in Figure 59 and Figure 60.

Figure 59. A picture of the northerly & west elevation of the development shortly after completion

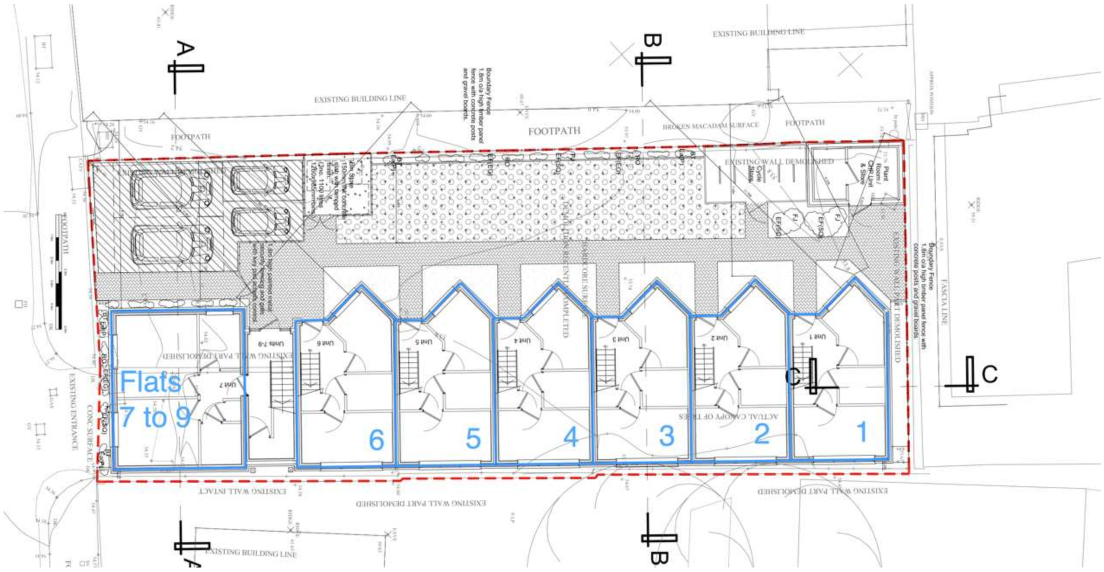


Figure 60. Floor plans of the dwellings

The inner city brown field site upon which it is built dictates the building orientation. The front of the building faces approximately north. The roof area is split in two levels; approximately 160m^2 on the apartments, and 70m^2 on top of the flats. The 230m^2 roof faces south with a 6 degree slope

The surface of the building is partially rendered with an ivory render, and partially clad with treated red cedar panelling. The emissivity of both materials is estimated between 0.86 and 0.9. The windows are triple glazed with no special coating. The emissivity of the windows is estimated at 0.92.

Figure 46 shows a plan view of the development; the dwellings are numbered from right (1 – two storey house) to left (6 – two storey house), and bottom (7 - flat) to top (9 - flat).

ICF outside wall:	Thermal conductivity (W/m°C)	Thickness (m)	Thermal resistance m^2°C/W
Outside surface resistance	25.00	1.000	0.040
EPS	0.030	0.150	5.000
Concrete	0.400	0.150	0.375
EPS	0.030	0.075	2.500
Plasterboard	0.160	0.013	0.081
Inside surface resistance	7.690	1.000	0.130
U value Wall (Wm^{-2}K^{-1}):			0.123

Table 12. Insulation calculation of the ICF outside wall

Kingspan roof:	**Thermal conductivity (W/m°C)**	**Thickness (m)**	**Thermal resistance m²°C/W**
Outside surface resistance	25.00	1.000	0.04
KS1000 roofpanel	0.020	0.120	6.25
EPS	0.030	0.150	5
Inside surface resistance	7.690	1.000	0.13
U value Roof ($Wm^{-2}K^{-1}$):			0.09

Table 13. Insulation calculation of the Kingspan roof.

Insulation build up of the floor slab:	**Thermal conductivity (W/m°C)**	**Thickness (m)**	**Thermal resistance m²°C/W**
Outside surface resistance	25.00	1.000	0.04
EPS	0.032	0.075	2.344
Concrete	2.3	0.175	0.076
EPS	0.032	0.33	14.348
Inside surface resistance	7.690	1.000	0.13
U value Floor ($Wm^{-2}K^{-1}$):			0.059

Table 14. Insulation calculation for the floor slab.

The wall material is Integrated Concrete Form (ICF) supplied by LOGIX UK; a highly insulating construction method that was specified with a U-value of 0.123 $Wm^{-2}K^{-1}$, elemental breakdown shown in Table 7. The U- value of the roof is estimated to be 0.09 $Wm^{-2}K^{-1}$, elemental breakdown shown in Table 13. The windows are triple glazed, with a U-value of 0.8 $Wm^{-2}K^{-1}$ and were supplied by the Litchfield Group. Insulation in the floor is estimated to be 0.059 W/m^2K, elemental breakdown shown in Table 14. It should be noted that the ground floor insulation of the six houses serves the dual purpose of insulating from ambient ground conditions and the elevated temperatures of the under ground aggregate based thermal stores. The building has an inner city location; winter solar gain is minimal due to the shading of adjacent buildings. Summer solar gain needs to be minimised to maintain thermal comfort within the dwellings. The heat losses through the fabric are estimated around 15 W/K for the houses and 9 W/K, 11 W/K and 15 W/K for the bottom, middle and top flat respectively.

Ventilation is assisted by a mechanical ventilation heat recovery (MVHR) unit, with an air exchange rate of 17 l/s, and has 0.43 exchanges per hour in the apartments, and 0.54 in the flats. The heat recovery capacity of the installed system is stated as 90%. There is a summer bypass function in the MVHR. In this mode, the heat exchanger of the heat recovery unit is bypassed, and the air intake is not preheated. The temperature where the summer bypass is switched on, is 25ºC. The temperature when the summer bypass is switched off, is 24ºC.

Desciption	End apart.	Middle apart.	Bottom flat	Middle flat	Top flat
Number of units	1	5	1	1	1
Floor area (m^2)	55	55	42	44	46
Volume (m^3)	140	140	105	110	115
External wall area (m^2)	75	45	47.5	50	52.5
Window area (m^2)	8.5	8.5	5.5	6.5	6.5
Roof area (m^2)	30	30	--	--	70
Ventilation rate (exch./hr)	0.43	0.43	0.54	0.54	0.54
Heat loss fabric (W/K)	18	15	9	11	15
Ventilation heat loss (W/K)	8	8	8	8	8

Table 15. key parameters of the development

Of all the dwellings, the end apartment (plot 1) has the highest theoretical total losses (the combination of fabric and ventilation losses), and this loss is around 26 W/K.

Comfort levels are aided by ‘upside down living’ in the apartments i.e. the living space is on the first floor, whilst the bed/bathrooms are located on the cooler ground floor, aiding sleep. As a result the bedrooms will stay cooler, whilst the living area will stay warmer and have more natural light.

This development uses a novel underground thermal storage solution consisting of a highly insulated aggregate bed situated under the six houses. Surplus heat from the large solar thermal array on the roof is transferred into this store over the summer months & can be extracted during the heating season using air-sourced heat pumps.

2 METHOD

This paper describes the thermographic tests conducted on the SHINE-ZC development at Woods Lane, Derby. Thermographic tests were conducted in accordance with BS:EN 13187. The equipment used was a Flir infra red camera, model FLIR B335, serial nr: 456000535.

The focal length of the infrared camera, and the constrained nature of the site prevented a clear picture of the whole development. Therefore the decision was taken to deal with the flats and house separately at the front of the site.

All internal pictures and temperature measurements were taken in plot 3 (house) and plot 7, (bottom flat), they were unoccupied and had no furnishings at the time. The rest of the site was occupied at the time of the study. The heating of both dwellings was set using the room thermostat at 23 ^{o}C, the temperature was maintained by the developments heating system for the duration of the study.

The study was conducted in two phases; the initial study was conducted over a week period in February 2012. A second study was undertaken during optimal conditions on the 5th May 2012 to clarify the technical details around heat leakage at the wall ground interface of the northerly elevation. Supplementary images from both investigations have been placed in appendix I.

During the second study we were able to take advantage of the structured interviews and BUS studies, providing qualitative data on the performance of the buildings through one heating session.

3 RESULTS AND DISCUSSION

The thermographic pictures were taken from 01:00 on the morning of 5th May, 2012. Table 16 below details the site conditions at the time the infrared thermal images were taken.

Site conditions	Measured values	Description
Ambient temperature	4.5 °C	Measurement taken at 01:00 on the 5th May 2012. Variation over the duration of the image taking 0.5 °C.
Temperature variation over the proceeding 24 hours	8.0 °C	Variation measured on site using roof mounted weather station temperature ranged from 12.5 to 4.5 °C.
Wind speed	1.69 m/s	Measured on site using roof mounted weather station.
Air humidity	73%	Measured on site using roof mounted weather station.
Barometric pressure 3	1000 hPa	Measured on site using roof mounted weather station.
Internal temperature of plots 3 and 7	22.5°C	Measured at mid room height in the living area and one bedroom.
No precipitation measured over the last 24 hours.		

Table 16. Site conditions at the time of thermographic image capture

With such low wind conditions there will be virtually no air pressure across the building, therefore, it is assumed that air movements due to pressure differences can be neglected.

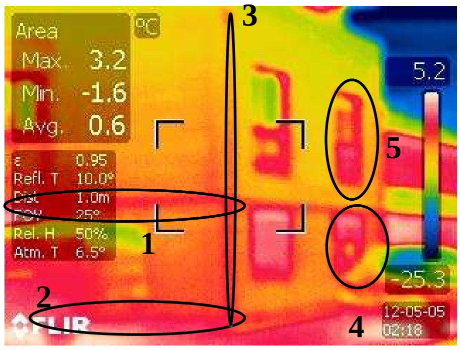


Figure 61. Infrared image of the western elevation of the development adjacent to the road

Figure 62. Photograph of the western elevation of the development adjacent to the road

Figure 61 shows the front west facing wall of the development, adjacent to the road, and the north facing elevation of the flats. The infrared image shows a homogeneous wall surface temperature as expected of between 3.5°C and 4.5°C, or close to ambient temperature conditions. Circled feature 1, is the small horizontal heat signature that has formed where the upper cedar clad portion of the wall overlaps the lower rendered wall at an elevated temperature of 4.7°C. Upon investigation, this heat feature can also be seen on the underside of all the overlapping cedar clad areas of the developments walls. Circled feature 2 is similar to circled feature 1, a small horizontal heat feature of approximately 4.5°C across the footings of the development walls. This appears at the change in section between the aluminium kick strip at the foot of the development wall, and the overlap of the rendered finish. These heat signatures are most likely due to a small heat build up under the overlapping features, as the temperature difference when compared to the rest of the wall structure is small. The design drawings of the walls show a homogenous ICF structures under the external render with no sections changes or discontinuities (see Figure 63 for details of the internal investigation). Circled feature 3, is a small vertical heat feature of between 5 and 5.3°C, running the height of the first two floors of the development on the corner formed by the northerly and westerly elevation. This feature is an artefact of the drainage down pipe running down the corner of the building and can be ignored. Circle feature 4 highlights one of the westerly external windows, this appeared to have thermal bridging on one of the closure seals and was investigated further internally, see Figure 67.

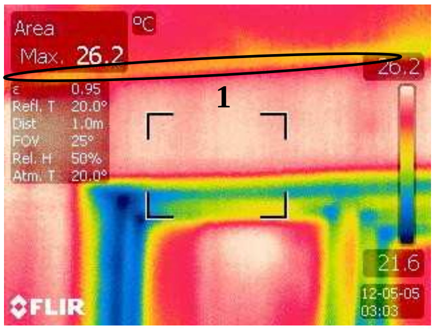


Figure 63. Infrared image of the interior of plot 7 northerly bedroom ceiling line at the cedar cladding height.

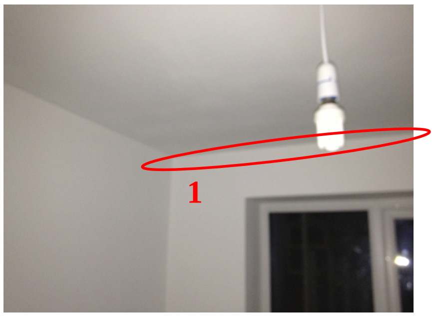


Figure 64. Photograph of the interior of plot 7 northerly bedroom ceiling line at the cedar cladding height.

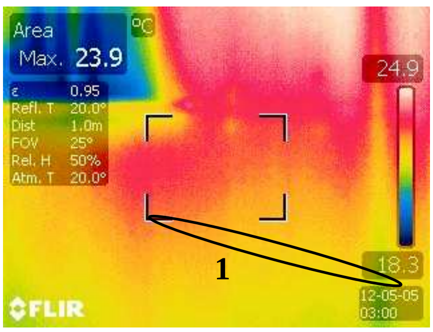


Figure 65. Infrared image of the interior of plot 7 northerly bedroom floor line at the aluminium kick strip height.

Figure 66. Photograph of the interior of plot 7 northerly bedroom floor line at the aluminium kick strip height.

An investigation within plot 7 showed no evidence of conductive thermal bridging through the ICF structure at points correlating to horizontal features 1 and 2 of Figure 61. Figure 63 circled feature 1, and Figure 65 circled feature 1 show clearly that here is no thermal bridging at either the cedar cladding height or aluminium kick strip height with the dwellings.

When examining the first storey fenestration on the western elevation, (see Figure 61 circled feature 5) the infrared image shows that the occluded glazed lower panel has a temperature slightly higher than the transparent upper glazed panel. A review of the design minutes showed that occluded panel did have a lower U value, as at the time the fenestration supplier was unable to source an occluded triple glazed unit from their European partners, and so it had been agreed that a double glazed unit be substituted.

Figure 67. Internal infrared image west facing bottom flat window dwelling 7

Figure 68. Internal photograph of west facing bottom flat window dwelling 7

When examining the ground floor fenestration on the western elevation, (see Figure 61 circled feature 4) the infrared image indicated a possible thermal bridge. Figure 67 shows some evidence of a conductive thermal bridge at the bottom left hand side of the opening window seal (circled feature 1), the spot temperature at this point was 11.5°C. This was not consistent with infrared temperature measurements of the rest of the windows in dwellings 3 and 7. Upon further investigation, it was found that the previous occupant had damaged the window seal by trapping an aerial lead in the window.

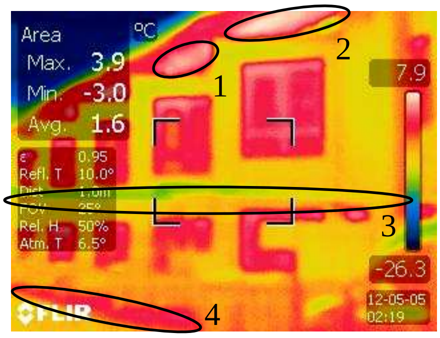


Figure 69. Infrared image of the northern and western elevations of the site.

Figure 70. Photographic image of the northern and western elevations of the site.

Figure 69 is an image of the north facing aspect of the six houses. The large thermal signature under the eaves of the building (circled feature 1 & 2), above each fenestration system, appears to be caused by a heat build up above the vent from the MVHR system (for a more in depth investigation of this issue see Figure 71). It was noted that the temperature of the upper fenestration of the houses, appears to be higher when compared to that of the lower fenestration (for a more in depth investigation of this issue see Figure 75). Circled feature 3 is a security barrier across the front of the site, and can be ignored. It was noted that there appears to be heat leakage at the base of the buildings circled feature 4 (this is investigated further in Figure 77).

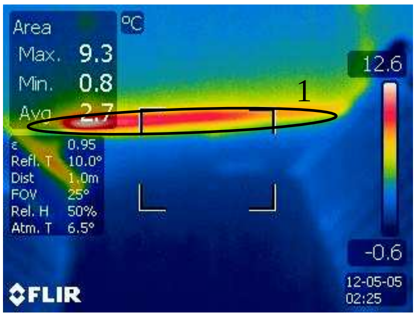


Figure 71. Infrared image of the exhaust of heat recovery unit from the houses.

Figure 72. Photographic image of the exhaust of heat recovery unit from the houses.

When investigating the northerly aspect of the development, it was discovered that there was a significant heat signature at the junction with the roof eaves. The circled feature in the infrared image of Figure 71 shows clear evidence of the thermal signature; the temperature was measured between 9.7 and 12.6^{o}C. The thermal signature appears above the air intake and outlet of the MVHR, these can be seen in the still image (see Figure 72) top middle, as two rectangular openings, one above the other.

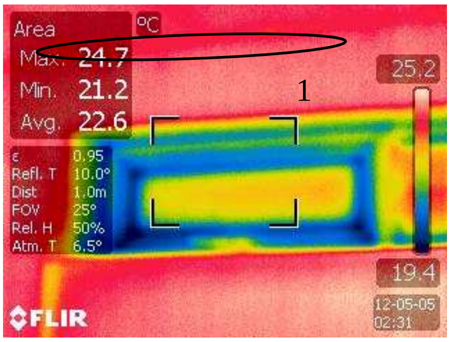


Figure 73. Internal image of the ceiling wall interface on the northerly aspect of house 3.

Figure 74. The corresponding photographic image of the ceiling wall interface for context

A thorough investigation was made within house 3 at the ceiling wall interface to identify thermal bridging at the roofline. No evidence of conductive thermal bridging at the junction between the roof and wall structures was found inside house 3, see Figure 73. On balance the evidence points towards the heat signature under the eves being caused by expelled air from the MVHR unit.

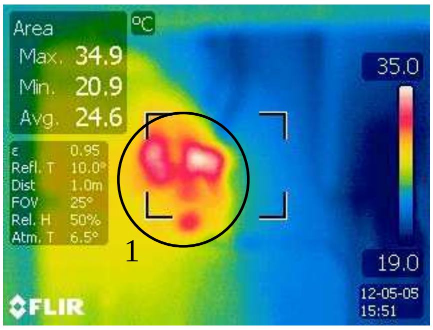


Figure 75. Infrared images of the thermal store.

Figure 76. Photograph of the thermal store.

Figure 59 appeared to show a higher than expected differential temperature between the ground floor and first floor windows. As the fenestration system used across the development has the same performance, the most likely cause of the differential in temperatures is an internal heat source. This was investigated further by using the infrared camera to identify internal heat gains within house 3, as it exhibited the same characteristic as the occupied houses. The only internal heat source that is common across all of the houses (dwellings 1 to 6) is the wet thermal store. This is located in a cupboard on the first floor, adjacent to the north elevation window. Figure 75 is an image of the thermal store; circled feature 1 is the isolation valve on the domestic hot water circuit, its temperature was measured as 35.1^{o}C. No other common heat source was identified across plots 1 to 6 that would account for the temperature differential seen.

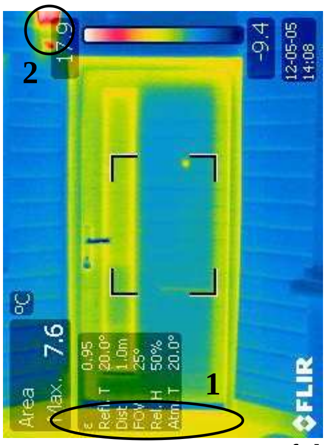


Figure 77. An image of the outside front door of house 3.

Figure 78. An image of the outside of the front door of house 3

Note: The large thermal signature in featured cirle 2 is an infrared security lamp.

When investigating the northerly aspect of the development there was evidence of a heat signature from the base of the development, circled feature 4 on

Figure 69Figure 77 is an image of the front elevation of house 3, circled feature 1 highlights the slightly higher thermal signature from the ground than the adjacent walls. The design drawings show that the ground floor slab extends beyond the building in this area and therefore there is a thermal bridge between the interior and exterior of the building. A high-grade polyurethane insulation has been specified above the ground floor slab to insulate it from ambient air condition and this accounts for the low level of leakage observed.

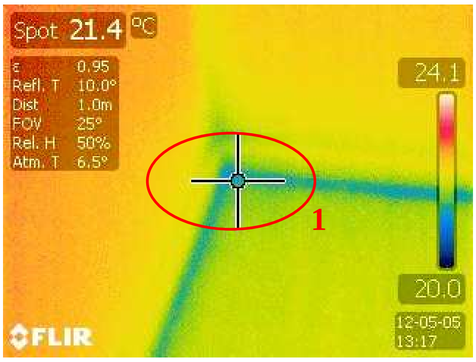


Figure 79. Infrared spot image of the interface between the ground floor and the adjacent wall in the front bedroom of house 3.

Figure 80. Photographic image showing were the infrared spot image was taken.

The investigation of thermal bridging on the ground floor slab was followed up with an internal investigation of house 3. In Figure 79 circled feature 1, you can see a spot measurement of the temperature at the interface between the floor and adjacent wall, at the apex of the bay on the northerly elevation. Spot measurements showed that there was a difference of around 1.5°C at this interface, when compared with the adjacent wall temperature. This supports the external measurements showed there is some thermal bridging through the ground floor slab. A review of the design minutes showed that this issue was understood, and that this was a design compromise made to accommodate the thermal stores built into the substructure of the building.

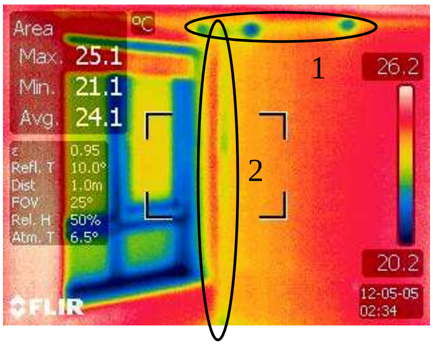


Figure 81. Internal infrared image of the house first floor triangular bay area dwelling 3

Figure 82. Photographic image of the house first floor triangular bay area dwelling 3

A conductive thermal bridge was identified in the junction between the walls and the roof of the triangular bay area on northerly elevation of dwelling 3 (see circled area 1). Inspection of the design drawings show the roof bolted to the wall structure in roughly the area of the cold bridges. Anecdotal evidence suggests that some of the insulation was removed to achieve these fixings. Circled area 2 highlights a faint vertical cold area, it was not possible to ascertain the cause of this without the removal of cladding material on the outside of the building or plaster board on the inside.

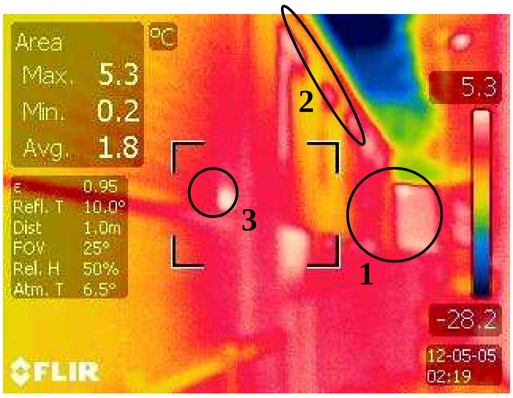


Figure 83. Infrared image of the southern elevation of the SHINE-ZC development

Figure 84. Photographic image of the southern elevation of the SHINE-ZC development.

Note: it can be seen clearly in the right hand comparison image that some windows are open. This was not the case when the infrared image was taken.

Figure 83 shows the southern elevation of the development, with the flats in the left foreground. The thermal image shows a homogeneous wall surface temperature of between 3.5°C and 4.1°C. Behind the development is a public house (circled feature 1); this can be seen clearly in the lower right hand side of the image behind the houses as it has a much higher temperature than the SHINE-ZC buildings. There is a small heat feature under the gutter and roof overlap of the development (see circled feature 2), measured at 4.5°C. Circled feature 3 is the outlet of the MVHR unit for plot 7 and can be ignored.

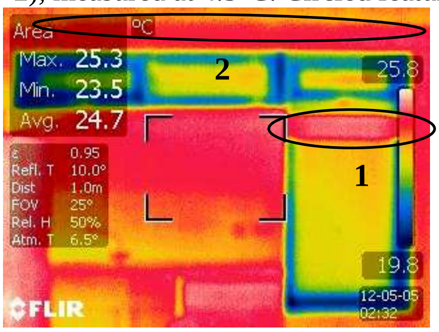


Figure 85. Internal infrared image of the house southern fenestration system

Figure 86. Photographic image of the house southern fenestration system

The heat feature at the roof line was investigated internally, the infrared image shown in Figure 85 is an internal image of dwelling 3's south facing fenestration system and wall. Circled feature 1 highlights a higher temperature area created by a blind; circled feature 2 highlights the interface between the wall and ceiling. No evidence was found inside dwelling 3 of any conductive thermal bridging at the ceiling and wall interface at the southern elevation.

4 CONCLUSION

Interfaces between walls, roofs and fenestration systems, are typically areas of heat losses in traditional builds. Two instances of this were identified; the first is the thermal bridging on the ground floor slab in the area of the front door on the northerly elevation (see Figure 77). This is a design compromise to accommodate the thermal stores under the houses. The second area of thermal bridging identified was in the junction between the roof and wall of the bay area, on the northerly elevation of dwelling 3 (see Figure 81). This has been identified as a quality control issue, were the steel roof fixings have not been correctly insulated at the time of installation.

ICF walling can exhibit thermal bridging if the hydraulic pressure exerted by the concrete core during pouring becomes too great to be retained by the insulating block work. This is sometimes referred to as ‘burst through’. Where this occurs, concrete material is pushed through the joints between the ICF blocks, this forms a thermal bridge. Cutting away the thermal bridge and filling in the resultant gap with insulation foam, can repair a ‘burst through’ if the damage isn’t to great. The investigation was careful to look for this problem, specifically at section changes in walls, and at corners where hydraulic pressure would have been at its greatest. No definitive evidence was found of an instance of a ‘burst through’ on the build, and the thermal signature from the walls was homogeneous. This was corroborated through discussion with the construction workers who stated that special shuttering had been constructed to reinforce key areas of ICF block work to prevent ‘burst through’.

We were unable to identify the cause of the faint vertical cold area at the apex of the bay area in Figure 81. During our investigation to ascertain what the cause might be we noted the following pertinent facts:

- A review of the design drawings revealed that ICF blocks were cut on site to form the bay apex as this profile could not be achieved with standard ICF block profiles. This will have produced a lower tolerance joint between the site cut ICF blocks, making it more prone to ‘burst through’.

- It was noted that there appears to be a difference in thermal signature between the adjacent walls. Additionally, the bay itself has a prominent position at the front of the development and therefore subject to higher heat losses through the movement of air over this exposed area. This could be a contributing factor to the heat signature.

- The plaster board fixings at the apex of the bay area (a metal fixing strip on this development) may have reduced the air gap normally present behind the plaster board, impacting on the efficacy of the insulation in this area.

- Finally, a review of the semi-structured interviews of the development’s occupants and the BUS studies showed no evidence that the occupants had noticed anything unusual regarding the thermal comfort of the bay area.

Fenestration and its interface with the superstructure is another area where thermal bridging can occur if quality control is not maintained. No evidence of heat leakage around fenestration systems was found on the site, the fenestration systems appear to be performing in a consistent manner across the development.

An extended pressure test was conducted in house 3 as part of the BPE 1 study, this yielded an average air permeability rate of 1.70 $m^3/(h.m^2)$. This was one year on from similar results obtained during the building regulation air permeability tests. This corroborated the lack of thermal bridging observed during this investigation and also indicates that air tightness is not degrading.

The MVHR ducting if not properly insulated on the external air intake and egress side can cause a thermal bridge. No evidence was found of duct work that wasn't properly insulated or sealed during our investigation work within plots 3 and 7.

Poor insulation of control valves and piping on the wet thermal store was identified in dwelling 3 as the potential to cause overheating in the dwellings during the summer months. A review of the design specification showed that this problem resulted from incorrectly specified insulation material during design. This is a relatively minor issue that can be rectified by the installation of higher performance pipe and valve insulation.

Overall the observed thermal bridging issues identified are minor and the build quality in terms of air tightness and thermal performance is exceptional.

APPENDIX F MODULES NAMES AND EXAMINATION RESULTS

Module Code	Module Title	Coursework Mark (%)	Exam Mark (%)	Total (%)
10ELP460	Engineering and Management of Capability	65	n.a	65
10ELP085	Group Systems Project	56	n.a	56
10ELP001	Postgraduate Research Dissertation	81	n.a	81
10CVP310	Advanced Thermal Modelling	71	60	66
10CVP309	Low Carbon Building Design	82	58	70
09ELP769	Innovation and Entrepreneurship for Engineers	75	n.a	75
09ELP461	Human Factors in Systems Design and Use	76	59	63
09ELP072	Systems Architecture	85	n.a	85
09ELD308	Financial Management	72	71	71
08ELP061	Systems Approach, Analysis and Concepts	77	n.a	77