THE POTENTIAL FOR SOLAR THERMAL TECHNOLOGIES AND THERMAL ENERGY STORAGE TO REDUCE THE ENERGY USE FROM WELSH HOUSING

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ABSTRACT

This thesis deals with the potential contribution that state-of-the-art solar thermal (ST) systems enhanced by thermal energy storage (TES) technologies might have in reducing the energy use in Welsh dwellings. The focus of this work lies with the share of the overall amount of conventional energy currently consumed for thermal comfort and hot water preparation that could be replaced by solar energy harvested by active, water-based, solar systems. Twelve typical Welsh dwellings drawn from a recent survey and considered as representative of the Welsh housing stock are modelled and the solar collectors' yield for different orientations and tilts is predicted. The subject is investigated with computer simulations using the TRNSYS simulation engine.

The methodology dictates at first prediction and analysis of the thermal energy demand profiles of 12x4 case studies; using average (smoothed) and actual (warmer) weather conditions, continuous and intermittent comfort maintenance. Next the ST potential is estimated considering solely a maximum (0.7) and an average (0.4) overall system efficiency and no other technical part for the ST system (modelling approach), in order to investigate the mismatch of energy demand and availability and the TES contribution. The performance characteristics of some representative European ST systems (short-term TES only), as derived from the IEA SHC Task 26 FSC method, are then applied to the simulations to reveal the potential with realistic losses and parasitic energy consumption included (applied only to 5 compatible models).

It is revealed that all these house types are possible candidates for effective ST applications, assuming that economies of scale would allow for large absorber areas in the near future. The modelling approach shows that ST systems could contribute to thermal savings between 9%- 34% solely with direct utilisation of the collected energy. Furthermore, for most cases, if reasonable sized stores would be used (up to 300kWh TES capacity) then the solar contribution to the overall thermal energy consumption, in the most favourable conditions, would be around 42-58%. Only a couple of models appear to have a lower potential, mainly due to lack of sufficient absorber areas. However for reaching the highest end of expectations for certain house types -up to 54% with average and up to 100% with warmer weather conditions- inter-seasonal storage would be required. In this case, the justifiable storage capacities predicted correspond to very large store volumes, revealing that these are currently not feasible options, as sensible heat storage is still the state-of-the-art for TES. Use of innovative storage types identified by the literature survey, that would only be available in the future, are required in order to achieve high solar contributions, considering space limitations in Welsh dwellings. The FSC results show that for the 5 models the use of solar energy would bring thermal energy savings of around 41-47% if the best system is employed compared to a conventional system, while if parasitic (electric) energy consumption is considered the expected energy savings could be as low as 10%.

The actual ST potential is analysed and is found to be in between the two approaches, as both methods have advantages and limitations and complement each other.

CURRICULUM VITAE

The author of this work is qualified as an architect, having obtained her B. Arch from the NTUA of Athens in 2003, before going on to practice architecture in Athens. She subsequently gained a Masters Degree in The Environmental Design of Buildings from the WSA, Cardiff University in 2005, supported by a grant from the Greek Institute of Scholarships (I.K.Y.). This PhD research was funded by a grant from the BRE Trust.

PUBLICATIONS

E. Ampatzi, I. Knight. The potential application of residential solar thermal cooling in the UK and the role of thermal energy storage technologies. *AIVC 28th Conference and Palenc 2nd Conference: Building Low Energy Cooling and Ventilation Technologies in the 21st Century*. Crete island, Greece (27-29 September 2007)

E. Ampatzi, I. Knight and M. Rhodes. The role of thermal energy storage in helping solar thermal reduce the heating and cooling demands of the housing stock in a northern European country. *1st International Conference on Solar Heating, Cooling and Buildings.* Lisbon (7-10 October 2008)

E. Ampatzi, I. Knight and M. Rhodes. Effect of Internal Gains on Thermal Comfort in Welsh Dwellings. *25th PLEA (Passive and Low Energy Architecture) International Conference.* Dublin (22-24 October 2008).

I. Knight, M. Rhodes, F. Agyenim and E. Ampatzi. The potential for solar thermal heating and cooling systems to reduce the carbon emissions of domestic properties in a northern European country. *1st International Conference on Solar Heating, Cooling and Buildings.* Lisbon (7-10 October 2008).

I. Knight, M. Rhodes, E. Ampatzi, F. Agyenim, T.Giles, E. Stanley. 2008. The Stacs project- Solar Thermal Absorption Cooling integration with domestic buildings. Final report. Cardiff, Welsh School of Architecture.

Contribution towards the work carried out at the BRE for the European Project PREHEAT (Intelligent Energy Europe) and in particular with working on the Work Package 3 deliverable. PREHEAT stands for Policy reinforcement regarding heat storage technologies and therefore the project's objective was to bring attention to decision makers and increase funding potential for heat storage (development and implementation) in EU. More information along with the final reports can be found at the website 1.

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LIST OF ACRONYMS AND ABBREVIATIONS

BRE	Building Research Establishment
DHW	Domestic hot water
ΔT	deltaT (temperature change of the TES material in the store)[1]
EST	Energy Saving Trust
ESTIF	European Solar Thermal Industry Federation
FP	Flat plate collector
$f_{sav,ext}$	Extended fractional energy savings (IEA SHC)
$f_{sav,therm}$	Fractional Energy Savings (IEA SHC)
FSC	Fractional Solar Consumption (IEA SHC)
IEA	International Energy Agency
IEA SHC	International Energy Agency Space Heating and Cooling Programme
NSC	Normalised space cooling (demand)
NSH	Normalised space heating (demand)
PMV	Predicted Mean Vote (on the thermal sensation scale)
SAT	Sodium Acetate Tri-hydrate
SC	Space cooling
SF	Solar fraction
SH	Space heating
ST	Solar thermal
STACS	Solar Thermal Absorption Cooling Systems
TES	Thermal energy storage

[1] Generally a term indicating a temperature relationship between two temperatures or temperature variation between two points, but here used mainly for TES systems.

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"... the seeming disadvantages and detriments of various locations and climate conditions are not particularly harmful. A well-optimised system dimensioning, a proper choice of components and the application of highly efficient products can make up for the difficulties. ***No region is excluded from being able to use solar energy".***

(PEUSER, F. A. et al., 2002)

1 INTRODUCTION

1.1 RESEARCH AIMS AND QUESTIONS

This work aims to investigate the potential of reducing energy consumption in typical Welsh housing (existing and newly built) by using solar thermal (ST) and thermal energy storage technologies (TES) for space heating (SH) and cooling (SC) and domestic hot water (DHW) preparation. The focus is on small scale installations, in the sense that only systems serving individual dwellings are considered and thus district heating options are not taken into account, but as the interest is to identify the maximum energy savings potential per house type, the largest possible share of the available roofs is used in each case, resulting -in some cases- to large absorber areas.

The approach taken here is to investigate the potential that arises mainly from the particular housing characteristics and the climate and less from the contribution that a particular ST system or configuration can have to the energy savings and carbon reduction goal in this context. The reason behind this idea is that, due to the nature of solar energy, the choice of a particular ST configuration might have a completely different outcome compared to another ST application, not only because of the selection of components but also due to the overall design strategy. The same applies to the TES components which are expected to be essential elements of any ST application for SH and DHW in the UK, due to the seriously fluctuating insolation levels resulting from the varying sky conditions. That means that the effect of different storage capacities is the principal focus here, rather than the contribution that a specific marketed product might have on the ST system performance. However this approach does not overlook the role that the actual systems and components would play in ST applications within this context. Therefore one of the aims is to identify what is the role that a selection of popular solar combisystems and state-of-the-art TES solutions could play in this situation.

To meet these aims the following questions considering the majority of the Welsh housing stock are raised and answered in this work:

- What are the thermal demands for SH, SC and DHW preparation for a number of representative house types for Wales?

  - What is the predicted range of the demands when detailed geometry and 'realistic' diurnal fluctuations in occupancy are modelled against actual and average weather conditions for Wales?

- What is the solar availability for these house types for a variety of roof orientations and tilts, considering an actual collector type (dimensions, performance) available in the market?

- What is the maximum theoretical potential for ST arising from the demands and the climate?

  - What share of the thermal demand for DHW, SH& SC can be reached by instantaneous use of the available solar energy and by employing TES technologies? What are the required system sizes (solar collectors and store capacities trade off) in order to reach a 50% solar fraction?

- What energy savings can be reached with the use of typical, state-of-the-art solar thermal systems (for SH and DHW combined) available in the market?

The next paragraph discusses the reasons why the researcher of this work considered ST as a potentially interesting technology for the UK and this research subject worthwhile.

1.2 THE UNDERLYING CONCEPT

There is an impression, shared even amongst architects and designers, that there is insufficient solar energy in the UK for solar thermal (ST) systems to achieve solar fractions which would bring significant energy savings and carbon reductions, within economically feasible solutions. In addition, the lack of supporting policies at a national level and the poor reputation that ST systems gained in the previous decades are responsible, to a large extent, for the limited installed ST capacity in this country, compared to the rest of Europe. In general it is usually the low energy buildings that these technologies are considered for. When it comes to retrofit scenarios, it is expected that all other 'passive' measures are first implemented, resulting in a low SH load to be (partially or fully) met by the ST system. With Welsh people being amongst the highest energy consumers in the world, and with an aging housing stock (see 1.4), one of the questions arising regarding the energy demands in existing Welsh dwellings is whether there is a realistic potential for energy savings and carbon reductions from the use of the solar energy incident on their sloped roofs.

On the other hand experts conclude ((PEUSER, F. A. et al., 2002) p.307) that ST applications could be used in any region of the world with the prerequisite that the systems are well designed and adapted to the particular climate and building types. Solar combisystems are systems which serve hot water, space heating and sometimes cooling[2] requirements. They are much more complicated than the solar water-heating systems, but can bring more benefits, as these serve more than one purpose. Solar water-heating systems are proved to be very effective in South Europe. Experience from France has shown (LENORMAND, P., 2005) that when it comes to systems making use of solar energy for water and SH combined, the energy savings are much higher for dwellings at the north of the country than those at the south. This is related to the length of the heating period and reveals a potential advantage for ST applications in conventional UK dwellings, where SH might be required throughout the year, even during the summer months. This is especially true as one of the main problems of the ST systems is stagnation i.e. when the system is idle because there is no demand. In low energy houses the non-heating periods tend to be longer than usual and therefore the stagnation risk for the solar system is more frequent.

ST systems for small scale residential applications are usually chosen for environmental reasons rather than economic ones. Obviously ST is one out of a range of possible technologies which could be employed to bring energy savings and hence carbon reductions from new and existing houses in Wales. In this study the potential contribution that the use of ST energy and TES technologies can bring in reducing the energy use in Welsh dwellings (for DHW preparation and SH[3]) is investigated. The carbon reduction potential is only indirectly addressed here.

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[2] Often also called solar combisystems+ when cooling is included.

[3] The space cooling requirement predicted for the Welsh dwellings was found (see chapter 5) to be relatively small and therefore it is not assessed in detail, although references to this are made where appropriate.

In section 1.3 a short description of the STACS Welsh housing survey, which overviewed the current Welsh housing stock and offered raw data for the building simulations of this PhD work, is given. In 1.4 a discussion on the carbon share of the domestic sector for the UK, with actual figures for the present and projected potential as found in existing national policies takes place to provide background information and highlight the importance of conducting this research within this particular context.

1.3 STACS PROJECT: WELSH HOUSING STOCK SURVEY

STACS stands for Solar Thermally Activated Cooling Systems and the project run in the Welsh School of Architecture for the period August 2006 – June 2008 (KNIGHT, I., 2006). Part of the project was the characterisation of the Welsh housing stock and the respective information was published in the final report and in a conference paper (KNIGHT, I. et al., 2008a) (RHODES, M. et al., 2007). This PhD work was coupled to the STACS project in the sense that direct access to the raw data of the project was allowed and the results of the models of this PhD work were also used in the project (KNIGHT, I. et al., 2008a). Therefore using the Welsh dwellings to investigate the aims of this research was the most reasonable option at the starting point of this work.

The STACS survey provided a database for the Welsh dwellings, comprising the twelve most common types which are representative for 50% of the entire stock. 2D geometry in CAD drawings, room heights, materials' data and orientation of the houses were available from the survey and therefore computer models could be built in order to study the thermal behaviour of the buildings. Although the results of this work correspond to the selected house types, it is expected that the predictions are likely to be applicable to other UK dwelling types. Nevertheless the results apply to half of the Welsh housing stock and future work is required in order to draw general conclusions for the whole of the UK, considering the entire housing population and climate-related aspects.

1.4 THE UK DOMESTIC SECTOR AND THE CARBON REDUCTIONS POTENTIAL

The Welsh Government has set the ambitious goal to meet zero carbon for new buildings by 2011, five years before the rest of the UK (WAG, 2008a). This is part of its commitment to achieve 3% reduction of carbon emissions by 2011 and it is in contrast to the fact that the carbon emissions per person in Wales were the 12th highest in the world in 2004 (CLUBB, G., 2007).

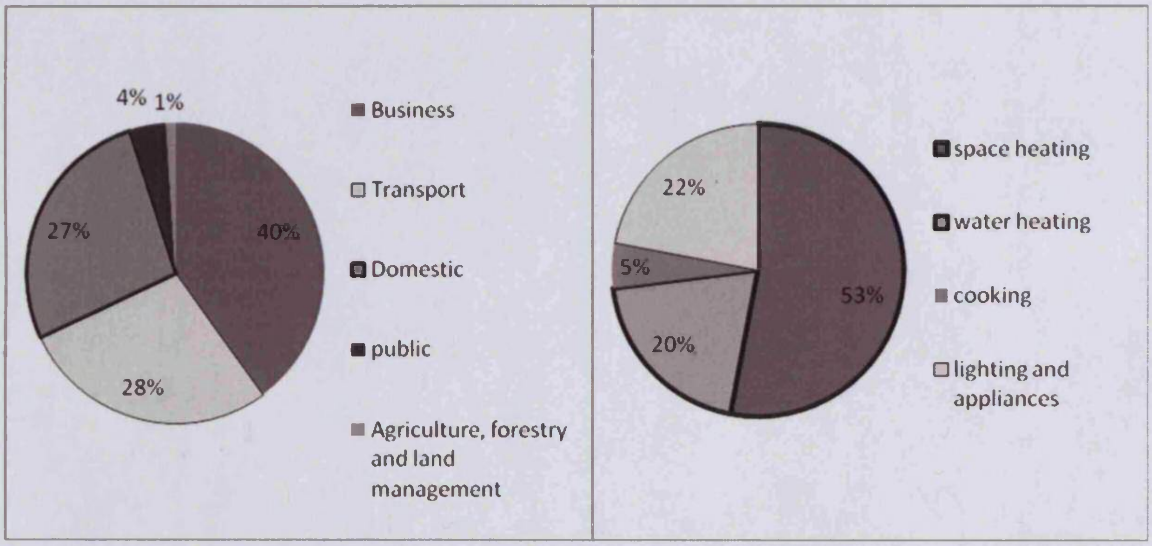

FIGURE 1: UK CARBON DIOXIDE EMISSIONS BY END USE, FOR 2004 (LEFT). UK TOTAL DOMESTIC CARBON EMISSIONS END USE FOR 2003 (RIGHT). (CLIMATE CHANGE: THE UK PROGRAMME 2006)

Dwellings are responsible for around 27% of total carbon dioxide emissions in Wales as shown in Figure 1 (left) (DEFRA, 2006; ; EST, 2005). According to the information published by the HM Government in 2006 (DEFRA, 2006) 73% of the total domestic emissions in the UK are produced by the water heating and SH systems (Figure 1, right). That shows that the need for SH is 2.65 times higher than the DHW preparation requirement, very far from the low carbon dwellings which are designed for requiring less than 15kWh/m^2 per annum for SH. The Welsh Assembly Government is currently working on the agenda of potential technologies which can contribute to the goal of carbon reductions (WAG, 2008b). In the last years several 'consultations' have been organised by the UK Government to bring input from all the involved stakeholders and to assist in identifying the best strategies for meeting the carbon reduction goals. In the related policies different approaches are suggested for the new and for existing dwellings. Both at a National and at a European level the focus is mostly on the new buildings, as with the existing ones the issue is more complicated.

It is obvious that in order to make substantial emission reductions, dealing just with the new buildings is not adequate, as the largest portion of tomorrow's dwellings has already been built. According to publications cited in the STACS survey (RHODES, M. et al., 2007) 5% of the UK houses in 2001 were in Wales, accounting for 1.3 million in 2004. From the same source it is found that around 8,000 new dwellings are built every year in Wales with a relatively stable rate over the last 10 years and in 2004 these new houses accounted for 0.6% of the total new UK stock. This shows that the overall Welsh housing stock is growing older compared to the rest of the UK. There are currently a few UK programmes and policies which aim to bring down carbon emissions and tackle fuel poverty within the existing domestic sector. As an example, Warmfront is a government funded programme which assisted one million vulnerable households between years 2000 and 2006 by implementing a series of heating and insulating measures. Similar programmes are the 'Decent Homes' and the 'Community Energy' programmes. Although the number of fuel poor households was reduced significantly within the last years, it is expected that the increase in energy prices could reverse this in the future (DEFRA, 2006).

Therefore, based on the arguments described above, it can roughly be estimated that around 20% of the carbon emissions in the UK are the result of the use of domestic SH and DHW conventional systems. This share in Wales is translated in higher emissions than most countries in the EU and the old houses are the dominant stock in this case. These factors justify why this work focuses on the energy savings potential that could arise from ST applications in the residential sector in this country, considering both old and new houses. The next chapter sets out the methodology that is used to investigate this potential.

2 METHODOLOGY

This chapter describes the methodology used in this research to meet the aims stated in 1.1, explaining how this research will add to the existing knowledge on ST and TES applications. Section 2.1 explains briefly how the literature survey conducted at the beginning of this research (and continued in parallel with the research till the completion of this work) influenced and even shaped the research method that was finally used in this work. It can also be seen as a short diary for this work as it demonstrates the allocation of research time during the 39 months of study. Paragraph 2.2 describes the boundary conditions for the research subject and paragraph 2.3 gives the layout of the research method used.

2.1 EXPECTATIONS AND REALITY ABOUT ST TECHNOLOGIES

For architects the interest in ST applications is usually limited to the aesthetic/design-related aspects of the integration of these technologies into buildings. At a step further, some architects could be interested in designing or refurbishing buildings which would also interact successfully with ST systems from an energetic point of view. This aspect of the integration of ST technologies into buildings was the initial incentive for this research. Thus, deep understanding of both the buildings and the ST systems was considered as fundamental for this research. Initially it was believed that the ST technologies are extensively analysed by researchers and that the state-of-the-art is already established and optimised, with the technology being developed for many decades. Therefore at the beginning of this work, the research focused on the TES technologies. Indeed, as shown in the literature review, this is where the attention is focussed during recent years in an attempt to increase the solar contribution in ST systems higher than 50%, so that the auxiliary source *"would really become the auxiliary and not the main contributor to the heating or cooling needs of the building"* (HADORN, J., 2005)[4]. Consequently, the initial research plan prescribed successive (a) modelling of a number of actual housing types to produce demands for the ST systems to meet, (b) modelling of the ST systems to meet these demands and (c) modelling of various TES

[4] One of the main considerations of the IEA SHC Task 32 "Thermal energy storage for solar and low energy buildings".

types to increase the solar contribution on the systems. This research structure presupposed the use of the state-of-the-art know-how for both ST and TES technologies and had as a desirable outcome the potential contribution that ST could make in existing dwellings and in a climate not noted for using solar energy for SH and DHW preparation.

In the process of the literature review a better understanding of the current situation in the area of ST was obtained,. Firstly, it became clear that existing tools, well established as able to handle the dynamic aspects of ST system simulations, such as TRNSYS, had the building component neglected compared to the other parts of the system, with either a poor or 'unfriendly' user interface. It appeared that little knowledge is available on detailed simulation of buildings in the ST system modelling. The building description usually suffers from major simplifications, especially when small scale buildings such as dwellings are simulated, even though the software is capable of handling the complexity. For example, in the simulations carried out within the International Energy Agency Space Heating and Cooling programme's (IEA SHC) Tasks the house model is usually described by one zone, given a constant occupancy (24/7) throughout the year. This can have a significant impact on the accuracy of the predicted results, especially in low energy housing where the solar gains or gains due to occupants or appliances play a critical role on the energy balance. Therefore after the initial literature review, a decision to describe the chosen buildings in a reasonable detail was taken, in order to provide confidence in the demands being asked of the ST systems. This proved to be time-consuming but also a prerequisite for the next phase of the research, as it gave a good understanding of the energy requirement for thermal comfort satisfaction in these dwellings.

In addition it became clear with the literature survey that the performance of solar combisystems is very complicated and cannot be predicted other than with detailed system modelling. Nevertheless, there is a wide variety of potential systems, each one with a different performance. There is no optimum system solution as the quality of the systems is strongly dependent on the project and the desirable aims that apply in each case. The solar fraction (SF) is not an indicator of the quality of the system, but rather a design variable.

Considering all the facts mentioned above it was decided that the results/conclusions of previous work in the area of ST and TES systems' performance would be used in order to assess broadly the ST potential in this PhD study. The author's research is a long-term study of which this PhD work is the start. Detailed system modelling of a selection of ST systems applied on these detailed building models will be the subject of future, post-doctoral work.

2.2 BOUNDARY CONDITIONS

One of the main assumptions of this work is that no retrofit measures are implemented and ST is applied to the housing stock at the condition that this is currently found[5]. Although it is appreciated that prior refurbishment of the houses in order to benefit from passive strategies is the most sensible way to start with before designing ST installations, this aspect was not tackled here, to allow for time to focus on the ST potential. In addition, there are circumstances when improvements to the building envelope might not be applicable. This is the case when e.g. major retrofits are not possible due to continuous occupancy or when there is a need for preserving historical and traditional features of the building envelope. Another example would be when privacy or security reasons do not allow for implementation of passive strategies (e.g. natural ventilation) or even when economics suggest other actions as more viable than improvements on the building envelope.

Only ST systems with water or other liquid mixture as heat-delivery medium are considered in this study, as these are the most efficient systems available on the market at present. ST air to water systems were not included in the research as the air-to-water heat conversion and the solar air collectors would result in less efficient systems compared to the state-of-the-art evacuated tube collectors which are considered to be more appropriate for the climate in question.

[5] Some of the houses of the database have been found altered since their original construction and modelled as such (e.g. glazing upgraded).

2.3 METHOD DESCRIPTION

To investigate the energy savings potential that ST and TES technologies can bring to the existing housing stock in the UK, the research method is structured as shown in Figure 2. The figure shows the consecutive research and analysis steps (dark gray arrows) and gives also an indication of the various evaluation/correction/iteration loops that were performed during optimisation of the models and analysis of the results (light gray arrows).

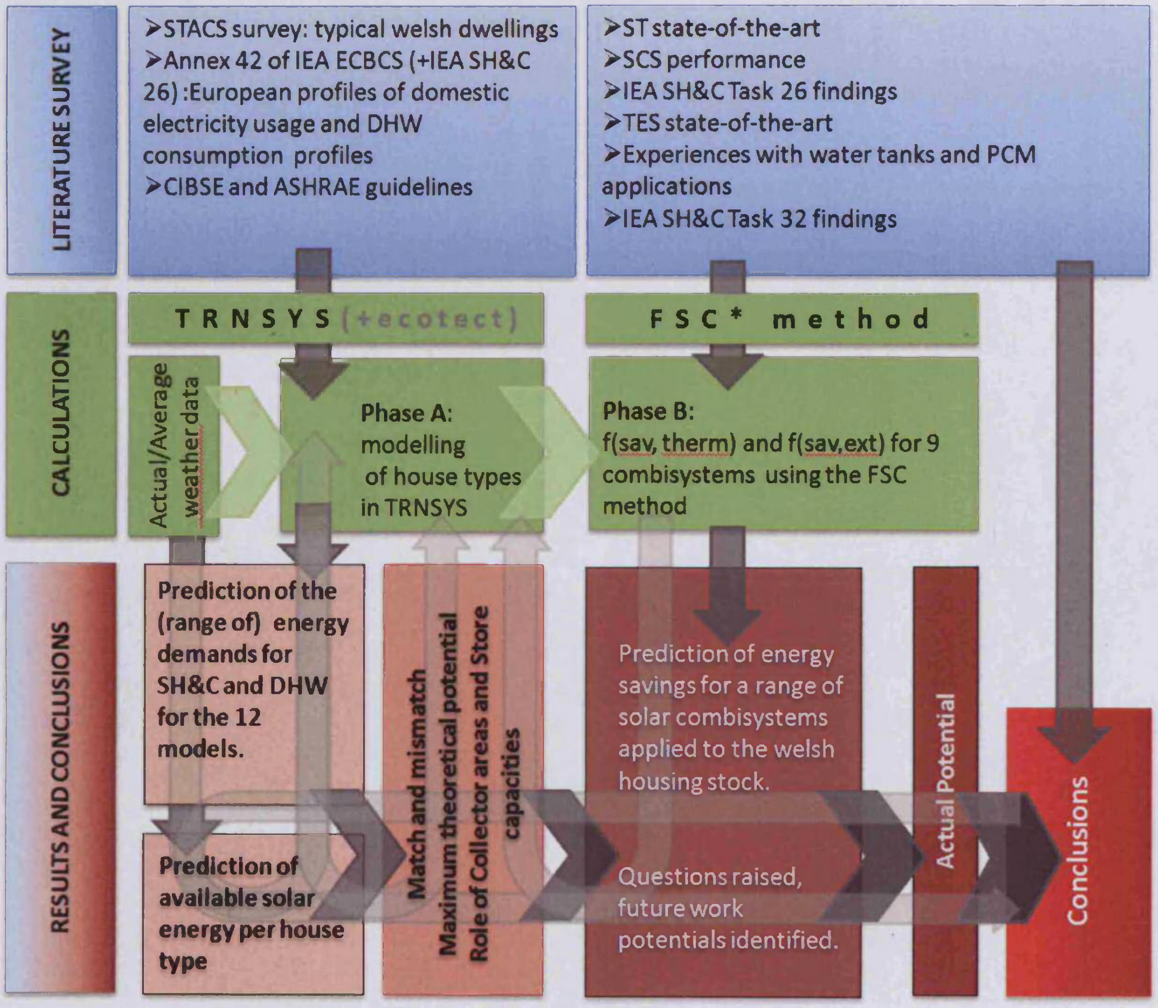

FIGURE 2: THE RESEARCH METHOD: THE GRAY ARROWS SHOW THE 'RESEARCH PATH' THAT IS FOLLOWED AND THE LIGHT GRAY ARROWS REPRESENT THE ITERATION/EVALUATION STEPS PERFORMED IN THE BACKGROUND.

The first stage of the research consists of a literature survey of preceding work in the area of ST and TES both in R&D and actual applications in Europe and worldwide. The major part of this survey is analysed in chapter **3**, but references to preceding relevant work are also given elsewhere throughout the analysis. This review provides essential background information of what is already known about ST and TES technologies and what is expected for the future from innovative technologies in the area. The Welsh housing stock was chosen to be used in this research, as an extensive housing stock survey has been recently undertaken under a Welsh Assembly Government (WAG) funded project called STACS, which ran in parallel to this PhD research (see 1.3). The 12 typical Welsh dwellings are modelled in TRNSYS and a range of energy demands for SH and DHW preparation is predicted for various comfort and weather conditions. In total 12x4 (48) case studies are modelled, 4 for each house type to account for two weather and two comfort conditions. The description of the modelling method for the 12 dwellings is given in chapter 4. The software TRNSYS was considered to be the most suitable program for this work, as it is the most popular software for ST building simulations even within the IEA SHC tasks. TRNSYS is generally considered to be the "classic and market leader among the simulation systems" for ST (GERMAN SOLAR ENERGY SOCIETY , 2005) and has been adequately validated (see also section 3.5.1 for more information).

The results of the predictions of the thermal demand profiles are presented and discussed at the beginning of chapter 5, along with the prediction of solar energy availability for the climate of Cardiff for the selected dwellings. The solar energy availability is calculated from the incident energy on the roofs of each dwelling (or walls if it is a flat) and has a collector efficiency applied to it that corresponds to the collector used. At first an assessment of the ST potential is conducted based on the particular characteristics of the thermal energy demands (for DHW preparation and thermal comfort satisfaction) of the Welsh housing stock and the solar energy availability for this region. Several conclusions can be drawn by analysing these two elements, as the ST potential is strongly dependent on both the house types and the climate and it is this very fact that links the findings with the particular context (housing stock and climate). Part of the conclusions of this analysis is dedicated to the role of TES, focusing on the improvement in solar yields and on the potential implications of using such components in dwellings, where the available free space is limited. Up to this level the ST potential for Wales is presented without considering any specific type or configuration for the ST delivery system (that means, other than the collector). At the last part of chapter 5, the actual behaviour of real ST systems applied to these dwellings is examined. Findings from previous research on the performance of specific solar combisystems are used at this stage (based on the Fractional Solar Consumption (FSC) method, developed within the IEA SHC Task 26).

Finally in chapter **6**, the conclusions of the entire research are analysed and future work potentials are discussed.

3 LITERATURE SURVEY; EXPERIENCE WITH ST AND TES SYSTEMS AND TECHNOLOGIES.

3.1 INTRODUCTION AND SOURCES OF INFORMATION FOR THE REVIEW

This chapter starts with a short discussion about the current capacities and market spread of ST in the world, the Europe and the UK presenting also the history of the uptake and the decline of the technology in the UK during the last decades (3.2-3.3). In addition to the lessons learnt from the past, the potential arising from existing supporting mechanisms (3.3.3) and the climatic conditions in this country are also analysed (3.3.4). The other half of the this chapter reviews bibliographic sources that report and analyse knowledge on ST and TES technologies accumulated either by research, development and demonstration projects or by short or long-term experiencing of the technologies in applications around the world.

As suggested by experts in the field, there are no general rules which can apply in ST applications as a whole. Several case studies are presented in the literature but the results cannot be widely generalised. It appears that lots of information and experience has been published in German or other languages than English. Reviews of ST technologies found in English literature (usually handbooks and guides translated from German) usually overlap and analyse mainly the components, such as collectors, hydraulic parts, heat production and delivery loops etc. In these documents it is very rare that quantitative information regarding the performance of the systems is found, which as a subject is anyway very complex to be defined or described in widely comprehensible terms. Specific information is published mainly as a result of research projects. These publications are addressed to researchers who already understand the technology and the conclusions correspond to the specific research boundaries only. These sources are usually written in English and are either journal or conference papers, creating a common ground of knowledge for researchers in the field of ST.

Since 1977 the International Energy Agency (IEA), runs the Solar Thermal Space Heating and Cooling Programme Implementing Agreement (IA) (under the 'Renewable Energy' *working party* of the IEA) with collaborative work of members around the world.A large amount of research has been produced and published under this collaboration, within Tasks and Subtasks organised by themes (IEA SHC, 2009). From the recently completed Tasks the following are of interest here:

- Task 32: Advanced Storage Concepts for Solar Thermal Systems in Low Energy Buildings
- Task 28: Solar Sustainable Housing
- Task 26: Solar Combisystems
- Task 20: Solar Energy in Building Renovation

Some books and reports found at the 'references' list are outcomes of these tasks. Task 26 and Task 32 are the most relevant to this research subject. Task 26 was related to the European Altener Programme Project "Solar Combisystems" which run in 2001-2003 (ALTENER, 2003a). The actual scope of the Altener project was the preparation of the Task 26 outcomes for dissemination and communication with the wider public.

In section 3.4 existing knowledge on the performance of solar combisystems in dwellings is reviewed. In 3.5 the available ST systems performance prediction methods and tools are presented. At this stage a short presentation of the software package TRNSYS which is used for the analysis in this research work is given. A solar output calculation method for ST systems suggested by a recently established European standard (implemented as a national standard in the UK) and the solar combisystems performance assessment/comparison method established in the IEA SHC Task 26 and extended in Task 32 are also described.

At the last section of this literature survey (3.6), an overview of the state-of-the-art TES technologies and applications suitable for ST is presented. Increasing interest regarding TES technologies and techniques is observed in the last few years, as the enabling and supporting role of these technologies for applications of low carbon and renewable energy sources is now acknowledged. Nevertheless, research in the area is found to be repetitive and lacks of long-term investments (PREHEAT, 2008). A few relevant bodies exist, which promote, organise and disseminate information regarding TES. The relevant activities (which have also been important data resources in this survey) are summarised below:

- In 1978 IEA established the Energy Conservation through Energy Storage (ECES) Programme Implementing Agreement (under the 'End use' *working party* of the IEA) which focuses on R&D of the energy storage technologies. Last January the IEA initiated a new joint Task (42) between the SHC and ECES programmes with subject the "Compact Thermal Energy Storage" technologies. This was the follow-up of the recently completed Task 32 of the IEA SHC.

- Although at the moment a dedicated Technology Platform for TES is not feasible, cooperation with existing Technology Platforms is greatly desirable (PREHEAT, 2008). Therefore a TES working group (WG 1b) operates under one of the three focus groups of the European Solar Thermal Technology Platform (ESTTP) working inter alia in the preparation of the TES chapter in the strategic agenda of the ESTTP (ESTTP, 2008).

- PREHEAT, a project supported by the Intelligent Energy Executive Agency, with a 3-year duration came to an end in June 2008. The project aimed at bringing attention to the TES technologies and creating a framework for policy making at a national and at a European level. Several workshops were organised to enhance dissemination of information regarding TES[6].

- At the moment two series of conferences dedicated to energy storage exist, including TES technologies:

    - The "Stock" conferences which are hosted every three years, and focus on TES technologies only. ECES is one of the major organisers.

    - The new international conference series with theme "International Renewable Energy Storage Conference"(IRES) which are organised since October 2006 by the EUROSOLAR and the World Council for Renewable Energy (WCRE, 2009). Both electric and thermal energy storage technologies are the subject of these series (two parallel streams).

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[6] Eleni Ampatzi is a co-editor of this report, along with Dr R. Wiltshire and Dr J. Williams. BRE was participating in the PREHEAT project and was responsible for the WP3 deliverables.

3.2 SOLAR THERMAL CAPACITIES AROUND THE WORLD

Before the 1990s, the main market of ST in Europe was in the Eastern Mediterranean. In the past two decades the focus on ST has moved to Northern Europe. According to the figures published by the European Solar Thermal Industry Federation (ESTIF) Germany, Austria and Greece accounted for 70% of the European ST total in 2007 (ESTIF, 2008) while this share was 80% in 2004 (IEA, 2004). Recent figures in the press refer to an even lower share held by these three countries, 55% of the total European ST market in 2008, also revealing that countries such as Spain, Italy and France are the fastest growing ST markets in Europe at the moment (AHMED, H., 2008).

Currently the domestic market is the largest market for ST applications (ESTIF, 2003a), with water heating being the dominant ST application. ST energy has also been widely used for pool heating and effective SH applications have been demonstrated with projects in Scandinavia and Germany. Peuser et al (PEUSER, F. A. et al., 2002)(p.30) reported an increase in ST systems installations reaching 15% in Germany, 40% in Denmark and 20% in Sweden as in 2002.

In the past the ST capacities worldwide were recorded typically with collector areas (ESTIF, 2006a). A uniform conversion factor of 0.7 kWth per 1m2 of collector area has been agreed in September 2004 in a meeting at Gleisdorf, Austria with representatives of the International Energy Agency's Solar Heating and Cooling Programme (IEA SHC) and some major ST trade associations (IEA-SHC, 2004). Therefore ESTIF and other solar associations are now mainly publishing statistics for ST according to the energy produced, rather than collector areas in existence. This is of major importance as comparisons with other energy sources are possible when energy-related data is available.

Evaluation and analysis of the ST statistical data around the world has been problematic due to several factors. This has been investigated in an project run by the European Renewable Energy Council (Key issues for Renewable Heat in Europe K4RES-H (EREC, 2007). Published information coming from different sources can vary in accuracy, e.g. the collection of raw data may have been done using different methods or different aggregation, or conversion methodologies may have been applied. It is often unclear what types of collectors are allowed for (unglazed, glazed, etc) and whether the figures represent just cumulative numbers, or take into account life expectancy scenarios for the ST systems (ESTIF, 2006a).

However there are some clear trends in the ST market globally. Cyprus and Israel had the highest solar capacity per capita in 2006 (0.68kW$_{th}$ and 0.5kW$_{th}$ respectively per inhabitant) (GSTEC, 2008). China is the main consumer of ST products with 15.4GWth sold only in 2007 which accounts for 77% of the global market for that year (GSTEC, 2008). This is equal to the total capacity in operation in Europe by the end of 2007(only systems built after 1990s included), compared to a total estimate of 79.9 GW$_{th}$ for China in 2009 (CHIU, A., 2009). Figure 3 shows the progress in European ST sales during the last decade, with an apparent decline in the recent years.

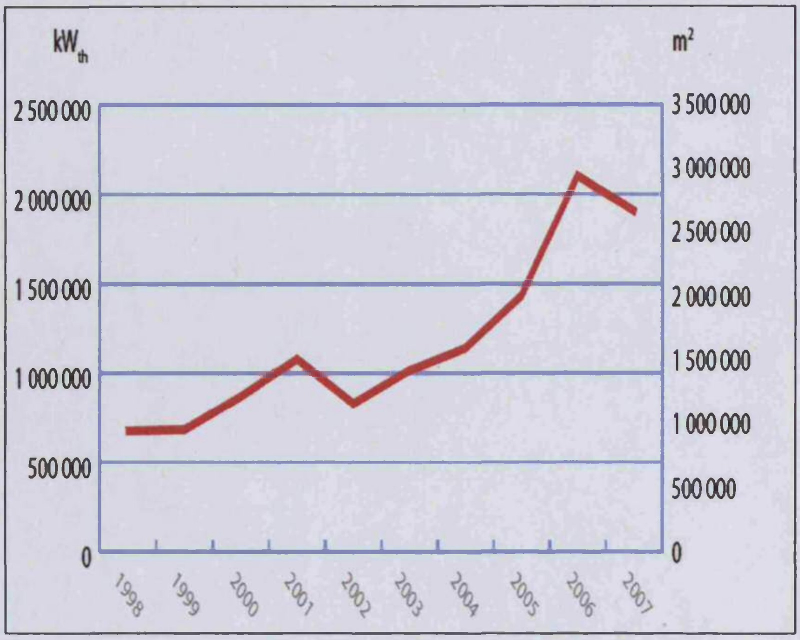
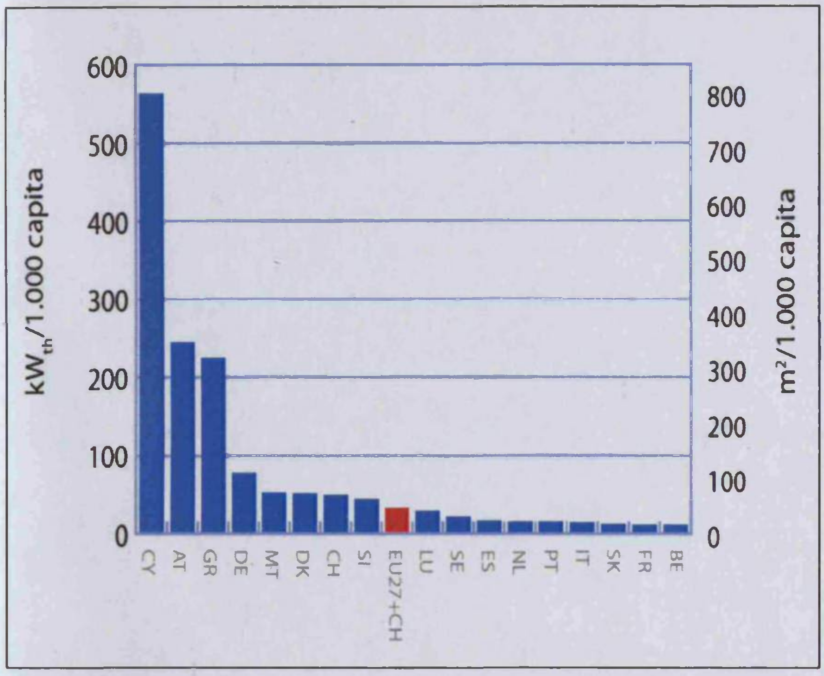


FIGURE 2: ST MARKET IN EU27+CH BETWEEN 1998-2007 (ESTIF, 2008).

Analyses on the ST market growth worldwide have shown that the ups and downs of the ST market at a national level are usually related to framework support or lack thereof (BRECHLIN, U., 2005)(ESTIF, 2006b). Germany is at the moment the strongest player in ST in Europe, albeit the recent 37% decrease in ST market between 2006 and 2007 (reflected also in Figure 3). It is interesting that in this country 90% of all the ST applications built after 1999 have been sponsored by a public funded financing scheme called "Market Stimulation Programme (MSP)" (ESTIF, 2006b). In 2002 the German Government increased the financial support for the installation of solar water heating systems from €95 to €125 per m^2 of collector area, boosting the ST market (CELIK, A. N. et al., 2009).



Legend:
AT: Austria
BE: Belgium
CH: Switzerland
CY: Cyprus
DE: Germany
DK: Denmark
ES: Spain
FR: France
GR: Greece
IT: Italy
LU: Luxemburg
MT: Malta
NL: Netherlands
PT: Portugal
SE: Sweden
SI: Slovenia
SK: Slovakia

FIGURE 4: ST CAPACITY IN OPERATION PER 1,000 CAPITA IN EU27 AND CH, IN 2007 (ESTIF, 2008).

Several other factors have influenced the growth of ST market in Europe, but it is in consensus that fiscal incentives (e.g. grants, tax reductions, ingratiatory loans, tradable certificates) have played an important role in the uptake of the technologies when and where implemented. Figure 4 shows the ST capacity in operation per capita in year 2007. Austria has a slightly higher capacity per capita than Greece, which is impressive for North Europe. This fact shows that there is a great unexploited potential throughout Europe, not only at the South sunny regions.

3.3 SOLAR THERMAL IN THE UK

3.3.1 THE ST CAPACITY IN NUMBERS

It is difficult to get the real picture of ST installations in the UK, as statistical data appears sometimes to be controversial, i.e. different numbers are published by different sources. Table 1 presents the data sourced by publications describing the history of ST installations in the UK with numbers. The shaded areas highlight data that is relevant to the arguments set out in the following paragraphs.

TABLE 1: UK ST CAPACITY IN OPERATION FOR THE PERIOD 1974-2008 (VARIOUS SOURCES).

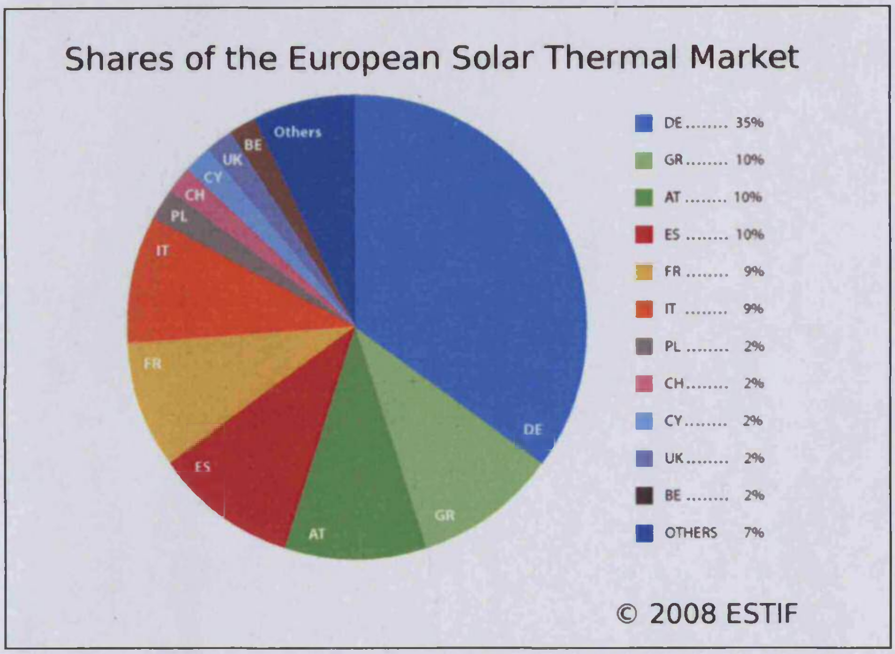
Year	Cumulative capacity in operation	Other type of data	Source	Type of collector
1974-1981		100,000m^2 aggregate for period	Sun-in-Action (ESIF, 1996)	Glazed (DHW)
		70,000 m^2 aggregate for period	As above	Unglazed (sw.pool)
1985		5,000 m^2 annual	Sun-in-Action (ESIF, 1996)	Glazed (DHW)
		9,000 m^2 annual	As above	Unglazed (sw.pool)
	39,000 m^2		Sun-in-Action II (ESTIF, 2003b)	Glazed only
1990		7,000 m^2 annual	Sun-in-Action (ESIF, 1996)	Glazed (DHW)
		4,000 m^2 annual	As above	Unglazed (sw.pool)
	65,000 m^2		Sun-in-Action II (ESTIF, 2003b)	Glazed only
1995	100,966 m^2		Sun-in-Action II (ESTIF, 2003b)	Glazed only
		7.596 m^2 annual	Sun-in-Action II (ESTIF, 2003b)	Not specified
1996		154,400m^2 of systems installed 1982- 1994 (before 1981 considered obsolete***)	Sun-in-Action (ESIF, 1996)	Glazed and Unglazed
	215,700 m^2		EurObserv'ER (PAPADOPOULOS, A., 2003)	Glazed only*
1997	206,200 m^2		EurObserv'ER (PAPADOPOULOS, A., 2003)	Glazed only
		-17,000m^2 estimated reduction from previous year (based on obsolete systems***)	Sun-in-Action (ESIF, 1996)	Glazed and Unglazed
1999	**195,000 m^2**		EurObserv'ER (PAPADOPOULOS, A., 2003)	Glazed only
2000	151,000 m^2	<3m^2 per 1000 inhabitants	(WEISS, W., 2003) IEA	Glazed only (non data for unglazed collector)**
	108,190 m^2	11,850m^2	Sun-in-Action II (ESTIF, 2003b)	Glazed only
2001	112,420 m^2	15,230 m^2 annual	Sun-in-Action II (ESTIF, 2003b)	Glazed only
2002		17,500 m^2 annual	(ESTIF, 2004)	Glazed only
2003	149,920 m^2	22,000 m^2 annual	(ESTIF, 2004)	Glazed only
2004	**168,920 m^2**	25,000 m^2 annual	(ESTIF, 2005)	Glazed only
2005	**196,920 m^2**	28,000 m^2 annual	(ESTIF, 2006c)	Glazed only
		42,000 installations of solar DHW in use	(EST, 2005)	Not known
		78,470 installations of solar DHW	(EST et al., 2005)	Not known
2006	250,920 m^2	**54,000 m^2 (27,000 m^2 FP+27,000 m^2VT) annual installations**	(ESTIF, 2007)	Glazed only

Year	Cumulative capacity in operation	Other type of data	Source	Type of collector
		54,000 m^2 (27,000 m^2 FP+27,000 m^{2}VT) annual installations	(EUROBSERV'ER, 2008)	Flat plate and evacuated tube
		28,000 m^2 annual	STA cited by (BAERBEL, E., 2009)	Not specified
2007	304,920 m^2	54,000m^2 annual	(ESTIF, 2008)	Glazed only
	306,106 m^2	5m^2 per 1000 inhabitants	(EUROBSERV'ER, 2008)	Glazed only
2008		81,000m^2 annual	STA cited by (BAERBEL, E., 2009)	Not specified

*It is assumed this way, as other data published by the sane source refers to these 3 types.
** Consider this along with the fact that unglazed collectors held a significant portion of the UK market for both years 1998 and 1999; more than 1/3 of the annual installed capacity (EurObserv'ER by (PAPADOPOULOS, A., 2003)).
*** This is calculated from Sun-in-Action annual capacity based on ESTIF's estimations for system lifetime: systems built before 1989 last for 15 years, and systems built after 1990 last for 20 years.

IEA reports that in the year 2000 only 151,000 m^2 of water glazed collectors (both flat plate and evacuated tube) were in operation in the UK (WEISS, W., 20035). This (according to the same source) equates to <3 m^2 of collector area per 1,000 capita, which is considerably lower compared to countries like Greece (264 m^2), Austria (198 m^2), Denmark (46 m^2), Switzerland (37 m^2) and Germany (34 m^2) for the same period. Cumulative data of installed collector capacity during the years 1996-1999 is also available from EurObserv'ER (cited by (PAPADOPOULOS, A., 2003). According to this source the total installed capacity of solar collectors in the UK was reduced from 215,700 m^2 to 195,000 m^2 in the period 1996- 1999 respectively. This reduction in the cumulative installed capacity is partially explained by the fact that systems installed 15 years before in the eighties had become (or considered) obsolete. Nevertheless, it is unlikely that during one year (1999-2000) the capacity could have been reduced so sharply by 44,000 m^2 to match the IEA numbers and therefore it is assumed that some - if not all- of these figures are based on estimations. According to the final report of the Sun-in-Action II the cumulative capacity for glazed only collectors in UK was 39.000m^2, 65.000m^2, 100.966m^2, 108.190m^2 and 112.420m^2 for the years 1985, 1990, 1995 2000 and 2001 respectively. Again these numbers do not compare well to the IEA ones, showing a difference of 42.810 m^2 between the two sources for year 2000.

The statistics for recent years are once again confusing. A report published in 2005 by the Energy Saving Trust (EST) refers to approximately 42.000 solar thermal DHW systems in operation in the UK (EST, 2005) while another report which analyses the microgeneration potential in the UK, also published by Energy Saving Trust (along with Element Energy and Econnect) refers to 78,470 solar water heating installations in the UK until 2005, most of them built before 2000 (EST et al., 2005). The latter report highlights that solar water heating is the largest microgeneration market in the UK, but with modest development and explains that 6,694 out of the total 78,470 installations, have been built with funding from UK Government programs since 2002.



Legend:
AT: Austria
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CY: Cyprus
DE: Germany
ES: Spain
FR: France
GR: Greece
IT: Italy
PL: Poland
UK: United Kingdom

FIGURE 5: NEWLY INSTALLED CAPACITY IN EUROPE IN 2007 (ESTIF, 2008).

According to ESTIF (ESTIF, 2008) in the year 2007 about 304,920 m^2 (306,106 m^2 - 5 m^2 per 1000 inhabitants (EUROBSERV'ER, 2008) total glazed collectors are found in operation in the UK. This figure compared to the IEA figures of 2000 reveals doubling of the installations in the last 7 years. According to the same source and as also published by Eur'ObservER (EUROBSERV'ER, 2008) around 54,000 m^2 new installations were installed in year 2006 (reflected in the 2007 ESTIF annual report as an 'awaken' market (ESTIF, 2007)) and another 54,000 m^2 in year 2007. It is very likely again that these numbers are based on estimations, judging by the identical values for flat plate and for evacuated tube (27,000 m^2 in both cases). The data provided by ESTIF shows that for year 2007 this accounted for 2% of the overall ST newly installed capacity in Europe (Figure 5). On the other hand, the Solar Trade Association refers to 28,000 m^2 installations in 2006, 54,000 m^2 in 2007 and 81,000 m^2 in 2008 (cited by (BAERBEL, E., 2009)) which again does not correspond to with the data published by ESTIF. Even the published data from ESTIF is contradictory in itself. The cumulative data for years 2004 and 2005 do not correspond to the annual installations stated by the annual reports of ESTIF. In addition, the data published in the SUN-IN-ACTION II report (prepared also by ESTIF) does not agree with the annual report of ESTIF for year 2003

In overall it is clear from the information presented above that at present the ST share in the UK remains small compared to other European countries, explaining why UK does not even appear on Figure 4.

3.3.2 HISTORY OF ST UPTAKE AND DECLINE

The UK, along with Belgium, Finland, Ireland and Denmark has one of the lowest solar radiation incomes[7] amongst the EU-15 countries and therefore its ST installed capacity is expected to be low (CELIK, A. N. et al., 2009). Nevertheless Denmark has the 4th highest installed solar capacity in EU-15, with new installations in 2007 being 35% of the total in Europe (Figure 5), indicating that there is a significant potential for the UK as well. This paragraph investigates the reasons behind the poor ST exploitation in this country by reviewing the history of the last decades.

The expansion of the ST market in UK that took place in the 70s was mainly invoked by the 1973 oil crisis. Enhanced by the governmental support for R&D, the sales boom lasted until the early 80s, with ST applications implemented inter alia in 75 trial house projects in Basingstoke, Lincoln and York through the Department of Energy's solar heating programme (WOZNIAK, S., 1981), in retrofit projects in council housing all over the country, in around 200 solar houses in London and in more than 300 solar projects in the Milton Keynes city (NATTA). A report prepared in 1976 by the UK section of the International Solar Energy Society, involving 39 panel members from industry, university, polytechnics and government, was highlighting the unexploited solar energy potential for the UK (UK-ISES, 1976). It was mainly due to bad product image created by unsuitable and poor quality installations (as there were no national standards at the time)(BRE, 1981) and lack of further governmental support that decline came after 1983 as shown in Figure 6 (ESIF, 1996). A contributory factor was the lower fossil fuel

[7] The 'solar radiation income' or 'solar energy income' is a term used often by analysts and researchers in the area and expresses the amount of sunlight that is received to the ground. It is therefore a measure of the solar radiation available or the solar potential for each country in this example.

prices than initially predicted. A report published by BRE in 1979 (WOZNIAK, S., 1979) explained that ST systems designed to serve SH were not suitable for the UK, mainly because the collectors could not provide warm water at suitable temperatures for SH applications and no effective means of inter-seasonal TES technologies were available. Nevertheless this report highlighted the potential of using solar energy to preheat domestic water in single-family houses throughout the year and to heat outdoor swimming pools' water during the summer months.

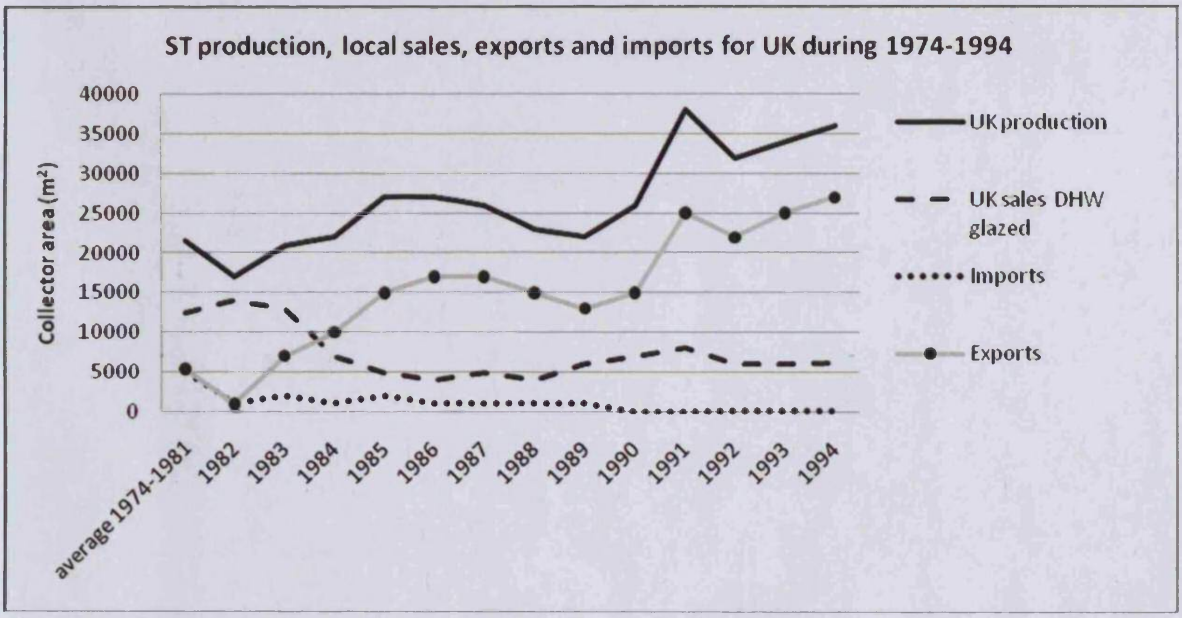

FIGURE 6: SOLAR COLLECTOR PRODUCTION AND SALES (BASED ON INFORMATION FOUND IN THE SUN-IN-ACTION REPORT (ESIF, 1996)).

A major impact on the ST development in the UK was a governmental report published in 1982. The report prepared by the UK Department of Energy with contributions from the Atomic Energy Research Establishment and the Energy Technology Support Unit entitled "Strategic review of the renewable energy technologies" (ENERGY TECHNOLOGY SUPPORT UNIT , 1982) described solar energy as an unsuitable renewable source for this country, causing drastic cut backs in active solar research funding (ALPER, B. et al., 1985) and evoked the negative reaction from the industry sector. On the other hand, in 1984 the final conclusions of the Government's Active solar heating R&D programme stated that active solar thermal DHW and SH is a viable technology for the UK especially when combined with low temperature applications (ALPER, B. et al., 1985). However it was 8 years later that a governmental review brought back a positive view towards ST applications in this country, predicting a potential energy resource of 12 TWh/y for solar DHW systems (cited by (DTI, 1994)). Finally a report published by DTI in 1994, restored the perception regarding the technology's potential in the UK (DTI, 1994).

Contrary to the ST sales in this country, exportation of ST products manufactured in the UK has been significant during the past three decades, as shown in Figure 6. In 2006 ESTIF ranked UK amongst the 3 strongest countries in the ST market, along with France and Germany, with a growth rate between 40-70% (ESTIF-NEWS, 2006).

3.3.3 INCENTIVES AND SUPPORT MECHANISMS

As explained also in 3.2, the ST market in the UK is weak due to lack of incentives and support mechanisms. Figure 7 shows the impact that a certain French governmental scheme had in the uptake of solar thermal in France allowing a large percentage of the hardware costs of a solar system to be reimbursed through the income tax declaration (BOKHOVEN, T., 2007). The growth in France is projected against the UK reality for years 2001-2006.

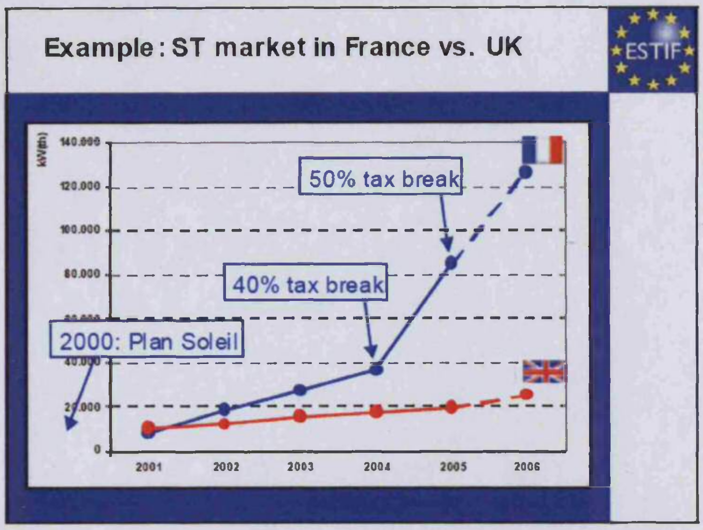

FIGURE 7: SOLAR THERMAL MARKET IN UK AND FRANCE BETWEEN 2001-2006 (BOKHOVEN, T., 2007).

In an attempt to introduce similar incentives for microgeneration technologies in dwellings in England the Department for Communities and Local Government amended relevant legislation and since April 2008, so that no planning permission is required when ST systems are installed on dwellings (exceptions for listed buildings or buildings within conservation areas apply). In addition, with a very recent measure, a reduced VAT rate at 5% applies for professionally installed ST installations, for both components and installation costs of solar DHW systems (EST, 2008). For ST-DHW installations a grant of £400 or 30% of the relevant eligible cost (whichever is the lowest) is available from the Low Carbon Building Programme (DECC, 2009). Phase 1 of the program which covers grants for residential application will last until June 2010.

Nowadays ST installations in the UK are governed by a number of national standards. The relevant standards are summarised in the list below:

- BS 6785: 1986 Solar heating for swimming pools
- BS 5918: 1989 British Standard Code of Practice for solar water heating systems for domestic hot water
- BS EN 12975 2006: Thermal solar systems and components- Solar collectors (part1: General requirements, part2: test methods)
- BS EN 12976 2006: Thermal solar systems and components- Factory made systems (only DHW systems)
    - BS EN 12976-2:2006 Thermal solar systems components. Factory made systems. Test methods
    - BS EN 12976-1:2006 Thermal solar systems and components. Factory made systems. General requirements
- DD ENV 12977 2001: Thermal solar systems and components- Custom made systems: (draft for development, not a British standard as yet)
    - DD ENV 12977-1:2001 Thermal solar systems and components. Custom built systems. General requirements
    - DD ENV 12977-2:2001 Thermal solar systems and components. Custom built systems. Test methods
    - DD ENV 12977-3:2001 Thermal solar systems and components. Custom built systems. Performance characterisation of stores for solar heating systems
- BS EN ISO 9488:2000 Solar energy vocabulary
- BS EN 15316-4-3:2007 Heating systems in buildings- Method for calculation of system energy requirements and system efficiencies. Part4-3: Heat generation systems, thermal solar systems.

3.3.4 THE POTENTIAL

Currently there is an increasing interest in ST applications for DHW preparation in the UK, especially in highly efficient housing. Recently CIBSE published a guide for ST water-heating systems only (CIBSE, 2007).

A report published by the Centre of Alternative Technology Wales in 2007 describes the potential of reaching zero carbon with existing technologies by 2027 (HELWEG-LARSEN, T., et al. 2007). Within this report ST applications are presented as more favourable for water heating (with a stated efficiency of 60%) than PVs (for electrical water heating with heat pumps). The overall projected target for ST is set at 28tWh of heat for year 2027. Nevertheless the report limits the consideration of ST applications to water-heating systems only and makes no references to solar combisystems.

The SUN-IN-ACTION II programme analysed the ST technical potential for the European countries. Table 2 shows the predicted long-term requirement in collector areas by taking into account the DHW, SH and SC demands, the solar radiation and the population per country (ESTIF, 2003a). It is assumed that the potential is fully implemented, and higher collector areas are required for colder climates, to compensate for both the higher demands and the lower solar yields. For the UK a potential capacity of 3,9m^2 (1.3m^2 for DHW and 2.6 m^2 for SH) of collector area per capita is estimated, which corresponds to 233,309,700 m^2 in total providing 102,196GWh annual energy output (427,5kWh/ m^2 for flat plate and 475kWh/m^2 for vacuum collectors annual production in this climate); 1/3 of this, equal to 34,065 GWh is dedicated to DHW preparation and is slightly higher than the one presented by Centre of Alternative Technology. The average SH demand used for the UK is lower than that of North Europe e.g. of Denmark (for which 5m^2 of collector area required for SH) and the average solar radiation available is lower than that of e.g. France.

The "Low or zero carbon energy sources: Strategic guide" (the Building Regulations 2000) (DCLG, 2006) suggests that active ST technologies are a viable technology for domestic hot water preparation covering typically 50-60% of the overall requirement in single dwellings. The guide's intention was to support the inclusion of low and zero energy sources in the relevant Building Regulations and promote their use in UK dwellings.

TABLE 2: TECHNICAL/ECONOMICAL POTENTIAL FOR ST IN THE EU, BASED ON AVERAGE HEAT DEMAND, SOLAR RADIATION AND POPULATION PER COUNTRY. (ESTIF, 2003A).

Technical - economical potential for solar thermal in the EU					
Country	Population	Potential (per 1.000 Capita)	Potential (absolute)	Annual Energy Output	
		m²	m²	GWh	Mtoe
AT	8.121.000	3.900	31.671.900	11.193	1,0
BE	10.262.000	3.900	40.021.800	16.827	1,4
DE	82.193.000	3.900	320.552.700	130.607	11,2
DK	5.349.000	6.300	33.698.700	13.483	1,2
ES	39.490.000	2.700	106.623.000	64.448	5,5
FI	5.181.000	6.300	32.640.300	9.810	0,8
FR	59.521.000	3.900	232.131.900	139.279	12,0
GR	10.565.000	2.700	28.525.500	11.068	1,0
IE	3.820.000	3.900	14.898.000	6.704	0,6
IT	57.844.000	3.300	190.885.200	116.543	10,0
LU	441.000	3.900	1.719.900	723	0,1
NL	15.983.000	3.900	62.333.700	26.180	2,3
PT	10.023.000	2.700	27.062.100	16.237	1,4
SE	8.883.000	6.300	55.962.900	16.849	1,4
UK	59.823.000	3.900	233.309.700	102.196	8,8
Total	**377.499.000**	**3.740**	**1.412.037.300**	**682.149**	**58,7**

To get a first idea of the solar potential arising purely from a climatic point of view, the published statistics for the sunshine and solar radiation levels in the UK are also presented in this section. Figure 8 shows the variation of solar radiation throughout the UK. On the left the average annual solar radiation incident on a 30° tilted surface facing South (STA, 2008) is shown. In North Wales 1000-1100 kWh per m² (for this azimuth and tilt) are expected, while in Cardiff the levels are slightly higher at 1100-1200 kWh per m². On the right of this figure a map produced by MetOffice sourced by a UK-ISES report shows the average daily total solar radiation incident on a horizontal surface (UK-ISES, 1976). The two figures compare well; 1200 kWh incident energy on 1 m² of 30° South facing surface correspond to 1115 kWh of incident energy on 1 m² of horizontal surface per annum.

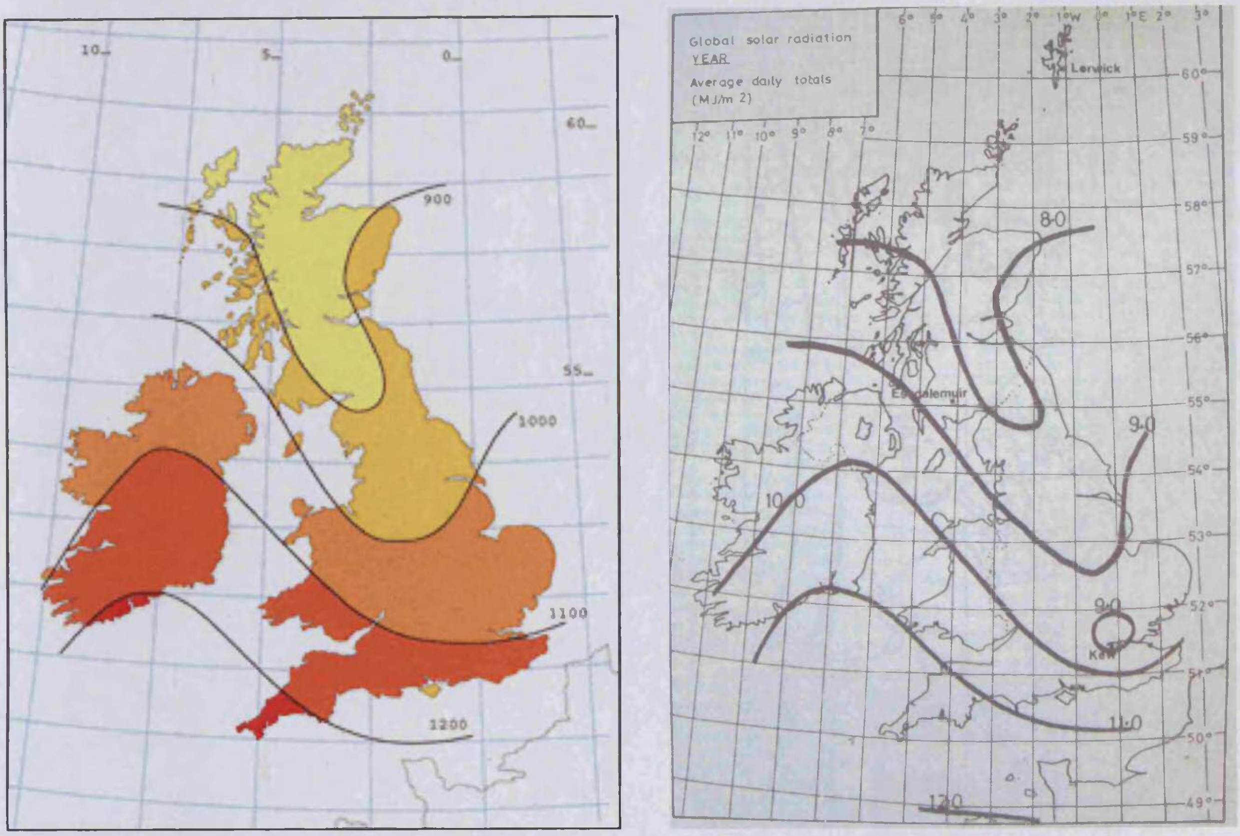

FIGURE 8: MAP SHOWING AVERAGE ANNUAL TOTAL SOLAR RADIATION INCIDENT ON A 30° INCLINED, SOUTH FACING SURFACE FOR THE UK IN KWH/SQ.M (LEFT, (STA, 2008)) AND MAP SHOWING AVERAGE DAILY TOTAL SOLAR RADIATION INCIDENT ON HORIZONTAL SURFACES FOR THE UK IN MJ/SQ.M (RIGHT, (UK-ISES, 1976) (1MJ= 0.2778 KWH)

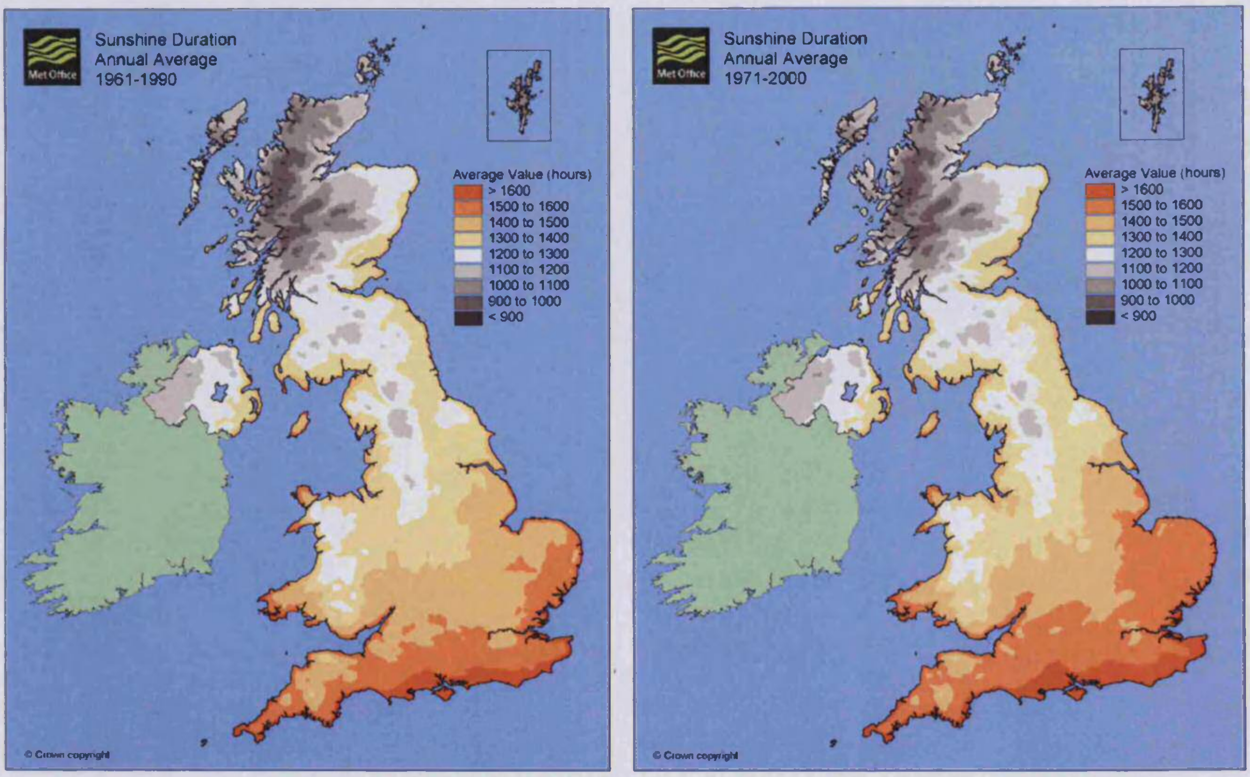

FIGURE 9: ANNUAL AVERAGE SUNSHINE DURATION FOR UK FOR THE PERIODS 1961-1990 (LEFT) AND 1971 2000 (RIGHT) (METOFFICE, 2009).

Furthermore the sunshine levels for the entire UK and for Wales are presented in Figure 9, Figure 10 and Figure 11. The maps are taken from MetOffice and are based on 1 km grid-point data sets which are derived from station data (METOFFICE, 2009). The comparison of the sunshine trends throughout the UK (Figure 9) with the average solar radiation data presented before (Figure 8) reveals that although e.g. London or Norwich receive more sunshine than Cardiff, the latter appears to have more solar radiation available for ST systems than the capital of the UK.

A comparison between the average sunshine data of years 1961-1990 with that of data of 1971-2000 shows that the South-East of the UK sees more sun now than a few decades ago. In general, a significant variation is observed throughout the country, with the South coast seeing the sun for more than 1600 hours a year while the mountains at the North of Scotland enjoy less than 900 hours of sunshine annually (by average). Figure 11 shows 30 year-average data regarding sunshine hours and sunshine variation across Wales for December, March, June and September (METOFFICE, 2009). Additional statistical information from the same source indicates that although cloudiness is a typical characteristic of the Welsh climate, mainly as a result of the proximity to the Atlantic Ocean and the hilly terrain, the South-west coastal areas (Pembrokeshire) have annual sunshine levels comparable to the South of England (around 1700 hours compared to 1750 hours). On the other extreme, the mountainous regions have the lowest sunshine availability of around 1200 hours per year (Figure 10). December is the dullest month, with highest average sunshine at the coastal areas ~55 hours. May and June are the months with the highest average sunshine levels with ~ 225 hours of sunshine at the coastal areas.

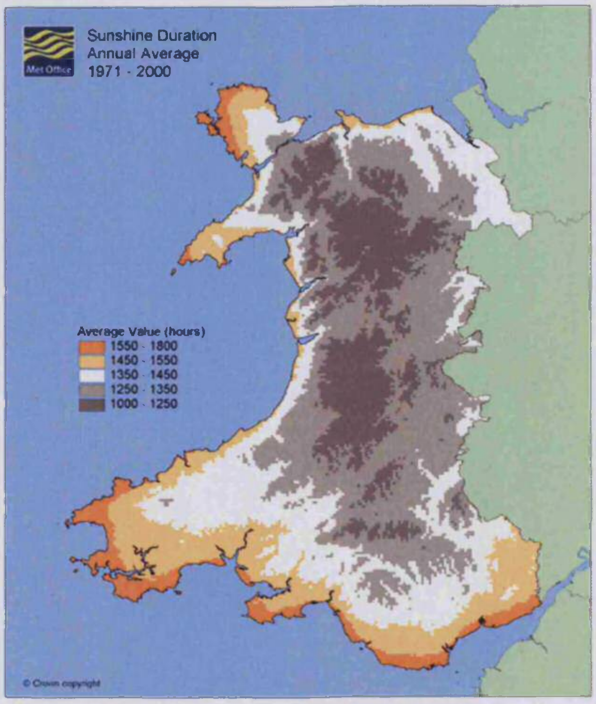

FIGURE 10: ANNUAL AVERAGE SUNSHINE DURATION FOR WALES FOR THE PERIOD 1971-2000 (METOFFICE, 2009).

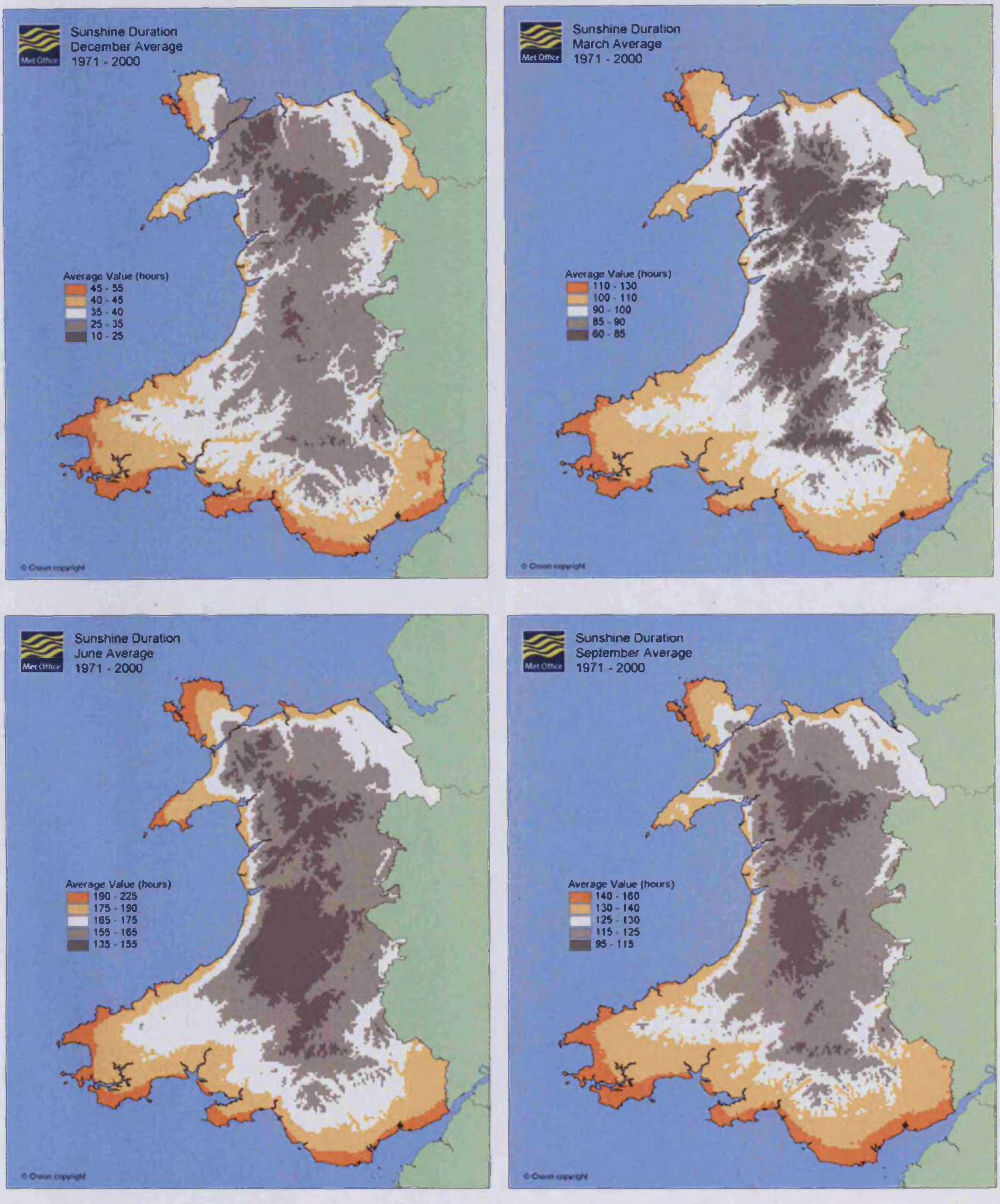

FIGURE 11: MONTHLY AVERAGE SUNSHINE DURATION FOR WALES FOR THE PERIOD 1971-2000, FOR DECEMBER, MARCH, JUNE AND SEPTEMBER (METOFFICE, 2009).

3.4 PERFORMANCE OF ST SYSTEMS.

3.4.1 DEFINITIONS OF QUALITY VALUES FOR ST SYSTEMS

Traditionally, three 'values' are used in order to characterise/assess the effectiveness of ST systems. The most popular one is the so-called 'solar fraction' (SF). The SF along with the 'degree of utilisation' and the 'cost of solar heat' are used to characterise a ST systems broadly, i.e. according to its dimensioning, operation and economy ((PEUSER, F. A. et al., 2002) (p.31)). The following definitions are given by Peuser et al. for these three *'characteristic values of solar energy systems'*:

Degree of utilisation:

For system: the ratio of (a) captured solar heat passed to the conventional system by the complete solar energy system (including all solar storage tanks and heat exchangers) to (b) the solar energy which arrived at the collector field within the same period.

For collector: the ratio of (a) the heat passing from the collector loop to the heat-exchanger or solar storage tank to (b) the solar energy which arrived on the collector field in the same period.

Cost of available solar heat: price per kWh of solar-thermal energy: calculated from the ration of (a) absolute debt servicing (annuity), (e.g. in £ defined by the complete construction costs of the solar installation, the service life of the system and the interest rate for the capital to be used) and (b) the yield of solar heat throughout one year in kWh (deduct any conventional components replaced by the solar heating system).

Solar fraction (of the total heat demand of the building): the ratio of the (a) available solar heat to (b) the energy demand for both hot water and space heating, including all losses.

Similar definitions for the solar fraction are given by the standard EN ISO 9488 and (BS_EN:15316-4-3:2007).

The terms *collection efficiency* and *system efficiency* described by Smith (SMITH, C., 1993) are similar to the *degree of utilisation* for the collector and the system respectively as defined above. In addition Smith gives the following definition of the

> *Electrical coefficient or performance* : the solar heat delivered to the load, divided by the electrical energy used to operate the system

In the framework of Task 26 the performance of solar combisystems is described in comparison to a reference case. Three so-called 'target functions' were introduced in this task to serve this purpose. The definitions given below have been taken from the handbook of the Task (WEISS, W., 2003). Recently these terms are becoming more and more popular in scientific publications, replacing the 'solar fraction' term.

> *Fractional Energy Savings ($f_{sav,therm}$): the saved combined auxiliary energy consumption of the solar combisystem (E_{aux}) compared with the final energy consumption of a reference system (E_{ref}) when no electrical devices other than a heating element are taken into account.*

> *Extended fractional energy savings ($f_{sav,ext}$): the saved combined total energy consumption of the solar combisystem (E_{aux}) compared to the combined total energy consumption of a reference system (E_{ref}) taking into account parasitic energy consumptions as well as boiler efficiencies.*

> *Fractional savings indicator (f_{si}): extends the definition of $f_{sav,ext}$ if the solar combisystem does not supply the required DHW or room temperature. For comparison reasons, an additional energy demand is assumed to compensate the reduction of comfort for the user.*

The difference between the SF and the $f_{sav,ext}$ is that the latter gives a clearer indication of the benefits of the ST system, by comparing its performance with that of a conventional system. The SF incorporates the penalties incurred by the ST system itself and gives no clear information on the actual savings.

3.4.2 FACTORS THAT INFLUENCE THE PERFORMANCE OF ST APPLICATIONS IN DWELLINGS.

The performance of solar combisystems systems is more complex than that of pure DHW solar systems as it is dependent on several factors. According to the definitions presented in 3.4.1, the reasons that lead to the use of ST technologies in each application dictate which quality values are of utmost importance when assessing the performance of the ST system. In the case of dwellings, it is more the environmental incentives (energy savings and carbon reductions) rather than economic reasons that would normally support this choice. Thus, it could be said that the focus in residential applications would be more on the SF or the fractional energy savings and less on the degree of utilisation or the cost of solar heat. Nevertheless the optimisation of a system should be a matter of an overall evaluation, including all factors involved, each with its own gravity. In general the quality of a solar combisystems cannot be determined by one value only (e.g SF or cost of solar heat) as each value describes one aspect of the system's performance only. Usually the higher the SF of the system, the lower the degree of utilisation and the higher the cost of solar heat achieved (and vice versa). This fact is apparent in the example presented in Table 3, as taken from Peuser et al (2002, p.333).

TABLE 3: SOLAR YIELDS AND SOLAR FRACTION OF A 15SQ.M ST INSTALLATION FOR DHW AND SH FOR VARIOUS INSULATION STANDARDS (LIVING UNIT: 100SQ.M, BUFFER STORAGE: 1,000L, LOCATION: FRANKFURT) (PEUSER, F. A. ET AL., 2002).

Standard	Low energy building	Insulation Standard 95	Insulation Standard 84
Specific SH demand [kWh/(m^2.a)	30	86	160
Energy SH [kWh/a]	3,000	8,600	16,600
Energy hot water [kWh/a]	3,000	3,000	3,000
Total energy demand [kWh/a]	6,000	11,600	19,000
Degree of utilisation [%]	17	20	24
Solar yield [kWh/ (m^2.a)	212	249	291
Solar fraction DHW [%]	69	66	63
Solar fraction SH [%]	33	19	14
Total solar fraction [%]	52	32	22

In this case the characteristic values of the same solar combisystems used in three dwellings are compared. The dwellings are of different insulation standards but otherwise identical. The example is for a stratified tank and for a low temperature heat delivery system (with a low ambient temperature set point for starting SH adapted in each case). The degree of utilisation of the less insulated house is 41% higher than that of the low energy building, although the overall solar fraction is around 42% of the solar fraction of the low energy house.

The factors which influence the performance of a domestic ST installation for DHW and SH can be grouped as follows:

1. Factors related to both the particular location and building type: Solar availability and heat demands for DHW and SH. (irrelevant of solar systems' components)
2. Choice of ST system (with standard components) and components which are not characteristic (e.g. pipe length) or not given as standard-integrated part of the system design (such as boilers, collectors etc).
3. Maintenance-related issues.
4. Parasitic auxiliary energy required for pumps and controls.

Sections 3.4.2.1 and 3.4.2.2 refer to the role of the first and the second group respectively. The influence of groups 3 and 4 is beyond the interests of this work and therefore it is not analysed here (parasitic energy consumption is only addressed in 5.5.2).

3.4.2.1 HEAT LOADS AND SOLAR AVAILABILITY

The first group consists of factors which are case-dependent. Both the location and the building characteristics

- have a major impact on the solar availability and
- determine the heat demands to be met by the solar system.

In the following paragraphs the role of these factors on the dimensioning and performance of a solar installation is investigated and explained with findings from the literature survey.

The solar energy availability is not only determined by the local climate. The suitable area for collector mounting in each dwelling is restricted by the building geometry, the orientation and the shading (by surrounding buildings or vegetation) of the available surfaces. These factors limit the amount of available solar energy which can be utilised by the overall system, and along with the climatic conditions define the maximum theoretical solar yield. Thus the quality of the weather data available when designing and sizing the system might influence the quality of the ST installation. Peuser et al. suggest that dimensioning of the ST system based only on annual mean values of solar radiation is bad practice ((PEUSER, F. A. et al., 2002) p.69). Observations of the solar radiation fluctuations at a monthly and at a daily basis are required. Adsten et al (ADSTEN, M. et al., 2001) found that the performance of both flat plate (FP) and vacuum tube (VT) collectors is mostly influenced by solar radiation variations, rather than ambient temperature fluctuations. Significant weather variations also occur at a yearly basis and this factor is of critical importance as well, as explained by Andersen et al. (ANDERSEN, E. and Furbo, S., 2008). In the latter study, the Danish design reference year (DRY) representing a typical year (derived by 15 year measured data)and 12 years of measured data from a Danish weather station were used in order to investigate how the weather variations affect the performance of solar collectors and ST systems. The variation of the measured global solar radiation for these years is around 16%, resulting in a predicted variation of incident annual total radiation (on a south-facing 45° tilted surface) of around 23%, with a mean value 1.7% lower than the mean value derived from DRY. This study shows that the solar radiation variations from one year to another would affect the performance of ST systems when high efficiency collectors are utilised. The effect of these yearly variations on the annual system performance cannot be estimated based on annual values of global radiation or total incident solar radiation on the collector area for each year. Within the years tested, the distribution of solar radiation throughout the winter, autumn and spring months varies significantly and the study shows that the total annual solar radiation on a tilted surface cannot be derived from the annual global solar radiation, probably due to the low angle of the winter sun which "sees" tilted surfaces more than horizontal ones. Therefore the performance of the solar collector or the annual utilised solar energy can only be predicted based on the incident total solar radiation on the collector plane, if the variation at a yearly basis is to be taken into account. According to a German guide, a maximum deviation of 10% is expected from mean values used as inputs to the simulations and therefore a corresponding deviation of system performance in the region of ±10% should always be taken into account in practice ((PEUSER, F. A. et al., 2002) p.307).

On the other hand, a prerequisite of a good system design is the accurate prediction of the energy demand profiles; in the relevant standards this heat load is called "the needs to satisfy" (BS_EN:15316-4-3:2007). An oversized system would add excessive costs on the delivered solar energy, without necessarily providing higher SF. Therefore any planned measures for improving a building's energy performance must be taken strictly prior to solar. Peuser et al explain that if for example a medium DHW solar system is sized for a demand 30% higher than what actually required, this would have as a result a 15% reduction on the actual annual degree of utilisation and a 20% rise on the cost of solar heat ((PEUSER, F. A. et al., 2002) p.313). The user behaviour has a significant impact on the SH requirement of residential buildings, to the extent that the SH requirement of dwellings that belong to the same heat load category[8] can be expected to vary by a factor of 2 (PEUSER, F. A. et al., 2002) p. 331). Therefore appropriate user-related patterns (schedules/profiles) should be carefully chosen and be used in the simulations, so that correct predictions are obtained and proper dimensioning of the ST system (including the TES component) is achieved. Finally, the SH demand is also affected by the ST system used, as the system interacts with the building and that is something to be taken into account when designing the ST systems. The hydraulic parts and the auxiliary boiler play a major role in this.

Solar hot water systems are the most popular ST systems mainly due to the existence of smooth, year-around demand for DHW in dwellings (only slightly reduced in the summer). In ST systems, the duration of the heating period and the existence and magnitude of a cooling requirement in the summer plays an important role in the design and performance of the system; the longer the period with no demand for solar energy, the higher the frequency of stagnation periods. For this reason steep collector angles are suggested as more suitable for ST systems, so that the solar yield is increased in

[8] Residential SH loads for middle Europe vary between 30-200 kWh/ [m^2.a] depending on insulation standards.

winter and reduced in the summer, to better match with the annual heat load profile ((BUCKLEY, S., 1979) p.63).

3.4.2.2 COMBISYSTEMS AND NON-STANDARD COMPONENTS

The characteristics of the individual ST components are not overviewed here, as this subject is extensively covered in the literature. This section summarises information on operational experience and performance of recent ST applications found in the literature as well as basic rules of thumb for ST systems dimensioning.

The solar combisystems are a mature technology and the wide variety of components and systems available in the market guarantees that no region is excluded from efficient ST applications. Nevertheless it is clear that the choice of a few high quality components will not necessarily result in good performance or high thermal energy savings. The overall performance of a solar system is dependent on both the quality of its parts and on the actual configuration and tuning of the system design. The usefulness of the system is affected by the collector's efficiency (maximum delivered temperature, utilisation of diffuse radiation etc), the controls of the system, the chosen flow rates, the charging/discharging methods of the store, the presence and the types of heat-exchangers, the quality of insulation on the pipes and the store, the return flow preventions, the type and management of the auxiliary heater, the choice of the heat delivery system and many other aspects of the solar system. In small scale installations the simplicity of the design is considered good practice. In the relevant publications the description of a good solar combisystem is always more or less the same: good quality VT collectors, a good stratified store, adequate insulation for the pipes and the store, and a low temperature heat delivery system. The problem is that the prediction of the real performance of an actual combisystem is a rather difficult task, although a rough evaluation is quite easy to achieve.

According to Peuser et al the contemporary ST systems make use of 30-60% of the energy that falls on the collectors ((PEUSER, F. A. et al., 2002) p. 18)). For North Europe, a solar system heat yield of 300-450kWh per m^2 of horizontal collector per annum is anticipated, as a result of an average 2.4-3.4 kWh/m^2 incident solar radiation per day ((GERMAN SOLAR ENERGY SOCIETY , 2005) p.7)). The large solar fractions achieved with solar water-heating systems are not possible in solar combisystems, due to the mismatch of availability and demand of energy, unless there is a seasonal storage. Due to this fact solar pre-heating is a common case, where the return temperatures of the SH and DHW loop are heated up with solar, to benefit from the 'free' energy. However even in cold or temperate climates, the energy savings are usually higher in solar combisystems than in solely DHW systems, even when the solar combisystems delivers only 10-20% of the SH load ((GERMAN SOLAR ENERGY SOCIETY , 2005) p.54)). Based on published information, for climatic conditions such as those of the UK or Germany, a normal sized combisystem would be able to deliver 35% of the entire SH requirement of a dwelling. For up to 70% SF, an inter-seasonal storage is required ((GERMAN SOLAR ENERGY SOCIETY , 2005) p.71)). Another source ((PEUSER, F. A. et al., 2002) p.55) states that, for regular insulated buildings and for systems moderately larger than typical DHW ones, solar fractions in the region between 20-50% are possible, with non frequent stagnation periods and with an overall system efficiency slightly lower than that for DHW-only. Furthermore, Papadopoulos (PAPADOPOULOS, A., 2003) explains that when VT collectors and low energy delivery systems are used, 30-70% solar fractions for SH and DHW demands are possible with reasonable systems, considering both size and cost.

The major part of the installed capacity in Europe is FP collectors. For higher collector yields and for colder climates, the VT collectors are recommended as they can provide higher temperatures, are virtually no-loss due to convection and with minimum conduction losses. solar combisystems with VT collectors are proved to achieve higher solar utilisation in years with less sunny hours, compared to systems using FP collectors, although this effect is slightly reduced for significantly sunnier years (ANDERSEN, E. and Furbo, S., 2008). For example, in a large-scale solar DHW installation (8,000 l per day) the use of VT will result in a reduced required collector area of around 73% and 66% of that with FP collectors for solar fractions of 25% and 50% respectively ((PEUSER, F. A. et al., 2002) p.311). This fact reveals that VT collectors are generally more suitable for the UK climate than the other types available in the market. Being more efficient, VT collectors are more expensive than FP collectors. In China, the major ST market globally, 35% of the total ST installations make use of VT collectors, a fact that shows that economics of scale are achievable for ST technologies (Zhang et al, as cited in (PAPADOPOULOS, A., 2003).

Basic rules of thumb for solar system dimensioning are also available in the literature. Based on experience from Germany ((GERMAN SOLAR ENERGY SOCIETY , 2005) p.72), relative collector areas of 0.8-1.1m^2 (glazed FP) or 0.5-0.8 m^2 (VT) per 10m^2 of heated living space will be suitable in systems designed for low SFs. The required store volume in this case will be at least 50l per m^2 of collector surface or 100-200l per kW of heat load. According to the same source, 1.5-3 m^2 of VT per 10m^2 of heated living space and a store volume of 250-1000 l per m^2 of collector surface will be required in systems designed for high SFs. Peuser et al. give also a rough estimation of system sizing based on the predicted annual heat load ((PEUSER, F. A. et al., 2002) p.97). For systems delivering 50% solar fractions, approximately 3m^2 of collector area per MWh of the total annual combined energy consumption (for DHW and SH) would be needed, assuming sufficient storage for a few weeks' energy. Jenni (in German only) as cited by Peuser et al (2002) suggests that in this case the recommended store size would be in the region of 120-150l per m^2 of collector area. For the same SF but for a low-energy house, Jenni states that 2.5m^2 of collector area per kW of SH are required, but due to the long non-heating-period a seasonal storage is needed as well and the degree of utilisation will be low, at ~ 20%.

For detached and mid terrace single family houses a store of 800-1500 litres is suggested as suitable for mid-term TES ((HASTINGS, R. and Wall, M., 2007) p.217). For seasonal energy storage, water tanks in the region of 30-50m^3 are considered appropriate for single family houses. More specifically, for 50% SF the appropriate store will be around 21m^3 and 61m^3 for a low energy (~3000 kWh) and a common-built house (8760kWh) respectively (PEUSER, F. A. et al., 2002), (HADORN, J., 2005). An auxiliary source is usually required even in systems with very high SFs. Meeting the remaining part of the energy required or reaching fractions at the region of 80% with solar energy would result in a significant drop of the degree of utilisation of the system and would demand the use of a very large store[9]. It is possible that in the future higher solar fractions with reasonably sized stores will become feasible with the use of innovative, other than sensible, means of TES. The state-of-the-art of TES technologies and the current potential are reviewed and analysed in a separate section below (3.6).

[9] An interesting option would be to use district heating scenarios to overcome this problem. That could also be the subject of post-doctoral research.

3.5 SIMULATION PROGRAMS AND PERFORMANCE ASSESSMENT METHODS

3.5.1 OVERVIEW

The F-chart method is the most popular method for rough calculations of ST system performance and was developed by Duffie and Beckman (1977). A software version of the method is also available at www.fchart.com. That is a static calculation program, simple but accurate for annual analysis of small systems, requiring monthly averages as input for the calculations (BECKMAN, W. A. et al., 1977). The calculation method described by the European standard for ST (see 3.5.2) is based on the F-chart method.

An overview of the available simulations programs for ST systems' design and performance prediction is presented in the guide published by GERMAN SOLAR ENERGY SOCIETY (GERMAN SOLAR ENERGY SOCIETY , 2005). A list of the so-called "time step analysis programs", including TSOL, POLYSUN, GETSOLAR etc, is given. These programs provide a more dynamic approach than the F-chart method introducing smaller timesteps of an hour or less. Again the building representation in the above programs is done in a simplified way, e.g. as a load. To introduce more detailed building representations in the ST analysis, simulation engines such as TRNSYS are required. In addition these programs are able to handle systems with increased complexity and work effectively with larger systems. TRNSYS (TRNSYS, 2007) is the most popular software for ST building simulations and is used extensively in the relevant IEA SHC tasks. It is considered as the "classic and market leader among the simulation systems" (GERMAN SOLAR ENERGY SOCIETY , 2005), as able to handle the modelling complexity of the testing methods for ST applications required by the European standards and it is the program actually recommended by the relevant standards (DD_ENV_12977-1:2001). The software package TRNSYS (version 16.01.0003) used in this research has a modular structure with a main visual interface known as the TRNSYS Simulation Studio. There is also a dedicated interface (TRNBuild) for the multizone building component (type 56) which has undergone testing under the ANSI/ASHRAE Standard 140 and IEA BESTEST with acceptable results. Validation tools have been also used during the development of the software (BRADLEY, D. E. et al., 2004)(KUMMERT, M. et al.).

3.5.2 THE EUROPEAN STANDARD

The European standard that defines the "Method for calculation of system energy requirements and system efficiencies" of ST systems had to be adopted at a national level by January 2008. In the UK it now has the status of a British Standard (BS_EN:15316-4-3:2007). Its purpose is to harmonize the calculation of energy performance of ST systems and to be used for either checking compliance with energy-related calculations for parametric studies/optimisation of a system design or for assessing the impact of various energy reduction strategies. It also standardizes the calculation method, the input and outputs required for solar systems either serving DHW requirements only, SH only or both. Two methods are described by the standard. Method A is only suitable for DHW systems .Method B is suggested for solar combisystems and is based on the f-chart method. The user needs to refer to other standards for input values to be used in the calculations. Especially for method B which makes use of components' data derived either by tests or taken from tables as default values the TRNSYS software appears to be as an approved simulation tool for calculating the required input values. That is because one of the related standards that describes the component testing methods and system simulations to be used for thermal performance characterisation and performance prediction of solar heating systems suggests TRNSYS and EMGP3 as exemplars simulation tools for dealing with the required level of detail (DD_ENV_12977-2:2001).

One of the inputs of the calculation is the "heat use applied to the system" ($Q_{sol,us,m}$) which includes the DHW and SH requirements along with the heat distribution losses, ignoring the collector loop losses and the storage tank losses. For solar combisystems the calculation is carried out in two stages; the method is applied twice, once for the DHW and once for the SH demands. The total solar output of the system sums up the solar output for DHW and the solar output for SH. To do this, the share of both the SH and DHW load on the total load are determined first (P_H and P_W respectively[10]). These ratios are then applied to the collector area and the store volume (if a single store exists for

[10] $P_H = Q_{H,sol,us} / (Q_{H,sol,us} + Q_{W,sol,us})$, $P_W = Q_{W,sol,us} / (Q_{H,sol,us} + Q_{W,sol,us})$

both SH and DHW subsystems) to predict what part of these resources/components is used for SH and DHW requirements respectively.

In this method two dimensionless quantities are defined, as with the f-chart method. The parameter X takes into account the heat losses (collectors, pipes and heat exchanger) in relation to the load and the Y is the ratio of the collector output (energy transmitted by the absorber to the collector fluid) to the heat load. When these values are determined then the system's solar output, is calculated, month by month, by:

$Q_{sol,out,m} = (aY + bX + cY^2 + dX^2 + eY_3 + fX_3) \cdot Q_{sol,us,m}$ [kWh] ,

with $0 < Q_{sol,out,m} < Q_{sol,us,m}$

where

a, b, c, d, e, f are the correlation factors depending on the storage type (water tank or direct solar floor) and are provided by the standard taken by the f-chart method (f is specific to direct solar floor).

In addition the potential for recovering part of the thermal losses of the solar system from the storage tank, the distribution system and the backup heater is also considered, based on the following assumptions:

- 50% of the auxiliary energy of pump is recoverable
- During the heating season, the losses from the storage tank and the distribution system between the ST system and the auxiliary heater are:
    - Fully recoverable if the component(s) are located in the heated space
    - 50% recoverable if the component(s) are located in an un-heated space
    - Not recoverable if the component(s) are located outside

For the calculations described above, four annexes within the standard provide examples and default values for the input required.

3.5.3 THE OUTCOMES OF THE IEA SHC TASKS 26 AND 32

3.5.3.1 INTRODUCTION

Task 26 of the IEA SHC programme ran in the period 1998-2002 with 35 participants from 9 European countries and the USA and 16 solar industries. In this collaborative work typical solar combisystems used in the participating countries were reviewed. In total, 21 systems originating from France, Denmark, the Netherlands, Finland, Switzerland, Austria, Norway, Sweden and Germany were considered. The selection of these systems summarises the most popular system categories in these countries for that period, excluding district heating applications, systems with seasonal storage and systems including a solar cooling mode (WEISS, W., 2003).

One of the aims of the task was to develop a method which would allow inter-comparison of systems which are different from each other. The method developed in the Task can be used to characterise in a simple way the effectiveness of a solar combisystem in relation to the maximum theoretical potential solar yield, dictated by the building and the location only. A few of these systems were further analysed with detailed simulations and, as a result, the so called 'FSC method' was established and validated within the Task. The information cited here is found in the publications of Task 26 and in particular in the Handbook of the Task (WEISS, W., 2003) and the report describing the FSC method (LETZ, T., 2002). For simplicity, no specific citations to these sources are given in this section, as these sources overlap and complement each other.

Five years after the method was first developed, the FSC concept and its capacity to handle larger systems were further investigated for the purposes of the IEA SHC Task 32. Thus the extended method (FSC') was developed and used in this Task (LETZ, T. et al., 2007).

3.5.3.2 THE FSC AND THE FSC' EXTENDED METHOD

Due to time restrictions within Task 26, and considering the complexity of accurate system modelling (validation of the overall system model is important as well as testing of the accuracy of the system, regardless of the use of validated components) 9 out of 21 systems were modelled. These were actually 8 different systems, one of which was modelled twice having either a gas or an oil backup boiler. The characteristics of the 9 generic systems are given in Table 5 (see p.60). A detailed description with the hydraulic scheme for each system is provided in the Appendices (A) (ALTENER, 2003a). In this literature review, identification of the reference conditions used in the simulations which resulted in the FSC method development was proved to be sometimes ambiguous and had to be cross-checked. For example, the system report files found in the Task 26 website give different values for the collector areas and store sizes used to those presented in the handbook or the Combisun software. The Combisun software is a computerized diagram-based tool which incorporates the FSC characteristics of the solar combisystems and was produced in the Task 26 (ALTENER, 2003b).

The concept behind the FSC method is to compare and correlate the target functions mentioned in 3.4.1 ($f_{sav,therm}$, $f_{sav,ext}$, f_{si}) to the Fractional Solar Contribution (FSC) which represents the maximum theoretical fractional energy savings when no system losses are considered and when seasonal TES is not used. The FSC is the ratio of the usable solar energy $Q_{solar,usable}$ to the reference consumption of the house E_{ref} (SH+DHW +losses from the reference store and the sum divided by the reference boiler's efficiency). The $Q_{solar,usable}$ is calculated on a monthly basis as the minimum of the E_{ref} and the available irradiation (incident on the total absorber area). Therefore the FSC factor takes into account the heat loads and the solar availability for the particular house and is unrelated to any solar system's characteristics. It is noted that the excess solar energy that is incident on the collectors during the summer months is not considered to be available for use. If this energy was also included in the ratio, then the final value would be close to the ratio Y defined by the f-chart and described in 3.5.2, apart from the fact that the Y factor has the collectors' efficiency data applied and therefore is relevant to the solar combisystem used.

The $f_{sav,therm}$ and the $f_{sav,ext}$ are values which can either be measured in actual systems or be calculated by detailed computer simulations and show the performance of a solar system in comparison to a reference non-solar conventional installation. These values represent the actual system performance within the particular boundary conditions. The relation between the FSC and the $f_{sav,therm}$ or the $f_{sav,ext}$ would show how effective a solar combisystem is; the closer the FSC is to the fractional energy savings, the less the amount of solar energy falling on the collector that is wasted by the system. With the simulations conducted for the 9 selected systems, it was found that the FSC can often be described as a function of the $f_{sav,therm}$ or the $f_{sav,ext}$ with a quadratic equation having a regression factor very close to 1 as follows:

$$f_{sav}= a.FSC^2+b.FSC+c$$

This equation and the curve corresponding to it are defined each time by a certain number of points - results of parametric studies on the system. For a particular set of points, the a, b, c values are characteristic coefficients of the solar combisystem when the regression factor R^2 is close to 1. In that case the curve represents the system behaviour for the boundary conditions used to calculate these points. It is possible for the selection of points not to give a good regression factor; in this case the system's performance is not adequately described by a single set of a, b, c values.

In Table 4 the values for the quadratic equation of FSC defined by the 9 systems' simulations in TRSNYS and other similar programs are presented (system #19 which is for multi-family dwellings and base case for system #12 are also included in this table, although they are not of interest for this research). The information was sourced from the handbook of Task 26 and the FSC report (LETZ, T., 2002). The points correspond to the results of the simulations conducted by varying the collector area, the store size (depending on the allowances of the system for both factors), the heat load (three specific heat demands used, as SH30, SH60 and SH100) and the climatic conditions (Stockholm, Zurich, Carpentras). The reference case was the same for all models (gas boiler efficiency 85% and 644 kWh annual DHW store losses). The collector used was the same for all systems and therefore the results do not strictly correspond to commercial systems, which would be using various collector types. The boiler and the store losses of each solar system are different as well. It is apparent from the results that the overall performance of each of the systems modelled within Task 26, can quite accurately fit to a quadratic equation with a high regression factor. This means that to a large extent the system characteristics (a,b,c,) are not affected by the solar availability or the heat load of the house, and inclusion of this kind of information in the calculation of the FSC value only, is adequate to give quite accurate estimations of the $f_{sav,therm}$ or the $f_{sav,ext}$ from the quadratic equation.

TABLE 4: CHARACTERISTIC COEFFICIENTS AND REGRESSION FACTORS FOR $F_{SAV,THERM}$=F(FSC) AND $F_{SAV,EXT}$=F(FSC) FOR THE 9 (+2) SYSTEMS MODELLED IN TASK 26 (WEISS, W., 2003).

	$f_{sav, therm}$				$f_{sav, ext}$				No# of points
System	**a**	**b**	**c**	**R**	**a**	**b**	**c**	**R**	
*** 2**	0.073	0.377	0.065	**0.98**	0.047	0.308	0.056	**0.971**	**18**
*** 3a**	0.244	0.292	0.178	**0.966**	0.199	0.324	0.178	**0.969**	**31**
*** 4**	0.145	0.368	0.107	**0.948**	0.1	0.337	0.093	**0.96**	**20**
*** 8**	0.315	0.245	0.131	**0.979**	0.212	0.292	0.105	**0.978**	**23**
*** 9b**	0.342	0.246	0.048	**0.967**	0.258	0.238	0.031	**0.971**	**46**
*** 11_gas**	0.306	0.153	0.155	**0.95**	0.237	0.142	0.131	**0.959**	**45**
*** 11 oil**	0.212	0.301	0.035	**0.963**	0.196	0.232	0.029	**0.969**	**23**
*** 12 base**	0.176	0.312	0.002	**0.979**	0.14	0.273	0.012	**0.973**	**16**
*** 12 opt**	0.047	0.487	0.091	**0.967**	0.055	0.388	0.079	**0.972**	**22**
*** 15**	0.322	0.182	0.243	**0.985**	0.143	0.252	0.224	**0.985**	**86**
*** 19**	0.161	0.39	0.036	**0.957**	0.119	0.379	0.014	**0.944**	**100**

Nevertheless within the Task further investigations on the scattering of points around the curves produced each time were performed, in order to identify which system elements have the strongest impact on the systems' efficiency. For the parametric studies performed in each system, a set of a,b,c and R^2 values was calculated each time and the results were then plotted in groups e.g. according to the climatic data used. Several curves were then produced to simulate each system and this allowed comparisons on the system's performance according to various factors e.g. showing the influence of the climatic conditions on the system's behaviour. Such data for the models is only selectively available in the relevant reports of the Task and were therefore not available for use in this study[11].

Within the same concept, the role of the storage size was investigated. A *storage capacity correction factor (SC)* was therefore introduced in the method to account for the scattering of points around the curves of Table 4 caused from the store capacity variation. The equation for the improved FSC and the equation for the SC (max value 1 for a specific storage size/collector area ratio) are given by Task 26 as:

$$f_{sav,therm} = SC\,(a'\,.\,FSC^2 + b'\,.\,FSC + c')$$

$$SC = ((V/a.\,A) + \beta))^{\gamma} - \gamma^* (1+\beta)^{(\gamma-1)}((V/\alpha\,.\,A) + \beta)) + 1 - (1-\gamma)(1+\beta)^{\gamma}$$

[11] Communication with the participants of the Task 26 revealed that this information could not be sourced and become available for use.

Where:

V is the store volume [l],

A is the collector area [m^2] and

α [l/m^2], β [-], γ[-] are calculated for the highest regression factor for the corresponding curve.

The results of the improved FSC-SC method applied on the same models showed that for some systems the role of the store capacity is significant and therefore the system performance would be better not represented by a single set as the use of the SC is required, while for other models the inclusion of the SC will not bring higher accuracy on the method. For model No#4 a constant size to collector area ratio was modelled and therefore the SC has no effect on the curve of the system. For system No#11-gas it was found that the regression factor of the curve produced with points from various storage sizes is significantly lower than that of the curves produced for each storage size. Therefore a single set of values for a',b',c' might not be adequate to describe the overall system performance, and one set per storage size will give a much better fit to a quadratic curve in this case. Of course this would also depend on the acceptable error. For system No#9b, the situation is different, as it was found that a single set for the a',b',c' will give as good a fit as would one defined per storage size. Within the Task's publications the datasets for a',b',c' and α,β,γ were not available for most of the systems simulated. Communication with some of the participants was attempted, but it was not possible to acquire the relevant information.

The method was built and validated for specific boundary conditions, due to time restrictions[12]. The method is limited for orientations up to 45 degrees from South and it has been tested for DHW consumption of 100-300 litres a day. The building model used as a reference case in all simulations is a single-zone simplified dwelling with constant occupancy both at a daily and at a yearly basis. Therefore the method is suggested as suitable for permanent occupation. The method has only been validated for these specific systems and it is unknown whether it will be valid for any other systems. That

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[12] Further investigations currently continue as part of a PhD research. This work is ongoing and results will be available in the future (LECONTE, A., 2009).

means that the method is not necessarily flexible and can only be applied considering the predefined reference conditions for these systems. Most importantly, the method is not valid when the FSC is equal, or higher than 1.

A few years after the method was developed, the role of larger collector areas and store volumes was further investigated within Task 32 (LETZ, T. et al., 2007). With the simulations it was observed that for large systems, as the FSC gets equal or larger than 1, the parabolic curve fails to 'predict' the scattering of the points. That is because the larger systems can make use of the excess solar energy i.e. the solar energy incident on the collectors that exceeds the corresponding demand for these periods of time, which is not accounted for in the FSC. Therefore it was found in Task 32 that the curve representing the system's behaviour is actually a sigmoid curve and can be split into two parts, with the parabolic being used for smaller systems' results and the remaining for the results of the larger sizes. Firstly the modified FSC' was defined as:

$$FSC' = FSC + \frac{1}{ENC^{a}} \cdot \frac{[\sum_{1}^{12} Qsolar.excess]}{[\sum_{1}^{12} Eref.month]}$$

Where

ENC is the so-called Equivalent Number of cycles[13] with ENC = $\frac{[\sum_{1}^{12} Eref.month]}{Qstore.cap}$,

$Q_{store,cap}$ is calculated by the specific heat capacity of the material for latent or for sensible storages or equals the enthalpy of the chemical reaction for thermo-chemical storages and the exponent α is introduced to bring a good curve fit in relation to the results of the calculations.

It was found by the investigation conducted in Task 32 that the extended method for FSC<1 gives results very close to the original method, and for α=2/3 the interpolation achieved for FSC>1 is very good. A storage correction factor was also introduced in the extended method. Again no datasets of points are provided and therefore further details are not included here.

[13] Possibly referring to storage 'cycles' (charge/discharge).

3.5.3.3 THE MAXLEAN AND THE TEMPLATE SOLAR SYSTEM

In Task 32 the "template solar system" a state-of-the-art solar combisystem was defined (HEIMRATH, R. and Haller, H., 2007a). A complete database, which also includes TRNSYS files, was developed for simulations and is available to the public (HEIMRATH, R. and Haller, M., 2007b). At the end of the task an optimised version of this template was presented, the "MaxLean" concept, which was developed with the criteria of both simplicity and optimisation based on economic and ecologic aspects of the overall system (HABERL, R. et al., 2008). For a particular case study with the MaxLean system under the climate of Zurich the simulations resulted in a 4.5% reduction of the auxiliary heating requirement compared to the template solar system. Both the template and the MaxLean systems were developed to work as reference cases when other storage solutions would be assessed by the participants of the IEA SHC Task 32.

The MaxLean system consists of four independent hydraulic circuits connected to the storage tank: the collector loop, the auxiliary loop, the space heating loop and the DHW loop. The use of heat exchangers (HXs) is limited to the DHW side. The elimination of HXs was considered to be beneficial, considering the flexibility of the system to different loads and collector areas and the overall system efficiency. The storage tank is non-pressurised and also works as a drainback vessel. Many storages of this type can be connected in parallel to meet the required storage capacity of any system. Two perfect stratifiers exist in the tank, at the inlet flow from the collector loop and at the return flow of the SH loop. A condensing gas boiler is used as an auxiliary energy source, although the MaxLean system was designed to work with other alternatives as well, such as heat pumps, wood boilers, and even existing auxiliary heaters of any kind that could be found in houses. A Direct Feed Flow Control (DFFC) strategy is implemented at the SH loop, so that in order to meet the demand, the delivered energy is modulated with a flow rate variation rather than a temperature variation.

The MaxLean system is believed to give thorough economic solutions as it makes use of few components and simple controls and it can be integrated in existing water based heating systems when retrofits are considered. It could be built with readily available components and the concept behind it involves reduction of both the embodied energy and the environmental impact due to material use. It is designed to be suitable for a range of loads and for large collector areas, which is critical for the future of ST, as higher than 50% solar fractions will be desirable. With the investigations done in the Task it was proved that the principles used by the system result in performance optimisation and cost reduction and therefore a pilot installation has been announced (HADORN, J., 2007).

TABLE 5: CHARACTERISTICS OF THE SOLAR COMBISYSTEMS MODELLED WITHIN TASK 26 (SOURCE: HTTP://WWW.IEA-SHC.ORG/PUBLICATIONS/TASK26/INDEX.HTML).

Characteristics / Generic system (description)	Solar loop connection	SH connection	Store	Heat delivery system	Auxiliary sources	Coll. areas (m^2)
System **2** (HX between collector and SH loops. Typical DHW solar system with oversized collectors to deliver energy to an existing SH system). Proved not suitable for low-energy houses (e.g. 30SFH) Denmark (most popular system for the period of the Task)	Immersed HX at the bottom of the tank	Solar loop with external flat plate HX in the return pipe of the SH loop.	No controlled store for SH. DHW only store. 0.28-0.6m^3	Heating floor preferable (building to work as store, due to lack of SH store)	Immersed HX at the top of tank. Not managed by the controller. All types of auxiliary source suitable. Even electric radiators for SH. SH loop may be fed by the auxiliary or by both solar collectors and auxiliary source connected in series.	5- 14
System **3a** (Advanced direct solar floor with improved strategy for solar heat sharing between DHW and SH. Made of compact-factory assembled units.) France: CLIPSOL (only). Marketed as a whole	Immersed HX at the bottom of the tank	Direct connection between solar and SH loops.	No store for SH. DHW only store: 0.5m^3. stores larger than 0.2m^3 required	Heating floor	Immersed HX at the top of tank. Managed by the controller. Gas, oil, electric boilers suitable. If wood boiler, then a buffer store required.	10-35
System **4** (DHW tank as a SH storage device. Typical DHW solar system with oversized collectors to deliver energy to an existing SH system.) Denmark (Batec A/S), The Netherlands (drainback version)	Immersed HX at the bottom of the tank	SH connected with a HX with the store	DHW&SH combined. Fixed spec. volume 0.05m^3/m^2	Radiators or heating floor. Intermediate immersed HX in store for SH return	Immersed HX at the top of tank. Not managed by the controller. All types of auxiliary source suitable. Even electric radiators for SH.	5- 15
System **8** (SH store with double-load side HX for DHW. Compact unit) Switzerland	Immersed HX at the bottom of the tank	Direct connection between SH loop and store	DHW&SH combined. 0.83m^3. 2 immersed HX for DHW (top & bottom)	Heating floor or radiators. Sophisticated control strategy for all components.	Integrated gas or oil burner. Managed by controller	8- 16

System **9b** (SH store with immersed DHW tank and external DHW store with auxiliary) Norway (SolarNor AS)	Direct with store	Direct with store (on/off operation & control parameters: outdoor T, incoming solar irradiance and wind speed)	SH store (1-4m^3) with immersed DHW store (0.2 m^3). At atmospheric pressure. Additional external DHW store (0.08-0.15 m^3)	Preferable heating floor or wall heating	Oil, gas or biomass burners suitable. In Norway electricity. Single control unit for entire system except the external DHW vessel's auxiliary.	10- 40
System **11** (SH store with DHW load side HX(s) and external auxiliary boiler. Finland, Sweden (in Finland systems smaller than in Sweden)	Immersed HX at the bottom of the tank	Direct with store (mixing valve delivering heat from the centre). No control	DHW&SH combined. 0.3-3m^3 (with optimum at 1.25 m^3).	Radiators (heating floor)	Electric heater integrated in the tank (controlled by a thermostat). External: boiler for solid wood, oil or pellets in Sweden, but an oil or gas boiler used in the simulations.	5- 30
System **12** – an optimised version of System **11** (Advanced version of SH store with DHW load-side HX(s) and external auxiliary boiler) Sweden	Two immersed HX at the bottom and centre of the tank (stratification)	Direct. A four-way valve delivering heat from the centre and top of the tank.	Store 0.3-3m^3	Radiators (heating floor)	Electric heater integrated in the tank (controlled by a thermostat, but locked out by the solar controller when collector pump in operation). External: boiler for solid wood, oil or pellets in Sweden, but a gas boiler used in the simulations	8- 30
System **15** (Two stratifiers in a SH storage tank with an external load-side HX for DHW. (Compact unit, all components integrated. The store works as an energy manager for all in-out energy flows) Germany (Solvis GMbH & Co KG)	Indirect: stratifying tube (low-flow)combined with an immersed HX	Direct. Stratified tube for the return of SH loop. Variable flow rate pump controlled from thermostatic valves	DHW&SH combined. 0.377- 1.423 m^3	Radiators (heated floor or wall heating) External HX for DHW preparation	Integrated condensing gas burner. All other auxiliary boilers can be connected with additional HX. Power 5-20kW, controlled by store temperature and demand of the SH loop	4-12

* The same FP collector used in all systems. System #19 designed for multi-family houses not included. HX stands for heat exchanger, SH for space heating and DHW for domestic hot water

3.6 OVERVIEW OF TES TECHNOLOGIES AND THEIR APPLICATIONS FOR ST

3.6.1 INTRODUCTION

3.6.1.1 THE ROLE OF TES

Thermal Energy Storage (TES) is an 'enabling' technology for ST and other renewable or even low carbon energy sources. TES technologies do not only bring benefits in low carbon and renewable energy systems. TES are also incorporated in fossil fuel-driven systems to increase the effectiveness of the equipment by reducing the cycles or to permit downsizing of the systems by significantly smoothing the load throughout the periods of operation.

The fluctuating character of solar energy which creates a mismatch between energy demand and supply makes TES components a prerequisite for good ST system performance. In ST applications the requirement for thermal energy might occur, or even peak, during times when the sun is down or is temporarily hidden behind clouds. TES technologies are therefore required to bridge these gaps and increase the solar energy utilisation of the system.

Many definitions of thermal energy storage are given in literature. A short but effective definition is given by Dincer et al, calling it a *'temporary holding of energy'* and describing it as *"a link buffer between a heat source and a heat user"* (DINCER, I. and Rosen, M. A., 2002). Enhanced with quality values, in Task 32 publications TES is described as *"unit or material that can store energy for some time in an efficient way, that is with few heat losses"* (Hadorn, 2005).

TES technologies vary according to the duration of energy holding, the method and material used and the way the chosen TES method/type is implemented. Depending on the performance targets, short-term, mid-term or long-term TES can be employed. Short term TES is often called 'diurnal' but can achieve energy storing for up to a few days. The purpose of long-term TES is for (inter)seasonal energy storing. It is also quite typical for thermal energy to be stored for intervals of a few days up to a few weeks, that being called mid-term storage. At present most cost effective is the short-term storage (DINCER I., R. M., 2002). Long term storages are not easily cost-justified but there are cases when large stores might be desirable as in district heating projects, or when limited collector area is available, or to take advantage of the reduced losses due to the low surface-to-volume ratio.

In solar applications there are different approaches with respect to TES. In general large storages would remain unused for large periods of time, and as sensible TES is the dominant type, this would result in high energy losses. A possible strategy would be to use highly efficient collectors and a large absorber area so that energy is collected even during low irradiance conditions. If thermal comfort can be tolerated then the TES requirement can be possibly reduced. In any case synergistic use of both the solar system and the auxiliary energy part with regards to the store(s) is essential.

At the following paragraphs an overview of the available TES methods, materials and applications suitable for ST systems is presented.

3.6.1.2 TES TYPES

> *"...Three methods of storing thermal energy...differ in the amount of heat that can be stored per unit weight or volume of storage medium, in the time-temperature history of the medium during heat storage and retrieval, and in the relative state of development of storage technology at the present time..."* (Lane, 1986).

The three concepts of storing solar energy are as follows:

1. Sensible heat storage
2. Latent heat storage
3. Sorption, thermo-chemical storage and storage in chemical reactions

The most common type is the sensible heat storage (1), when heat is stored by rising the temperature of a material e.g. when water warms up; at the discharge process the storage medium cools down and heat is released. Latent heat (2) is the heat stored when a material undergoes a phase change while absorbing heat e.g. when a solid material melts. At the discharge phase the material returns to the previous state, e.g. it solidifies, and releases the stored heat. The same material could also store sensible heat before and after the phase change but the heat during the phase change is stored without losses and the latent heat content is usually higher than the sensible one. The volumetric heat capacity of the phase change materials (PCMs) is 4-15 times higher than that of sensible heat storage of water or rock (SHARMA, A. et al., 2009). The last category (3) includes techniques of transforming (solar) heat to chemical energy. Chemical reactions which are not involving a thermal conversion also belong to this group. Therefore these types are not verbatim TES technologies, but are mentioned here as with these methods solar thermal energy can be discharged and utilised when required. The volumetric thermal capacity of these types is several hundred times higher than that achieved with PCMs; according to an example of selected representative materials for each type, the ratio of sensible, latent and chemical volumetric heat capacities is quoted as approximately 1:100:1000 ((HADORN, J., 2005) p.9).

3.6.2 SENSIBLE HEAT STORAGE

Various materials can be used for sensible heat storage such as water, rock, oil, sand, soil or air. The effectiveness of a sensible store depends on the specific heat c_p of the material used. The heat stored (Q) in a material which had its temperature changed for ΔT is

EQUATION 1

$$Q = mc_p\Delta T \text{ with } m = \rho V$$

This equation shows that the density (ρ) of the material can be a crucial factor, as volume (V) is usually an issue in ST installations.

3.6.2.1 WATER STORES

Water has many advantages compared to other materials suitable for sensible heat storage. It has a high specific heat at 4,186 KJ/[kg.K] (three times that of rock), it is liquid (therefore pump-able), inexpensive, and non-corrosive. At present, in domestic active ST water-based systems the most common TES type used are the water tanks. A Lot of experience has been accumulated throughout the years as the technology has been used for many decades.

Water stores can be unvented or vented and are usually built from (stainless, enamelled or plastic coated) steel, copper, plastic, concrete or fibreglass (GERMAN SOLAR ENERGY SOCIETY , 2005) (ATAER, O., 2006) (HASNAIN, S., 1998). The water tanks have to be adequately insulated (all around the perimeter and the bottom of the tank) so that a large part of the (sensible) heat charged is maintained for the required period of time and unnecessary losses to the ambient are minimised. A reasonable heat loss rate of a good store is around 1.5W/K with a thermal conductivity (λ) at 0.035 W/[m.K] ((GERMAN SOLAR ENERGY SOCIETY , 2005)p.33). Common insulation materials are glass wool, mineral wool and polyurethane (HASNAIN, S., 1998). Advanced concepts such as vacuum insulation have to be used if the best performing polyurethane foam is not able to meet the targets (SCHULTZ, J. M., 2005). Usually the thickness of the insulation can be in the range of 10-20cm up to 60cm in reasonably insulated stores (HADORN, J., 2005). As some thermal dissipation from the stores is unavoidable, storages can be arranged so that losses are beneficial as heat gains to the dwelling, although this passive 'trick' should be used with care as an overheating problem might emerge during the summer months.

For water tanks with a ΔT>20°C it is important that mixing of water quantities of different temperatures is avoided throughout the store volume (STREICHER, W. and Bales, C., 2005). That applies to the way cold and hot water flows in and out of the store. The idea is that a thermal gradient with zones which thermally correspond to the DHW and SH delivery loops or to the heat sources is achieved. This effect is called stratification and plays a multiple role. It can enhance the collector's efficiency by lowering its inlet water temperature, it increases the effectiveness of the system by ensuring that the highest possible temperatures are available to the demand side and it ensures that losses are minimised (PEUSER, F. A. et al., 2002). In liquid stores it is more difficult to maintain stratification than in solid stores (e.g. rock beds). Slim and tall water stores maintain better stratification and the recommended height-diameter ratio is 2.5:1 at least (GERMAN SOLAR ENERGY SOCIETY , 2005).

Due to the importance of stratification in the overall system efficiency lots of R&D work has been focusing on testing various methods and techniques for creating effective thermal gradients during charging/discharging of water tanks. Information on this subject is found in many sources (STREICHER, W. and Bales, C., 2005), (PEUSER, F. A. et al., 2002), (DINCER I., R. M., 2002) (WEISS, W., 2003). In solar combisystems due to the large numbers of heat sources and sinks the issue of stratification is more complicated. In general, charging with direct connections favours stratification while charging with internal HXs destroys stratification. In active, simple stratification systems with direct/indirect connections, 2-3 feeding levels are usually used at maximum. Stratification can be also performed with stratifying tubes/units as the water flow from a heat source into a tank is the result of natural convection. These stratifying devices can be very effective especially when the temperature of the inlet water is varying, as in a solar system, because the water would 'find its way' to a zone of approximately the same temperature. This is the best strategy but requires attention, especially as far as the water flow is concerned:

- The momentum in flow versus the force caused by density difference would determine the choice of the outlet in the stratifying tube.
- Mixing might be caused when water is drawn in from outlets which are located into the passing flow in the tube.

Advances in thermal stratification of water tanks include vertical plates (VOGELSANGER, P. et al., 2007), stratifying devices with non-return flaps (ANDERSEN, E. and Furbo, S., 2007) and the use of fabric elements (ANDERSEN, E. et al., 2007).

The connection with the collector loop is always found at a low level, while the auxiliary inlet is high. The exact positioning is optimised based on the minimum running time of the burner and to allow as much possible volume for the solar part. According to the temperature requirements, the DHW outlet is located at the top, the SH outlet in the middle and the fresh water inlet at the bottom of the tank. To avoid energy losses a thermosyphon break can be used to avoid natural convection in pipes at the top and at the sides of the storage. Either side inlets or plates acting as diffusers on vertical inlets could be used to avoid mixing caused by the momentum of incoming water at the bottom (GERMAN SOLAR ENERGY SOCIETY , 2005).

Usually a heat exchanger connects the collector and the store, except if the drainback principle is used. The heat exchanger uses an anti-freeze/water mixture. For high flow systems (50l/hr.m^2) with a ΔT of 10°C, the input should be near the bottom while in low flow cases (10l/hr.m^2) and ΔT 40-50°C the inlet should be higher, and it is better realised with a stratifying unit (STREICHER, W. and Bales, C., 2005). For collector areas less than 15m^2 an internal heat exchanger is recommended along with a high flow strategy, while for larger collector areas external HXs are recommended. A store temperature sensor should exist in the middle of the solar heat exchanger so that the system has the chance to recharge even when small draw offs take place. A sensor for the auxiliary system should be placed at the height of the heat exchanger or higher. To prevent scalding, a thermostatic mixing valve is installed immediately at the hot water outlets (GERMAN SOLAR ENERGY SOCIETY , 2005).

The method for testing solar hot water stores is set by the European pre-standard ENV 12977-3 (test sequences and then parameters identification for a simulation model), part of system method ENV 12977-2, where each component is tested separately and then the whole system is simulated to calculate annual system performance.

State-of-the-art water tanks are available from several companies such as *Solvis* (information in English by the Irish distributors (GOSOLAR)) and *Solartank* by *Jenni Energietechnik* (JENNI, 2009 (2)). The latter is a Swiss manufacturer of large water tanks for inter-seasonal energy storage for meeting high SFs in low energy housing with solutions claiming to be cost-comparable to an oil-heating installation (JENNI, 2009). *Jenni* installations have been extensively presented in solar conferences, being infamous for their enormous size as seen in Figure 12, designed for 100% solar space heated and solar-DHW fed dwellings.

FIGURE 12: IMAGES FROM JENNI. FITTING THE STORAGE PRIOR TO BUILDING CONSTRUCTION (LEFT). TRANSPORTATION OF A 60CB.M WATER TANK (RIGHT) (WWW.JENNI.CH).

3.6.2.2 OTHER TYPES

Rock beds are the most common type of TES used in solar-air systems (HASTINGS, R. and Morck, O., 2000). Buried pipes in the building structure ('hypocaust' systems) or in containers which work as heat buffers for pre-heating the ventilation air are another type used in solar-air systems (HASTINGS, R. and Morck, O., 2000)(HOLLMULLER, P. and Lachal, B., 2001). Water-rock combined storages have been also developed for solar systems with water-collectors and air-displacement pre-heating systems; a conventional water tank, storing solar energy for DHW use is surrounded by a rock bed , so that losses from the tank are beneficial for the air-preheating (DINCER I., R. M., 2002) ((MOSCHATOS, A., 1993) p.129). Other solid media that can be used are metals, concrete, sand bricks, pebbles or sand. (HASNAIN, S., 1998). These technologies are not of interest here, because the focus of this work is on ST systems using liquid mediums both at the energy collection and at the delivery loops.

Hastings summarises the sensible seasonal storage techniques used in conjunction with ST systems (HASTINGS, R. and Wall, M., 2007); large on-ground and under-ground water tanks, aquifers, (partly or fully) insulated earth pits, rock caverns and vertical holes in the ground are all suitable for large-scale commercial; industrial or community heating ST installations. Water or gravel-water pits, also called "artificial aquifers" (SWET, C., 1986) are large storages built outdoor to store thermal energy seasonally. Under the Solarthermie-2000 and its successor, a government funded project in Germany, a number of solar assisted district heating systems of this type were built. The larger system is using a 63,300m^3 water pit. Most of the systems of this type have a volume of a few thousand m^3 (SCHMIDT, T. and Mangold, D., 2008) and are usually very costly and therefore not very popular.

The Aquifer Thermal Energy Storage technique uses underground natural layers of sand, chalk, water etc to store cold or heat. Two wells are used; one to store and extract warm water and one to store and extract cold water. These are suitable for bulk storage and therefore are not suitable for small loads (HASNAIN, S., 1998). Solar ponds is another technology used for large scale-applications, such as community heating, where large pieces of land are available ((DINCER I., R. M., 2002)p. 139). The use of salt in these ponds ensures that the warm water never rises to the surface and therefore warms up and remains stored at the bottom. Other TES techniques using abandoned mined or partitioned lakes have been employed for large seasonal storages of thermal energy (SWET, C., 1986).

Systems using the ground source heat- the low enthalpy heat found in 'shallow' depths - can be also seen as systems involving some type of TES. These types of systems make use of the heat that is stored at normal temperatures and 'lift' it with the use of heat pumps, thus usually called as Ground Source Heat Pumps (GSHPs). These are different from the high enthalpy systems which are utilising geothermal energy at temperatures higher than 30°C, available in areas such as Iceland. Ground source heat systems can be built virtually anywhere. There are two ways of using the ground source heat, depending on the geology of the ground on site. The open-loop systems are only applicable to situations where water can be physically abstracted from the sea, a river, lake or aquifer, with the use of wells. The closed-loop systems can be constructed almost anywhere and their operation is based on circulating a heat transfer fluid in buried pipes either located within vertical boreholes or laid horizontally in depths of 1-3m deep(BANKS, D., 2008).

The Welsh Assembly is being heated by a borehole heat exchanger system, using 27 drilled holes with 100m depth, all located beneath the footprint of the building (VAN GELDER, A. et al., 2006). U-shaped pipes immersed in these water-filled wells distribute warm water and store energy at large depths. These systems have water, land, groundwork and cost (mostly drilling) implications and are not suitable to all sites (geological tests at various depths are required). This GSHP type could be used for individual dwellings as a couple of boreholes could be sufficient for a domestic application, provided that special requirements regarding the site and the economics of the system are met. The system using horizontally buried pipes (slinky or straight) is suggested for remote areas, but it can be impractical for domestic installations as an area twice the footprint of the dwelling would normally be required for the laying of the pipes (VIESSMANN, 2009). GSHPs are a special technology in its own, as it comes with the integration of heat pumps and it is usually not coupled to any source of heat rather than the ground. Therefore this technology is no further analysed here[14].

Many other TES techniques exist, and are being used for high temperature applications (>100°C), employing organic fluids, molten salts, oils or liquid metals (SWET, C., 1986)

[14] Although this could be the subject of future work i.e. investigating the combination of GSHP with ST technologies to meet the residential thermal energy demands for Wales; use of solar energy to reduce electricity consumption by the system.

(HASNAIN, S., 1998). These are all beyond the scope of this work, which deals with marketed TES systems suitable for small scale domestic ST applications.

3.6.3 LATENT HEAT STORAGE

3.6.3.1 INTRODUCTION

The major advantage of using Phase Change Materials (PCMs) for storing thermal energy is the high storing capacity at small temperature changes. As the sensible heat capacity of PCMs is lower than that of water (STREICHER, W. et al., 2007a), in applications operating at a large temperature range the sensible heat is dominant and therefore the advantages of the use of a PCM are weak. The heat storage capacity of PCM materials is determined as a function of the heat of fusion (melting point) or the heat of vaporisation (boiling point). The most important drawback of PCM-related storage is the low thermal conductivity of PCM materials.

Several reviews on PCMs and their state-of-the-art applications are found in the literature (HASNAIN, S., 1998), (SHARMA, A. et al., 2009), (KENISARIN, M. and Mahkamov, K., 2007), (FARID, M. et al., 2004), (ZALBA, B. et al., 2003). The theory behind latent heat storage has been published in various books (LANE, G., 1983), (DINCER I., R. M., 2002) and latent TES technologies were the focus of the subtask C of the IEA SHC Task 32(HADORN, J., 2005), (STREICHER, W. et al., 2008a). The report C2 of the Subtask presents a state-of-the-art inventory of PCM materials (STREICHER, W. et al., 2007a). Several other sources of information were advised during this literature review and are cited appropriately in the following discussion.

For the purposes of this work it was not considered necessary to conduct a complete primary survey of technical and other advances on PCM materials and applications as this has been done by researchers in the area and is available through the publications cited above.

3.6.3.2 HISTORY OF PCM USE IN TES APPLICATIONS

Applications of PCMs are historically traced back to the beginning of the 20th century. Lane (LANE, G., 1983) records a variety of related patents and products such as warmth/cold releasing devices used for food or drink consumption and pain relief, warming suits for humans, sleeping bags and space technology products. Dincer et al.

((DINCER I., R. M., 2002) p.144) refers to a very early application of a PCM at the beginning of the 20th century for seat warmers in the British rail coaches. The first actual building application of a ST integrated TES system including PCM is traced back in 1948, in a purpose-designed dwelling in Dover, Massachusetts (BUTTI, K. and Perlin, J., 1981). The concept of a 100% solar heated house was the incentive for Telkes to design a solar system combined with TES walls filled with Glauber's salt (sodium sulphate decahydrate). The vast amount of PCM used in this case made it difficult at the time to assess whether the sensible or the latent character of the store was the dominant one. The system failed after two and a half winters of fair operation because of the decomposition of the salt (BUTTI, K. and Perlin, J., 1981) (LANE, G., 1983). Another dwelling built in 1950 in Las Cruces Mexico by Lawrence Gardenhire, again with Telkes' contribution, had similar results. Dr Telkes was also the leader of the experimental innovative project "Solar-One", a building using PCM for cool storage (TELKES, M., 1980). Similar outcomes had the experimental work of Hodgins and Hoffman in 1957, also using the Glauber's salt in an active solar heating application for a building in Canada (cited by (KENISARIN, M. and Mahkamov, K., 2007)).

In general the research conducted at the time focused on the problems of deterioration, segregation and subcooling of the PCM materials (TELKES, M., 1997). Technically successful products were marketed that period but the decline of the solar industry had a huge impact on this market ((DINCER, I. and Rosen, M. A., 2002) p.144). The interest in PCM materials was boosted recently when focus was drawn again on renewable energy sources and TES technologies.

3.6.3.3 MATERIALS AND TECHNOLOGIES

3.6.3.3.1 CRITERIA FOR APPLICABILITY

Latent heat storage is a promising type of TES as it offers compactness, nearly constant storage temperature and a wide range of applications, from advanced storage tanks solutions up to integration into construction elements and building systems. The choice of the appropriate PCM material depends on several factors, influenced also by the system's boundary conditions. The right material would have a suitable melting point temperature, high latent heat fusion per unit mass and high density. High thermal conductivity is essential for good heat transfer in small temperature differences and high specific heat is also desirable, in order to benefit from the sensible heat storage potential of the material (if a large temperature span, exceeding the transition zone of PCM, is used by the systems).

The following examples of PCM use in active solar (water) systems are suggested in the literature:

- For space cooling with an absorption chiller and a PCM with a melting point at:
    - 100-175°C (DINCER, I. and Rosen, M. A., 2002)
    - ~80°C (STREICHER, W. et al., 2007a)
    - >90°C (FARID, M. et al., 2004)
- For solar heating and load levelling, a PCM with a melting point at 15°-90°C (FARID, M. et al., 2004), or according to (DINCER, I. and Rosen, M. A., 2002)
    - At 60-95°C for SH with a baseboard system
    - At 55-70°C for DHW preheating
    - At 20-35°C for a solar and heat-pump combined system for SH&C.

3.6.3.3.2 PCM CATEGORIES AND THEIR CHARACTERISTICS

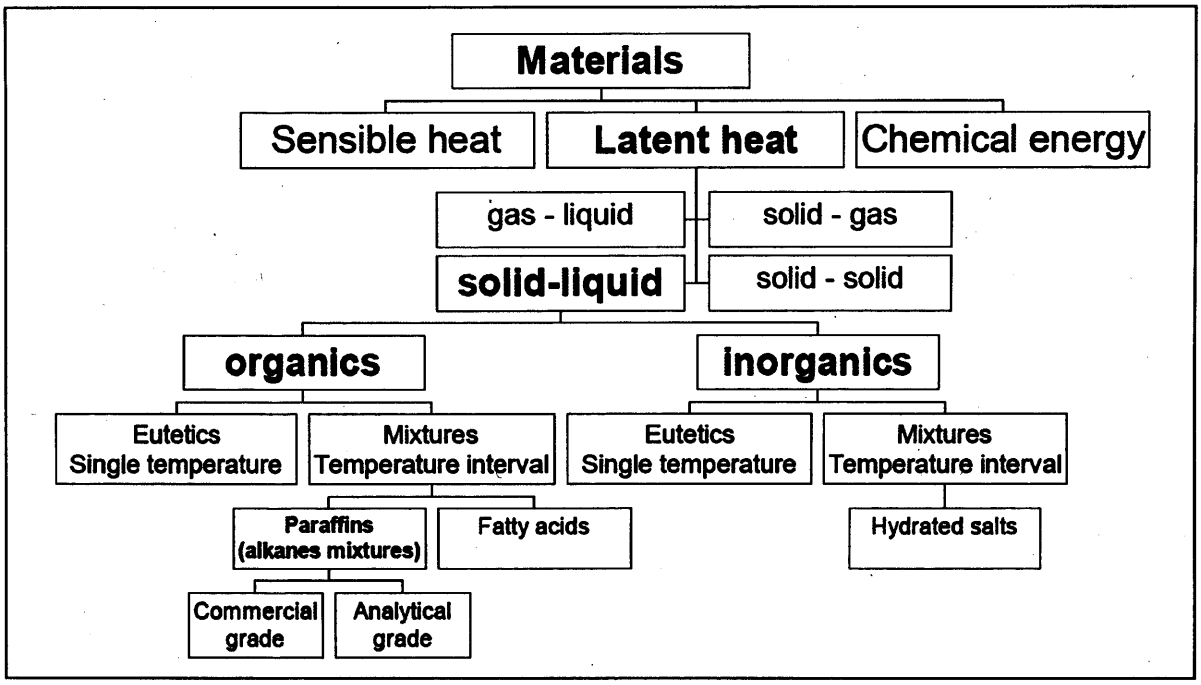

FIGURE 13: LATENT HEAT STORAGE CLASSIFICATION AMONG OTHER TES TYPES (ABHAT CITED BY (STREICHER, W. ET AL., 2007A)).

Figure 13 presents the various PCM materials' groups available for TES (Abhat, taken from (STREICHER, W. et al., 2007a)).

Tables of the PCM materials investigated by various researchers in the field and of the commercially available products have been recently prepared by the IEA SHC programme (STREICHER, W. et al., 2007a) and can be found in the Appendices (B, table 1-7). Solid-liquid PCMs are the most economically attractive type (SHARMA, A. et al., 2009) including paraffins (more popular than fatty acids other non-paraffins), hydrated salts (metallics not currently developed for TES due to weight issues), eutectics and mixtures (STREICHER, W. et al., 2007a). Salt-hydrates and paraffins have melting points in the region 0-100 °C, which make them suitable for ST domestic applications. Solid to solid[15] phase change TES applications have also shown good results regarding both heat transfer and thermal storage density but have not been pushed forward due to cost implications (FARID, M. et al., 2004). In general, technical problems associated with use of PCM for TES are:

1. Incongruent or semi-congruent melting, resulting in segregation and changes in the chemical composition of the material (and in decline of storage efficiency).

2. Supercooling: crystallization takes place at temperatures much lower than the melting point (Figure 14).

3. Low heat conductivity 0.15-0.3 W/[m.K] for organic PCMs and 0.4-0.7 W/[m.K] for salt hydrates; most PCMs in solid phase behave as insulating materials, impeding heat discharge (HASNAIN, S., 1998).

4. (Significant) volume changes at the transition phases, affecting encapsulation and heat exchanger use.

5. Chemical instability, chemical decomposition after a number of cycles, corrosiveness, flammability and toxicity.

Paraffins (only technical grade, as pure paraffins are very expensive) are considered as good candidates for ST applications (DINCER, I. and Rosen, M. A., 2002). They have a

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[15] Solid/solid phase change is the change of the crystalline structure of materials from one lattice configuration to another at a fixed temperature.

moderate heat of fusion (mean value 35-40kcal/kg according to (DINCER, I. and Rosen, M. A., 2002), and ~200kJ/kg or 150 Mj/m^3 according to (FARID, M. et al., 2004) and a higher specific heat compared to salt hydrates. They are non-toxic, non-irritant, non-corrosive, stable and chemically inert, but are subject to slow oxidization in long-term exposure in high temperatures. They give reversible cycles with a volume change at 10% (manageable), they are inexpensive and their transition zone can be adjusted. Paraffins crystallize rapidly thus presenting little or no supercooling. Regarding encapsulation, the use of metals and alloys normally comes without problems but plastic containers can be problematic.

Solutions of salt hydrates in water are regarded as the most practical types of PCM for TES (DINCER, I. and Rosen, M. A., 2002) p.141). Their hydration-dehydration process resembles thermodynamically the freeze-thaw cycle and they are therefore regarded as PCM materials (SHARMA, A. et al., 2009). They have a high volumetric heat density at ~350 MJ/m^3 and a relatively high thermal conductivity of ~0.5 W//[m.K] (FARID, M. et al., 2004). Their 'phase change' takes place with small volume changes and they are not toxic or flammable. The problem is that they lose water in the course of time and their thermal behaviour is altered; the water released in solidification is insufficient to dissolve the salt which deposits due to density difference (SHARMA, A. et al., 2009). Therefore incongruent or semi-congruent 'melting' occurs. Supercooling is another issue associated with the salt-hydrates but this is no longer regarded merely as a disadvantage (see below). They also have variable chemical stability, can be irritants and long-term degradation by chemical reactions is a common problem. Water can introduce corrosion in some salt hydrates and finding a suitable encapsulation material is a difficult task (corrosion/fatigue with metals, water loss through plastic). Pure salt hydrates' transition zones are not easily modified being around 15-65°C (DINCER, I. and Rosen, M. A., 2002) p.151).

Fatty acids have been proved to be attractive candidates for SH applications according to (FARID, M. et al., 2004) who reviewed research in this area. They have a heat of fusion at 153-182 kJ/kg and they melt congruently, thus they have recently attracted the attention of researchers. However there are cost-related issues associated with their use as TES materials as suggested in literature (DINCER, I. and Rosen, M. A., 2002), although they have also been reported as "relatively cheap" PCM candidates by some researchers (FARID, M. et al., 2004).

3.6.3.4 R&D OUTCOMES

Extensive R&D has been conducted in the area of PCMs and various solutions to the problems associated with their use in TES applications have been found. These techniques are described in the reviews cited in 3.6.3.1 (sources overlap and complement each other) and are only summarised here for completeness reasons.

To overcome the segregation problem (mostly for salt hydrates), the addition of water or other substances (e.g. gels or thickeners to hold the salt hydrate together), the use of sealed encapsulation or rough container walls have been investigated and shown to improve the performance of the final product. It has been shown that solution to the problem of supercooling is achieved either by putting the PCM in direct contact with an immiscible heat transfer fluid (agitation caused by the bubbles prevents phase segregation and enhances heat transfer), by adding nucleators, and by using rotating storage devices or internal metallic surfaces in storages. However supercooling can also be regarded as an advantage for PCM materials, introducing a losses-free TES potential. Triggering the solidification when heat is required, is the concept behind an innovative seasonal storage investigated under the IEA SHC Task 32 (SCHULTZ, J., 2008) and discussed in 3.6.3.5.2.

The low heat transfer from PCM stores is probably the most serious drawback of these technologies. Several techniques have been investigated by researchers in the area. One concept tested is the use of direct contact between the heat transfer fluid (HTF) and the PCM material. Farid et al (2004) overviewed research of this type using salts as PCM and mineral oils, varsol or hot kerosene as HTF. The results of these experimental works showed that good heat transfer rates can be achieved if suitable PCM materials are chosen. Nevertheless interest in these systems has faded in recent years, and no investigation of actual size stores and realistically long-term operation of TES systems has been carried out to reveal the actual potential of this type (FARID, M. et al., 2004).

Another method to overcome the low heat transfer rates, in indirect contact heat exchange this time, is the use of extended heat transfer surfaces. Several experiments have been performed under this concept. Some common types are: PCM in thin (aluminium, metallic) flat containers (as in plate-type HXs) or in tubes with HTF flow along or across the tube and tube-in-a-tube (concentric filling) heat exchange techniques (FARID, M. et al., 2004). Within the same concept, but stretching even further the contact surface finned elements (aluminium, copper, steel) aluminium shavings, Lessing (or Leasing) rings and others similar techniques have been proved effective (KENISARIN, M. and Mahkamov, K., 2007). Embedding the PCM material in metal matrix structures, aluminium honeycomb discs or graphite composite materials (HAILLOT, D. et al., 2008) has been also proved to work. Encapsulation (analysed below) is promoting heat transfer as well, by increasing the contact surface of the PCM with the heat transfer fluid.

Encapsulation can be implemented in two scales:

- Micro, resulting in powder-like spheres. At the moment the technique is applied only on paraffins and can be used either in pump-able slurries (R&D stage) or incorporated in construction materials (market stage) (STREICHER, W. et al., 2007a).
- Macro, with capsules being a few centimetres (usually plastic container) or larger and many times using common containers such as cans etc.

Encapsulation is employed to prevent mixing of the PCM material with the heat transfer fluid but it also assists heat transfer, working as a heat exchanger. Therefore the use a good conductor material for the encapsulation is of critical importance. However direct contact of the PCM with the heat transfer medium is also used, but this requires that the PCM presents chemical stability and solidifies in small particles.

3.6.3.5 CURRENT STATUS IN PCM APPLICATIONS

Some recent studies (KENISARIN, M. and Mahkamov, K., 2007), (ZALBA, B. et al., 2003) reviewing existing research in the area of PCM highlight that although the potential of using the latent heat of materials for TES appears to be promising, there are still problems which hinder the wide market penetration of these technologies. Cost is a serious drawback but it is not the only one. These researchers underline that a critical issue is the fact that there is no comprehensive database on PCMs and their thermo-physical properties and that research on this subject is seriously fragmented across the various research institutes. The reliability of data found in the various publications is sometimes questionable as discrepancies are often encountered and there is often lack of verification of the reported data.

Even in the case of marketed PCMs, essential data is often missing or its reliability is questionable as there are no standards or quality certificates (KENISARIN, M. and Mahkamov, K., 2007). The market of materials in suitable temperatures for domestic ST applications is generally quite limited[16]. In addition properties of fully formulated products are not easily available. It is suggested that verified properties of final products should be used when designing/sizing a TES system, as these deviate strongly from reported values of the pure PCM material because impurities and third elements in the composition of the material and the structure of the store affect its transition zone determination (DINCER, I. and Rosen, M. A., 2002) (HASNAIN, S., 1998) (also Gibbs cited by (STREICHER, W. et al., 2007a)). Differential Scanning Calorimetry (DSC) and Thermal Differential Analysis (DTA) are often suggested as suitable methods for calculating the properties of PCM materials (SHARMA, A. et al., 2009), while some researchers find these methods to be insufficient in order to produce accurate results (KENISARIN, M. and Mahkamov, K., 2007) and suggest others as more suitable, such as the T-history method (by Zhang et al, cited and compared with DSC by (GÜNTHER, E. et al., 2006)).

Kenisarin et al (2007) suggest that as there are no standards or criteria for the conductivity it is difficult to decide whether certain PCMs are appropriate for solar, or how feasible a PCM application would eventually be. Another major issue is that there is no long term experience with most of the materials and their behaviour after a large number of cycles is uncertain e.g. for >1000 cycles, (KENISARIN, M. and Mahkamov, K., 2007)) as only a limited number of cycles can be tested in the laboratories. Thus, there is a risk of material failure for both the PCM and the container.

At the moment current R&D is oriented towards two directions; investigation of materials and materials' properties and heat transfer. Several researchers appear to be enthusiastic about the advantages of the PCM use. The solutions presented in 3.6.3.4 have brought improvements in the properties and behaviour of PCM materials.

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[16] Popular companies in the market are Cristopia, Rubitherm Gmbh, BASF, TEAP, Climator and Mitsubishi Chemical, EPS Ltd and Pluss Polymers Pvt Ltd.

Combinations of the above mentioned techniques have been tested and researchers are often reporting success regarding some of these aspects, e.g. behaviour of the material after a certain number of cycles and heat transfer rates. In spite of these achievements there are still unresolved issues with these technologies. In general the additives increase the cost of the final product making PCM applications attractive for research and demonstration projects only. But more critically the use of third elements or substances decreases the storage efficiency of the final product as it reduces the concentration of PCM on the overall store. This was one of the most important conclusions of the investigations conducted under the Subtask C of Task 32 of the IEA SHC programme.

In Subtask C the state-of-the-art of PCM storage applications for solar heating and cooling of individual or small groups of low energy houses (<100kWh/m^2 for Zurich specific demands only) were reviewed, potentials were firstly identified and a number of innovative techniques were then assessed with laboratory prototypes and computer simulations. The work has been published in the handbook of the Task (HADORN, J., 2005) and in project reports. Five projects with the use of PCM as a storage medium were tested; three projects using macro-encapsulated PCM modules immersed in water tanks, one using PCM-slurries for load-smoothing in conventional boilers and one innovative seasonal storage using the supercooling effect of a PCM material. These projects aimed to shed some light on the potential contribution of a selection of PCM storage types and to produce validated computer tools for simulating the thermal behaviour of these technologies, as such tools were lacking when the Task initiated. Thus prototype concepts and validated simulation models for use with the simulation engine TRNSYS were developed within the subtask. It has to be noted that several well-established researchers and institutes in the area of PCM have participated in this subtask, making it the only case where international expertise on latent heat storage has cooperated on identifying the real potential of the technologies for increasing the share of ST and other low-carbon energy sources. The results are summarised in the next two sections. In general the benefits of PCM are higher in small temperature ranges. In Task 32 it was found that the benefits of a PCM store exist in the case when a ΔT of 20°C with a bulk PCM storage and an immersed heat exchanger are used. In this case 1/3 volume reduction is possible. It was concluded through the Task though, that the advantages are lessened in solar combisystems where the temperature lift is ~50-65 °C and therefore the effect on the store volume reduction is negligible.

Application of PCM materials incorporated in structural elements such as walls (QUANYING, Y. et al., 2008), window curtains (ISMAIL, K. and Henriquez, J., 2001), insulation boards (J., K. et al., 2006)(KONDO, T. and Iwamoto, S., 2006), with integration in materials such as gypsum (FELDMAN, D. et al., 1995), concrete (CASTELLON, C. et al., 2006) etc. have attracted attention the last years. TES technologies integrated in the building envelope have been investigated since 1975 [Barkmann et al, as mentioned by (ZALBA, B. et al., 2003)]. Commercially available products exist, such as the product DuPont Energain (DUPONT, 2008) which was used in the prototype building Sigma Home by Stewart Milne Group in the BRE Innovation Park, Garston UK. The panels contain a copolymer and paraffin wax compound with a melting temperature of 22 °C. In the evening, when the temperature reaches 18 °C, the material solidifies discharging the heat stored during the day. The use of these panels brings additional thermal mass in structures with low thermal inertia, smoothing the temperature variation indoors: slowing down the temperature rise by as much as 7 °C (cooling effect) and releasing the useful heat at night when it is required. The use of a mechanical ventilation system is required for the proper charge/discharge of the PCM panel. These innovative applications are not of direct interest here as are passive means of storing energy. Other applications of PCM, which are of general interest but are not included here, are the incorporation of materials in mechanical ventilation systems (ARKAR, C. and Medved, S., 2007) (STRITIH, U. and Novak, P., 2002) or air-conditioning systems (VELRAJ, R. and Pasupathy, A., 2006), or in the structure of solar collectors (METTAWEE, E. and Assassa, G., 2006).

3.6.3.5.1 PCM IN WATER TANKS AND PCM SLURRIES

Two out of the five projects of Subtask C investigate the use of a short-term storage using macro-encapsulated PCM (Sodium Acetate Tri-hydrate (SAT) and graphite) immersed into a water tank, for ST applications. One of these two projects took place in the University of Lleida and the other in the University of Applied Sciences of Western Switzerland.

Two systems were investigated at the University of Lleida in comparison to a conventional water tank (SOLÉ, C. and Cabeza, L. F., 2008). The first had the coil heat exchanger found immersed in the middle of the tank filled with PCM material and had three additional aluminium bottles of PCM immersed in the tank volume. The second had only aluminium bottles immersed in the tank. The water tank had no integral burner. With a temperature lift from 24°C to 65°C, the PCM-graphite composite demonstrated improved performance both at charging and discharging of the store. A stratifying inlet was used in the tank and the existence of PCM in the store was proved not to disturb stratification. Only charging-discharging tests were performed in that case.

At the experiment that took place at the University Of Applied Sciences Of Western Switzerland (HEIG-VD) the water tank includes an integral burner. Due to lack of available space (volume occupied by burner and the two heat exchanger) and the fact that the immersed bottles (102 in total, 40% with paraffin, 60% with SAT) are not entirely filled to allow for expansion of the material at phase change, a maximum concentration of 15% of the PCM on the entire store volume was achieved. This PCM-water store was compared to a situation where the bottles were filled with water. The tests were actually two 7-day testing sequences, with two extreme weather conditions used, to meet the SH and DHW demands for a single family house. The temperature lift in this case varied was between 25°C to 85°C. For the DHW demand the PCM performed worse (higher specific power required) than the water-only tank due to the lower heat transfer rates and therefore the auxiliary boiler had to switch on more often. In the SH tests it was concluded that no significant improvement is achieved with the use of the PCM (again due to low concentration). This experiment was conducted mainly to provide validation to the recently developed TRNSYS component type 860 (C5). (CITHERLET, S. and Bony, J., 2007).

The outcomes of these tests showed that PCM integration in water tanks brings little or no benefit to TES techniques and therefore water tanks are still the state-of-the- art for ST applications. At the institute of Thermal Engineering at the Graz University in Austria, some tests for reducing the cycles of the operation of boilers were performed. Water tanks, water tanks with macro-encapsulated PCMs (50-75% concentration) and bulk PCM storages were tested showing that there is some improvement caused by the use of the PCM. Nevertheless this improvement in comparison to the performance of simple water stores is not significant and the carbon emissions saved are not enough to justify the costs of the system (HEINZ, A., 2007). At the same institute two systems using stores with PCM slurries were also tested. Both direct/indirect strategies for charging/discharging the stores were assessed. The results showed that the performance of the store was poor showing little improvement compared to water tanks, while presenting serious disadvantages such as low latent heat capacity, and problems with separation and blocking tubes (STREICHER, W. et al., 2007b).

3.6.3.5.2 AN INNOVATIVE PCM SEASONAL STORAGE WITH LOW VOLUME

The effect of super-cooling can been seen both as an advantage or a disadvantage for a PCM thermal energy store. For a PCM material presenting the so-called "stable supercooling", the effect shown in Figure 14 (STREICHER, W. et al., 2007b) is observed. In the charging mode, as the PCM heats up, it undergoes a phase change at its melting point, but when it cools down it passes the melting point without being solidified, maintaining the energy stored at melting. In the context of Task 32 of the IEA SHC program the potential of using the super-cooling characteristic of a PCM material to achieve seasonal storing of solar energy was investigated.

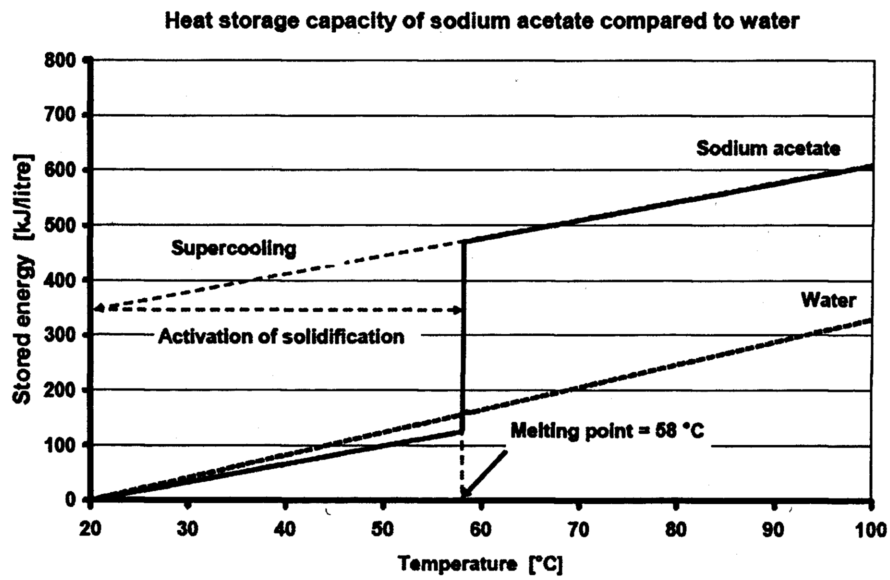

Figure 2.1.1 Diagram showing the heat storage capacity of sodium acetate trihydrate compared to water and the supercooling effect.

FIGURE 14: THE STABLE SUPERCOOLING OF SODIUM ACETATE TRIHYDRATE. (SCHULTZ, J., 2008)

The focus was on meeting solely with solar energy the SH and DHW demand of a $135m^2$ house in Copenhagen built with the passive house standards (NSH at only $15kWh/m^2$ per annum, temperature lift from 35°C to 70°C). It was found that although with traditional water tanks it would be impossible to reach more than 80-90% SFs, even with storages larger than $20m^3$, it was feasible to reach a higher solar fraction with the use of a 10 m^3 (or 6 m^3 with heat-recovery) storage system making use of $Na(CH_3COO)\cdot 3H_2O$, Sodium Acetate Tri-hydrate (SAT)[17]) (SCHULTZ, J., 2008). Published work describes the findings resulting from a small scale laboratory facility (STREICHER, W. et al., 2007b) and the full system predictions using the TRNSYS simulation software (STREICHER, W. et al., 2008b). A component compatible with the TRNSYS engine (type 185) was built in this subtask to simulate the store and has been validated against laboratory measurements (STREICHER, W. et al., 2008b). Optimization of the complete system has not been performed and validation of the system built in TRNSYS was not possible as storage at an actual-scale has not been built yet. All the work was carried out by the Department of Civil Engineering, Technical University of Denmark (DTU).

For the tests performed at the DTU the SAT was chosen as it melts at a convenient temperature for residential applications (58 °C). One of the aims of this work was to provide answers to a series of questions before attempting a full scale experimental application:

- Aspects of handling of the liquid SAT when melted or super-cooled
- Observe the characteristics of super-cooling
- Methods of activating the solidification on demand
- Heat transfer performance to and from the PCM
- Insulation requirement for the store

At the beginning the thermal behaviour of SAT was investigated. Melting of 150 litres of SAT was performed with the use of a mantled stainless steel tank, by circulating hot

[17] Cost of material estimated at 1€/kg in report C3.

water through the mantle and by mixing the liquid of the PCM to avoid sediment production. It was found that the SAT has the ability of stable super-cooling. It was known from previous work that the water content in the solution is critical and that it has to be a bit more than 40%. Filling bags with melted SAT could be done without problems, but when liquid super-cooled SAT was exposed to the air, solidification was observed due to evaporation. It was therefore concluded that handling of the super-cooled SAT requires sealed conditions. For the activation of solidification three methods were tested: ultrasound, local heating or mechanical. The latter, which was performed with a piston injected into the salt with the use of an electromagnet, was found to be the most effective.

At the next stage, 3 bags filled with SAT were used in the small scale laboratory prototype. The bags were made from laminate plastic foil to minimise the parasitic thermal capacity and to allow for contraction and expansion of the material. They provided a cheap solution (compared to stainless steel) which is resistant at 100°C and eliminate the problem of water evaporation when filling with SAT, as the bags contain very little air when empty (deflated). The prototype storage consists of 7 subsections, as the idea behind this seasonal storage is to discharge a few parts of the SAT at a time, in order to meet the demand (not activating the total super-cooled PCM at once). Four bags containing water and the 3 bags filled with SAT were positioned alternately on top of each other and were independently controlled. This prototype was built in order to investigate a few aspects of the storage medium, but it is not large enough to be representative of a final product.

To assess the performance of a complete solar system with adequate PCM storage to meet 100% of the thermal requirement with solar energy, simulations were carried out. The system consisted of the solar loop and the load loop which were linked with the storage and the heat exchanger. Apart from the inter-seasonal PCM storage, a 180 litres water tank which serves the DHW requirement was included in the system (the PCM storage is not used for the DHW needs). The PCM storage was made of subsections which are independently controlled. A low temperature heating system (under floor system or radiators) with a fixed return temperature (25 °C) was considered. An auxiliary heater was included in case of extreme weather conditions or system failure. Pipes between collector and storage were not simulated. The pump at the collector starts if the temperature of the collector is higher than either the minimum temperature of the PCM subsections, or the minimum temperature of the DHW water tank or the return temperature of the space heating loop. The priorities for the available solar energy in that case are:

1. First serve the space heating demand, then
2. Heat up the DHW tank up to 50°C
3. Charge one by one the subsections of the PCM store. Full melting if possible, otherwise up to the maximum obtainable temperature
4. Heat up the DHW tank up to 70°C

The pump stops if:

- The temperature at the collector output is lower than, either the minimum temperature of the PCM subsections, or the minimum temperature of the DHW water tank, or the return temperature of the SH loop
- If the temperature of the DHW tank is 70 °C and of the PCM subsections 90°C.

The results of the parametric study show:

If the collector is increased from 18-36 m^2 then the required storage volume for 100%SF is reduced from 23m^3 to 10 m^3. It was also found that the smaller the subsections of the PCM storage the better, with a limit at around 0.25 m^3, as there is no difference if they are between 0.1-0.25 m^3. But if the subsection volume increases from 0.25 m^3 to 0.5 m^3 the volume of the PCM storage increases from 10 m^3 to 12 m^3. Heat loss was proven to be important, even in the PCM storage. If the heat loss coefficient decreases from 0.6 W/ [m2.K] to 0.4 W/ [m2.K] the store volume can decrease from 10m^3 to 8m^3. If the heat can be recovered to serve part of the SH demand, the results are further improved.

Further computer simulations with TRNSYS allowed for comparisons between this innovative TES approach and a simple water store of identical size and construction. The same system configuration described above was used to asses the performance of a water store replacing the SAT store. In this case the new component that was built within Task 32 for modelling of the SAT store was used to simulate a purely water store; the subsection concept provided a perfect stratification strategy for water. The simulations showed that, in contrast to the store using the SAT, the use of a water store would not bring SF close to 100%, even with very large TES volumes (>20m³). It is still required for this finding to be validated against real data (actual size installations) but the computer modelling reveals that a potential for 100% solar-heated houses with reasonably sized TES components arises with this innovative TES approach.

3.6.4 SORPTION, THERMO-CHEMICAL STORAGE AND STORAGE IN CHEMICAL REACTIONS

Figure 15 (HADORN, J., 2005) presents the classification of types of thermal energy storing with chemical and thermo-chemical processes. These technologies are new for ST systems and some of them are believed to represent the future of thermal energy storing (HADORN, J., 2005). The high theoretical energy density of these materials and processes and the theoretical indefinite energy holding potential that is held with these methods suggest that one day these methods will replace sensible and latent heat storage.

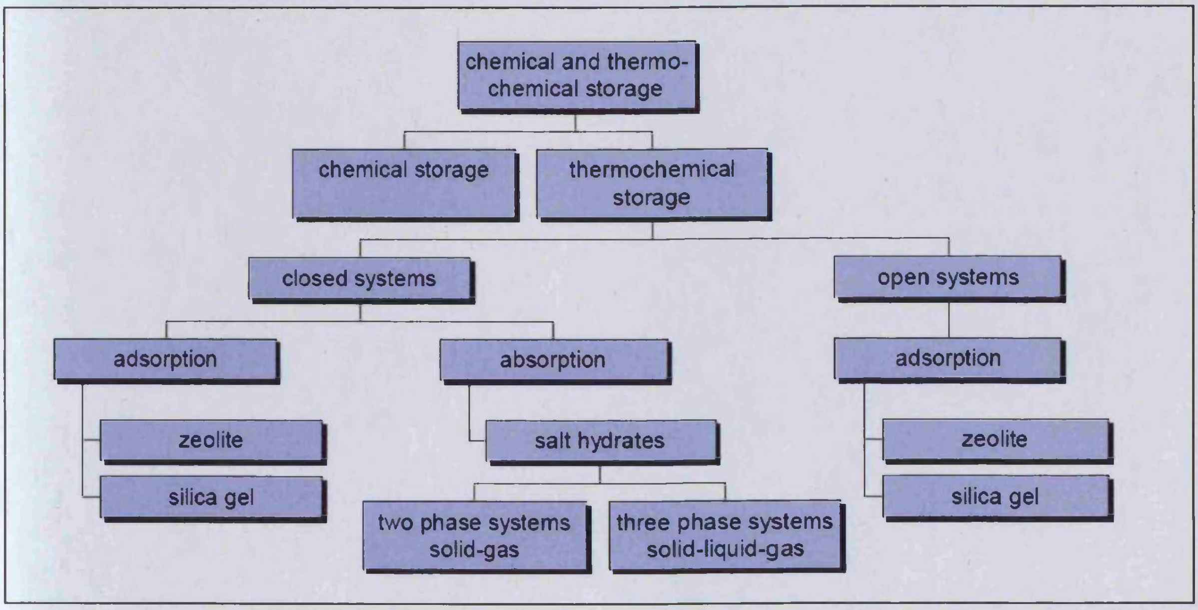

FIGURE 15: CLASSIFICATION OF CHEMICAL AND THERMO-CHEMICAL PROCESSES FOR HEAT STORAGE APPLICATIONS (BALES, C. ET AL., 2005).

Nevertheless at the moment there are lots of barriers to the uptake of the technologies e.g. high costs, lower energy densities of actual systems compared to the theoretical potential, high charging temperatures etc (BALES, C. et al., 2005), (BALES, C. et al., 2008). These systems are still either in demonstration or development phase and are not yet ready for market distribution. New materials with suitable properties need to be investigated and R&D regarding efficiency and reliability of these technologies is still required. Up to now in thermo-chemistry emphasis was given to high temperature processes which are not used in ST domestic applications. The subtask B of the IEA SHC Task 32 was devoted to these thermo-chemical processes which can be used as TES types in domestic ST applications. There are many ways of converting solar energy to chemical energy. According to the photo-thermo-chemical concept solar energy is transformed first into heat (through the collectors) and then evokes an endothermic chemical reaction, which can later be inversed (exothermic reaction) to release the stored energy. On the other hand, the photo-chemical concept describes in general the processes when sunlight is converted to chemical energy without the thermal conversion step. Examples of this type are the production of electricity, biomass (photosynthesis) or hydrogen (BERKEL, J. V., 2005). This last type is chemical storage and is not of interest here.

The thermo-chemical storage is indirect energy storage; the systems are *"thermally charged and discharged"* (DINCER, I. and Rosen, M. A., 2002) via reversible chemical reactions or processes like absorption or adsorption. The underlying principle of these types is that a sorption material "releases water vapour when heated and heat when water vapour is adsorbed or absorbed" (BALES, C. et al., 2005). These systems which can be open or closed -in the sense that exchange with the ambient is permitted or not- are actually chemical heat pumps.

In Task 32 five prototypes of sorption storages were tested in laboratories. The outcome of this assessment revealed that although some of the systems appear to be promising, there is still only minor advantage in their use compared to conventional TES and their high cost remains a serious drawback. Most of the TES prototypes achieved lower energy densities than expected, due to the fact that space is taken by reactors, condensers/evaporators, HXs and other components which are required for the operation of the system. This problem is more apparent in small stores than in larger stores. In addition charge and discharge temperatures are not identical and therefore a sensible heat load is also involved in the process. This causes some irreversibility in the thermo-chemical processes which causes energy losses. Due to these reasons, the potential identified for short term storage appears to not be highly competitive to water stores operating with a ΔT of 65°C. In addition further work regarding materials is required as some materials which are measured with high energy densities proved not to work as well in prototypes (BALES, C. et al., 2008). Cost is also a major issue for large storages.

However some promising systems and products have been developed within the last few years. A simple open sorption system protype called *Monosorp* which was also tested under Task 32 was proved to be one of the most advantageous concepts of this selection. Incorporated in the ventilation system, it uses the wet ambient air to drive the adsorption process in the honeycomb-structured-bed of zeolite and the released heat is then available for the SH needs. The temperature lift in the air stream of the ventilation system is in the range of 15-25°C and during the discharge of the store the solar combisystem operates independently and heats up the radiators. To charge the store at the reverse mode, temperatures at 160°C are required, and therefore only high quality VT collectors are suitable for this system. At the laboratory test the *Monosorp* appeared to be an effective short-term store (70kWh capacity) achieving an energy density twice that of water (KERSKES, H. and Asenbeck, S., 2008). In addition a chemical heat pump has recently become available in the market by a Swedish company called *ClimateWell*. A number of projects using this product have been realised in Spain and feedback of its use is anticipated in the following years (BALES, C. et al., 2008).

3.7 CONCLUSIONS OF THE LITERATURE REVIEW

To put the research into context, this chapter analysed first the politics of ST around the world. The fact that the UK is amongst the weakest countries in ST in Europe is no news. However several lessons for ST dissemination can be learnt from other countries. First of all, as it is shown with the example of China, where a large number of VT collectors is installed, the current high cost of ST systems cannot stand as a constraining argument for their further development, as economics of scale are always possible. It was also seen with this overview that the European ST map is now changing, with new countries developing a ST market. In addition, the ST spread around Europe is strongly dependent on the existence of fiscal incentives and support mechanisms and is apparently less affected by the climate, as suggested by the ST capacity of Austria –comparable to that of Greece- and the poor ST capacities of 'sunny' countries such as Italy and Portugal. Therefore, whereas people believe that there is insufficient solar energy in the UK for ST applications that would be energetically and economically justifiable, UK can be considered from a climatic point of view as good a candidate for ST as Denmark or Germany. Denmark, which has a similar 'radiation income' as the UK, has the 4th highest accumulative ST capacity in Europe, and its newly installed capacity in 2007 was 35% of the overall European. Therefore there is definitely an unexploited ST potential in the UK, comparable to the one already achieved in these countries and which is not even saturated there.

It is unfortunate that the ST statistics for the UK are found to be unreliable, as useful feedback cannot be returned from these numbers. As highlighted from the review a potential ST promotion strategy should always take into account experience gained not only abroad but within the country as well, as e.g. bad practice and lack of supporting mechanisms were the major reasons for the decline of ST applications after 1983. On the other hand the considerable exportation of ST products manufactured in the UK in the last three decades, to countries such as Germany, the strongest player of ST in Europe, could stand as a strong argument for the exploitation of ST technologies in the UK. Influenced from its European neighbours, the UK has also recently introduced some basic incentives for ST applications, such as exclusion from planning permission requirements, a reduced VAT rate at 5% and small grants.

Further to the discussion about policies and statistics regarding ST the review also dealt with the technical aspects of ST technologies. Nevertheless the characteristics of the individual ST components were not analysed in this thesis as this subject is extensively covered in the literature. The interest was in the operational experience and performance of recent ST applications as well as in basic rules of thumb for ST systems dimensioning. It was revealed from the analysis of the bibliographic sources that the technology is quite mature and one can design for a low or high SF. Usually the higher the SF of the system, the lower the degree of utilisation and the higher the cost of solar heat achieved (and vice versa). There are highly efficient applications but these are not only dependent on the quality of the products, as is the case with fossil fuel-driven systems. It is the correct system sizing, the choice of components, the tuning and design of the overall installation that determine how effectively the solar energy incident on the collectors will be delivered to the demand-side. As it is explained in the literature the performance of a ST installation depends strongly on the climate, the building characteristics, the choice of the solar combisystem and its components. There is a parasitic auxiliary load resulting from pumps and controls and this should always be dealt with.

It was therefore found that a prerequisite of a good system design is the accurate prediction of the energy demand profiles that the system is supposed to meet. Within the same house typology the specific SH demands could fluctuate with a factor of 2, a fact altering the economics and performance of the ST installation. This finding underlined the importance of modelling the building in a realistic way. Nevertheless it is common in ST simulations for the building description to suffer from major simplifications and it appears that little knowledge is available on detailed simulation of buildings in this field. Even in most of the simulations conducted for the purposes of the IEA SHC Tasks the house model is usually described by one zone, given a constant occupancy throughout the year. Existing tools, well established as able to handle with the dynamic aspects of ST system simulations, have the building component neglected compared to the other parts of the system, with either a poor or 'unfriendly' user interface. In addition to that, the quality and type of the weather data used in the simulations is of critical importance too. The performance of the solar collector or the annual utilised solar energy can only be predicted based on the incident total solar radiation on the collector plane. Sizing of a ST system with making use of monthly values for solar energy or monthly loads is bad practice and hourly or smaller time-steps are required for this purpose. Weather variations between years would also affect the system's performance. It therefore became clear through the review that for the purposes of this work both the building component and the climatic environment should be simulated with sufficient detail to introduce confidence to the conclusions drawn at the end.

On the other hand it was revealed that the prediction of the real performance of an actual combisystem is a very difficult task although a rough evaluation is very easy to achieve. To deal with the complexities of the solar combisystem modelling and to introduce more detailed building representations in interaction with the solar part of the model, the use of simulation engines such as TRNSYS is required. Experience with such simulation programs has reported a steep learning curve and the modelling procedure is found to be time consuming. TRNSYS appeared to be the most appropriate choice for this subject, considering also that detailed ST system simulations were the initial intention of this research work. Furthermore it became clear with the survey that the wide variety of ST components and systems available in the market guarantees that no region is excluded from efficient ST applications and that the current ST systems can harvest 30-60% of the energy falling on the collectors. However it was revealed that there are no optimum solutions and the quality of the systems is strongly dependent on the project and the desirable aims. Therefore to be able to quantify the contribution of ST technologies to energy savings in Welsh housing, a range of potential ST systems should be considered, rather than a ready-made solution for all house types. For this reason the review focused on relevant publications of collaborative work organised within the IEA SHC programme, mainly those of Task 26 and the method established to allow inter-comparison of systems which are different from each other. With the established FSC method the performance of a solar combisystem can be adequately expressed by a quadratic equation which relates the actual system performance to the theoretical potential derived only by the building and the location. If this relation has been derived by monitoring or simulations for a particular system then the performance of the system in other contexts e.g. location and building envelope can be easily estimated with relative accuracy and more importantly can be compared to that of other solar combisystems that have been characterised using the same method. In particular in Task 26 the performance characteristics of nine typical European solar combisystems have become available and were therefore considered for use in this PhD work.

The last section of the literature review focused on established knowledge on TES technologies. The outcomes of the survey showed that at present, in domestic active ST water-based systems the most common TES type used are the water tanks. Water has many advantages compared to other materials suitable for sensible heat storage. The technology has been used for many decades and is mature. Due to the importance of stratification in the overall system efficiency lots of R&D work has been focusing on testing various methods and techniques for creating effective thermal gradients during charging/discharging of water tanks. Nevertheless high capacity water tanks occupy large volumes and heights. The Welsh housing stock is characterised by small room volumes and very rarely volume would not be a problem when ST with TES are to be implemented. To identify potential solutions/alternatives to this type an extensive review of innovative TES types was also conducted.

The use of Phase Change Materials (PCMs) for storing thermal energy has the advantage of high storing capacities at small temperature changes. In applications operating at a large temperature range the sensible heat is dominant and therefore the advantages of the use of a PCM are weak. As the survey revealed, cost is a serious drawback for latent heat storage technologies but it is not the only one. At the moment there is no comprehensive database on PCMs and their thermo-physical properties and research on this subject is seriously fragmented across various research institutes. The reliability of data found in the various publications is sometimes questionable as discrepancies are often encountered and there is often lack of verification of the reported information. Even for marketed PCMs essential data is often missing or its reliability is questionable as there are no standards or quality certificates. Although researchers in the area have presented great advances in the use of PCM for TES and the potential of using the latent heat of materials for TES appears to be promising, work in Task 32 of the IEA SHC, showed that integration of macro-encapsulated PCMs in water tanks brings little benefit to TES techniques. It was proved with the tests performed in the above task that there is an improvement caused by the use of the PCM, but this is not significant in comparison to simple water stores. Additionally the carbon emission savings are not enough to justify the costs of the system. Similar were the findings about PCM slurries which also behaved poorly with regards to the pump-ability and the latent heat capacity. Further work is still required in this area before highly attractive solutions become available in the market.

On the other hand, advantageous use of super-cooling of a PCM material was proved feasible in the Task, revealing an inter-seasonal storing potential. It was found that although with traditional water tanks it would be impossible to reach more than 80-90% SFs, even with storages larger than 20m^3, with the use of a 10 m^3 (or 6 m^3 with heat-recovery) storage system making use of a particular PCM it was feasible to reach a higher SF, up to 100%. Nevertheless further testing and development of this TES type is still required to turn it to a reliable solution. In addition, thermo-chemical energy storage could be the future of TES, but at the moment there are lots of barriers to the uptake of the technologies e.g. high costs, lower energy densities of actual systems compared to the theoretical potential, high charging temperatures etc. These systems are still either in demonstration or development phase and are not yet ready for market distribution. New materials with suitable properties need to be investigated and R&D regarding efficiency and reliability of these technologies is still required.

Concluding on the findings of the TES survey, it appears that a range of available technologies for heat storage exist at an R&D level. Many of these technologies are expected to be further optimised and reach the market within the near future. The choice of the appropriate TES technique for a particular ST installation would be strongly influenced by the required storage duration (for hours, days or seasonally) as this would determine the desired characteristics for the store. Nevertheless one of the main conclusions of this survey was that at this moment of time the technology of water stores is not only the most popular and economically attractive solution for residential applications of TES, but it is also the state-of-the-art TES type for this purpose. As in this research the ST potential for the Welsh housing is investigated under current conditions, only TES technologies which are mature and have been proved to work effectively in ST applications could be considered at this stage. Therefore sensible heat storage using water as the store medium is the TES type used in the following analyses.

4 MODELLING OF 12 REPRESENTATIVE WELSH DWELLINGS

In this study, as explained in the methodology, the Welsh housing stock was described by 12 typical case studies, considered as representative of 50% of the Welsh Housing stock. These twelve dwellings were modelled with the use of both the Ecotect and TRNSYS simulation programs.

This chapter discusses the input and the modelling procedure used in the building simulations of this work. The focus here is on the building which the solar installation is designed for, as in current practice this part of the system model is usually neglected. The literature survey highlighted that accurate prediction of the demands to be met by a solar system is an important prerequisite for a good system design and for reliable predictions. As mentioned before, previous research in the area explains that an oversized system would add excessive costs on the delivered solar energy, without necessarily providing higher SF (see section 3.4.2.1).

The problem is that in any simulation only aspects of the reality are incorporated in the model and the modeller's choices will determine whether the simulated environment is representative or not for the particular research context. The following paragraphs present the input of the 12 house models and describe the rationale behind the choices made.

4.1 SOFTWARE: ECOTECT AND TRNSYS

For the simulations conducted in this study, the software package TRNSYS (version 16.01.0003) is used (TRNSYS, 2007). The software has a modular structure with a main visual interface known as the TRNSYS Simulation Studio. The idea behind its modular structure is that any complex problem can be broken down into smaller components (parts of the entire system) and new models created by users can be easily incorporated in the simulations.

TRNBuild is both the interface for the multizone building component (called type 56) and the pre-processor that simplifies the modelling procedure for the building by creating a file that sets out the input and output data required for its description. The fundamentals of the multizone building model are based on a thesis by Seem (SEEM, J., 1987). 'Type 56' is a non geometric balance model that uses one air-node per zone to represent the thermal capacities of the air-volume and the quantities that are closely connected to it (such as the furniture or internal partitions). The model works out the thermal balance at each node, breaking it down into three parts i.e. convection, radiation and coupling with other zones. The walls are modelled according to the transfer function relationships of Mitalas and Arseneault (MITALAS, G. P. and Arseneault, J. G.). The level of detail of type 56 building model, which makes it compliant to the ASHRAE standard (see also 3.5.1), is also enhanced by its ability to read detailed window data from the WINDOW 4.1 program developed by the Lawrence Berkeley Laboratory (WINDOW_4.1, 1994). Type 56 computes the interaction of the various modelled zones with the use of coupled differential equations. TRNSYS solves the system of algebraic and differential equations that represent the whole system instantaneously with the building envelope thermal balance and air network.

Ecotect (AUTODESK, I., 2008) was used at the beginning of this research to identify some general trends on this subject (AMPATZI, E. and Knight, I., 2007) as the author is an experienced user of the software. It is appreciated that the admittance method, used to calculate the thermal model in Ecotect, is a simplified calculation with well-known limitations (REES, S. J. et al., 2000) and the software is more likely to be used in the design process as a tool of comparing alternative strategies, rather than providing accurate predictions. In addition Ecotect does not model complete ST systems and the smallest timestep for the output is that of an hour. Therefore it was decided that TRNSYS (validated for purpose) will be used for the dynamic simulations, since it is also widely adopted by the ST research community, e.g. IEA SHC programme.

Nevertheless Ecotect provides a user-friendly 3D interface, suitable for architects and designers. In order to model accurately the complex geometry of the 12 dwellings in TRNbuild a 3D model is required. In TRNbuild the model is broken down in zones and each zone is composed of a number of surfaces. Each surface (generally called 'wall', but can be also a floor or a ceiling) is not defined by coordinates but is described as an internal, external, boundary or adjacent element and then it is further given an area, orientation (if external), materials etc. When modelling real buildings, adding this information in TRNbuild can be time-consuming and it requires a good knowledge and understanding of the 3D geometry. Therefore it was decided that Ecotect would be used as a front-end for the modelling in TRNSYS. As there is no direct way to export the geometry information from Ecotect to TRNbuild, a spreadsheet was built to store all the elements' attributes (zone name, surface area, type of element etc) per house type to facilitate the modelling in TRNbuild. An example of the content of such a file is shown in Table 6. This file is enriched in the process by other kind of modelling information and is used as an archive for the entire model. The dwellings are simulated with the accuracy shown in Figure 16.

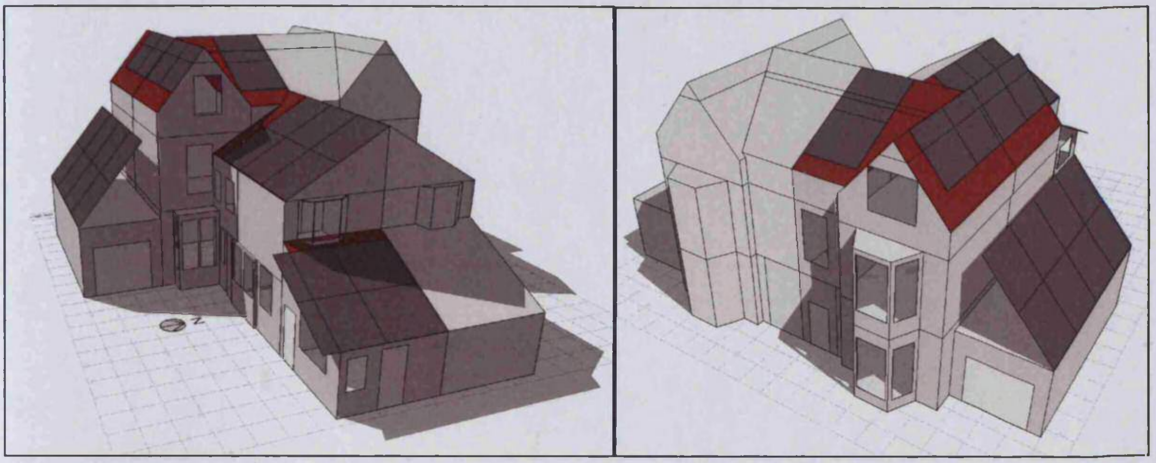

FIGURE 16:TWO OPEN GL VIEWS OF THE 1850-1919 SEMI DETACHED HOUSE (NO#3) TAKEN FROM THE ECOTECT MODEL.

As discussed also in 2.1the detailed representation of the building models in this case is critical, as the liability of the final results and the conclusions to be drawn from them will depend on the accuracy of the demands to be met by the solar system. The use of the multizone building model in TRNSYS instead of a single-zone, simplified model is justified by the fact that the simplified representation will not be able to predict a realistic demand profile in each case and the assessment of the ST systems' applicability will be therefore constrained. More specifically, a single zone, constantly occupied building model would fail to predict the peaks and troughs of the heating system needs that in reality would coincide with the variations on the occupancy and appliance use throughout the day, the solar gains admitted by the windows of the differently oriented rooms etc. This effect is discussed later along with the results in 5.5.3. Furthermore the detailed modelling approach is employed in this study for one more (secondary) reason. Although the overall energy demands are assessed here against the solar availability per house type, it is the intention of the author of this work to use, at a post-doctoral level, the same models for further analyses which would require the use of the outputs from individual zones e.g. to examine the use of the ST and the auxiliary system selectively and by turns between the various rooms and compare that against a whole-house strategy.

TABLE 6: EXAMPLE OF THE CONTENTS OF THE *.XLS FILES THAT STORE THE INPUT OF THE MODELS' GEOMETRY AND MATERIALS.

Zone where element belongs to	Category	Adjacent to zone....	Front or back	including windows (m^2)	Window Area (m^2)	Orientation	Plane number*	Wall type	Material	Zone volume m^3
KITCHEN	EXTERNAL	NA	NA	8.76	2.02	WEST	1	WALL	PRE1850FLAT_SS600	41.61
KITCHEN	EXTERNAL	NA	NA	9.27	0	SOUTH	2	WALL	PRE1850FLAT_SB300	
KITCHEN	ADJACENT	CORRIDOR	BACK	11.85	NA	NA	3	WALL	PRE1850FLAT_INTWALL	
KITCHEN	ADJACENT	BEDROOM1	FRONT	8.76	NA	NA	4	WALL	PRE1850FLAT_INTWALL	
KITCHEN	ADJACENT	CORRIDOR	FRONT	4.02	NA	NA	5	FLOOR	PRE1850FLAT_FFLOOR	
KITCHEN	ADJACENT	GROUNDFLOOR	FRONT	13.00	NA	NA	5	FLOOR	PRE1850FLAT_FFLOOR	
KITCHEN	ADJACENT	ROOF1	BACK	13.22	NA	NA	6	CEILING	PRE1850FLAT_CEILING	
KITCHEN	EXTERNAL	NA	NA	4.59	0	SOUTH_34 VIEW FAC: 0.81	6	ROOF	PRE1850FLAT_ROOF	
LOUNGEDINING	EXTERNAL	NA	NA	8.90	2.43	WEST	1	WALL	PRE1850FLAT_SB250	75.83
LOUNGEDINING	EXTERNAL	NA	NA	12.95	0	SOUTH	2	WALL	PRE1850FLAT_SS530	
LOUNGEDINING	EXTERNAL	NA	NA	2.40	0	EAST	3	WALL	PRE1850FLAT_SS530	
LOUNGEDINING	BOUNDARY.	NA	NA	12.95	NA	NA	4	WALL	PRE1850FLAT_SS500_b	
LOUNGEDINING	ADJACENT	BEDROOM2	BACK	1.26	NA	NA	8	ROOF	PRE1850FLAT_SB115	
LOUNGEDINING	ADJACENT	BEDROOM2	BACK	7.14	NA	NA	3	WALL	PRE1850FLAT_SB115	
LOUNGEDINING	ADJACENT	CORRIDOR	BACK	0.36	NA	NA	8	ROOF	PRE1850FLAT_SB115	
LOUNGEDINING	ADJACENT	CORRIDOR	BACK	2.14	NA	NA	3	WALL	PRE1850FLAT_SB115	
LOUNGEDINING	ADJACENT	GROUNDFLOOR	FRONT	32.35	NA	NA	5	FLOOR	PRE1850FLAT_FFLOOR	
LOUNGEDINING	ADJACENT	ROOF1	BACK	0.56	NA	NA	8	ROOF	PRE1850FLAT_SB115	
LOUNGEDINING	ADJACENT	ROOF2	BACK	24.87	NA	NA	6	CEILING	PRE1850FLAT_CEIL2	
LOUNGEDINING	EXTERNAL	NA	NA	7.31	NA	WEST (46 from horizontal, view fac: 0.74)	7	ROOF	PRE1850FLAT_ROOF	
LOUNGEDINING	EXTERNAL	NA	NA	1.28	NA	EAST (46 from horizontal, view fac: 0.74)	8	ROOF	PRE1850FLAT_ROOF	

* Elements with the same plane number belong to the same surface, but they differ in category and/or adjacency.

4.2 CHOICE OF BUILDINGS TO MODEL - STACS PROJECT

TABLE 7: PERCENTAGE OF WELSH HOUSING STOCK BY TYPE AND AGE

	Age of dwelling							
Dwelling Type	**Pre-1919**	**1920-1944**	**1945-1964**	**1965-1980**	**1981-1999**	**2000-2006**	**Post-2006**	**%**
High-rise purpose-built Flat	N/A	N/A					X	-
Low-rise purpose-built Flat	0.1	0.0	**2.8**	2.8	**1.6**			7.3
Converted Flat	**0.6**	0.0	0.0	0.0	0.0			0.6
End-terraced Bungalow	0.2	0.0	0.1	0.2	0.0			0.5
Mid-terraced Bungalow	0.3	0.0	0.1	0.2	0.0			0.6
Semi-detached Bungalow	0.1	0.3	0.9	0.9	0.8			3
Detached Bungalow	0.3	0.4	0.8	2.2	1.0			4.7
End-terraced House	5.6	0.6	1.1	1.0	0.5			8.8
Mid-terraced House	16.8	0.9	1.4	**1.3**	**0.6**			21
Semi-detached House	**8.1**	**9.6**	**18.9**	6.2	1.2	X		44
Detached House	**3.1**	0.8	0.8	**3.0**	1.8			9.5
Percentage	35.0	12.7	27.0	17.7	7.6			100

As mentioned in 1.3 the 12 typical Welsh housing types identified by the STACS survey are used in this study to meet the research goals. The information presented in this paragraph is sourced from the STACS project's publications. Table 7 taken from Knight et al. (2008b) shows the percentage of the total housing stock occupied by the 11 main Welsh dwelling forms[18] categorised according their age. Excluding the houses built after 2000 (as no data is available for them), the semi-detached house is by far the most common residential property type, accounting for 44% of the total housing stockThe values in **bold** format indicate the 12 dwelling types which are modelled in this research, accounting for around 50% of the total housing stock. A suitable case study for the mid-terrace house of pre 1919 was not found by the survey and therefore this type was not included in the database, although it accounts for a large percentage of the housing stock. Table 8 shows the 12 types drawn from the categorisation described above. House No#3 is the largest dwelling of this database (with ~220m^2 floor area) and was used in this research as a representative type for the 1850-1919 era and also to allow for consideration of dwellings with a large volume.

[18] Here the term 'forms' refers to the division suggested by Rhodes et al (2007), i.e. flats can be high-rise or low-rise purpose-built and converted from an existing building. Houses and bungalows can be mid-terrace, end-terrace, semi-detached and detached.

TABLE 8: 12 TYPICAL DWELLINGS OF WALES (STACS)

NO	DWELLING TYPE	AREA (M^2)
1	PRE-1850 DETACHED HOUSE	87.27
2	PRE-1850 CONVERTED FLAT	103.52
3	1850-1919 SEMI DETACHED HOUSE	220.09
4	1920-1944 SEMI DETACHED HOUSE	93.32
5	1945 - 1964 LOW-RISE FLAT	65.74
6	1945-1964 SEMI-DETACHED HOUSE	89.17
7	1965-1980 DETACHED HOUSE	116.72
8	1965-1980 MID-TERRACE HOUSE	105.42
9	1981-1999 LOW-RISE FLAT	44.70
10	1981-1999 MID-TERRACE HOUSE	55.82
11	2000-2006 SEMI-DETACHED HOUSE	74.92
12	POST-2006 HIGH-RISE FLAT	57.47

The STACS survey provided geometry, materials and orientation for the 12 house types. The size of the dwellings varies between 45-220m^2. 3D images of the dwellings are shown in Figure 16 and 17 and in the Appendices (C).

4.3 GEOMETRY, MATERIALS AND OTHER DETAILS OF THE BUILDING COMPONENT

In this study, each house is modelled in its original orientation. For the overshadowing assessment, the impact of the volumes of the building itself and of the buildings attached to it (e.g. if semi-detached or mid-terrace) were only taken into account, ignoring other neighbouring buildings and vegetation.

As discussed before, it was decided that in the 12 building models used in this study, each room would be simulated as a thermal zone, unlike normal practice in ST simulations. This was done as thermal conditions in different rooms of dwellings are likely to vary widely due to:

- existence of heating/cooling equipment
- variation in exposure to solar radiation
- variation of internal gains due to appliances and occupants.

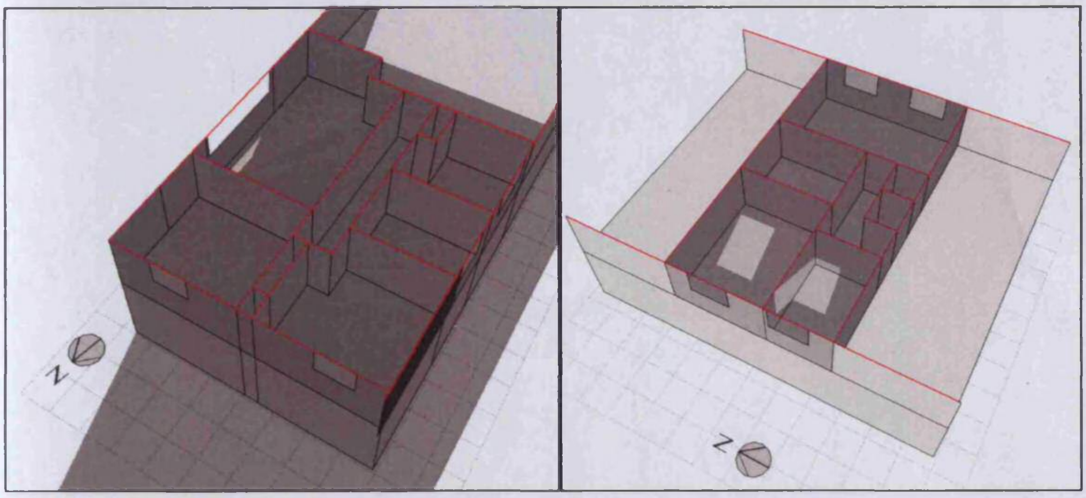

FIGURE 17: OPEN GL VIEWS OF THE 1945-1964 (NO#5, LEFT) AND THE 1981-1999 (NO#9, RIGHT) LOW-RISE FLATS, WITH SECTION PLANE AT THE Z AXIS.

The walls, ceilings and floors have no thickness with regards to the 3D geometry in Ecotect (the correct thickness of layers is then assigned to the material's data) and therefore, as can be seen in Figure 17, the planar walls were positioned relative to the actual element as seen in a 2D plan:

- either in the middle of the actual width if it is an internal wall, or
- at the internal side of the actual width if it is an external wall.

The same applies to ceilings and floors. Specific data per house type is listed in the Appendices (C). In particular, solar absorptance coefficients and convective heat transfer coefficients per surface type are presented at this section along with a comprehensive list of materials and layers per house type.

In TRNSYS it is possible to take into account the effect of direct solar radiation incident to the various surfaces of the zones by using the shortwave radiation distribution factor, called GEOSURF. However use of this feature requires that the factor is predicted somehow outside the building component and is fed to it as a constant value or as a profile for all walls and floors in each model. At this stageit was assumed that this effect could be neglected without causing a significant error in the calculations, as the impact of heavy mass materials (which are anyway limited in this house database) is not the focus here. Therefore the direct incident solar energy is treated as diffuse, in that it is equally distributed to all surfaces of the zone.

For the convective heat transfer coefficient of the materials, common values are used e.g. for inside: 11kJ/(hr.m².K), for outside 64kJ/(hr.m².K) and for boundary 0.0009(kJ/hr.m².K) (to force the surface temperature of the wall to be equal to the boundary temperature). 'Boundary' elements in TRNSYS are either those where adiabatic conditions are applied to (no heat transfer due to identical conditions on both sides) or those where a user-defined temperature (constant or profile) would better describe the conditions on the external side of the elements. For walls attached to neighbouring buildings maintenance of identical thermal conditions was assumed for both sides. The same applies to flats, when simulating the neighbouring spaces around the flat (except of the outside air).

TABLE 9: TRNSYS TYPES USED AND THEIR ROLE.

type	Description	Role	Remarks
109	Weather Data reading and processing: modes 1 & 2	Reading weather data files in standard and user's format	Standard TRNSYS 16.01.0003
69	Sky Temperature	Defines Tsky for type 56	Standard TRNSYS 16.01.0003
33	Psychrometrics	Defines Tamb and RH for type 56	Standard TRNSYS 16.01.0003
56	Multizone Building	Reads the building data. File is edited in TRNbuild	Standard TRNSYS 16.01.0003
9	Text Data Reader	Reading internal gains profiles to type 56)	Standard TRNSYS 16.01.0003
703	Slab on ground	Calculating the outside boundary temperature of the slab	TESS libraries
equation	general	Defining timestep (e.g. 15/60)	Standard TRNSYS 16.01.0003
equation	general	Defining orientations	Standard TRNSYS 16.01.0003
equation	general	Defining/Renaming radiation	Standard TRNSYS 16.01.0003
equation	general	Averaging the surface temperatures of the slab partitions	Standard TRNSYS 16.01.0003

For ground coupling, a component (type 703) of the TESS libraries (compatible with the TRNSYS engine) was used in order to calculate the outside boundary temperature of the slab. The component allows a detailed 3D modelling of the soil underneath the house. For some models, such as the 1850-1919 Semi Detached House, several type-703 components were used, as the ground slab is not rectangular and/or the ground materials vary between the different rooms. One of the inputs of the component is the inside surface temperature of the slab. In all models the slab is shared by more than one zone, and an average surface temperature for the ground is therefore calculated, based on area-weighted factors. For houses that 'sit' on a ventilated air cavity the ground floor is modelled as an external element, with a view factor to sky equal to 0 and a convective heat transfer coefficient of 11 kJ / h m^2 K (no exposure to wind).

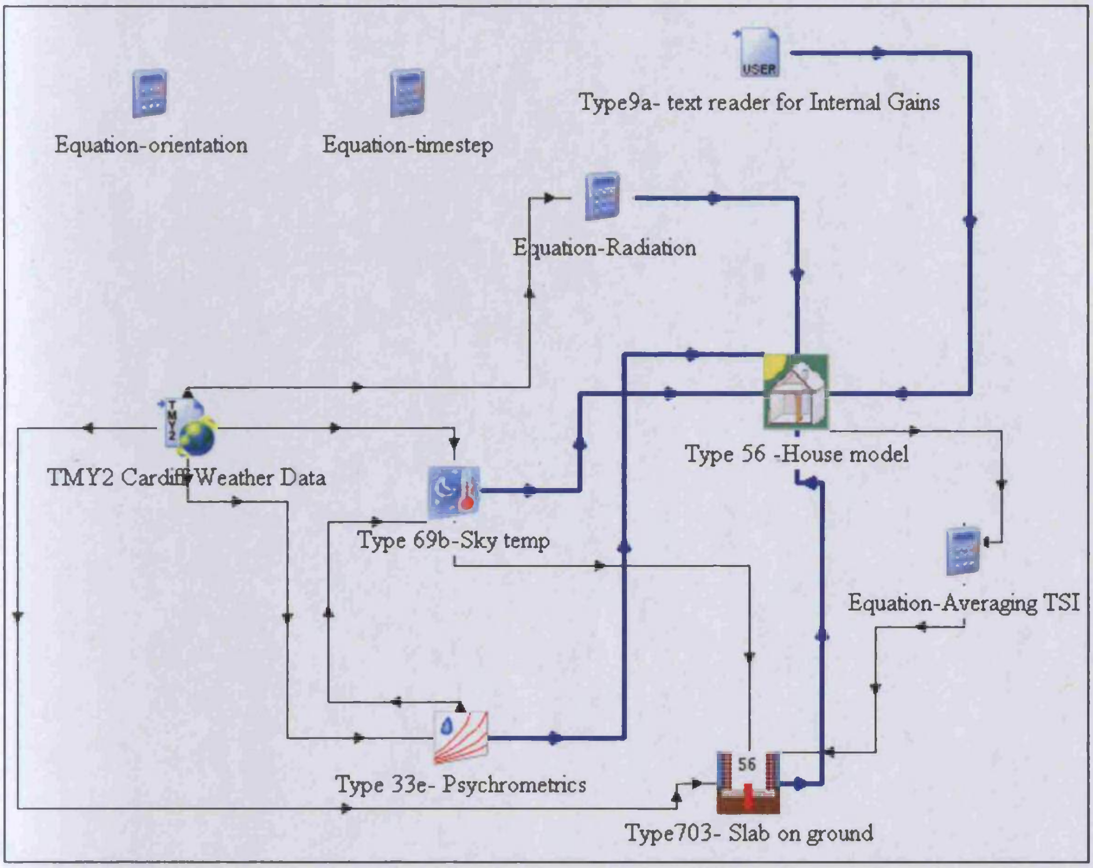

FIGURE 18: AN EXAMPLE MODEL IN TRNSYS STUDIO.

In the Simulation Studio in TRNSYS the building component (type 56) is linked to the other components as shown in Figure 18. Table 9 summarises the types used at this stage and gives a short description of their role. The following paragraphs discuss specific input information.

4.4 WEATHER DATA

As discussed previously in the literature review the type and quality of weather data used in the simulations of ST systems is of critical importance for the accuracy of the predictions (see 3.4.2.1). It was found in relevant publications that the solar yield and the system efficiency of solar systems might vary from average by ±10% for an actual year, due to weather conditions variation and this percentage might be higher in the future due to the climate change ((PEUSER, F. A. et al., 2002) pp307). For this reason both actual and average weather data is used in this study, for the calculation of the thermal energy demand profiles of the dwellings and the prediction of the solar energy availability for each house type (with the latter being discussed at section 0). In TRNSYS use of weather data of small timesteps is feasible.

Average data for the city of Cardiff (capital of Wales) is provided from the weather library of TRNSYS in TMY2 format. The TMY2 average year is built in METEONORM and in the case of Cardiff is based on measurements from a local weather station (TRNSYS, 2006). This data is similar (CRAWLEY, D. B. and Huang, Y. J., 1997) to the Test Reference year (TRY) data (CIBSE, 2002) recommended by the UK building regulations but it is different to the latter in the fact that it contains actual/measured solar radiation data. It is therefore apparent that the TMY2 data is more appropriate to be used in this research than the CIBSE TRY data that actually contains computed global and diffuse irradiances, based on synoptic data i.e. sunshine duration and cloud cover (CIBSE, 2008). To account for the likely extreme weather conditions (as peak values are also of interest in this analysis), one year data taken with actual measurements (year 2007) from a weather station located at the roof of the Welsh School of Architecture was also used in this study (CRIBE, 2009). Air temperature and humidity are measured by a Rotronic in radiation shield, global and diffuse horizontal solar irradiation with Kipp and Zonen KM5 solarimeters. All measurements are monitored by a Campbell Instruments CR10 data logger, scanned at second intervals and recorded at 5 minute intervals. Again the CIBSE recommended weather file for simulating the building performance during a hot summer, the so-called Design Summer Year (DSY) for Cardiff, was considered as inappropriate for this study as it uses computed solar radiation information (CIBSE, 2008) and therefore decision was taken to use the measured data from the WSA. To gain confidence on using the two weather files, i.e. the TMY2 and the MET, the data of these sources was compared to 30 year (1941-70) average weather data (PAGE, J. and Lebens, R., 1986).

Figure 19 shows the difference between predictions using the three datasets. The values represent the total incident solar irradiation (diffuse and direct) on a $10m^2$ surface facing South and tilted for 45° in Cardiff calculated with the TMY2 weather data, the actual 2007 data (MET) and the average values given by Page and Lebens. It is apparent that the two average datasets compare well to the average one. In addition the actual data deviates from the average values in accordance with the statistical analysis of that year given by MetOffice (executive Agency of the Ministry of Defence in the UK). More specifically the MetOffice website (METOFFICE, 2007) describes that in August and March 2007 the sunshine levels were above average (in some cases above 120% for 8/2007 and 150% for 4/2007) while some areas of the UK had their sunniest April on record in the same year. The curve in Figure 19 of the Met data shows a dip in solar radiation in June, which is also described in MetOffice's statistics for sunshine: *'The final total for the month is 142.3 hours, which is 81% of the 1961-1990 average. Dullest June since 1998...'.*

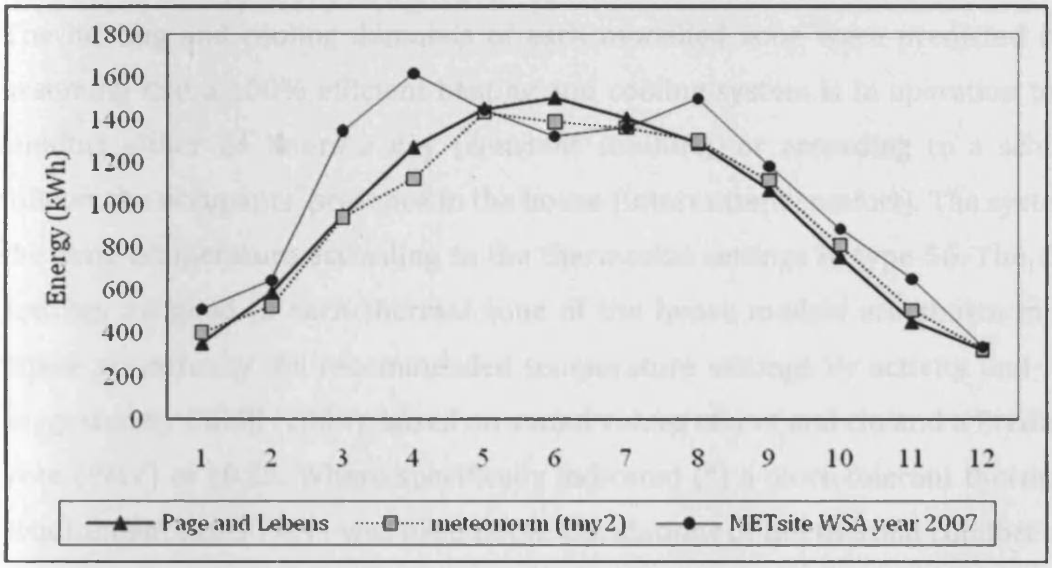

FIGURE 19: MONTHLY INCIDENT TOTAL (DIRECT & DIFFUSE) SOLAR ENERGY (KWH) FALLING ON 10SQ.M, SOUTH FACING, 45° TILTED, COLLECTOR AREA PREDICTED WITH THE 3 WEATHER DATASETS FOR CARDIFF.

In TRNSYS the two datasets are read by two different modes of the same component, called type 109. The standard-format-mode (mode 2) reads the TMY2 files of the TRNSYS library. The user-format-mode (mode 1) works with a user-friendly predefined format. It was found that there is a bug with the component and the data is misread if it is given in 5 minute-intervals and therefore the MET year data was averaged in 15 minute-intervals. Type 109 reads the radiation values in [W/m^2] and the output is given in [Kj/hr.m^2]. Amongst the available options, to calculate the solar radiation on tilted surfaces from the data provided, the 'Perez et. Al' model was selected which is generally suggested as the best available for this reason. It is an anisotropic model which calculates contribution from all three parts of diffuse radiation (including circumsolar radiation from the area around the sun disc and horizon brightening).

4.5 THERMAL COMFORT CONDITIONS

In order to predict the SH and SC needs of this housing stock, the thermal conditions considered as appropriate for thermal comfort have to be defined. In this study two types of comfort scenarios were considered; constant and intermittent comfort maintenance. In reality the occupants would be the ones to control the system's operation and thus any comfort strategy could be chosen. As it is impossible to model all potential scenarios, these two examples are built (with comfort recommendations existing in this country) to represent two likely HVAC operating strategies.

The heating and cooling demands of each modelled zone were predicted in TRNSYS assuming that a 100% efficient heating and cooling system is in operation to maintain comfort either 24 hours a day (constant comfort), or according to a schedule that follows the occupants' presence in the house (intermittent comfort). The system adjusts the zone temperature according to the thermostat settings in type-56. The thermostat settings assigned to each thermal zone of the house models are shown in Table 10. These are actually the recommended temperature settings by activity and room type suggested by CIBSE (2006), based on stated values of met and clo and a Predicted Mean Vote (PMV) of ±0.25. Where specifically indicated (*) a more tolerant thermal comfort requirement (±0.5 PMV) was used in the calculations of the thermal comfort conditions which gave these values. For the intermittent comfort scenario the heating is activated during a weekday for the period 6:30 to7:30 and 16:30 to 22:30 and for the weekend between 6:30 and 23:00. The heating and cooling system adjusts the zone temperature according to the comfort temperature range that is defined for each room type. That means that the heating will go off when the zone air temperature is below the lower threshold and the cooling will go off when the zone air temperature is higher than the upper threshold.

It could be suggested that the thermal comfort modelling should be based on adaptive comfort theories for dwellings (PEETERS, L. et al., 2008). However little evidence is yet available to support these in dwellings and in order to use them here variable thermostat settings dependent on the external ambient temperature would be required.

This of course would not correspond to real practice and therefore the approach taken in this work was to use the values suggested by CIBSE. It is appreciated that the heating and cooling demand prediction applied here could be overestimating the actual energy requirement for comfort as it corresponds to a PMV of ±0.25 for most rooms and makes use of a very narrow band for zone air temperature. This limitation was acknowledged but decision was taken to use the recommendations by CIBSE as the interest was on the demands that correspond to comfort maintenance (ideal conditions for occupants) and assess the ST potential based on the resulting energy requirement.

TABLE 10: THERMAL COMFORT REQUIREMENTS PER ROOM TYPE ACCORDING TO CIBSE, GUIDE A (TABLE 1.1, 1-3).

room type	Winter dry resultant temperature range for stated activity and range clothing levels			Summer dry resultant temperature range for stated activity and clothing levels		
	Temp. (°C)	Activity (met)	Clothing (clo)	Temp. (°C)	Activity (met)	Clothing (clo)
bathrooms	26–27	1.2	0.25	26–27	1.2	0.25
bedrooms	17–19	0.9	2.50	23–25	0.9	1.20
hall/stairs/landings	19–24*	1.8	0.75	21–25*	1.8	0.65
Kitchen	17–19	1.6	1.00	21–23	1.6	0.65
living rooms	22–23	1.1	1.00	23–25	1.1	0.65
toilets	19–21	1.4	1.00	21–23	1.4	0.65

4.6 INFILTRATION AND VENTILATION RATES

According to ASHRAE the heat losses due to infiltration account for around 20-50% of a building's thermal load (ASHRAE, 2005). This fact highlights the importance of simulating the infiltration losses correctly in thermal models. Unfortunately there are no typical or measured infiltration rates available for the building types used in this study and thus previous research in the area was advised.

Information about air leakage of UK dwellings is available from two sources. An infiltration study of British Gas is based on measurements on 200 dwellings and a study conducted by BRE is based on measurements on 471 dwellings (STEPHEN, R. K., 1998).

Both studies use the fan pressurization or otherwise called "blower door" method (SHERMAN, M., 1995). The results of the tests described by Stephen (1998) show in general that the air leakage rates variation across the whole database is very wide, hence the author concludes that it is *"currently impossible to make a realistic estimate"* of the infiltration of a dwelling without carrying out measurements. Both studies reveal that there are some general trends relating the build date of the dwellings and the air leakage rates but the variation of the air leakage rates is significant even within these categories and no general rule relating infiltration rates and age of dwelling can be drawn from this sample. Furthermore the BRE study reveals that although there are some clear trends identified which relate certain aspects of the building structure (e.g. construction materials of walls and floors or window types) to the infiltration, the air leakage caused from "known" sources of leakage accounts only for 29% of the total infiltration and the remaining 71% is put down to "confounding" factors such as little cracks anywhere on the building envelope.

For the purposes of this PhD research the average air leakage rate found by the BRE study was used (13.1 ACH_{50}). To calculate the infiltration rate under normal conditions the "divide by 20" rule is used, along with the corrections for building height which are shown in Table 11 (SHERMAN, M., 1987; ANSI/ASHRAE, 1993). No correction due to shielding and weather has been used here as such information is not available for this database or for the climate of Cardiff. The infiltration rates used in the 12 models can be seen in Table 12.

TABLE 11: CORRECTION FOR THE NORMALISED LEAKAGE CALCULATED FROM RATES IN ACH50 (SHERMAN, M., 1987).

Dwelling height correction factor			
Number of storeys	1	2	3
Correction factor H	1.0	0.8	0.7

As no information is available regarding the ventilation strategies typically used in the selected dwellings, the ventilation rates used in the models are based on the ANSI/ ASHRAE Standard 62.2-2007 (ANSI/ASHRAE, 2007). The minimum whole building ventilation rates suggested by the standard are derived by Equation 2. These include a default infiltration rate of 10l/s per 100m^2. The standard also defines that if a higher infiltration rate applies then the minimum ventilation rate can be decreased by half of the excess of the known infiltration rate. For bathrooms and kitchens the continuous ventilation rates suggested by the same standard were used and it is 10 l/s and 5 ACH respectively [(ANSI/ASHRAE, 2007) tables 5.1, 5.2). Table 12 shows the ventilation rates used for the various zones of the house as calculated in relation to the average infiltration rates for these houses.

EQUATION 2

$$Q_{fan} = 0.05A_{floor} + 3.5\ (N_{br} + 1)$$

Where,

Q_{fan}=fan flow rate. l/s, A_{floor}=floor area, m², N_{br}= number of bedrooms; >1.

TABLE 12: CALCULATED INFILTRATION AND VENTILATION RATES FOR THE 12 HOUSE TYPES IN AC/H.

dwelling	Infiltration	Vent_house	Vent_Bath	Vent_WC1	Vent_WC2	Vent_Kitchen
1	0.82	0.11	1.67	NA	NA	4.18
2	0.82	0	1.65	NA	NA	4.18
3	0.94	0	1.89	3.59	2.85	4.06
4	0.82	0.11	3.41	8.25	NA	4.18
5	0.82	0.17	2.48	NA	NA	4.18
6	0.82	0.04	5.1	9.1	NA	4.18
7	0.82	0.05	2.38	3.52	NA	4.18
8	0.82	0	3.64	6.87	NA	4.18
9	0.82	0.06	2.23	NA	NA	4.18
10	0.82	0.13	4.09	NA	NA	4.18
11	0.82	0	3.5	6.89	NA	4.18
12	0.94	0	3.22	NA	NA	0.7*

* Open plan room (kitchen and living room combined).

4.7 INTERNAL GAINS: ELECTRICAL APPLIANCES AND LIGHTING

For recent housing types it is clear that the internal gains caused by appliances and lighting can have a major impact on the annual heating or cooling load, thus affecting significantly the annual delivered heating or cooling energy in these houses.

As a result of Subtask A of the FC+COGEN-SIM *"The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems"* Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme, standard European and Canadian non-HVAC Electric Load and domestic hot water profiles have become available (KNIGHT, I. and Ribberink, H., 2007). The European non-HVAC Electric Energy Consumption profiles of this study which have been suggested as "a good first estimate of domestic electrical energy consumption profiles for many European countries" are based on the UK domestic profiles monitored by EETS Ltd and the Welsh School of Architecture (KREUTZER, N. and Knight, I., 2006). The measurements for these profiles were taken in 24 months and with a time interval of 5 minutes. Using this data to simulate the internal gains due to appliances and lighting for the Welsh housing stock can therefore be considered the most accurate and realistic approach available for this purpose. However there are a couple of issues to be considered in relation to the applicability of these profiles in representing typical heat dissipation due to electrical appliances in the Welsh housing stock:

- These profiles are based on measurements obtained from dwellings of the social sector. Comparison with published data of the Electricity Association (as cited by (KREUTZER, N. and Knight, I., 2006)) shows that the electricity consumption at the social sector is relatively lower than the UK average one, e.g. typical winter day being 10kWh compared to 11.5 kWh or 43 instead of 55kWh/m^2 per year. Nevertheless it had been found (KREUTZER, N. and Knight, I., 2006) that the patterns of the daily electrical consumption are relatively similar between social and total occupant groups despite the social housing group not having a defined occupancy profile on average (lower employment rate) and despite the differences in terms of appliances' ownership between the two groups.

- The data of the social sector is based on measurements from 69 useable records which are all fossil fuelled heated dwellings. Therefore the profiles provide non-HVAC electricity usage. However within the sample there are 29 households with electric cookers/showers, 30 households with electric cookers and fossil fuel heated water for the showers and 10 households with fossil fuel powered cookers/showers. It is appreciated that by using these profiles an error occurs for ignoring heat dissipation of fossil fuelled appliances for cooking (found in 15% of the total sample) and DHW preparation (found in 58% of the total sample). In addition, when converting the electrical consumption to heat dissipation it has to be considered that not 100% of the heat released will count as heat gains in the house (HEIMRATH, R. and Haller, M., 2008) . Firstly a part of the electrical energy is consumed by appliances located outside the house i.e. garden. Additionally a large amount of the energy consumed by cookers, dishwashers, clothes washers and mainly by showers is to heat up water. A significant part of this energy will not count as heat gains in the dwelling as it will be drained off. Unfortunately nothing is known about the exact amount of heat losses due to these two cases (external appliances & heat going down the drain). As it was stated before nearly 60% of the records of this sample do not include the energy consumed by the water heaters as these were fossil fuel driven. Ideally in order to calculate the correct gains from the appliances the fossil fuelled water heaters' share had to be added and then the hot water discarded to be subtracted by the sum. In this case it was assumed that by using the data as found will not result to a significant error as the two penalties would almost compensate each other.

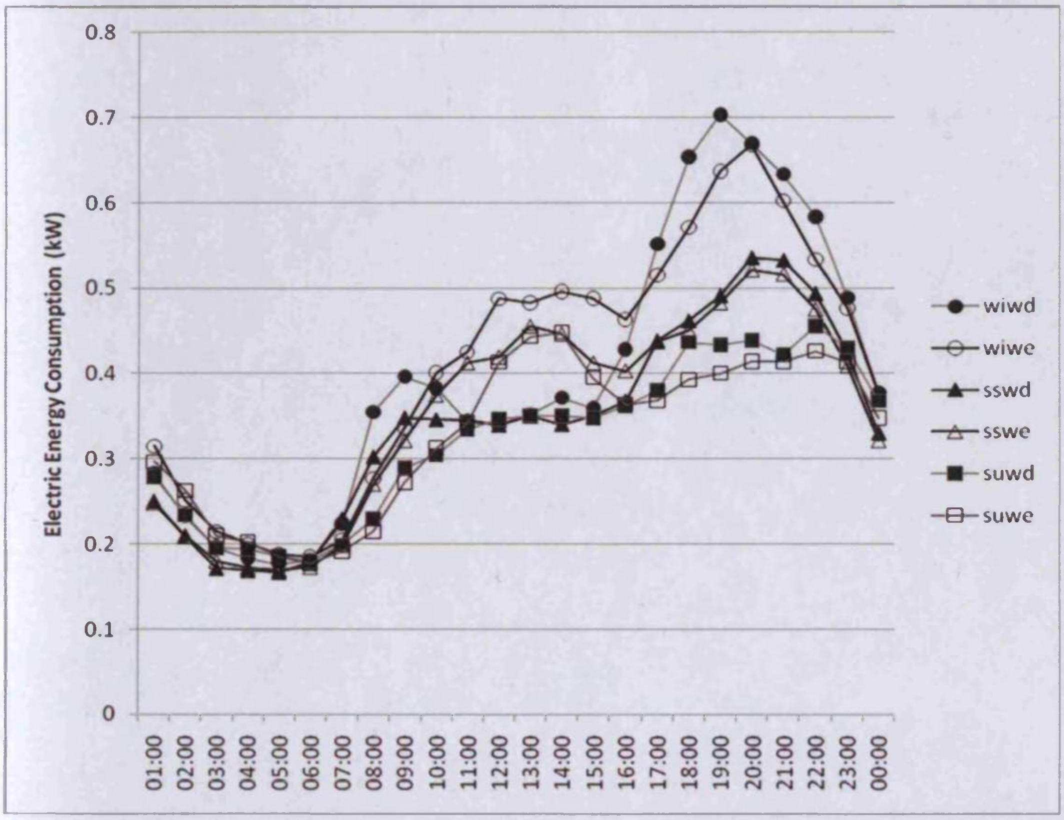

FIGURE 20: THE 6 DAILY PROFILES COMPOSING THE 'STANDARD AVERAGE EUROPEAN PROFILE' OF ANNEX 42 (SHOWN IN HOURLY INTERVALS FOR ILLUSTRATION PURPOSES).

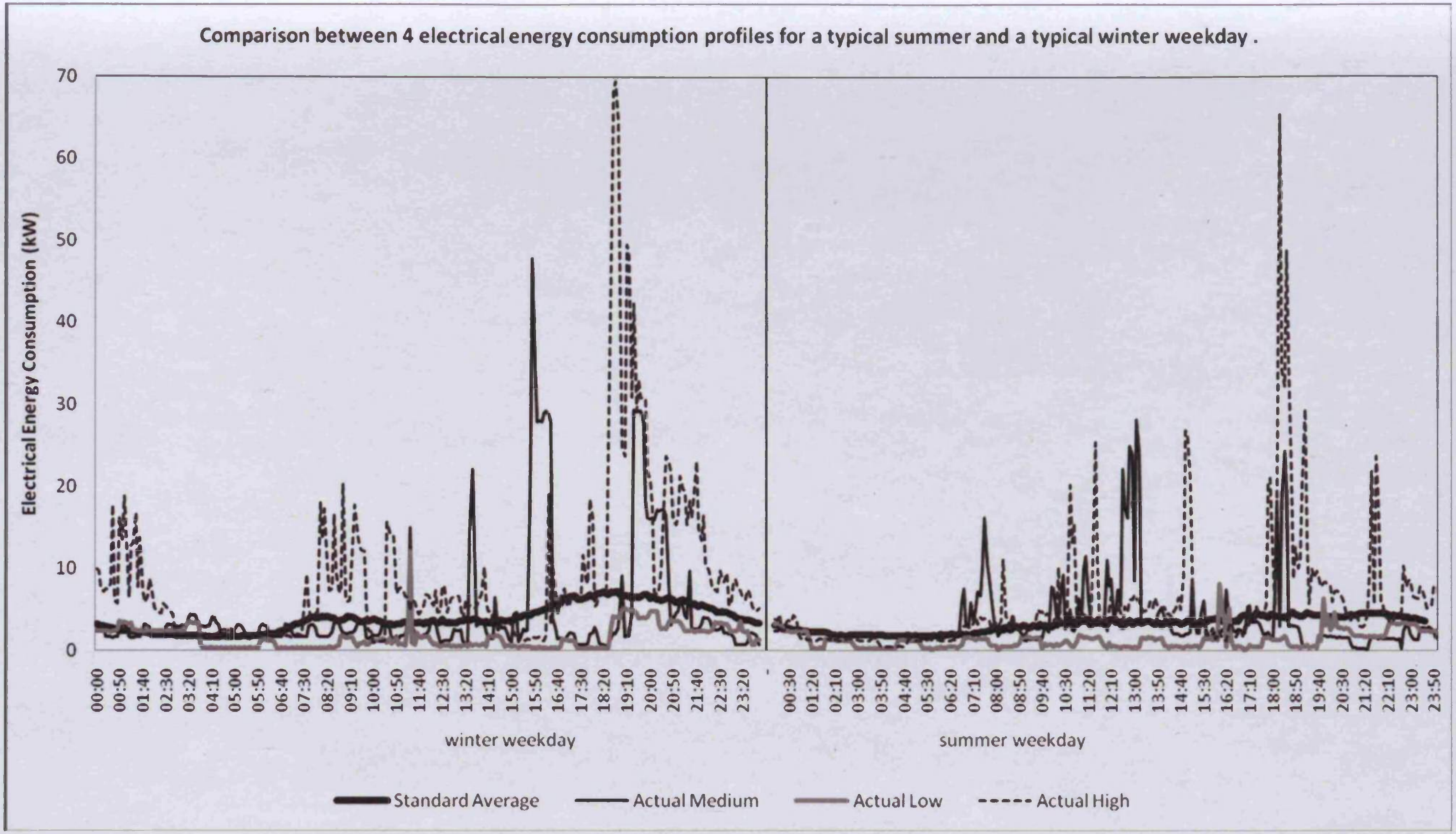

FIGURE 21: COMPARISON BETWEEN THE 4 ELECTRICAL ENERGY CONSUMPTION PROFILES DISCUSSED; STANDARD AVERAGE, ACTUAL LOW, ACTUAL MEDIUM AND ACTUAL HIGH. TYPICAL SUMMER WINTER DAY (FEBRUARY-LEFT) AND TYPICAL WINTER WEEK DAY (JULY-RIGHT).

The Subtask provides a 'Standard Average' and 3 'Actual' profiles of low, medium and high electrical consumption for domestic properties. The 'Standard Average' consists of six profiles corresponding to the 3 typical seasons of the year (winter, summer and shoulder season) and to the 2 typical days of the week (weekday and weekend). The data is in 5-min intervals and the unit is Watts. Figure 20 shows the 6 profiles. The prefixes 'wi', 'ss' and 'su' stand for winter, shoulder season and summer respectively and the endings 'we' and 'wd' stand for weekend and weekday respectively.

For the purposes of this study the 'Average Standard' profile is used in order to simulate the heat realised by appliances. Furthermore and prior to the ST analysis, the effect of the magnitude and fluctuating pattern of the internal gains due to appliances and lighting on the thermal demands of the 12 houses is assessed in 5.1.1 For the purposes of this sensitivity analysis the 'Average Standard' profile and the three specific profiles are used at this stage. Table 13 shows the details of the 4 profiles as found in Annex 42 and Figure 21 shows the 4 profiles during a typical winter and a typical summer day.

TABLE 13: THE 4 ELECTRICAL CONSUMPTION PROFILES DUE TO APPLIANCES AND LIGHTING USED IN THE SIMULATIONS (KNIGHT, I. AND RIBBERINK, H., 2007).

File Name	Annual Consumption [kWh]	Year	Size of dwelling [m²]	Occupancy type (as in annex 42)
Actual low	1155 (1179 for 2007)	2005	65	Single male
Actual medium	3028 (3126 for 2007)	2003	65	Mother and two children
Actual high	8387 (8765 for 2007)	2005	108	Mother and 5 children
Stand. average	3242	2007	NA	NA

TABLE 14: ELECTRIC ENERGY USE FROM APPLIANCES IN CANADIAN HOUSES (KNIGHT, I. AND RIBBERINK, H., 2007).

appliance	appl/dwel (Canadian)	kWh/y (Canadian)	%
Refrigerator	1	801.00	11.06
Freezer	1	614.00	8.48
Dishwasher	1	94.00	1.30
Clothes washer	1	99.00	1.37
Clothes dryer	1	1284.00	17.74
Range	1	769.00	10.62
Other appliances	8.98	2465.00	34.05
Lighting (/m2)	141 m2	1113.12	15.38
Kitchen (1-6)	6 in total	3661.00	50.57
Remaining (7-8)	unknown	3578.12	49.43
Total		7239.12	100

According to a Canadian survey included in the same study of Annex 42 (KNIGHT, I. and Ribberink, H., 2007) the electric energy in dwellings is consumed by two groups of appliances (excluding HVAC systems) as shown in Table 14. Almost half of the energy is used by the 6 major appliances (dishwasher, clothes washer, tumble dryer, range, fridge and freezer) which are normally found in the kitchen zone. The remaining part is used by lighting (7.9 KWh/m^2 p.a.) and smaller appliances. The exact share consumed by each of the two groups of appliances varies between models as it depends on the floor area (due to lighting). This data was used here in order to apportion the heat gains due to appliances in the various zones of the house models. In the twelve models, the share of the gains caused by lighting and the small appliances was distributed evenly over the zones of each dwelling (even in stores and utility rooms, as they can contain appliances) with volume-based factors. The share caused by the 6 major appliances was added only to the kitchen zone in all house models of this study. In the Simulation Studio (TRNSYS) a text data reader (type 9) read the internal-gains' profiles to type 56 and the apportionment was done internally in the building component.

4.8 INTERNAL GAINS: OCCUPANTS

The number of occupants and their living trends in these 12 dwellings were not known and therefore it was assumed that all houses are occupied by 2.4 inhabitants, which is the average occupancy for the area (WAG, 1998). The rationale used to set the occupancy patterns during weekdays and weekends was rather simple. For the non-sleeping period, during a typical weekday the house was considered as occupied between 07:00 to 08:00 and 17:00 to 23:00, and in the weekend between 07:00 to 23:00. The gains from occupancy during these intervals were distributed over the living zones with area-based factors. The activity used was the same for all the zones and it was considered to be an average of "Standing, Light work or working slowly" (total heat output 185 Watts per person). For the sleeping period, taken to be 23:00 to 07:00, the gains (100 Watts per person) were evenly distributed over the bedrooms.

It is appreciated that the use of a single occupancy type and pattern, especially along with a selection of internal gains profiles could introduce some inaccuracy to the predictions. For example, in the sensitivity analyses at 5.1.1 the same (standard) occupancy type is used along with both the low and high gains profiles, whereas the actual occupancy for these profiles is 1 single male for the first and 1 mother with 5 children for the second (see also Table 13), all measured from social houses. Acknowledging the potential error introduced in the calculations, decision was taken to keep the same occupancy type for all prediction for simplicity reasons, and this approach was also supported by the fact that the patterns of the daily electrical consumption has been found by researchers in the area to be relatively similar between social and total occupant groups, despite the social housing group not having a defined occupancy profile on average (also discussed in the previous paragraph, citing (KREUTZER, N. and Knight, I., 2006)).

4.9 DOMESTIC HOT WATER CONSUMPTION

Due to the popularity of the solar water heating systems, DHW profiling is not a novel aspect for ST simulations. Therefore this input is briefly explained in this section and does not get the attention that was drawn on the electricity usage patterns described in 4.7.

For the domestic hot water consumption the information found in the Subtask A of the FC+COGEN-SIM mentioned before (KNIGHT, I. and Ribberink, H., 2007) were used. The report of the subtask refers to two studies which suggest 116 litres per household per day as an average daily DHW consumption, based on a 45°C rise, for the UK. Therefore the energy required for the average daily draw off of DHW for the models was calculated to be around 6.06 kWh.

In the Subtask A of Annex 42 the DHW consumption prediction model developed in Task 26 of the IEA SHC Programme has been validated against measured data from various sources in Europe, US and Canada. It was found within the Subtask that the model compared well to those datasets and therefore was used for the purposes of the Annex. The probability model for DHW consumption built in Task 26 provides volume draw off data in 100-litres step, assuming a cold feed temperature of 10 °C and a delivery temperature of 45 °C. As in most cases in the UK the delivery temperature would be around 55-60 °C and therefore a larger temperature lift would apply, a correction factor for the volume (provided by the model) is applied to the profile. According to Equation 3 (KNIGHT, I. and Ribberink, H., 2007) the 200 litres profile provided by Task 26 for a 35 K temperature lift could be used to simulate a 155 litres daily draw off for a 45 K temperature lift.

EQUATION 3: VOLUME CORRECTION OF DHW CONSUMPTION PROFILE PREDICTED BY TASK 26 FOR A DIFFERENT THAN 35 K TEMPERATURE LIFT. AS GIVEN BY ANNEX 42.

$$Actual\ volume = profile\ volume\ x \frac{35}{stored\ water\ temperatue - cold\ fed\ temperature}$$

Therefore for the Welsh house types the 116 litres daily consumption of hot water is simulated by using the 200 litres probability profiles of Task 26 scaled by a factor of 75% ($\sim\frac{116}{155}$).

4.10 LIMITATIONS OF THE MODELLING APPROACH AND CONCLUSIONS

This paragraph discusses the input selection and the quality assurance methods used in this modelling work.

The quality assurance assessment is an essential aspect of any modelling exercise. There are several methods to acquire quality assurance in energy modelling:

- By using state-of-the-art processes of building and site representation i.e. existing validated simulation programs or 'well'-tested original codes
- By using reliable, realistic, good quality input data in the modelling descriptions
- By comparing the outputs and calibrate the models against real performance data
- By evaluating the outputs with the use of well-trusted predicted outputs i.e. existence of a constantly updated database for benchmarking purposes, where the same modelling method has been applied.

It is obvious that in this study only the first two conditions have been satisfied. Unfortunately no real data or previous, reliable predicted data was available to compare the results against[19]. Therefore the focus for quality assurance was on the software and the input used. The use of TRNSYS in this study has brought significant confidence to the modelling outputs. As far as it concerns the input data, there were a number of assumptions made, as it happens in any simulation. Nevertheless in order to assess the limitations of the input choices and the quality of the models produced the idea behind the creation of the models has to be recalled.

The aim here is definitely not the prediction of the entire range of demands expected within the housing stock of this region, as this would be a research subject on its own. The concept is that a set of typical/representative, for the Welsh housing stock and climate, thermal energy demands, which incorporate realistic fluctuations on their profiling can be produced by the models in order to give useful answers on the ST analysis. Therefore, considering the aims of this work, the building modelling methodology identified the essential aspects of the simulations and used these for determining the number of variables and case studies to be analysed:

- The weather data used in the analysis was considered as critical, due to the impact that this would have both on the solar availability and the predicted demands. Therefore both average and actual data for the city of Cardiff were used.
- The operation time-schedule for the space heating (and cooling) system was acknowledged that it would have a significant impact on the predicted demands. As there is no typical/common type to use for these houses two different strategies were employed, one for constant and one for intermittent operation for the HVAC system.

The selection of the 12 houses has a wide variety on characteristics such as the size and shape, the number of rooms, the roof orientations, the construction materials etc. It was therefore decided that the scope of this work is satisfied if the models are treated as case studies. Thus some of the input data used in these models was considered as *de*

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[19] Apart from some rough comparisons with accumulative data derived from utility bills that became available for a couple of the dwellings. Nevertheless the quality of this assessment does not comply with the academic standards and was only used at the initial stage to ensure that a reasonable range of demands are predicted.

facto for the particular project e.g. materials and geometry data according to the research context described in 2.2 and was therefore non-negotiable. For the remaining input parameters, common values (for the specific housing stock), where available, were used. This applies to the 'variable' input i.e. input that can be thought as uncertain or changeable within the life span of the dwelling or the system used, such as the infiltration and ventilation rates, the internal gains due to occupancy and appliances' use. The discussion in this chapter explained that for these input parameters the most reasonable assumptions were made when there was no actual data available.

Specifically for the internal gains due to appliances and lighting, a number of input profiles were used because this modelling study was seen as a good opportunity to test the new range of realistic data that recently became available to modellers. The reaction of the models against the change of this input has also resulted to a number of iteration/optimisation loops on the modelling procedure i.e. cross-comparisons between the output (demand) and input (gains) profiles reassured that the links between the various components in TRNSYS operated correctly and corrections were made when necessary. It has to be keep in mind that the input of the models was revised in many instances and the simulations were re-run; the modelling process was not linear. The sensitivity analysis on the heat gains from electrical appliances (the results of which are presented in the following chapter) has to be perceived as an 'extra' exercise that gave an indication of the wider range of expected demands for the Welsh housing stock.

As explained also above, it was by no means the aim of this work to assess the effect of the variation of any input value on the resultant demands but the prediction uncertainties that were associated to the assumptions made were not ignored. For the infiltration and ventilation rates, due to lack of available measured or representative (profile) data, average values were used. Similarly the occupancy input was treated as average and a simple estimation for the occupancy presence in the house was made. An interesting option would be to test occupancy variations within the sample and investigate the derivation of realistic occupancy profiles using the underlying data from the Electrical Consumption profiles of Annex 42. Nevertheless the assumptions made do not affect the liability of the models and the results, considering again the purpose of these simulations. The models are capable of delivering the results required, as they represent one aspect of the reality. For the ventilation gains concerned, there could be indeed a number of alternative scenarios employed such as modelling manual window operation, but no data exists to support these assumptions for Welsh dwellings. In any case it could be argued that the used values for air replacement in the dwellings might return a slightly higher SH demand than what would be normally expected for a ST project. That means that in practice, all necessary measures would be normally taken prior to the ST installation to result to a lower SH demand e.g. by replacing air-liking windows and/or by employing mechanical ventilation strategies with heat recovery. With regards to uncertain input, the choices taken ensured that the SH demand results are at the average level and therefore an unrealistically optimistic estimation for the ST potential is avoided.

Based on the arguments discussed above and considering previous work in the area and experience shared within the TRNSYS forum the building component modelling in this study has reached the initial aims of sufficiently detailed building simulations which were discussed in paragraphs 2.1 and 3.7. For the purposes of this study the 12 dwellings were treated as representative case studies and the results were considered only indicative for the entire housing stock of Wales. It is understood that the results that will be presented at the next chapter cannot be directly generalised for the entire Welsh stock, but a good understanding of the Welsh residential thermal energy demands can be obtained from this selection. It is also expected that the results will be applicable to other areas of the UK too.

The presentation of the modelling procedure in this chapter highlighted the effort and time that was spent for the prediction of the thermal energy demand profiles in this study. It has to be noted that the modelling was done in parallel with the familiarisation with the software, which has anyway a non-friendly modelling environment for complex geometries and lacks of a 2-D or a 3-D front-end tool.. There is a large amount of information resulting from these models and only a small part of it has been utilised in this work but it is anticipated that further studies, regarding ST and other low carbon applications on these dwellings, would be feasible under post-doctoral opportunities. Additionally future work on these models could shed some further light on the debate of handling them with such detail or treating them as 'heuristic constructs' thus simplified and built for a task (ORESKES, N. et al., 1994).

The next chapter presents the results of the building simulations and further investigates the ST potential that arises considering the thermal demands, the climate and current ST and TES technologies.

5 RESIDENTIAL THERMAL ENERGY PROFILES AND SOLAR ENERGY AVAILABILITY FOR WALES; A MATCH-MISMATCH STUDY

The first part of the chapter presents the thermal energy requirements for SH&C and DHW preparation for the 12 houses predicted with the building models described in chapter 4. The sensitivity analysis on modelling input is also discussed in this section. The calculations for the SH&C demands were done in TRNSYS considering a 100% efficient HVAC system that works according to the thermostat settings and schedules set out in 4.5 and 4.8. The cooling demand predicted was multiplied with a factor of $\frac{1}{0.6}$ to account for the conversion from cold to heat, assuming the use of an absorption chiller with COP of 0.6 -thermal to cold thermal- efficiency. The solar availability calculated with the weather data described in 4.4 and considering the external surfaces of the dwellings that are available for roof mounting is presented in 0.

At the second half of this chapter the ST potential corresponding to this solar energy demand and availability is investigated. The literature review showed that current ST systems can utilise effectively 30-60% of the solar energy incident on their absorbers (3.4.2.2). The exact share would depend on many reasons, with the solar system design and tuning having a major role to play on that. At first and in order to eliminate the influence of potentially poor performing ST systems, the ST potential arising solely from the demand profile and the collectors' yield is analysed for each house type. It is assumed that with the use of VT collectors 70% (see also Table 18) of the incident solar energy on the absorber area is passed to the solar system. Then in order to derive more reliable conclusions it is assumed that only 40% of the solar energy incident on the absorbers is harvested by the entire solar system(to be within the range 30-60%). The maximum and the average ST potential is then further analysed considering a range of TES capacities, with target to achieve 50% and the highest feasible solar fraction in each case.

Further to this exercise, as also described in the literature review chapter, the findings of performance analyses on 9 typical European solar combisystems are applied on the thermal demands of the Welsh housing stock to reveal the actual potential that arises with systems currently available in the market. These predictions are based on the performance characteristics of these 9 solar combisystems that became available as a result of the Task 26 of the IEA SHC. No detailed ST computer simulations were conducted for this study. Simulating a range of potential ST solutions with sufficient detail in TRNSYS would not be possible within the time available for this research.

All building simulations in TRNSYS run for one and a half year, for 4344 to 17520 hours. The results of the period 8760-17520 hours (a full year) are analysed. For the store requirement assessment, data from the 1st of March until December is repeated before the full year to reveal likely advantages of inter-seasonal energy storing.

5.1 SENSITIVITY ANALYSES

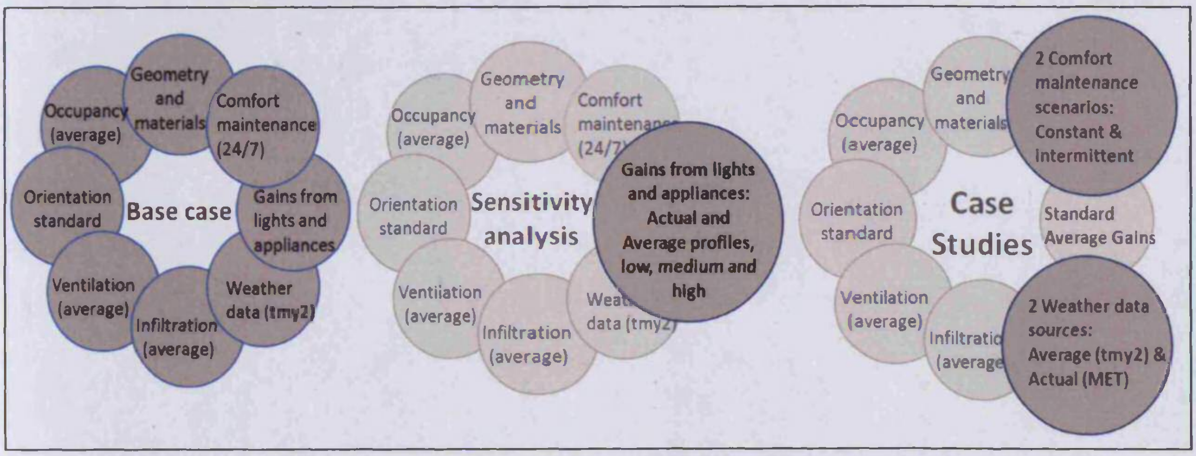


FIGURE 22: DESCRIPTION OF THE BASE CASE, THE SENSITIVITY ANALYSIS AND THE CASE STUDIES FINALLY ANALYSED IN THIS WORK.

A critical aspect of any simulation is the ability of the model to give reliable and useful conclusions for the subject in question. This issue is of particular importance here as special attention was drawn on the representation of the buildings in the computer simulations.

For all the calculations conducted within this study it was decided that only inputs that would significantly influence the returned conclusions will be tested with sensitivity analyses. The fact that the 'model use' could determine which factors have to be the subject of sensitivity analysis has been analysed in the literature (SALTELLI, A. et al., 2000) where inter alia the role of the sensitivity analysis as a tool for reassuring correct output and input connection, for determination of the most influential input factors regarding the output variance and for identification of issues related to 'uncertain evidence' or poor modelling mechanisms has been addressed. According to this concept the influence of smooth (average) and actual climatic data was considered as an important subject for sensitivity analysis in this study as a strong relation between this factor and the resulting solar yield was anticipated. Similarly the comfort strategy used for controlling the HVAC mechanism was considered as critical, as it was expected that it would strongly influence the resulting SH&C demands. For this reason in the sections 5.2-5.5 results of the simulations making use of both weather data types and both thermal comfort strategies are presented and analysed according to the research aims. That means that the ST potential is assessed for 12x4 case studies (Figure 22).

Furthermore the influence of both the magnitude and the fluctuating patterns of the heat dissipation of electrical appliances to the resulting thermal performance of the 12 dwellings was assessed with a separate sensitivity analysis. That was decided because the electric consumption profiles used here are very recent and no experience with their use has been presented in the literature as yet. This assessment revealed that, due to lack of solid evidence, the choice of some input parameters (with the example of the electric heat gains) can be problematic, as this uncertainty may widen significantly the range of the predicted thermal demands. This was actually the subject of a conference paper presented in *'PLEA 2008'* in Dublin (AMPATZI, E. et al., 2008). The paper used a semi-final version of the models but the conclusions can be considered as valid for the final models of this work as the differences between the two databases are minor to this effect. The results are analysed in section 5.1.1. Figure 22 shows the relation between the sensitivity analysis presented in 5.1.1 and the actual case studies analysed after 5.2. In the 12x4 case studies that are used in the ST analysis only the Standard Average European profile for electric consumption is used to simulate the gains due to appliances and lighting.

5.1.1 SENSITIVITY ANALYSIS ON BUILDING MODELS' INPUT: THE EXAMPLE OF HEAT GAINS DUE TO APPLIANCES AND LIGHTING

5.1.1.1 PREDICTED SH&C DEMANDS FOR A RANGE OF ELECTRICAL CONSUMPTION PROFILES.

TABLE 15: PREDICTED ANNUAL SPACE HEATING AND COOLING DEMANDS FOR THE 12 MODELS (VERSION PRESENTED IN PLEA 2008) WITH: NO INTERNAL GAINS, ACTUAL LOW, STANDARD AVERAGE AND ACTUAL HIGH INTERNAL GAINS PROFILES..

House type	No gains (kWh)		AcLo (kWh)		StAv (kWh)		AcHi (kWh)		Max diff (kWh)	
	H*	C*	H	C	H	C	H	C	H	C
1. Pre-1850 Detached House	9538	13	8766	38	7503	107	5499	2245	4039	2232
2. Pre-1850 Converted Flat	20010	462	19160	544	17640	670	14650	1764	5360	1302
3. 1850-1919 Semi Detached House	39430	155	38410	169	36580	190	32510	551	**6920**	**396**
4. 1920-1944 Semi Detached House	16450	314	15600	335	14070	368	11030	917	5420	603
5. 1945 - 1964 Low-rise Flat	8097	80	7327	156	6023	320	3879	2295	4218	2215
6. 1945-1964 Semi-detached House	12010	164	11270	239	9991	384	7937	2420	4073	2256
7. 1965-1980 Detached House	14110	126	13340	168	12000	236	9584	1560	4526	1434
8. 1965-1980 Mid-terrace House	13560	279	12750	318	11340	383	8598	1236	4962	957
9. 1981-1999 Low-rise Flat	3847	206	3186	355	2188	737	1233	4436	2614	4230
10. 1981-1999 Mid-terrace House	5667	161	4953	238	3786	416	2195	2946	3472	2785
11. 2000-2006 Semi-detached House	10620	10	9734	31	8304	53	6223	2237	4397	2227
12 Post-2006 High-rise Flat	2943	21	2275	84	1298	365	530	3908	**2413**	**3887**

*'H' and 'C' stand for the heating and cooling demands respectively.

Table 15 summarises the predicted total annual SH&C loads of the 12 models for the reference case and for the cases with *Actual Low, Standard Average* and *Actual High* gains due to appliances and lighting (for information regarding the profiles see also 4.7). For the simulations it is assumed that comfort is maintained 24 hours/day across the whole year, i.e. heating and cooling on demand. It is appreciated that this assumption results to higher annual thermal energy demands, and lower system sizing requirements, compared to the intermittent comfort strategy.

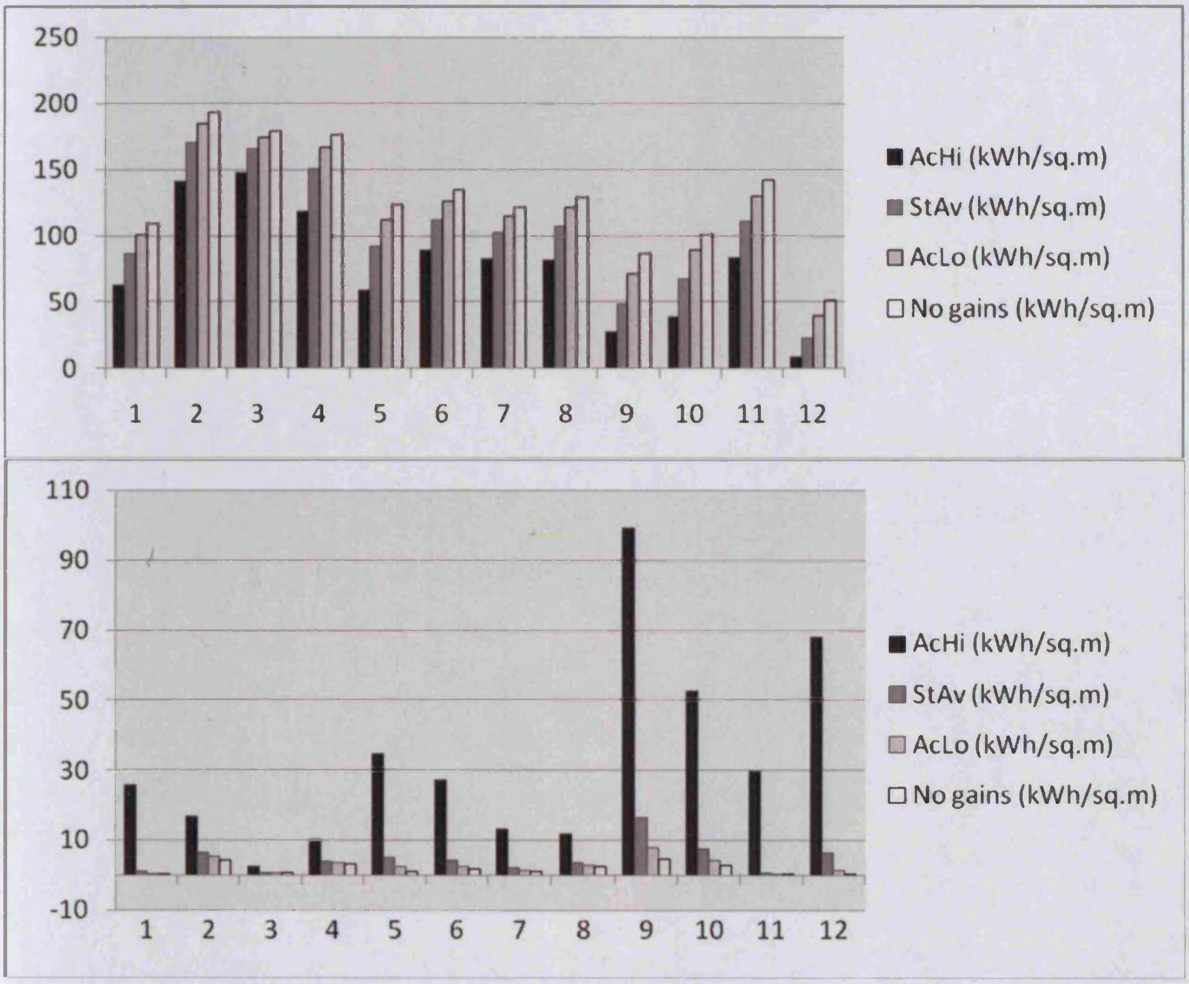


FIGURE 23: ANNUAL NORMALISED SPACE HEATING (ABOVE) AND COOLING (BELOW) DEMANDS FOR THE 12 DWELLINGS AND FOR 4 DIFFERENT TYPES OF INTERNAL GAINS.

The results of the 3rd and the 12th model were thoroughly analysed in the conference paper as they represent two extremes with regards to the overall annual energy requirement for SH&C. The 3rd model is the 1850-1919 Semi Detached House and is the largest dwelling of this database. Mainly due to the high volume and the poor insulation of the building envelope, the impact of these gains on the overall SH&C loads is relatively small compared to other factors such as fabric quality, ventilation and infiltration rates. Therefore the maximum variation of 6920 kWh, caused by including or not the gains due to appliances and lighting, is considered to be small compared to the total average consumption for this dwelling which is 36,580kWh p.a.

On the other hand, the 12th model is a modern new-built high rise flat, constructed according to the latest insulation standards and with low room volumes. For this model, the electrical consumption due to lighting and appliances plays a major role in the energy requirement for thermal comfort satisfaction. In the High gains scenario the overall cooling demand is much higher than the heating one. The same applies to the 9th and 10th models of this database. This is of critical importance for a Northern European climate where no cooling systems are traditionally used. It is shown that for the new-built small dwellings the expanding number of appliances used by the occupants on a daily basis is responsible to a large extent for the emerging cooling requirement in these climates.

To identify some general trends for the category that each house represents, Figure 23 shows the same results in normalised space heating (NSH) and cooling (NSC) demands (kWh/m^2). It is shown that the heat dissipation from appliances can reduce the annual heating demands of these dwellings (compared to the 'zero gains' scenario) around 31.5 - 64.2 kWh/m^2. The same comparison but with regards to the cooling demand shows a greater variation of this effect within the database; the maximum increase of the cooling demand is between 2 -95 kWh/m^2, again comparing with the dwellings modelled without gains. For models 9, 10 and 12 the gains due to electrical appliances are significant in the gains/losses balance and therefore the use of the *Actual High* gains profiles in these models results in relatively high cooling demands as shown in Figure 23.

5.1.1.2 THE IMPACT OF VARIOUS HEAT GAINS PROFILES ON SYSTEM SIZING

The overall heating and cooling demands determine the total energy consumption of the dwellings and hence the impact on carbon emissions released for this reason, but the actual size of the SH&C system suitable for each dwelling depends on the anticipated peak heating and cooling demands. The interest here is to identify the potential error which exists in predictions using only average profiles. The results show that if the two extreme profiles are used for the 12 models (*Actual High* and

Actual Low gains) the maximum difference in peak demands is of 0.61kW (3rd model) with an average value of 0.29kW within the whole database.

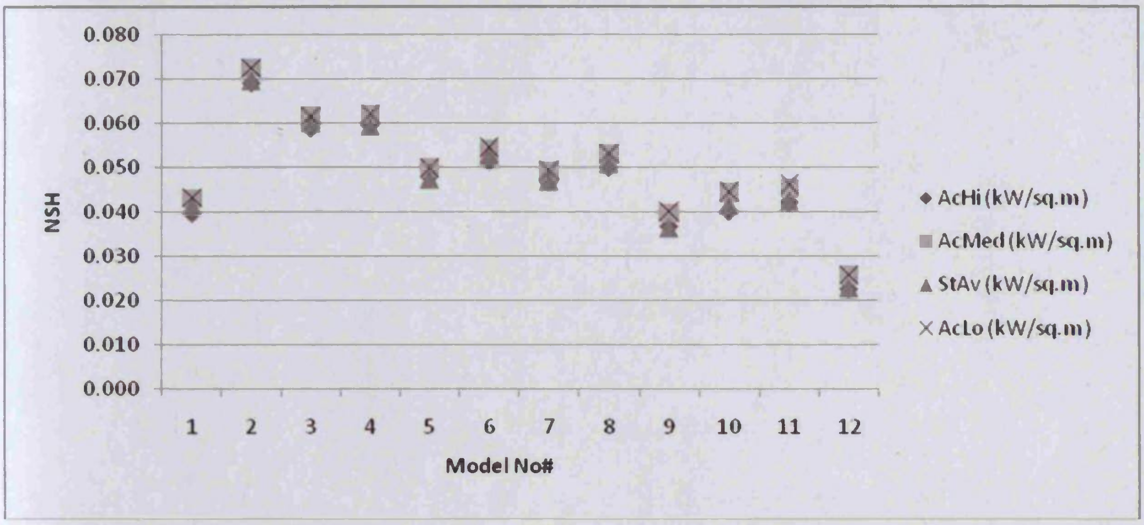


FIGURE 24: PEAK NORMALISED SPACE HEATING (NSH) DEMANDS (KW/SQ.M) FOR THE 12 HOUSE TYPES AND FOR A RANGE OF INTERNAL GAIN PROFILES (ACTUAL HIGH, ACTUAL MEDIUM, STANDARD AVERAGE AND ACTUAL LOW GAINS).

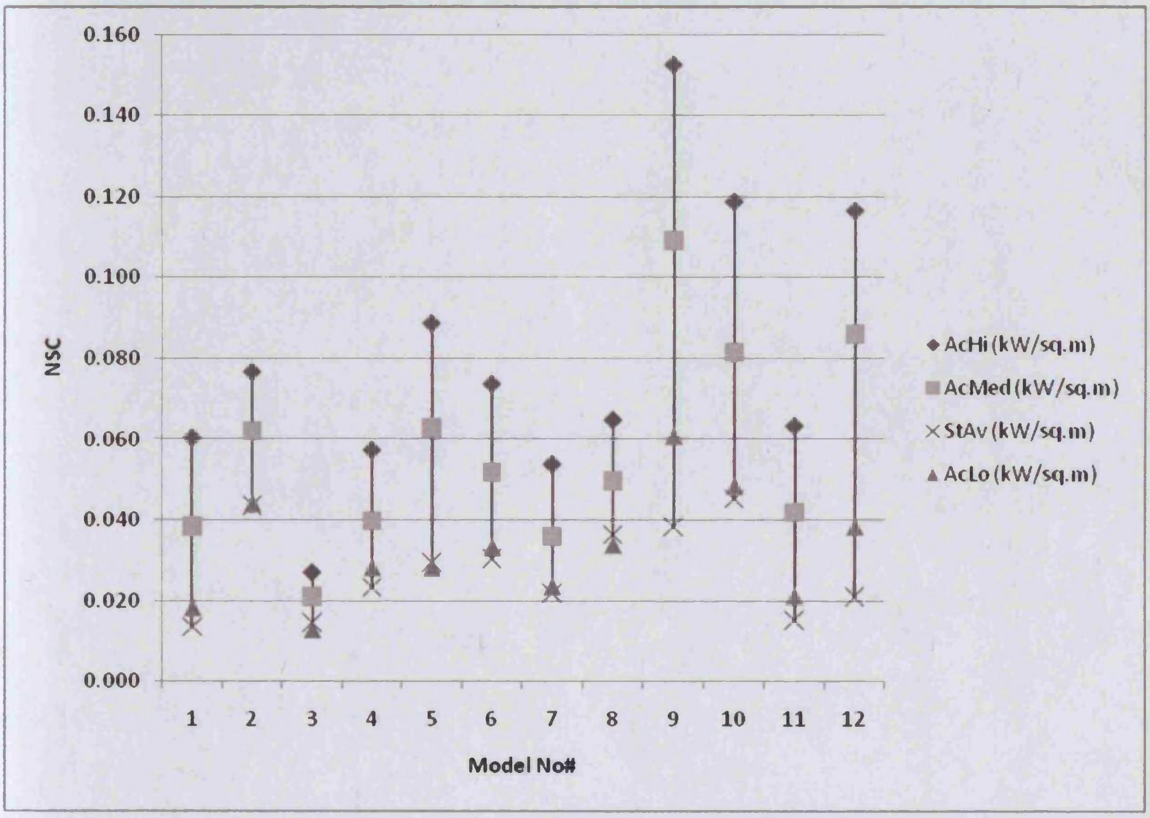


FIGURE 25: PEAK NORMALISED SPACE COOLING (NSC) DEMANDS (KW/SQ.M) FOR THE 12 HOUSE TYPES AND FOR A RANGE OF INTERNAL GAIN PROFILES (ACTUAL HIGH, ACTUAL MEDIUM, STANDARD AVERAGE AND ACTUAL LOW GAINS).

Thus, Figure 24 shows that the actual size of the heating system required for any of the house types will not change significantly if low, medium or high consumption profiles, actual or average, are used in the predictions. However the analysis reveals that regarding the NSC the findings are different. Figure 25 shows that if a non-realistic assumption regarding the gains due to appliances and lighting is made in the simulations, the predicted cooling system can be seriously oversized or downsized. In addition, the simulations show that the use of the *Standard Average* profile brings similar results to the use of the *Actual Low* profile. In the predictions, the use of the correct actual profile would ensure that the likely extremes of internal gains from electrical demands are taken into account both at a daily and at an annual basis and the proposed cooling system would operate effectively

5.1.1.3 THE EXAMPLES OF MODELS 3 AND 12

At the next stage the contribution that the internal gains have on the heating and cooling demands of the 3rd and the 12th models is investigated in more detail. Figure 26 and Figure 27 show the share of the heating demand (as calculated for the reference case, no gains) met by the internal gains, with 3 types of profiles used; *Actual High, Actual Low* and *Actual Medium.*

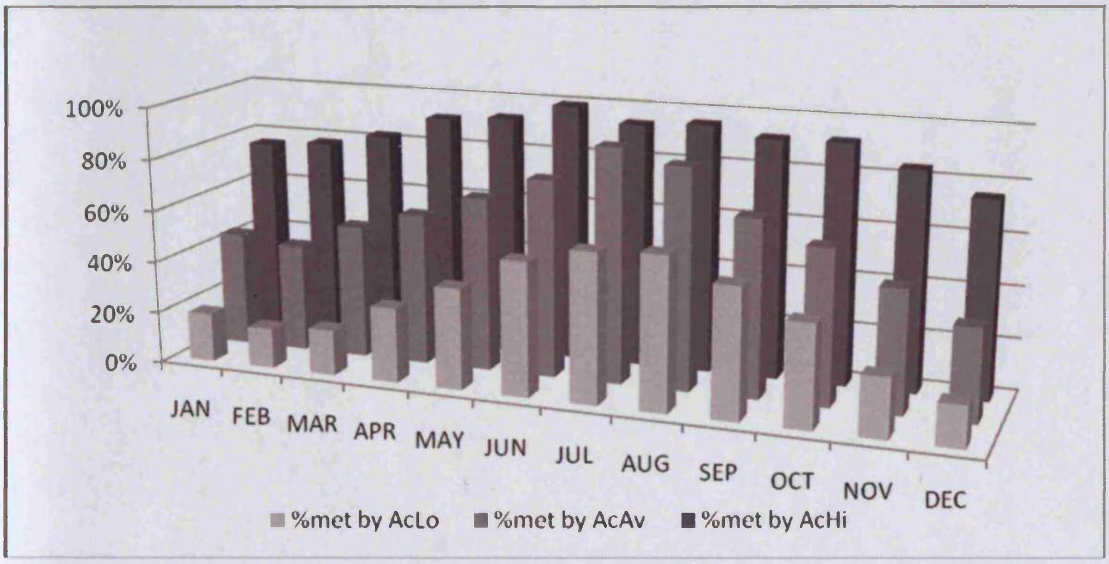


FIGURE 26: SHARE OF THE MONTHLY HEATING DEMAND OF DWELLING NO# 12 MET BY THE INTERNAL GAINS; FOR THREE ACTUAL INTERNAL GAIN PROFILES.

For the post-2006 flat the reduction with *Actual medium* gains is around 60% on average per month. For the 1850 – 1919 Semi detached house model with including

Actual High gains the monthly heat load is reduced at an average of 20% compared to the no-heat gains model.

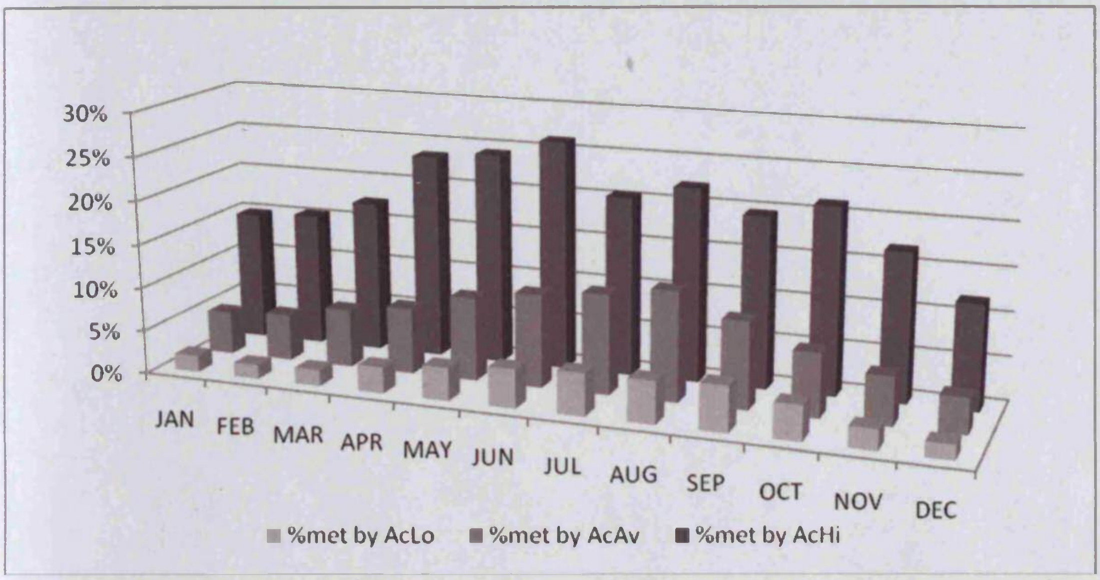


FIGURE 27: SHARE OF THE MONTHLY HEATING DEMAND OF DWELLING NO #3 MET BY THE INTERNAL GAINS; FOR THREE ACTUAL INTERNAL GAIN PROFILES.

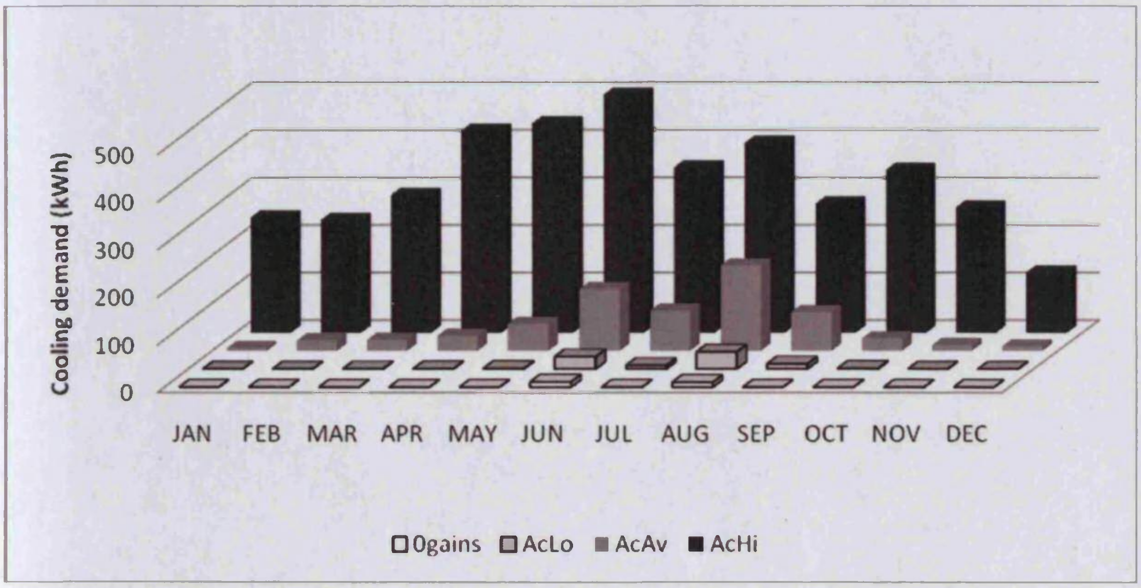


FIGURE 28: IMPACT OF INTERNAL GAINS ON THE MONTHLY COOLING DEMANDS FOR DWELLING NO #12; FOR THREE ACTUAL INTERNAL GAIN PROFILES AND A ZERO-GAINS CASE.

The impact of the use of the three actual profiles on the cooling demand for dwellings 3 and 12 compared to the reference case calculated with no gains is shown in Figure 28 and in Figure 29. It is apparent that the post-2006 flat is more sensitive to changes in internal gains than the 1850-1919 semi-detached house.

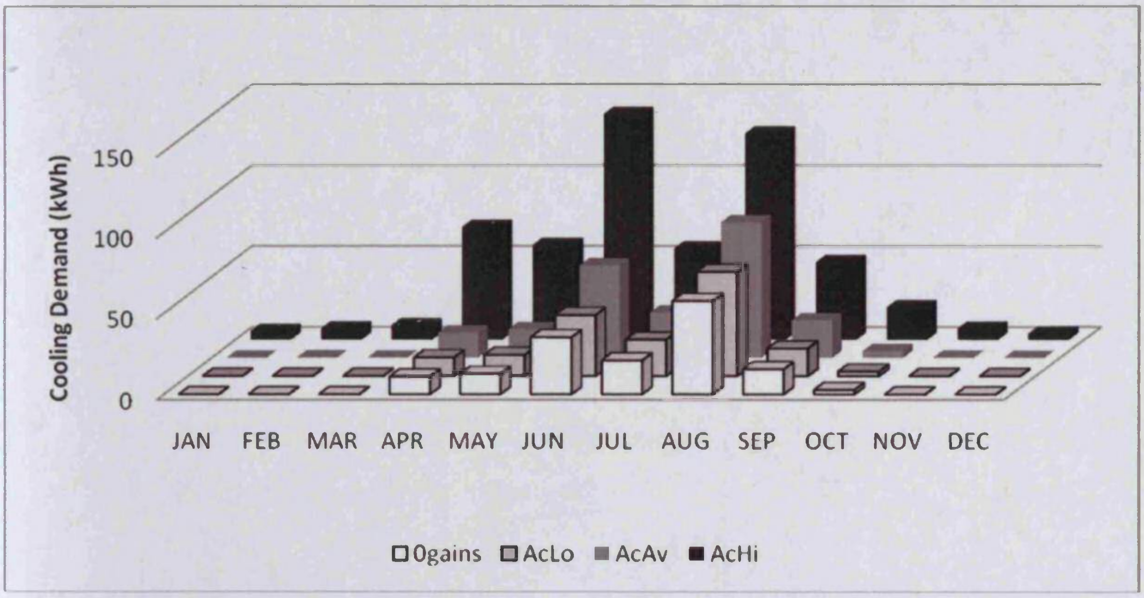


FIGURE 29: IMPACT OF INTERNAL GAINS ON THE MONTHLY COOLING DEMANDS FOR DWELLING NO#3; FOR THREE ACTUAL PROFILES AND A ZERO-GAINS CASE.

5.1.1.4 CONCLUSIONS

The internal gains from appliances and lighting have an effect on the heating and cooling demands across all house ages and types. These effects are more marked in more recent heavily insulated housing. It was shown that, in particular, for new-built high rise flats in the UK a significant share of the total heating demand can be met solely by the gains due to lighting and appliances. For the summer months these gains can result in a significant cooling requirement for these dwellings.

It is also highlighted that the variation of internal gains actually found in practice can in itself be problematic when trying to decide which one is appropriate for use. It is therefore shown that for new buildings which are intended to meet the needs of the forthcoming low energy era the use of a range of internal gains is necessary to ensure the final designs have robustness to a range of possible occupancies.

5.2 ANNUAL THERMAL ENERGY REQUIREMENTS FOR SH, SC AND DHW

Table 16 shows the predicted annual heat requirements for SH&C[20] for the 12 dwellings and the heat required for DHW needs (as taken from Annex 42). Four cases per house type are calculated by varying the weather and comfort conditions:

- The weather data used in the calculations is either the TMY2 or the 2007 actual year data (MET).
- Both constant and intermittent thermal comfort maintenance on a daily basis are considered.

It can be seen that the comfort strategy affects significantly the SH requirement in most dwellings; for example model 2 and 4 show a doubling of the SH between the Intermittent and continuous comfort maintenance scenarios. That is something that should be kept in mind while interpreting the ST potential presenting in the following paragraphs. A 30% share on the intermittent comfort (IntComf) scenario could mean fewer kilowatt-hours saved compared to the continuous comfort (ContComf) scenario.

Table 17 presents the normalised annual heat requirement for SH, SC and DHW in kWh per m^2 of living space. The NSH requirements, as calculated with average weather data for 24/7 use of the heating system, range between 43kWh/m^2 (Post 2006 flat) and 242kWh/m^2 (Pre-1850 converted flat). The NSH requirement for intermittent comfort maintenance and with average weather data is significantly lower, varying between 30-138 kWh/m^2 within the database. With the use of the actual-year weather data in the simulations the results are very different from those predicted with the tmy2 data, as 2007 was a warmer than average year for Cardiff (see 4.4).

[20] Note that the thermal requirement for SC has been converted to a <u>heat</u> requirement with the thermal to cold thermal efficiency for the chiller at 0.6 applied.

TABLE 16: ANNUAL HEAT REQUIREMENT FOR SH, SC & DHW OF THE 12 DWELLINGS. PREDICTED FOR TWO TYPES OF COMFORT (INTERMITTENT AND CONSTANT COMFORT MAINTENANCE) AND WITH AVERAGE (TMY2) AND ACTUAL (MET 2007) WEATHER DATA.

No	Dwelling type	Space Heating (kWh)				Space Cooling kWh)				DHW (kWh)	Total (kWh)			
		Tmy2		met		Tmy2		met			Tmy2		met	
		IntComf	ContComf	IntComf	ContComf	IntComf	ContComf	IntComf	ContComf		IntComf	ContComf	IntComf	ContComf
1	Pre-1850 det. house	8,171	11,438	5,384	7,637	23	48	109	173	2227	10,422	13,712	7,720	10,036
2	Pre-1850 converted Flat	13,557	25,072	9,385	17,789	61	133	517	747	2227	15,846	27,431	12,128	20,763
3	1850-1919 semi-det. house	30,337	49,862	20,339	34,370	255	679	1926	2813	2227	32,819	52,766	24,492	39,410
4	1920-1944 semi-det. house	12,102	22,109	8,166	15,320	1,173	2,726	2,635	4,547	2227	15,501	27,062	13,029	22,090
5	1945 - 1964 low-rise flat	6,441	9,101	4,267	6,115	74	105	442	548	2227	8,742	11,430	6,936	8,888
6	1945-1964 semi-det. house	8,995	15,697	5,902	10,744	1,218	2,365	2,440	3,861	2227	12,441	20,289	10,569	16,832
7	1965-1980 det. house	10,986	17,634	7,096	11,714	48	114	282	462	2227	13,261	19,974	9,605	14,403
8	1965-1980 mid-terrace house	10,893	16,643	6,975	10,896	52	84	740	887	2227	13,171	18,953	9,941	14,010
9	1981-1999 low-rise flat	2,262	3,701	1,420	2,404	547	786	1,348	1,703	2227	5,036	6,714	4,996	6,335
10	1981-1999 mid-terrace house	4,173	6,110	2,544	3,811	135	210	677	817	2227	6,535	8,547	8,545	6,855
11	2000-2006 semi-det. house	7,391	10,836	5,390	8,093	17	40	41	93	2227	9,635	13,100	7,658	10,412
12	Post-2006 high-rise flat	1,696	2,480	904	1,376	272	326	721	810	2227	4,195	5,033	3,852	4,413

TABLE 17: NORMALISED HEAT REQUIREMENT FOR SH, SC & DHW OF THE 12 DWELLINGS. PREDICTED FOR TWO TYPES OF COMFORT (INTERMITTENT AND CONSTANT COMFORT MAINTENANCE) AND WITH AVERAGE (TMY2) AND ACTUAL (MET 2007) WEATHER DATA.

No	Dwelling type	Space Heating (kWh/m2)				Space Cooling kWh/m2)				DHW (kWh)	Total (kWh/m2)			
		Tmy2		met		Tmy2		met			Tmy2		met	
		IntComf	ContComf	IntComf	ContComf	IntComf	ContComf	IntComf	ContComf		IntComf	ContComf	IntComf	ContComf
1	Pre-1850 det. house	94	131	62	88	0	1	1	2	2227	119	157	88	115
2	Pre-1850 converted flat	131	242	91	172	1	1	5	7	2227	153	265	117	201
3	1850-1919 semi-det. house	138	227	92	156	1	3	9	13	2227	149	240	111	179
4	1920-1944 semi-det. house	130	237	88	164	13	29	28	49	2227	166	290	140	237
5	1945 - 1964 low-rise flat	98	138	65	93	1	2	7	8	2227	133	174	106	135
6	1945-1964 semi-det. house	101	176	66	120	14	27	27	43	2227	140	228	119	189
7	1965-1980 det. house	94	151	61	100	0	1	2	4	2227	114	171	82	123
8	1965-1980 mid-terrace house	103	158	66	103	0	1	7	8	2227	125	180	94	133
9	1981-1999 low-rise flat	51	83	32	54	12	18	30	38	2227	113	150	112	142
10	1981-1999 mid-terrace house	75	109	46	68	2	4	12	15	2227	117	153	153	123
11	2000-2006 semi-det. house	99	145	72	108	0	1	1	1	2227	129	175	102	139
12	Post-2006 High-rise Flat	30	43	16	24	5	6	13	14	2227	73	88	67	77

The specific SH requirement for intermittent and constant thermal comfort for year 2007 ranges between 16-92 kWh/m^2 and 24-172 kWh/m^2 respectively. For the predictions of that year, a maximum cooling demand of 49kWh/m^2 is calculated for the continuous comfort scenario (1920-1944 semi-detached house).

As shown in Table 17 conclusions relating the date-of-build and the thermal behaviour of the dwellings cannot be drawn from this sample. That can be partially explained by the fact that some of these dwellings have been altered since construction and therefore are not strictly representative of that era. That is the case e.g. for the Pre-1850 detached house, which is found to be much more energy efficient than the same era Pre-1850 converted flat.

5.3 SOLAR ENERGY AVAILABILITY

Before analysing the results at a smaller timestep, the solar energy availability for the dwellings of this database is presented. The theoretical solar yield that could be "captured" from the collector units accommodated on the external surfaces of the dwellings is investigated in this section. As explained in the methodology the interest at this stage is on the solar yield rather than the system yield. Nevertheless it is actually the collectors' yield that equals to the maximum amount of available energy that would pass to the ST delivery system. It was appreciated that the use of the incident solar energy would result in unrealistic estimations and therefore it was decided that it is reasonable to use the collectors' yield in this initial mismatch assessment.

The collector considered in this study is a Direct Flow evacuated tube collector (THERMOMAX, 2005) which was part of the STACS project. Thermomax Ltd is the only UK manufacturer of VT collectors (now part of the Kingspan Group PLC), and since 1994 a production unit exists in Blackwood, Wales. The Thermomax VT collector is the only VT registered with the Low Carbon Building Program Phase 2. It was therefore considered that the specific collector type would be a possible candidate for solar systems in this location, considering also the climatic characteristics which necessitate the use of highly efficient absorbers. The gross area of each collector unit is 4.245 m^2 (1.996mX2.127m) and the absorber area per unit is 3.02m^2. The collector's performance has been tested within the STACS project and Table 18 (KNIGHT, I. et al., 2008a) presents the efficiency data for different angles of inclination. The table shows that for a tilt of 15° from vertical (75° from horizontal) the efficiency at 0.8531 is very close to the maximum (0.9 for 45° tilt). Incident solar energy on a steep collector tilt will be slightly higher in winter, when comparing to a 45° tilt, due to the lower sun position.

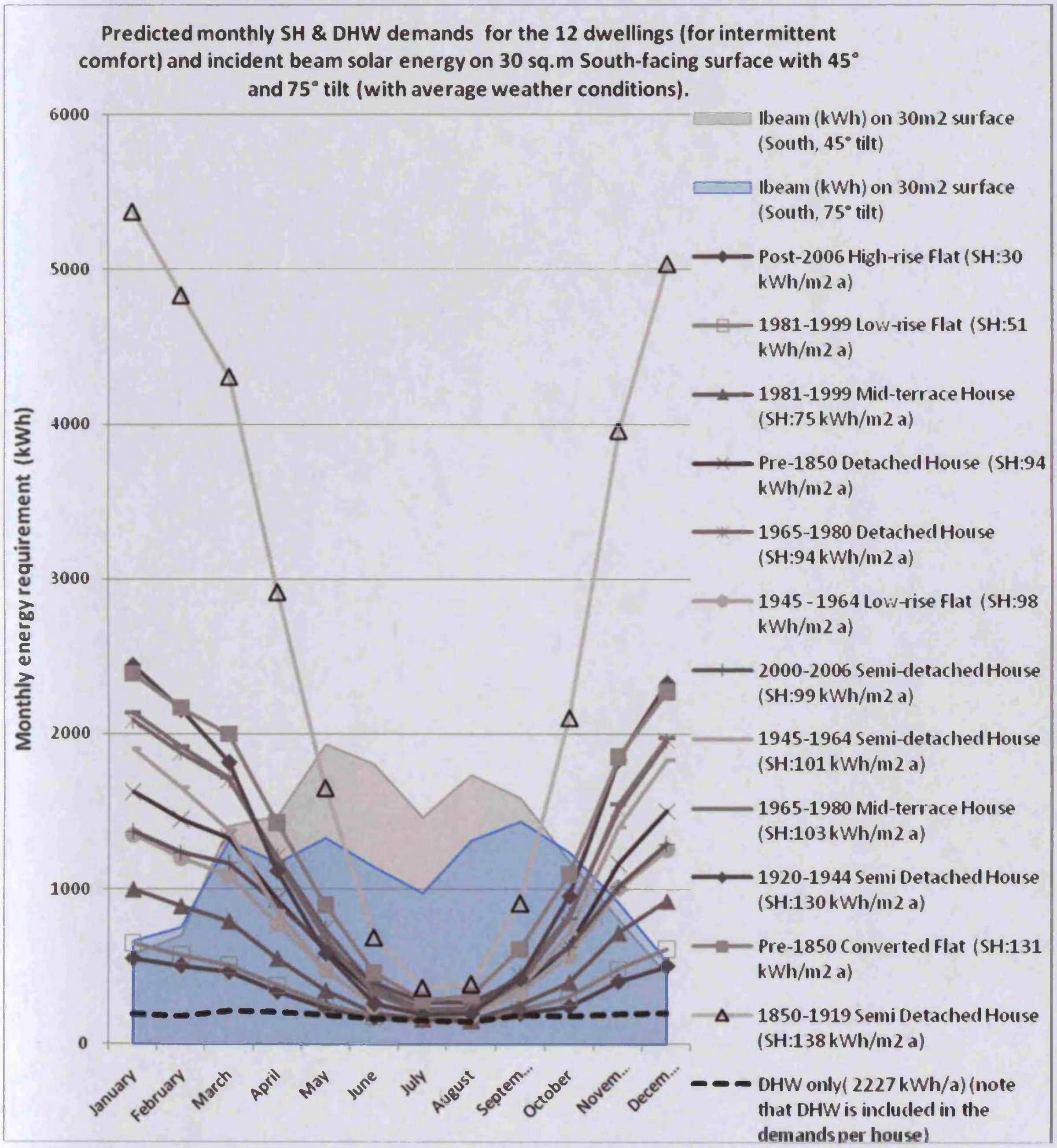


FIGURE 30: PREDICTED MONTHLY SH & DHW DEMANDS FOR THE 12 DWELLINGS AND INCIDENT BEAM SOLAR ENERGY ON 30 SQ.M SOUTH FACING SURFACE WITH 45° OR 75° TILT (FOR INTERMITTENT COMFORT AND AVERAGE WEATHER CONDITIONS).

TABLE 18: COLLECTOR EFFICIENCY VARYING WITH ANGLE OF INCLINATION TO THE VERTICAL (KNIGHT, I. ET AL., 2008A).

Irradiance (W/m^2)	Mass Flowrate (Kg/min)	Inclination Angle to the vertical (°)	Efficiency
626	6.24	0	0.686
626	6.24	15	0.8531
626	6.24	30	0.7552
626	6.24	45	0.9
626	6.24	60	0.7802
626	6.24	75	0.781

TABLE 19: NUMBER OF POTENTIAL COLLECTOR UNITS, ROOF TILTS AND AZIMUTHS, AND TOTAL COLLECTOR YIELD VS TOTAL HEAT ENERGY (SH, SC & DHW) REQUIRED PER HOUSE TYPE (PREDICTED FOR VARIOUS COMFORT AND WEATHER CONDITIONS).

No	Dwelling type	1. No Units/ azimuth/ tilt	2. No Units/ azimuth/ tilt	3. No Units/ azimuth / tilt	4. No Units/ azimuth / tilt	5. No Units/ azimuth / tilt	6. No Units/ azimuth / tilt	Total yield (kWh)	Total energy required		Weather data
									ConComf	IntComf	
1	Pre-1850 det. house	3 units/ S / (35°)	2 units/ S/ (35°)	-	-	-	-	5,323	13,712	10,422	Tmy2
								7,566	10,036	7,720	met
2	Pre-1850 converted flat	6 units/ S +15°/ (46°)	7 units/ E +15°/ (34°)	7 units/ W+15°/ (34°)	-	-	-	16,201	27,431	15,846	Tmy2
								23,172	20,763	12,128	met
3	1850-1919 semi-det. house	2 units/ E /(28°)	2 units/ S/ (28°)	4 units/ E /(26°)	4 units/ S /(50°)	6 units/ S /(31°)	8 units/ S /(50°) *	24,129	52,766	32,819	Tmy2
								33,482	39,410	24,492	met
4	1920-1944 semi-det. house	3 units/ NW / (38°)	3 units/ SE/ (38°)	4 units/ horizontal	-	-	-	7,434	27,062	15,501	Tmy2
								10,709	22,090	13,029	met
5	1945 - 1964 low-rise flat	2 units/ W–10°/ (90°)	3 units/ E – 10°/ (90°)	-	-	-	-	2,265	11,430	8,742	Tmy2
								3,741	8,888	6,936	met
6	1945-1964 semi-det. house	6 units/ S/ (40°)	-	-	-	-	-	6,428	20,289	12,441	Tmy2
								9,155	16,832	10,569	met
7	1965-1980 detached house	8 units/ S/ (29°)	-	-	-	-	-	8,370	19,974	13,261	Tmy2
								11,182	14,403	9,605	met
8	1965-1980 mid-terrace house	4 units/ W +5°/ (26°)	4 units/ E +5°/ (26°)	3 units/ horizontal	-	-	-	7,760	18,953	13,171	Tmy2
								10,893	14,010	9,941	met
9	1981-1999 low-rise flat	4 units/ E /(14°)	4 units/ W/(14°)	-	-	-	-	6,316	6,714	5,036	Tmy2
								8,972	6,335	4,996	met
10	1981-1999 mid-terrace house	4 units/ W +5°/ (29°)	4 units/ E +5°/ (29°)	-	-	-	-	5,991	8,545	6,535	Tmy2
								8,682	6,855	5,448	met
11	2000-2006 semi-det. house	4 units/ S / (46°)	-	-	-	-	-	4,276	13,100	9,635	Tmy2
								6,106	10,412	7,658	met
12	Post-2006 high-rise flat	2 units/ NW / (90°)	4 units/ NE / (90°)	-	-	-	-	1,000	5,033	4,195	Tmy2
								1,392	4,413	3,852	met
(*units accommodated above garage)											

Both facts suggest that a 75° tilt from horizontal is a good option for ST systems with VT collectors, reducing also the stagnation risk in summer. Figure 30 shows the predicted thermal demands per house type in contrast to the incident beam solar energy on a 30m² South-facing surface with 45° or 75° tilt, highlighting this aspect. However in the UK usually non-flat roofs are available and therefore the collectors' tilt would be dictated by the building's geometry.

It is appreciated that in any case thecollector yield would clearly depend on the geometry of the house e.g. roof size, orientation and overshadowing as mentioned in 4.2. For flats 2 and 9 the total roof area of the building is assumed to be available for use of these flats (top floor flats). For flats 5 and 12 it is unknown what share of the building's roof or terrace could be used, therefore only vertical collectors are assumed to be mounted on external walls. As it has been shown by Iqbal and Janke et al (IQBAL, M., 1981) if vertical surfaces facing off-south and south are compared, the off-south orientation receives higher daily insolation levels during the summer months, although on a yearly basis south orientations are the most favourable. That could be of importance for a dwelling similar to flat #12 which has a relatively smooth demand throughout the year and a considerable cooling demand during summer as it will be shown below, if only DHW and cooling applications are fed with ST. For the houses all the roof areas (except those facing north) are considered as suitable, but no vertical external surfaces are used.

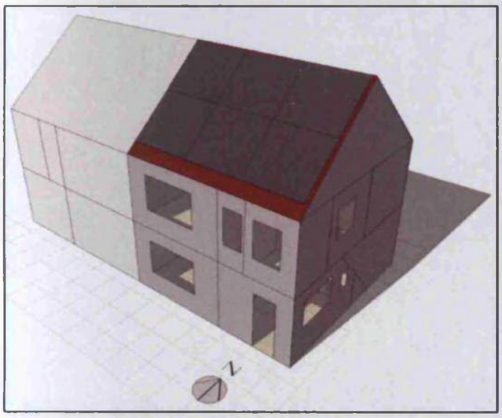


FIGURE 31: EXAMPLE SHOWING THE AMOUNT OF ROOF THAT CANNOT BE USED FOR COLLECTOR MOUNTING (RED AREA) IN THE 1945-1964 SEMI-DETACHED HOUSE (MODEL NO#6).

By using the maximum number of VT collector units that can be physically accommodated within the boundaries of each roof, the potential collectors' yield for each house was calculated and is shown in table 18. It was found by manual assessment that a significant part of the roofs of the models cannot be used for collector mounting, due to the fact that the specific collector type comes in a standard size (see Figure 31). That means that in practice some roof space will be covered by common roof material as no odd custom-sized collector elements would be available. Figure 32 presents the percentage of roof area (or external wall area for models 5 &12) that remains unused for the 12 houses. This figure reveals that if more collectors' sizes become available in the future, then a larger solar thermal yield could be achieved.

The overshadowing analysis for the collector surfaces was done in Ecotect. The results revealed the portion of the total collectors' area which remains non-shaded for every hour of the year and it was calculated for each available roof (non-shade parameter). The incident direct solar radiation for each surface was then calculated in TRNSYS in Kj/[hr.m2], using the same components that read the weather data and calculate the solar radiation for use by the building component (see Figure 18). It has to be underlined that in this analysis only the incident beam energy is taken into account. It is unclear what share of the diffuse energy would be harvested by the collectors in practice, as the subject is not covered by the literature. Nevertheless, as shown by published test results on a number of flat plate and tubular collectors available in market (SRCC, 2009), in cloudy conditions the collector output for applications at 50°C - 80°C is nearly zero in most cases. According to the same database, some individual tubular collectors are able to use a substantial part of the available diffuse energy, especially in useful energy up to 50°C. However, due to lack of further information, the diffuse part of the available energy will be ignored at this stage, assuming that the results would slightly underestimate the actual potential, by ignoring the diffuse contribution.

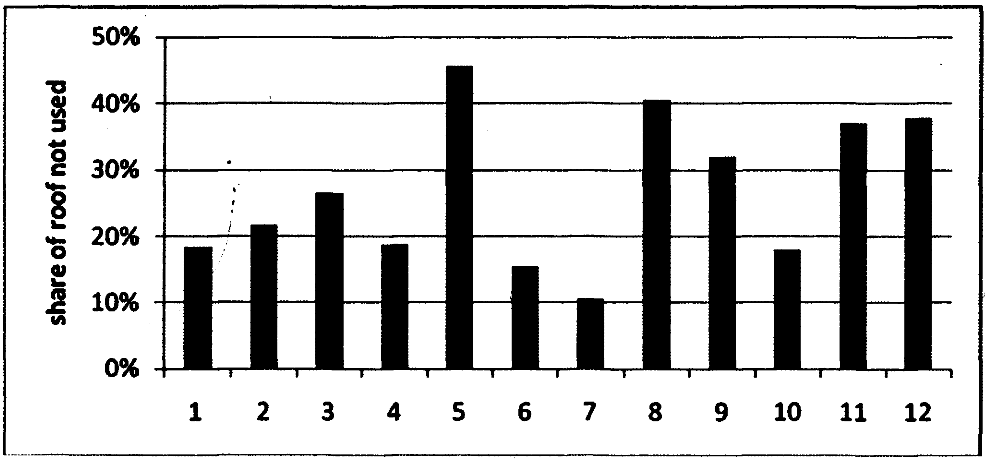


FIGURE 32: PERCENTAGE OF COLLECTOR-FREE ROOF AREA (OR EXT WALL AREA FOR 5 &12).

The collectors' yield used in the following analysis was adjusted with the non-shade parameter and with the efficiency of the collector which was taken as 0.7; an average value for the collector's efficiency was used for all different tilts, as a complex model for adjusting the efficiency based on the angle of incident would be otherwise required.

It is appreciated that by using a standard collector efficiency for all orientations an error is introduced in the calculation. As the collector in question is a tubular collector the actual incident energy on the collector array could be different from the incident energy on a flat surface with the same orientation, especially if a u-shaped absorber exists or if the inner tube is provided with an absorber coating ((GERMAN SOLAR ENERGY SOCIETY , 2005) p.26-27). At the moment detailed models exist for this reason and a TRNSYS model which applies the flat plate collector performance equations on the whole (tubular) absorber circumference (by 'breaking' it in small slices) and also takes into account shadowing effects occurring from the tubular parts of the array to each other has also been recently developed (SHAH, L. and Furbo, S., 2005). As the particular VT has a flat absorber the error from not using this model is avoided.

If a VT collector with a rounded absorber was used then a higher fraction of the incident radiation would be transmitted through the tubes absorbed there, as shown in Figure 33. For certain angles the sun rays would strike the FP collector at an angle different than normal while at the same time they would strike the tubes of the VT collector vertically. Energy could also be absorbed at the back of the tubes. For the specific VT type used in this work the tubes themselves can be rotated longitudinally up to 20° offering a greater level of flexibility regarding collector's orientation (KINGSPAN and Rayotec, 2008). Nevertheless modelling of this complexity was not considered as appropriate here, but based on the ideas described above it is believed that if tubular collectors were

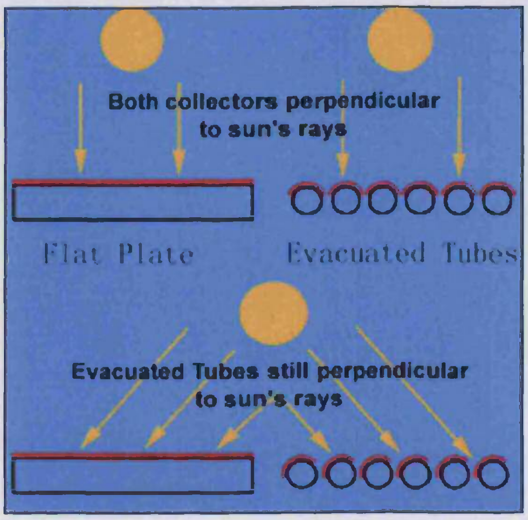


FIGURE 33: THE EFFECT OF INCREASED COLLECTOR YIELD IN THE CASE OF VT WITH ROUNDED ABSORBER (HTTP://WWW.HONGLESOLAR.COM/VACUUMSOLARTUBES.HTM).

employed in applications where collectors are orientated further than SE and SW, the performance could be less affected by this fact than in systems using FPs.

Only incident beam energy is taken into account in this analysis. In reality a part of the diffuse solar energy would also be usable and therefore it is expected that the predictions analysed here slightly underestimate the potential from this point of view.

5.4 MATCH-MISMATCH OF ENERGY DEMAND AND AVAILABILITY

5.4.1 MONTHLY BASIS

Figure 34, Figure 35 and Figure 36 contain 12 graphs, one for each of the 12 houses modelled, showing the monthly thermal energy requirement in relation to the monthly collectors' yield, for two comfort and weather conditions. The thermal requirement is for SH&C and DHW needs.

Year 2007 was a significantly warmer year than average for Cardiff and therefore the predicted SH demand is much lower than average and the solar energy availability calculated with this data is much higher. This comparison reveals a much larger potential for ST use as average temperatures increase. During 2007 for all house models apart from the Post-2006 flat (which has only vertical NW and NE facing collectors and therefore limited solar yield) the quantity of energy absorbed by the collectors on a monthly basis during the period April to September is higher than what is actually required for thermal comfort and DHW. For models 2, 3, 6, 7, 9, 10 this period is even longer, between March and October. It is appreciated that in reality only a share of this energy would be actually harvested by the solar installation, depending on the design and quality of the chosen system.

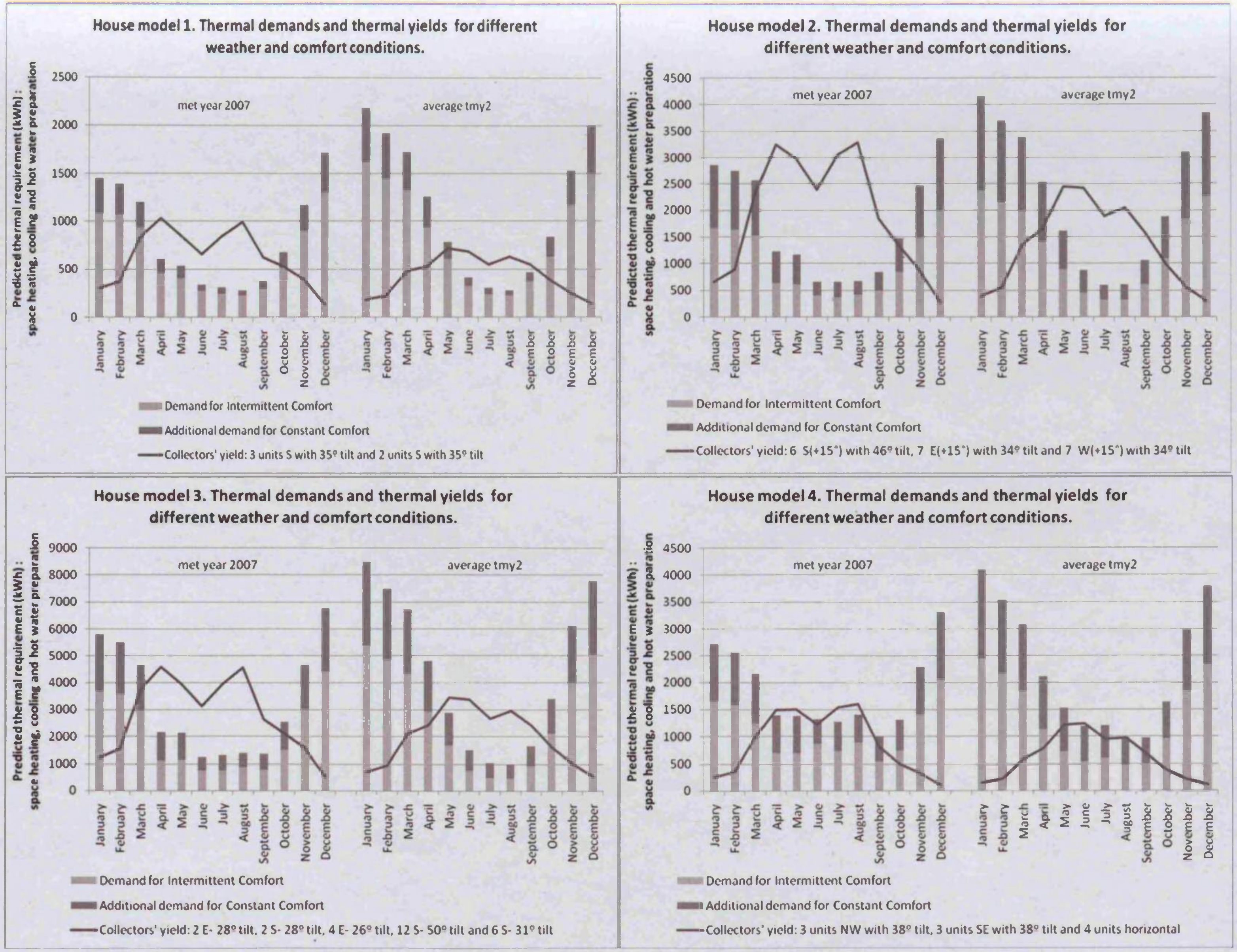


FIGURE 34: PREDICTED MONTHLY THERMAL DEMANDS AND COLLECTOR YIELDS FOR MODELS NO#1-4 (COLLECTOR EFFICIENCY AT 0.7, INCIDENT BEAM ENERGY ONLY).

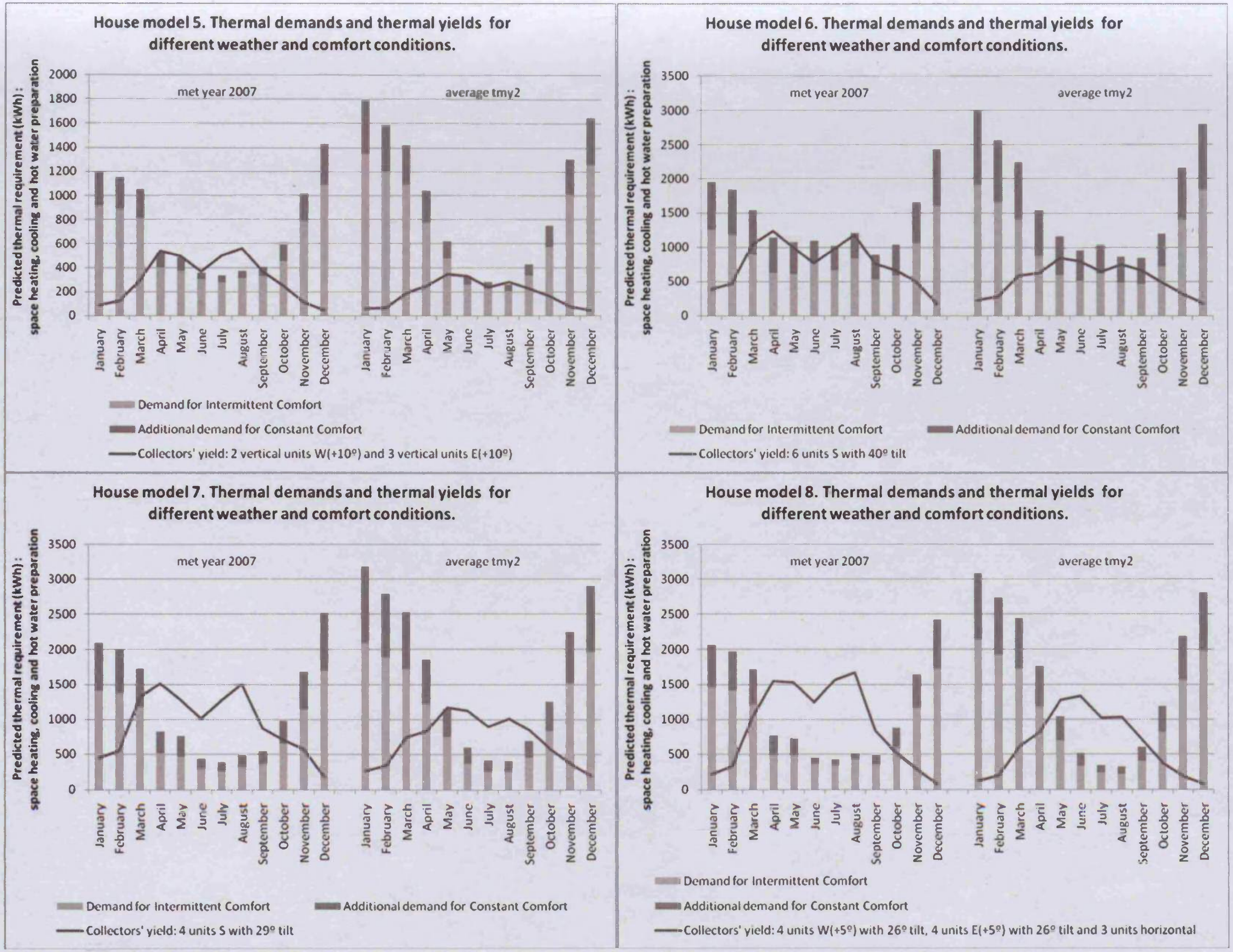


FIGURE 35: PREDICTED MONTHLY THERMAL DEMANDS AND COLLECTOR YIELDS FOR MODELS NO#5-8 (COLLECTOR EFFICIENCY AT 0.7, INCIDENT BEAM ENERGY ONLY).

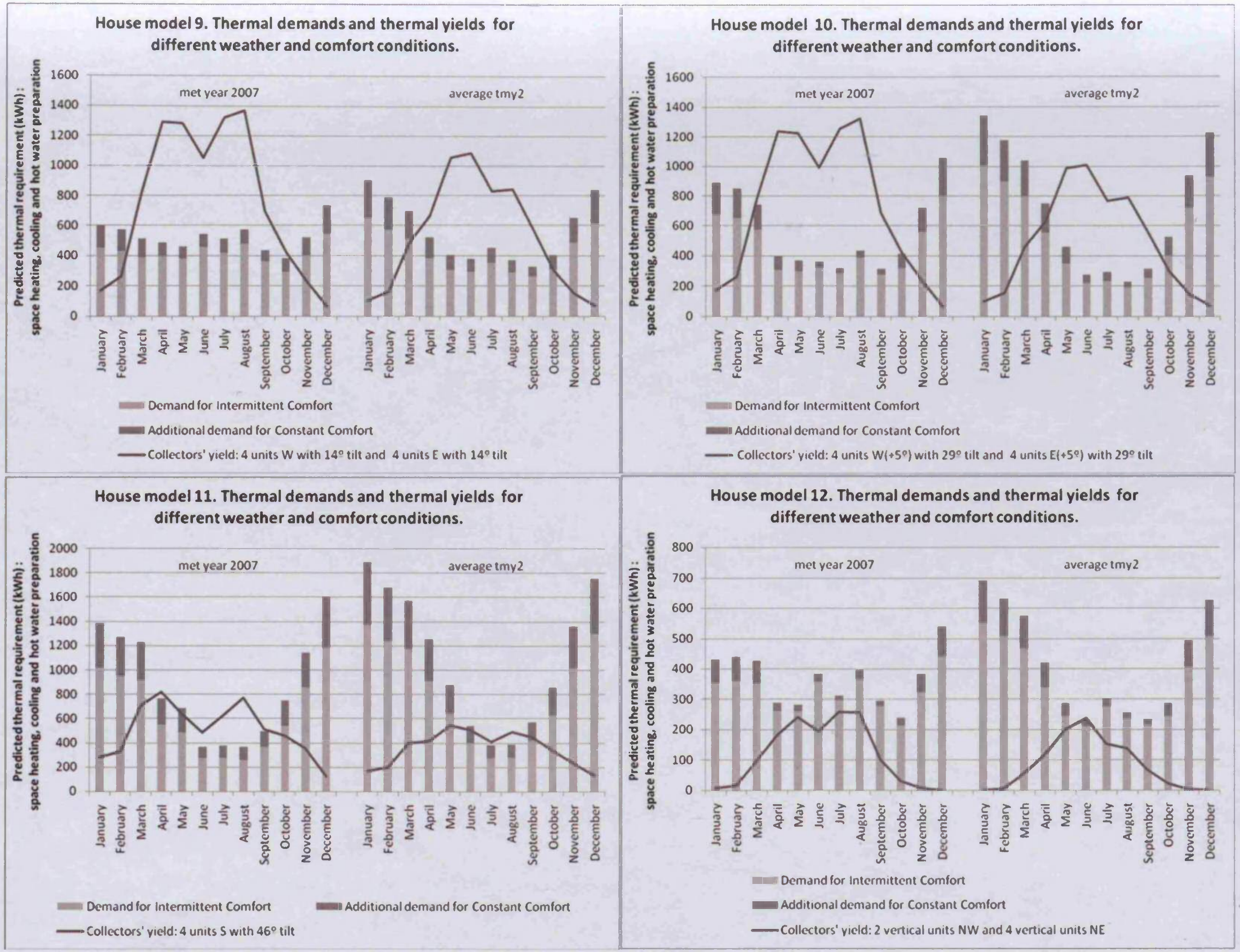
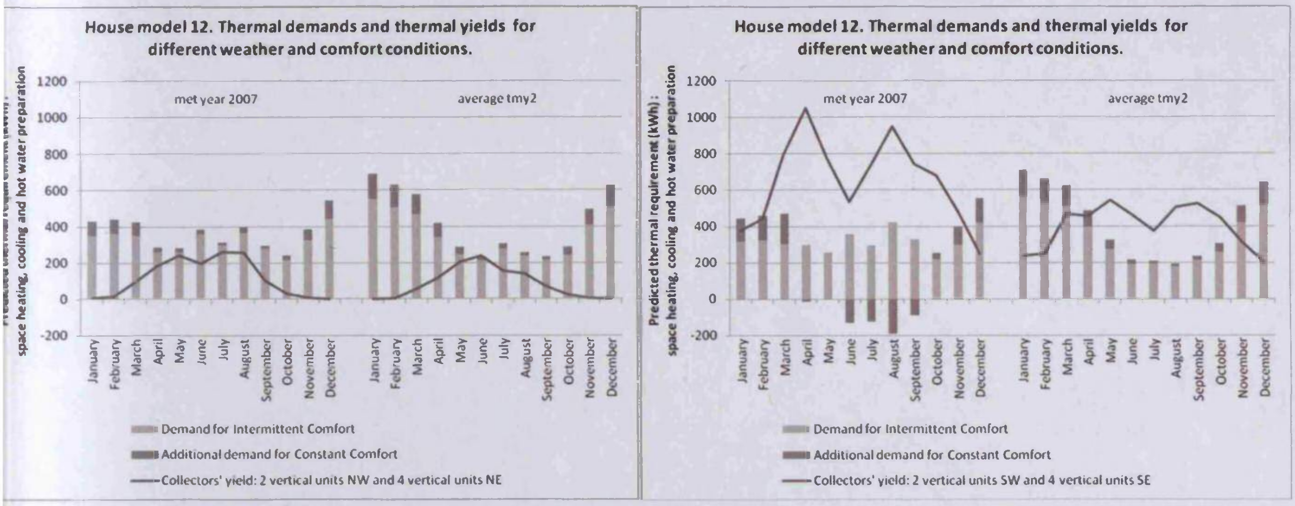


FIGURE 36: PREDICTED MONTHLY THERMAL DEMANDS AND COLLECTOR YIELDS FOR MODELS NO#9-12 (COLLECTOR EFFICIENCY AT 0.7, INCIDENT BEAM ENERGY ONLY).



IGURE 37: PREDICTED MONTHLY THERMAL DEMANDS AND COLLECTOR YIELDS FOR HOUSE MODEL IO#12 AS BUILT (LEFT) AND WITH AZIMUTH ROTATED BY 360 DEGREES (RIGHT)

The available roof area plays a major role on this match-mismatch assessment. The 12 houses are treated here as case studies i.e. orientated as built[21]. The solar yield in each house type is expected to vary significantly for different orientations while the predicted thermal energy requirement is expected to change only slightly, depending on the building envelope characteristics (building materials and size of openings). As an example the Post-2006 flat was modelled having its azimuth rotated 180 degrees. The NE and NW facades are now SE and SW. Figure 37 compares the two different cases for model 12, confirming the assumptions made above.

Figure 38 shows the relation between the total annual collectors' yield and the total annual thermal energy requirement per house type. As expected, and as shown in this figure the heating requirement for intermittent comfort maintenance is lower than that for constant comfort maintenance and therefore the potential savings for intermittent SH&C system use appears to be greater (as a percentage) than that for a 24/7 comfort maintenance. For some cases the collectors could absorb a large quantity of energy, up to 190% of the actual demand. In many cases the total annual collectors' yield appears to be adequate to cover the entire thermal energy requirement of the dwellings. In

[21] Modelling of a range of orientations per house type would be the subject of post-doctoral work as it was not possible to be done within the time limits of this PhD work.

reality this would be true if there were means of delivering and storing the solar energy 100% efficiently and without losses.

Again it has to be noted that this assessment shows a rough estimate of the solar thermal potential, since only the building and location characteristics are considered, ignoring the solar installation itself at this stage. Note also that no losses for the solar system are taken into account here, which are however included in the solar fraction concept. Therefore in the following paragraphs the term 'solar contribution' is used to describe the ratio of the solar energy *absorbed* by the ST system to the predicted space heating, cooling and DHW demand per house type in this simplified -energy quantities balancing- approach. That term is close to the FSC value described in 3.5.3, apart from the fact that includes the collector's efficiency.

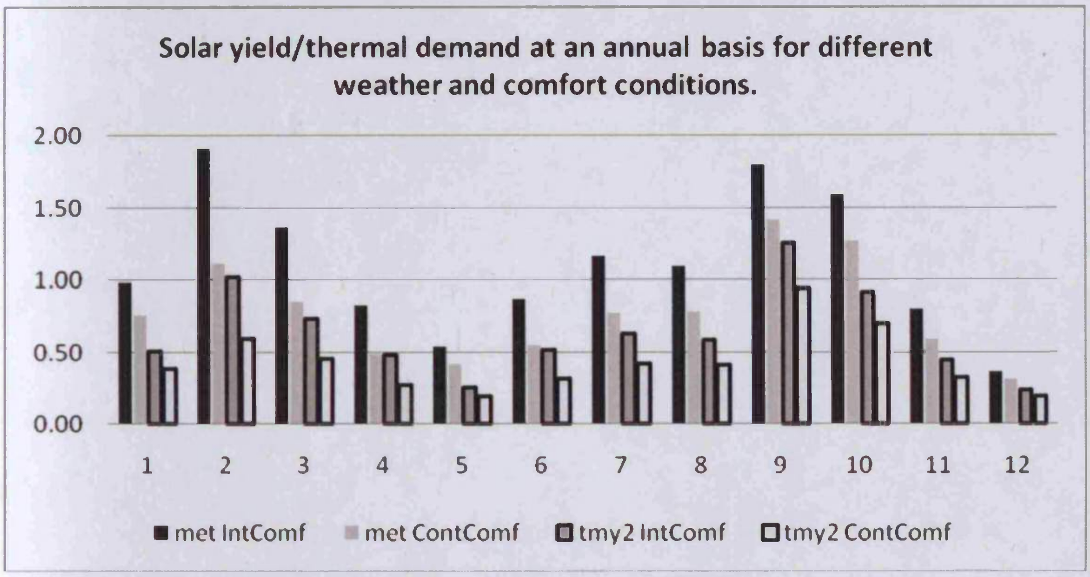


FIGURE 38: TOTAL ANNUAL SOLAR YIELD DIVIDED BY TOTAL ANNUAL THERMAL ENERGY REQUIREMENT FOR THE 12 MODELS; BOTH PREDICTED WITH AVERAGE AND ACTUAL WEATHER DATA AND FOR INTERMITTENT AND CONSTANT COMFORT MAINTENANCE.

5.4.2 HOURLY TIMESTEP

By looking now at the results using an hourly timestep, the match-mismatch of energy demand and supply is assessed for each one of the 12x4 case studies. Based on the analysis of these hourly profiles, Figure 39 shows the share of the annual thermal energy requirement that could be met directly by the collectors' yield for each house type. Thermal savings in the range of 9% to 34% could be achieved without considering some type of thermal energy storage (TES). Again this finding is based on the assumption that all energy absorbed by the collectors -70% of the incident- is delivered instantly and 100% efficiently by the solar system to the energy demand side. This is of course not accurate, as energy losses occur in many parts of the solar installation, not only from the store, and the energy is not necessarily delivered at adequate high temperatures. Nevertheless since the energy is not stored, the overall efficiency of the system would be higher compared to a system including a store.

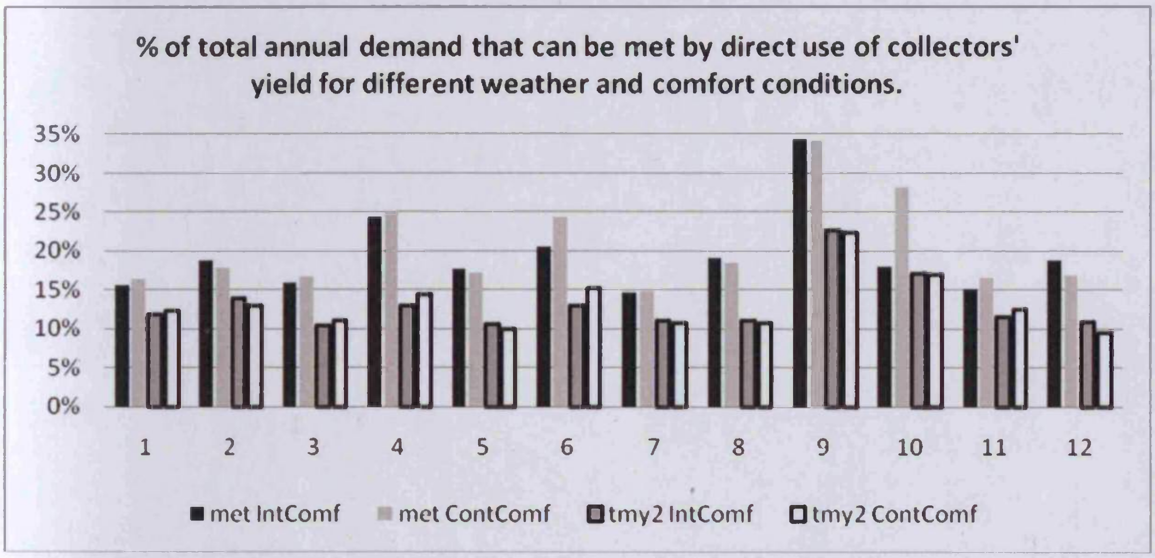


FIGURE 39: PERCENTAGE OF TOTAL ANNUAL THERMAL ENERGY REQUIREMENT MET BY DIRECT USE OF THE COLLECTOR YIELD (PREDICTED FOR 2 WEATHER AND 2 COMFORT CONDITIONS) PER HOUSE TYPE.

Figure 39 shows that for 7 out of the 12 dwellings the share of solar energy delivered to the systems instantaneously (without store) for constant comfort conditions would be either the same or even higher than that for intermittent comfort. This is explained by the energy mismatch occurring due to the scheduled comfort maintenance. At noon, when the solar irradiation incident on the collectors is at its daily maximum, the house remains unoccupied. For the intermittent comfort scenario the heating/cooling system would be switched off during that time (see also 4.8). That is more obvious for models 6 (1945-1964 Semi-detached House) and 10 (1981-1999 Mid-terrace House) when the actual 2007 weather data is used. For example, in house model 10, which has 12m^2 of East facing and 12m^2 of West facing collectors, all the energy absorbed by the East facing collectors is not used directly by the system and has to be stored. In solar combisystems' design this is something to be considered as in a case like this the energy could be introduced into the heat delivery system during the day and not fed into the store. The effectiveness of a scenario like this would depend on the occupants' presence patterns and the ability of the house envelope to store the heat for a certain period of time. Note also that the actual number of kilowatt-hours saved in each case depends on the thermal demand, which is always higher in the continuous comfort scenario. Nevertheless for house types 2, 5, 8, 9 and 12 the 'instantaneous' solar yield appears to be higher for intermittent rather than for continuous comfort conditions. For No#5 and No#12 the reason for this effect is the poor solar yield achieved (see also Figure 38 and Table 9) due to the limited- and vertically mounted- absorber area; it is reasonable in these cases that the lower demand would be better met by the solar system. In No#2, No#9 and No#12 the effect of the energy mismatch occurring due to the scheduled comfort maintenance is minimised as incident energy is distributed evenly across the day. That happens because there is a large horizontal or slightly inclined absorber area (see also Figure 38 and Table 9) and/or there is a variety of collector orientations. In these cases the comfort strategy used would make little difference on the 'instantaneous' solar yield.

5.4.3 CONSIDERING TES

Furthermore to the previous findings and as shown also with Figure 34, Figure 35, Figure 36and Figure 38 for some of the models there is an opportunity to achieve higher solar contributions with the use of medium and seasonal TES techniques. For a first investigation of this aspect, a simplified model including a store is used. The store is fed with excess solar energy (when no demand exists) and provides an energy back up when the sun is down. Initially it was assumed that no energy losses occur from the store, and that it's charged and discharged without reduction of the energy quality; the concept of an ideal system with highly efficient collectors producing hot water at adequately high temperatures to feed a perfectly stratified water tank with a perfect heat discharging mechanism.

For this assessment the store starts empty the 1st of March of the previous year, so that potential benefits from inter-seasonal thermal energy storage are revealed. The collector considered is the same for all house types and is south facing with a 45° tilt.

The incident energy is again multiplied with 0.7 (collector efficiency) to give the collector yield. No energy losses from the system are taken into account at this stage.

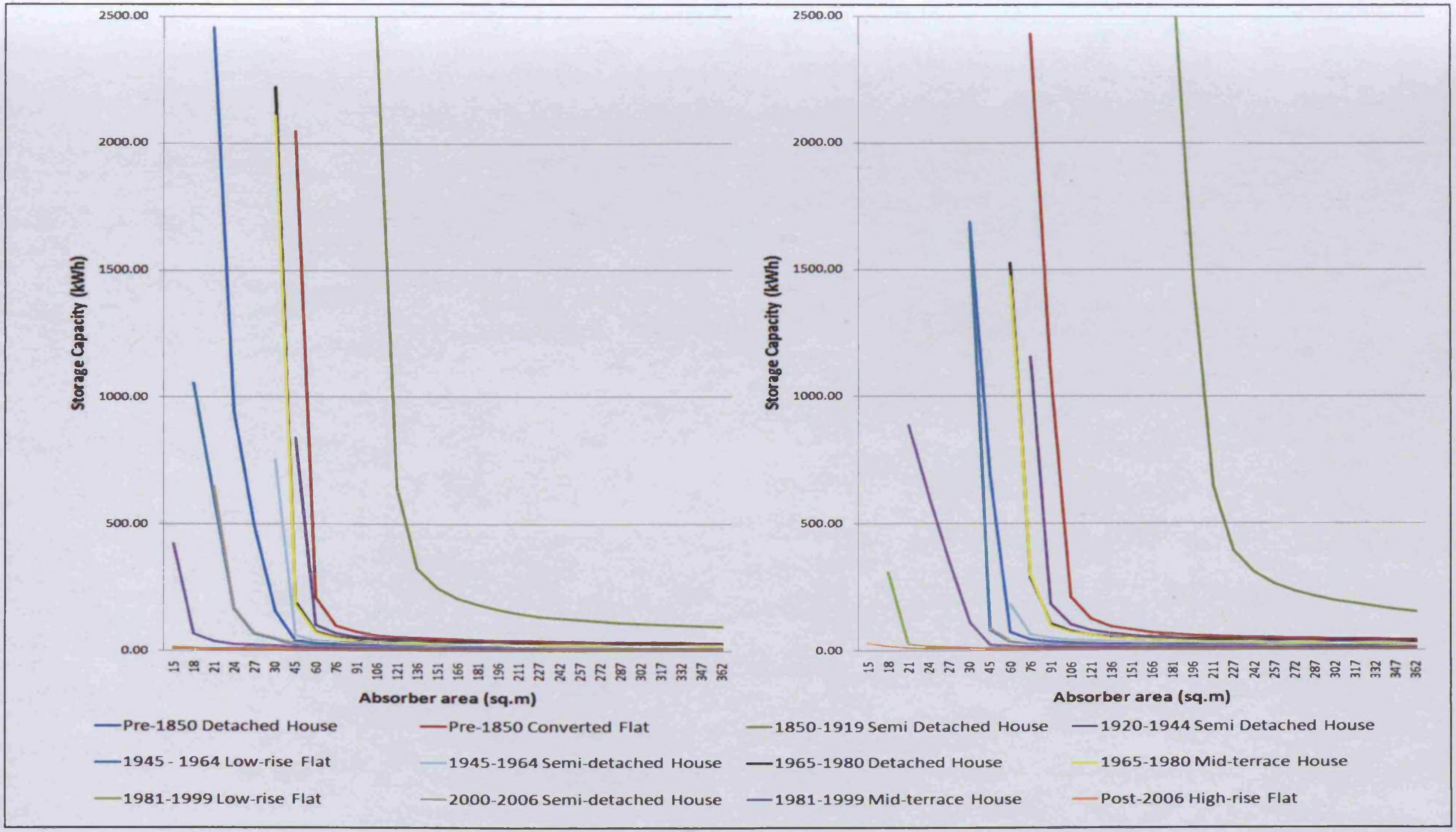


FIGURE 40: STORAGE CAPACITY AND ABSORBER AREA TRADE OFF FOR REACHING 50% SOLAR CONTRIBUTION PER HOUSE TYPE; PREDICTED FOR CONTINUOUS COMFORT MAINTENANCE AND AVERAGE WEATHER CONDITIONS, WITH SYSTEM EFFICIENCY OF 0.7 (LEFT) AND 0.4 (RIGHT) AND SOUTH FACING, 45° TILTED COLLECTORS. PERFECT STORE.

The left graph in Figure 40 shows the predicted storage capacities required per house type in order to achieve 50% solar contribution for a range of collector areas. The calculations are done with TMY2 weather data and for continuous comfort satisfaction. The graph shows that a clear threshold on the required collector capacities exists for each house type and this effect follows the "law of diminishing returns"; absorber areas larger than a certain size would not contribute to higher energy savings or smaller TES sizes. It is also shown that in certain cases (e.g. house 12) few collector units would suffice to achieve the 50% solar contribution, while for others (e.g. house 3) a very large collector area would be required in order to 'meet' 50% of the energy needs with reasonable store sizes.

In this graph (as with the graph beside it and the one showed in figure 41) most of the lines look truncated. This is because the starting point of the line in each case corresponds to the minimum absorber area required for providing 50% solar contribution. Smaller absorber areas will not allow for a solar contribution up to 50% even if very large stores are employed, as there will not be enough energy collected. For the example of the house model 1, with the limited available south facing roof area which permits mounting of 5 collector units only (15m^2 absorber area) it would not be possible to achieve 50% solar contribution as a larger absorber area is required; e.g. for 21 m^2 and 30 m^2 absorber areas, stores with corresponding capacities of 2458kWh and 156kWh are needed for the usable solar energy to reach 50% of the demand. This would translate to 30m^3 and 2 m^3 store volumes respectively assuming the use of water as a storage medium (ΔT 70°C), although in reality due to heat losses the volumes required would be much higher than these, with at least 60cm insulating material.

The previous paragraphs show the maximum theoretical solar thermal potential for the 12 case studies. In practice the overall system yield would be much lower than the collector's yield. As mentioned in 3.4.2.2 today's systems can harvest 30-60% of the energy incident on the collectors. To investigate the potential in a more realistic way, the same assessment was repeated assuming an overall system's efficiency of 40%. The energy is again fed to the 'perfect' store as described before. All other parameters are identical and the results are shown at the right graph of Figure 40. Now larger absorber areas are required to collect energy equal of 50% of the demand, compared to the graph on the left; the offset of the curve for building model 3 (1850-1919 Semi-detached house) corresponds to collector areas of around 100m².

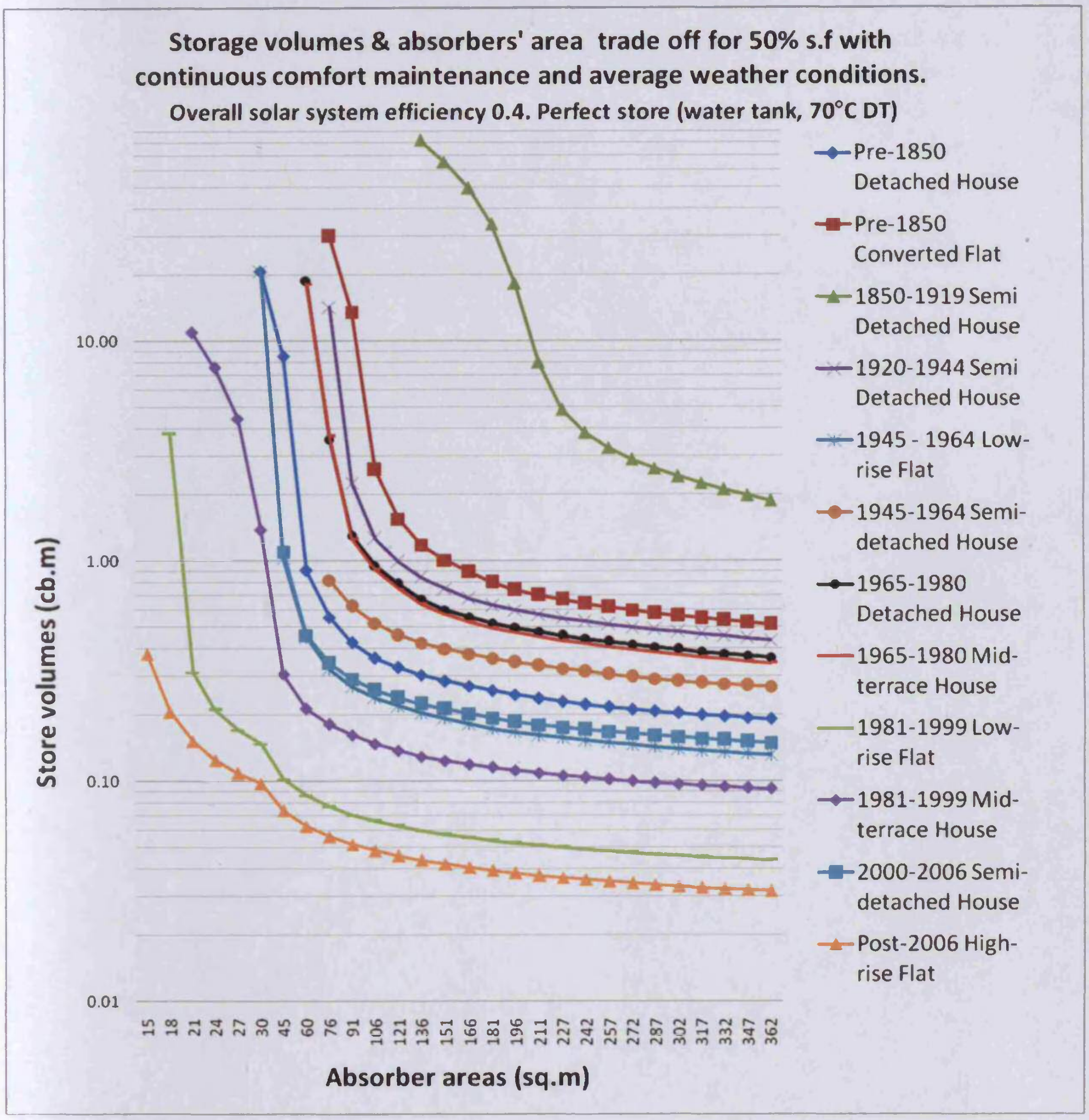


FIGURE 41: STORAGE VOLUMES AND ABSORBER AREA TRADE OFF PER HOUSE TYPE FOR REACHING 50% SOLAR CONTRIBUTION WITH CONTINUOUS COMFORT MAINTENANCE AND AVERAGE WEATHER CONDITIONS, WITH AN OVERALL ST SYSTEM EFFICIENCY OF 0.4, A 'PERFECT' WATER STORE WITH ΔT 70°C AND SOUTH FACING, 45° TILTED, COLLECTORS.

Although the system performance is not really under focus at this stage, this comparison presents the 'higher' (theoretical maximum, unreachable) and a potential 'average'-at the lower level- for the TES requirement within these 12 case studies.

Figure 41 converts the data presented before in water quantities required to store these quantities of heat if a temperature difference of 70°C is achieved within the store and if energy quality reduction and energy losses from the store are ignored. As the results vary significantly between the various building models, the vertical axis of the graph is presented in a logarithmic scale with gridlines to facilitate the reader.

It has to be noted that for this assessment south facing collector mounting was used for all house types. Therefore the most promising cases for solar thermal in that case are the flats and houses with the lowest demands. The optimum balance between TES capacities and collector areas would be defined by the economics of the systems and the space limitations regarding collector mounting (available roofs, external walls and other external space) and TES accommodation.

As mentioned before the solar availability for the 12x4 case studies was calculated considering the orientation of the houses as built. Therefore at the next step the solar contribution of a 0.4 efficient solar system, for 2 comfort scenarios and for actual and average weather conditions, was predicted for a range of storage capacities. The results are presented in Figure 42 and Figure 43. Figure 42 shows the results if intermittent use of the SH&C system is assumed. For the storage capacities assessed in this example, up to nearly 100% solar contribution could be achieved with warm actual weather conditions for the 1981-1999 low-rise flat. The lowest potential in this case is 20%, for the Post-2006 flat. If average weather conditions are considered up to 72% solar contribution is predicted (lower 14%). Figure 43shows the results if comfort is to be maintained 24/7. In this case the worst case ST potential is predicted for average weather conditions, and the maximum solar contribution predicted is 54% of the demand, with the lowest being 11%. With actual weather data and continuous comfort maintenance then fractions between 18-81% are achieved.

These maximum solar contributions were predicted considering a limit on the potential store capacities at 3500 kWh. As a general conclusion, for the best case situation with intermittent comfort and actual 2007 weather data, the use of large storage capacities is justified for half of the models (1981-1999 low-rise flat, Pre-1850 converted flat, 1981-1999 mid-terrace house, 1850-1919 Semi-detached house and 1965-1980 both mid-terrace and detached houses) as the solar contribution is increasing linearly with the store capacity for a few hundred kilowatt-hours. For the remaining dwellings a small store is required, as insufficient energy is available to the solar system and a higher solar contribution is not feasible with the available absorber area.

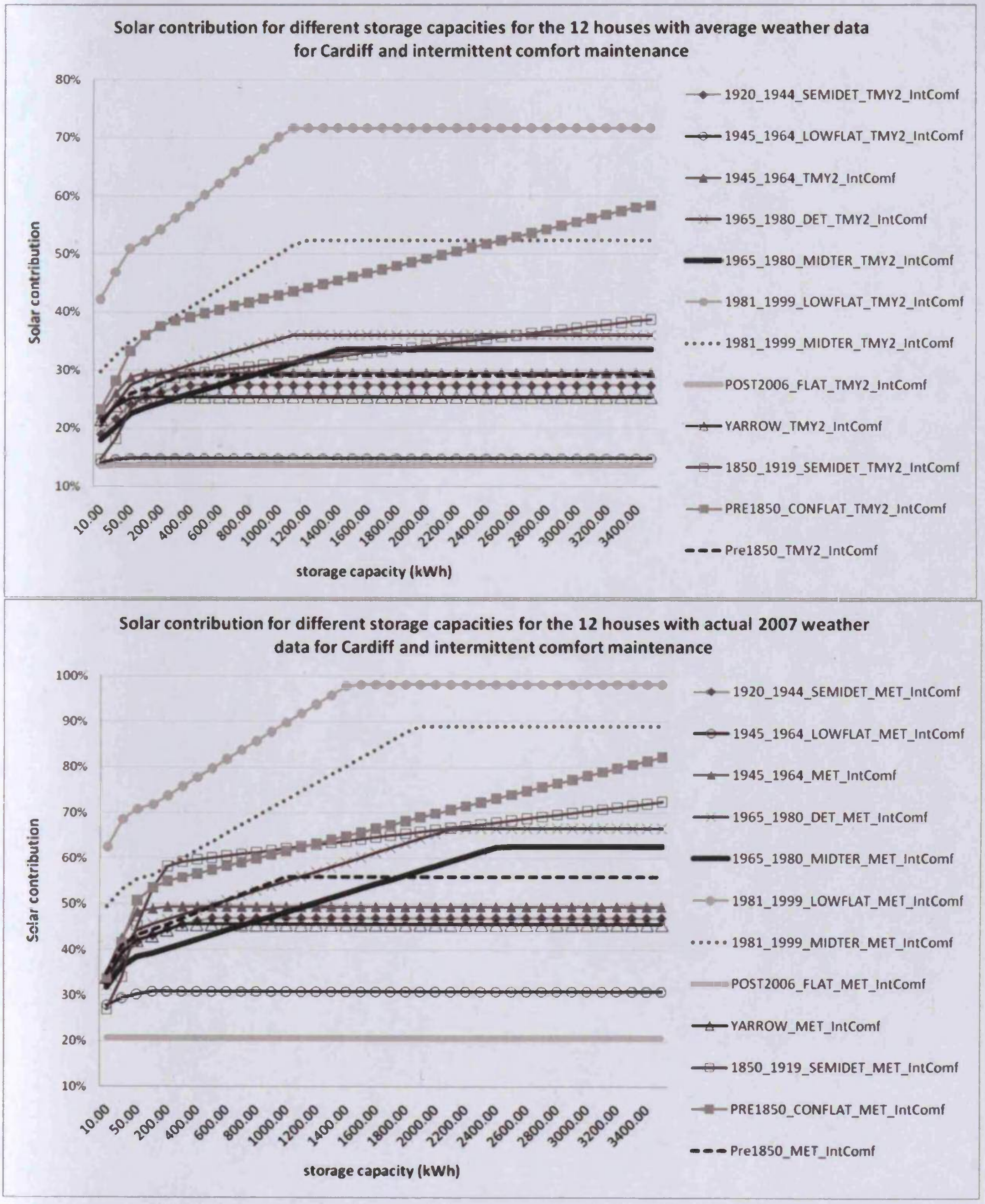


FIGURE 42: SOLAR CONTRIBUTION FOR DIFFERENT STORAGE CAPACITIES PER HOUSE TYPE; PREDICTED FOR INTERMITTENT COMFORT CONDITIONS, TWO TYPES OF WEATHER DATA AND FOR A 40% EFFICIENT SOLAR SYSTEM.

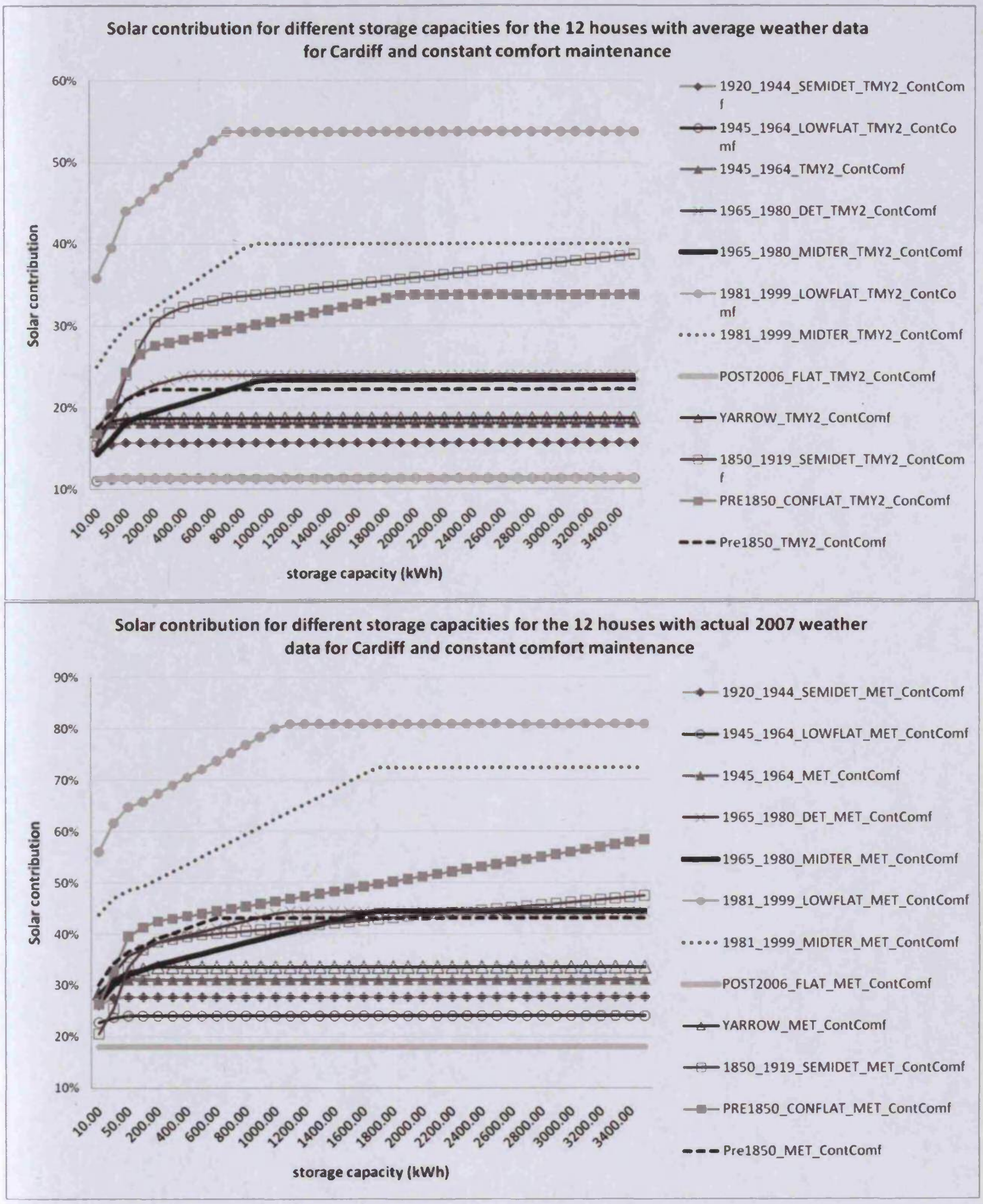


FIGURE 43: SOLAR CONTRIBUTION FOR DIFFERENT STORAGE CAPACITIES PER HOUSE TYPE; PREDICTED FOR CONSTANT COMFORT CONDITIONS, TWO TYPES OF WEATHER DATA AND FOR A 40% EFFICIENT SOLAR SYSTEM.

Again in some cases it can be seen that the share of the solar energy on the overall thermal requirement appears to be greater in continuous comfort maintenance compared to the intermittent comfort; that does not mean that the actual savings will be higher too (as the demand is also higher in 24/7 heating system operation), but shows that a better match of the energy availability and demand is observed in that case, as discussed previously in 5.4.2.

The information contained in these four graphs is summarised in Table 20 and is further discussed in chapter 6, where the results per house type are summarised.

For the less-promising conditions such as with average weather and constant comfort maintenance the solar system's sizing threshold is found to be in small storage capacities, with the exception of the 1850-1919 semi-detached house, which still shows that a higher share could be met if inter-seasonal energy storage would be employed.

TABLE 20: SUMMARY OF THE RESULTS PER HOUSE TYPE.

No	House type/era	N# of collector units, tilts and azimuths	Roof % covered	Range of results for 2 comfort (intermittent and continuous maintenance) and 2 weather (actual 2007 and average) conditions. System losses ignored.			Maximum solar contribution and respective store requirement predicted for a ST system with overall efficiency at 0.4			
				NSH demand (kWh/m². a)	$\frac{\text{annual collectors' yield}}{\text{annual overall demand}}$ %	Direct use of collectors' yield (hourly intervals)	Interm. Comf. met		Cont.comf. tmy2	
1	Pre-1850 Detached	5 S (35° tilt)	72%	62-131	39-98%	12-16%	56%	1100kWh	22%	100kWh
2	Pre-1850 Converted Flat	6 S (46° tilt) 7 E & 7W (34° tilt)	78%	91-242	41-191%	13-19%	100%	5600kWh	34%	1800kWh
3	1850-1919 Semi Detached	2 E (28° tilt), 2 S (28° tilt), 4 E (26° tilt), 12 S (50° tilt), 6 S (31° tilt)	74%	92-227	54-137%	10-17%	100%	10300kWh	45%	7000kWh
4	1920-1944 Semi Detached	3 NW & 3 SE (38° tilt), 4 horizontal	81%	88-237	27-82%	13-25%	47%	500kWh	16%	300kWh
5	1945 - 1964 Low-rise Flat	2 W & 3E -10° (90° tilt)	54%	65-138	20-54%	10-18%	31%	100kWh	11%	10kWh
6	1945-1964 Semi-detached	6 S (40° tilt)	85%	66-176	32-87%	13-24%	50%	200kWh	18%	20kWh
7	1965-1980 Detached	8 S (29° tilt)	89%	61-151	42-116%	11-15%	67%	2200kWh	24%	400kWh
8	1965-1980 Mid-terrace	4 W & 4E +5° (26°tilt), 3 horizontal	59%	66-158	41-110%	11-19%	63%	2500kWh	23%	800kWh
9	1981-1999 Low-rise Flat	4 W & 4E (14° tilt)	68%	32-83	70-180%	22-34%	98%	1400kWh	54%	700kWh
10	1981-1999 Mid-terrace	4 W & 4E+5° (29° tilt)	82%	46-109	70-159%	17-28%	89%	1900kWh	40%	900kWh
11	2000-6 Semi-detached	4 S (46° tilt)	63%	72-145	33-80%	12-17%	46%	300kWh	19%	50kWh
12	Post-2006 High-rise Flat	2NW& 2NE (90° tilt)	62%	16-43	20-32%	10-19%	21%	10kWh	11%	20kWh

5.4.4 LIMITATIONS OF THIS APPROACH

Up to this point a preliminary estimation of the ST potential for the 12x4 case studies, considering solely the buildings characteristics and the climatic conditions for Cardiff was presented. The findings of this part of the analysis are initially based on the assumption that no energy losses take place in the solar installation and thus the entire collector yield is delivered as 'high quality' energy to the demand side. Although this concept ignores the energy losses and the reduction of energy quality expected to occur in any solar installation, it gives some useful answers regarding the solar thermal potential for Welsh dwellings by isolating any aspects related to the solar systems themselves. This theoretical potential could be not very far from the actual one in some cases e.g. when solar energy is fed to a store located at a strategic point within the building structure so that energy losses are beneficial to the thermal comfort balancing, or when the store is very small and the solar energy is saved for a small period of time. In general the results of the first part are representative of the house types and exclude any penalties associated with solar system design or component failure. Another reason for conducting this assessment is that the solar systems' performance is a subject of continuous research and development and therefore it is anticipated that the systems' performance will be further improved in the future. Conclusions regarding future potentials could therefore be drawn from this data.

The potential revealed at the beginning of the analysis could be considered as the maximum theoretical potential (which would be expected only to increase in the future due to climate change) and can be used as an indicator of any system's quality. This concept works also well with the solar combisystem performance assessment method built within Task 26 of the IEA SH&C programme which is discussed at 3.5.3 and is applied at 5.5.2. At the second stage of this analysis and in order to assess the role of TES technologies, an "average" overall system efficiency of 0.4 was assumed. This was done so that a more realistic estimation of the required storage capacities is predicted here, along with the maximum theoretical one. Although this approach was simplified it gave a good insight on the energy match/mismatch at an hourly timestep, identifying the role of the thermal comfort strategies and the weather conditions.

The contribution of the diffuse part of the hemispherical solar irradiation in the collector plane was not taken into account with this simplified approach. It is believed that this introduces a small error in the conclusions drawn. This will also be investigated with comparisons between these findings and the results presented at the next stage, where both beam and direct solar energy was used in the calculations.

5.5 THE ST POTENTIAL FOR WALES CONSIDERING ACTUAL SYSTEMS' PERFORMANCE.

There are a number of assumptions made in the previous analysis and it is appreciated that some discrepancy from reality exists in the conclusions drawn. This chapter investigates the ST potential for the selected housing stock if real systems are considered. At this stage both the building related aspects per dwelling type- energy demand and availability- and the solar systems' performance are combined. Basic rules of thumb identified in 3.4.2 are initially applied to the particular case studies. Secondly, the FSC method described in 3.5.3 is used to reveal the potential that arises if the 9 generic combisystems tested by the participants of Task 26 of the IEA SH&C program are applied to the housing stock and climate of Wales. A discussion on the limitations of these two approaches is given and future work potential is suggested.

5.5.1 RULES OF THUMB – NO SPECIFIC SYSTEM CONSIDERED

As seen in the previous paragraphs, depending on the building geometry and orientation, a significant amount of solar energy could be absorbed by the collectors mounted on the roofs. In practice it is the system design and quality that determines what portion of this energy will be actually delivered as useful energy for the occupants' DHW needs and thermal comfort satisfaction. Figure 40 shows the required storage capacities in order to meet a 50% solar contribution for a range of collector areas, as calculated with the solar availability (with system efficiencies at 0.4 and 0.7), the predicted thermal energy demands and a simplified store model. Peuser et al suggest that for solar systems without inter-seasonal storage designed for 50% SF the collector area required can be roughly estimated as 3m² per MWh of annual demand with the use of a store of 150l/m² of collector area [3.4.2].

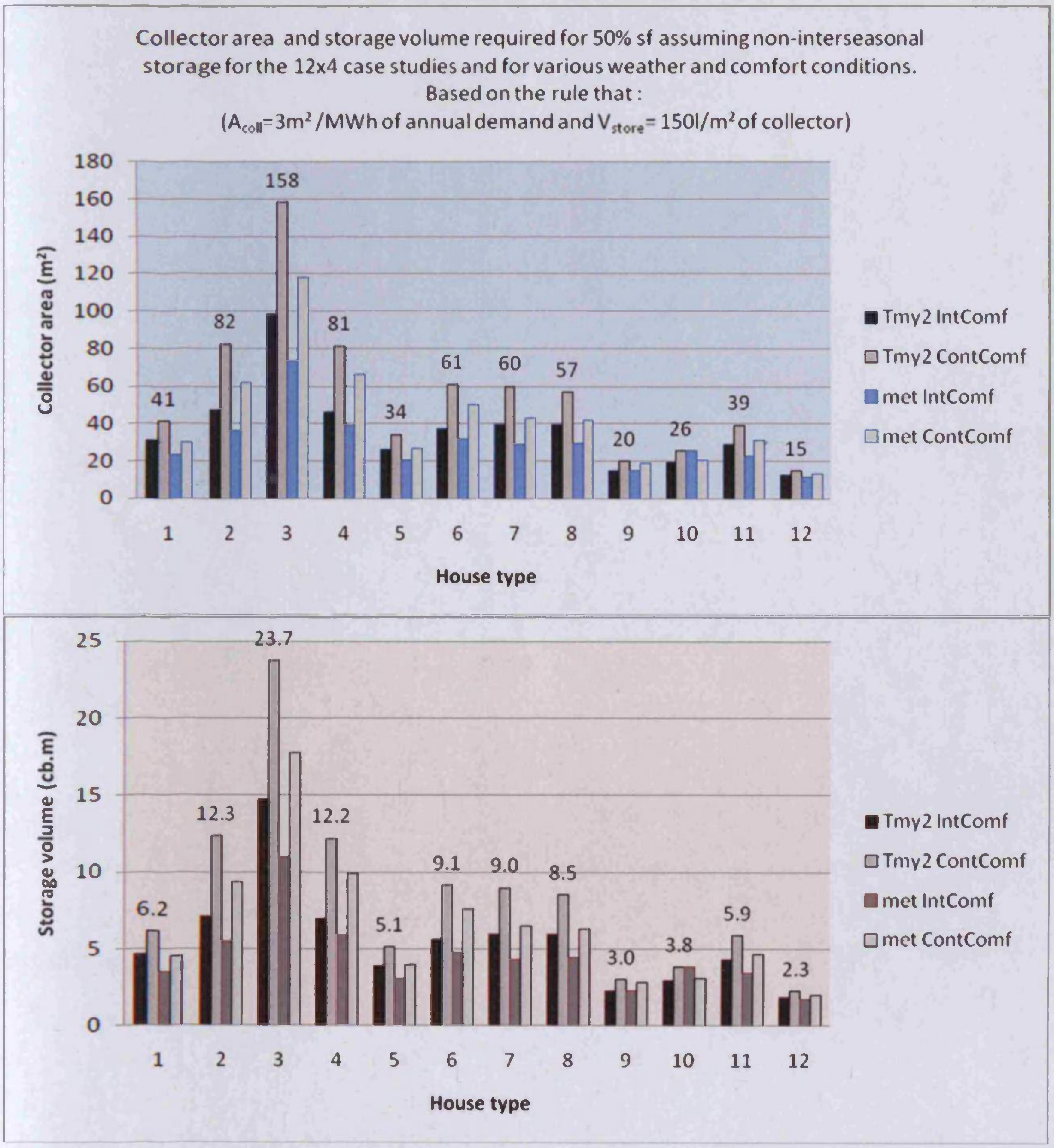


FIGURE 44: COLLECTOR AREAS AND STORAGE VOLUME REQUIRED FOR 50% SF ASSUMING NON-INTERSEASONAL STORAGE FOR THE 12X4 CASE STUDIES AND FOR VARIOUS WEATHER AND COMFORT CONDITIONS (A_{COLL}=3M² /MWH OF ANNUAL DEMAND AND V_{STORE}= 150L/M² OF COLLECTOR AREA).

This basic rule of thumb was applied to the demands presented in the previous chapter, and the results are shown in Figure 44. It is not known what system, collector type or absorber orientation is taken as standard in this rule, but collectors facing approximately South are most likely to be the case.

TABLE 21: COMPARISON OF PREDICTED ST SYSTEM SIZE REQUIREMENT (COLLECTOR AREA & STORE VOLUME) FOR 50% S.F. BETWEEN RULES OF THUMB AND THE MODEL ANALYSED IN 5.4, USING FOR THE LATTER TWO SYSTEM EFFICIENCIES AT 0.4 AND 0.46. (CONTINUOUS COMFORT AND TMY2 WEATHER DATA).

NO	DWELLING TYPE	A_{COLL} (M^2)	Peuser et al. V_{STORE}(M^3)	RESULTS OF MODEL ANALYSED IN 5.4 SYSTEM EFFICIENCY 0.4 V_{STORE}(M^3)	SYSTEM EFFICIENCY 0.46 V_{STORE}(M^3)
1	**PRE-1850 DETACHED HOUSE**	41	**6.2**	12.7	**6.2**
2	PRE-1850 CONVERTED FLAT	82	12.3	21.7	9
3	1850-1919 SEMI DETACHED HOUSE	158	23.7	56.7	32
4	1920-1944 SEMI DETACHED HOUSE	81	12.2	8	1.8
5	**1945 - 1964 LOW-RISE FLAT**	34	**5.1**	10.3	**5.1**
6	1945-1964 SEMI-DETACHED HOUSE	61	9.1	1.9	1
7	**1965-1980 DETACHED HOUSE**	60	**9**	18.7	**9.4**
8	1965-1980 MID-TERRACE HOUSE	57	8.5	21.3	12.4
9	1981-1999 LOW-RISE FLAT	20	3	0.4	0.2
10	1981-1999 MID-TERRACE HOUSE	26	3.8	5.5	1.4
11	**2000-2006 SEMI-DETACHED HOUSE**	39	**5.9**	5	1.2
12	POST-2006 HIGH-RISE FLAT	15	2.3	0.4	0.2

Table 21 makes a comparison between the results of this basic calculation and the outcomes of the model described in 5.4.3 and **Error! Reference source not found.** with a system efficiency set at 0.4 and for continuous comfort and average weather conditions and for South facing collectors with 45° tilt Table 21. Furthermore for the purposes of this investigation, other values for the system efficiency used in the model of 5.4.3 were tested and it was found that in 50% of the cases a system efficiency between 0.4-0.46 will bring results that compare well with the rules of thumb. This is a rough comparison assuming that the solar fraction is similar to the 'solar contribution' discussed before. More analytically:

- For house model 11 (2000-2006 Semi-detached house) the required volume for 50% SF is predicted to be around 5-6m^3 with both the rule of thumb and the simplified model (efficiency **0.4**).
- For models 1 (pre-1850 detached house), 5 (1945-1964 low-rise flat) and 7 (1965-1980 detached house) it was found that the simplified model using a system efficiency at **0.46** gives identical prediction for the required store volume with the rule of Peuser et al.
- For models 2 and 10 system efficiencies in the range between **0.4-0.46** for the simplified model would result in predictions similar to the rules of thumb.
- For models 3 and 8 a **higher than 0.46** efficiency for the simplified system will bring results similar to the rule applied
- For models 4, 6, 9 and 12 a **lower than 0.4** efficiency for the simplified system will bring results similar to the rule applied.

The results show a great variation in store volumes between the three calculations (rules of thumb, model with a 0.4 system efficiency, and model with a 0.46 system efficiency). Even for the simplified model in 5.4.3 a change in efficiency from 0.46 to 0.4 results in doubling of the predicted store volume. This fact suggests that the use of basic rules and simple models has to be cautiously used, as there is a wide error range associated with them. This shows what is generally suggested by experts in the field i.e. no general rules can apply to ST systems as a whole and detailed simulations are required for accurate estimations their performance. The effectiveness of ST systems varies with different configurations, tuning and choice of components. The next paragraphs analyse the performance of specific solar combisystems and the potential emerging with their use on Welsh housing.

5.5.2 USE OF THE 9 GENERIC SYSTEMS TESTED IN TASK 26

A copy of Table 5 which describes the 9 generic solar combisystems is printed in A3 paper and is included in the Appendices (A). It is advised that this is unfolded so that the information can be on hand when reading the following discussion.

The simulations conducted within Task 26 for the production of the characteristics curves of 9 typical solar combisystems were actually done for the development and validation of the FSC method and to create the grounds for practical means of system inter-comparisons (see 3.5.3.2). The method investigates the effectiveness of a solar combisystem by isolating the actual system's characteristics from the load and the climate. It was therefore considered that in this study the outcomes of systems' characterisation predicted in Task 26 could be applied to the Welsh housing stock in order to reveal the potential held by commercially available and state-of-the-art solar combisystems in meeting the thermal requirements of dwellings in this region.

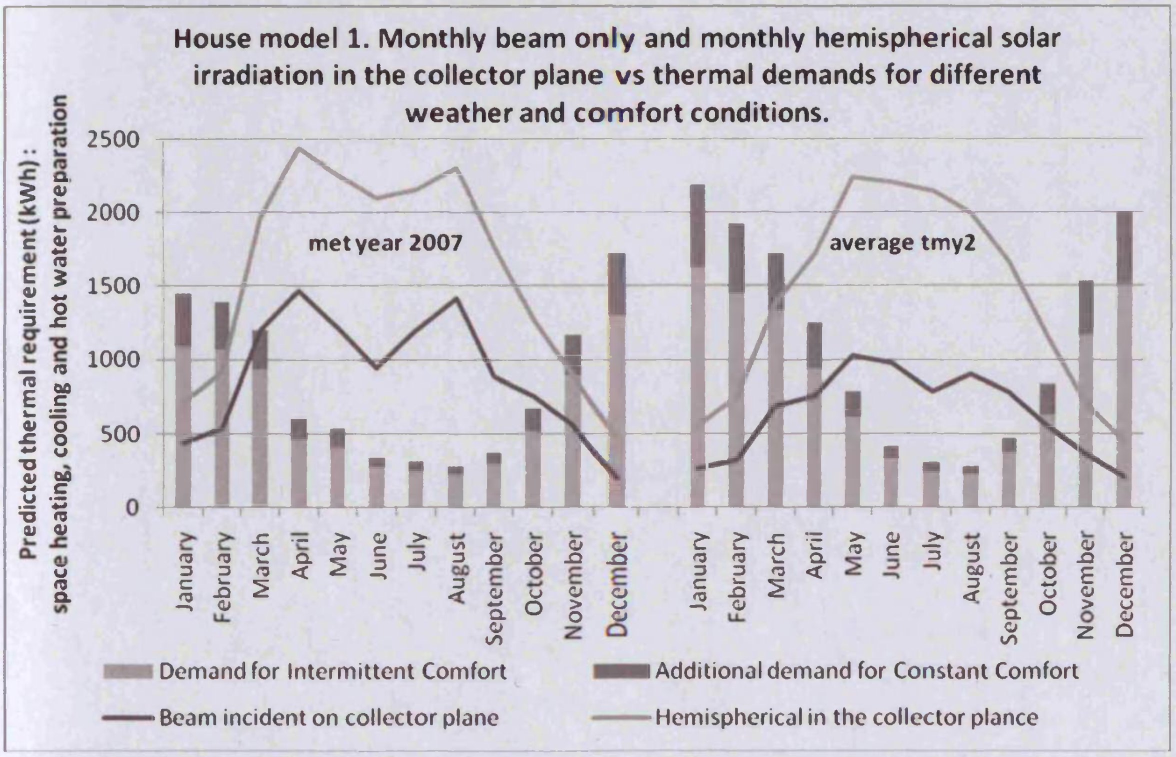


FIGURE 45: MONTHLY BEAM ONLY AND MONTHLY HEMISPHERICAL SOLAR IRRADIATION IN THE COLLECTOR PLANE VS THERMAL DEMANDS FOR DIFFERENT WEATHER AND COMFORT CONDITIONS FOR HOUSE MODEL NO#1 (PRE-1850 DETACHED); 15SQ.M, SOUTH FACING, 35° TILTED COLLECTOR AREA.

The FSC method defines that the solar irradiation on the collector area would be calculated by multiplying the *solar collector area by the monthly hemispherical solar irradiation in the collector plane* i.e. both direct and diffuse solar radiation included. In the previous analysis only beam solar radiation was taken into account, as in reality only a small part of the diffuse light is harvested by the solar collectors (see discussion at 0). Figure 45 shows the amount of diffuse energy incident on the collectors in the case of model 1, represented by the area between the two curves for 'beam' and 'beam & diffuse' radiation. In the results presented here both the diffuse and direct solar energy are accounted for in the FSC value predicted in each case, in compliance with the method's restrictions.

The graphs in Figure 46, Figure 47 and Figure 48 show the $f_{sav,therm}$ and the $f_{sav,ext}$ calculated for the 9 combisystems and for 5 models of the Welsh housing database. The method is applied to those dwellings which have only South facing collectors. For the case of model 3 only the South facing collector areas are considered in this assessment, omitting those that could be accommodated on the East facing roofs. The results of all 4 case studies per model are analysed here. Nevertheless since one of the basic restrictions of the FSC was the smooth occupancy of the dwellings, the focus is on the continuous comfort maintenance scenario, with average weather conditions. The outcomes of this assessment, including the critical conclusions for the systems as identified in Task 26 are summarised below.

For all 5 models the maximum $f_{sav,therm}$ reached is around 41-47%, when the maximum number of collector units has been fitted on the roofs. That means that comparing with a conventional space heating and DHW production strategy the use of solar energy would bring up to 41-47% thermal energy savings if the best system (among the 9 considered in the Task 26 study) is employed. If the parasitic (electric) energy consumption of these systems is of interest (e.g. if PV modules are not installed to cover this load) the energy savings can be as low as 10% or as high as 44% for the selection of the house models, depending again on the chosen system. That shows that within this selection of solar combisystems a large variation of system qualities exists.

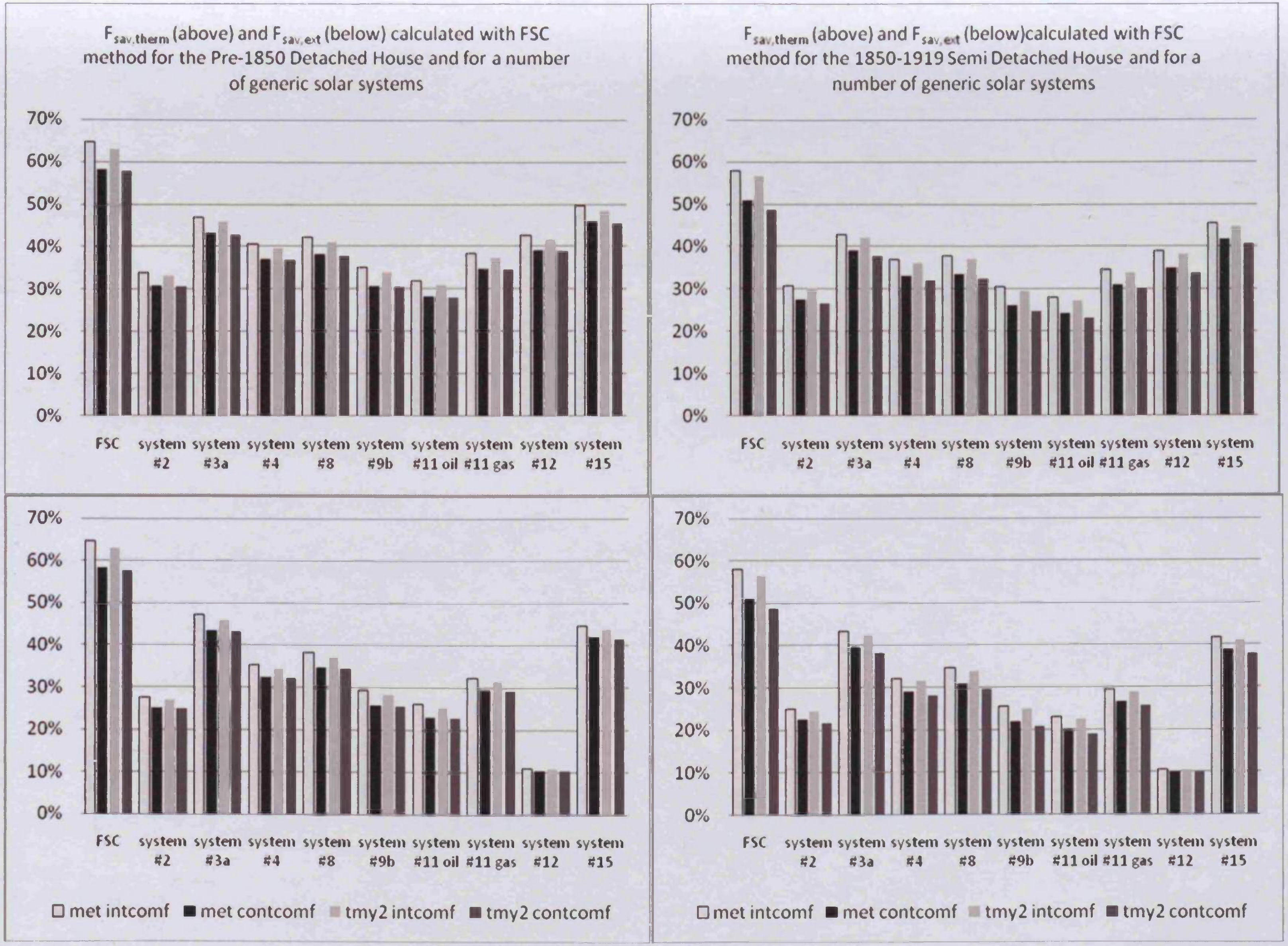


FIGURE 46: $F_{SAV,THERM}$ (ABOVE) AND $F_{SAV,EXT}$ (BELOW) CALCULATED WITH THE FSC METHOD FOR THE PRE-1850 DETACHED HOUSE (LEFT) AND FOR THE 1850-1919 SEMI DETACHED HOUSE (RIGHT) WITH A NUMBER OF GENERIC SOLAR SYSTEMS (TASK 26 FINDINGS).

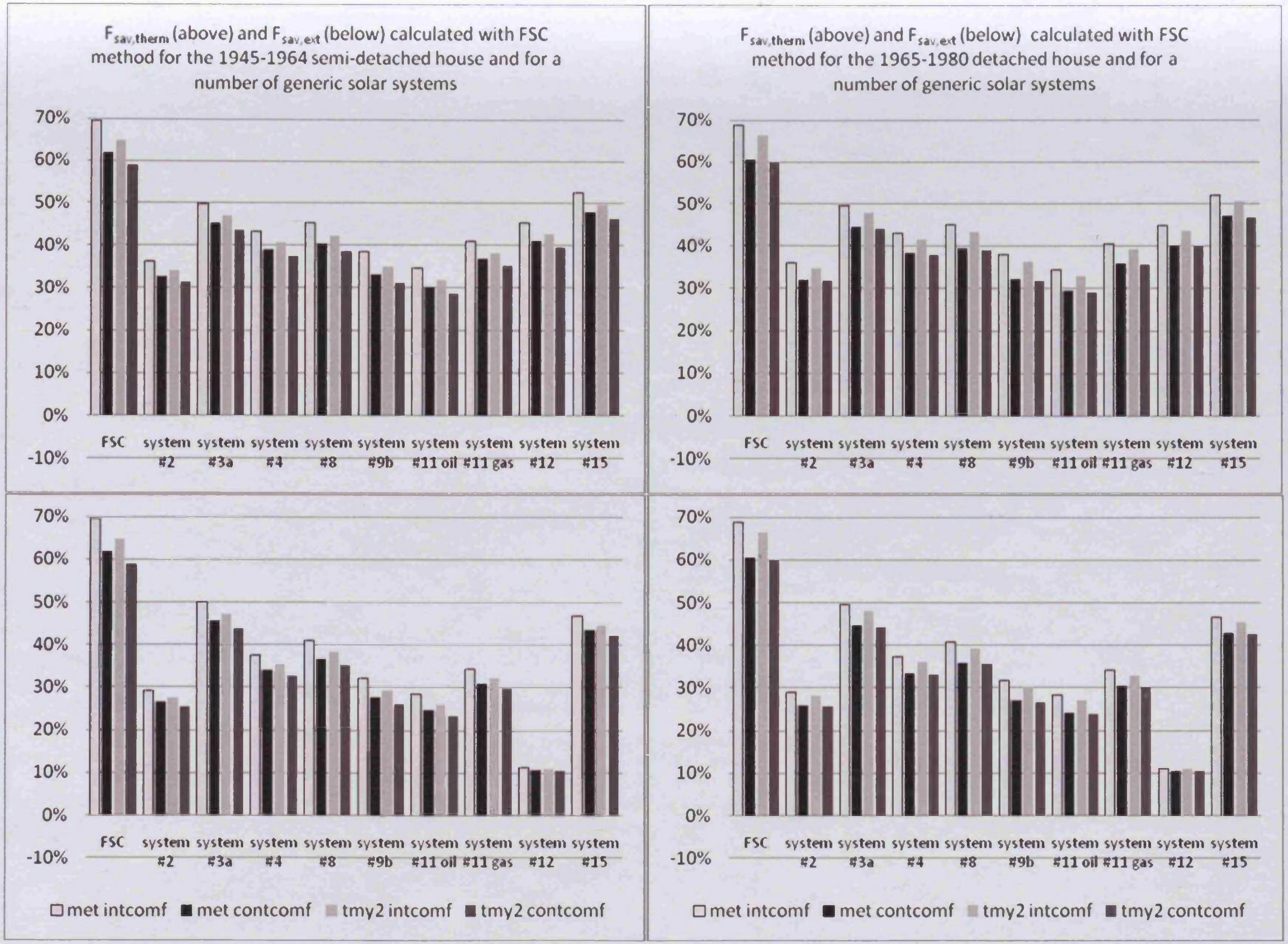


FIGURE 47: $F_{SAV,THERM}$ (ABOVE) AND $F_{SAV,EXT}$ (BELOW) CALCULATED WITH THE FSC METHOD FOR THE 1945-1964 SEMI-DETACHED HOUSE (LEFT) AND FOR THE 1965-1980 DETACHED HOUSE (RIGHT) WITH A NUMBER OF GENERIC SOLAR SYSTEMS (TASK 26 FINDINGS).

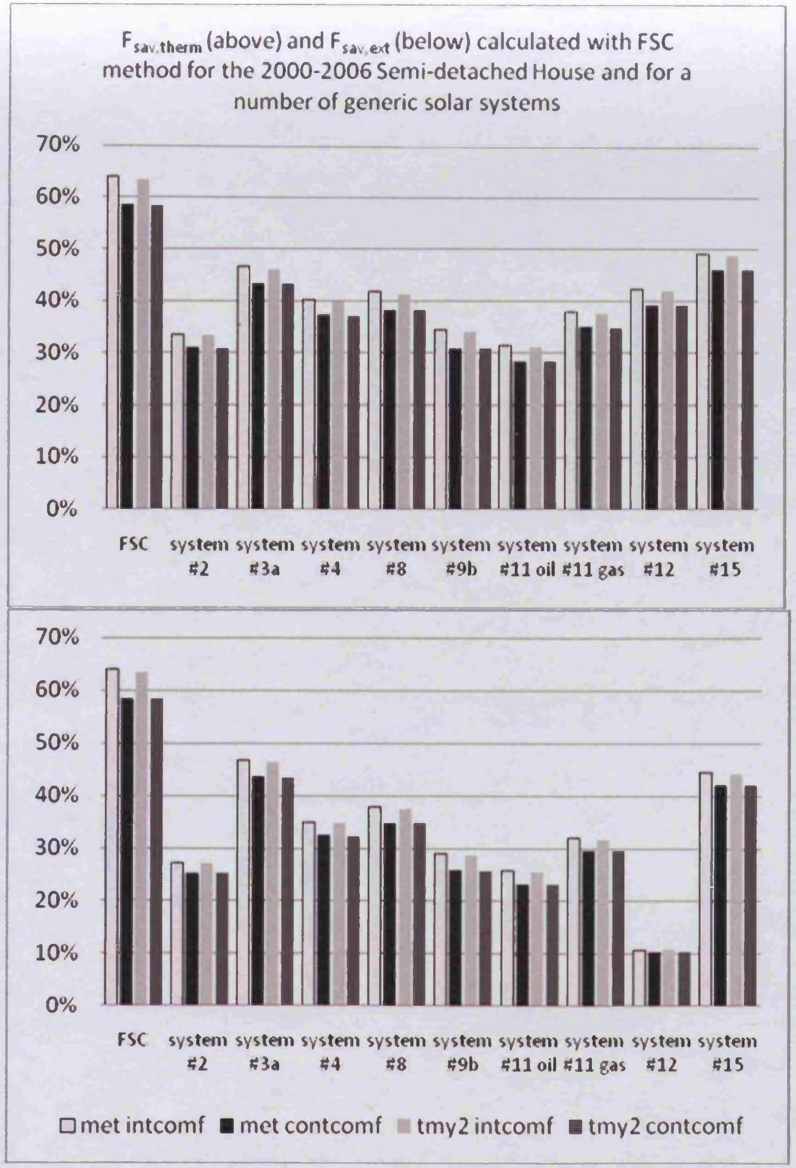


FIGURE 48: $F_{SAV,THERM}$ (ABOVE) AND $F_{SAV,EXT}$ (BELOW) CALCULATED WITH THE FSC METHOD FOR THE 2000-2006 SEMI-DET. HOUSE FOR A NUMBER OF GENERIC SOLAR SYSTEMS (TASK 26 FINDINGS).

TABLE 22:STORE AND BURNER DATA FOR ONE OF THE CASE STUDIES USED IN THE CALCULATIONS IN TASK 26 (SFH 60, A_{COLL} ~10SQ.M, ZURICH).

System	Auxiliary energy source	Mean annual boiler efficiency	Heat loss rate from store (W/K)	Storage tank size (litres)
#2	Gas	88.3%	1.9	280
#3a	Gas	100.4%	4.48	500
#4	Gas	90.8%	1.94	750
#8	Gas	98.8%	6.3 (integrated burner losses incl.)	830
#9	Electricity	90.0%	1.79	1000
#11 oil	Oil	82.2%	2.36	700
#11 gas	Gas	92.1%	2.36	700
15	gas	105.1%	2.37	635

As shown previously in Figure 32 there is an unused roof potential of 11-37% between the 5 models, due to the 'standardized' collector units. If more flexible collector sizing was possible, then the respective energy savings could be significantly higher. In addition, 6 East-facing collector units were ignored for model 3 (1850-1919 Semi detached) as the FSC method has been validated for South facing collector mounting only. Therefore the energy savings presented in Figure 46 (right graphs) for this model are considered to predict an under-estimated potential, as a reasonable amount of solar energy could be delivered to the system in the morning hours by this 'extra' 18m^2 East-facing absorber area.

The graphs show that the FSC value and the $f_{sav,therm}$ potential per system type is more or less the same for actual and average weather conditions and it varies only according to the comfort strategy used. As was mentioned above, the results for the intermittent comfort are presented here only for completeness but it is acknowledged that they are not compliable to the restrictions of the FSC method. With the simplified approach it became clear that in a sunnier year, the savings due to ST would be higher, as the thermal demand would be lower and more solar energy would be available. So that shows that the two methods do not compare well. By comparing the two weather data sources in Figure 45 it can be seen that on average at this climate the levels of diffuse solar radiation are higher than those experienced in year 2007. Although the levels of incident beam energy were much higher than average in 2007, the levels of total incident energy at a monthly basis differ only a little between the two weather data sources (total annual for this example is predicted around 17MWh with MET and 19MWh with TMY2). Thus, although the E_{ref} is predicted to be higher with the use of the TMY2 than with the MET data, the available irradiation is almost the same. As mentioned in 3.5.3.2 the FSC is calculated as the ratio of the $Q_{solar,usable}$ to the E_{ref}. The $Q_{solar,usable}$ is calculated on a monthly basis as the minimum of the E_{ref} and the available irradiation (total incident on the total absorber area). With the use of the average weather data the thermal requirement is higher than the one predicted with the actual weather data and so is the $Q_{solar,usable}$ as a higher portion of the available solar energy coincides with the demand on a monthly basis. This fact explains why the FSC values calculated with the TMY2 and MET weather data sources are almost identical. Table 23 highlights this effect with the example of model No#1.

TABLE 23: FSC CALCULATION FOR MODEL NO#1 (SEE ALSO FIGURE 45).

climate	comfort	E_{ref} (kWh)	$Q_{solar,usable}$ (kWh)	FSC
met	intcomf	9840	6367	65%
	contcomf	12565	7323	58%
tmy2	intcomf	13018	8187	63%
	contcomf	16889	9745	58%

Therefore it is shown that the findings of the FSC might be not directly applicable to any location or climatic data, mainly due to this unpredictable balance between the diffuse and beam share of the incident solar irradiation around the world which misleads the calculations. This is also revealed when comparing the results of the two methods (see also Table 24). The predicted $f_{sav,therm}$ for the continuous comfort and average weather conditions for the 4 models tested (excluding model No#3 which has the East collectors emitted in the FSC approach and thus cannot be compared with the version presented in 5.4 is between 28-47%. This in comparison to the results of the simplified method is very high. It could be said that the assumed low efficiency of 0.4 used in the calculations at 5.4 causes this discrepancy, but this alone cannot stand as a reason.

TABLE 24: COMPARISON OF THE RESULTS OF THE TWO METHODS APPLIED.

	Continuous comfort maintenance and average weather conditions		
	Simplified method-beam only. Solar contribution		FSC –total energy 9 systems $F_{sav,therm}$
Model No#	0.4 system efficiency	0.7 system efficiency	
1	22%	39%	28-46%
6	18%	32%	29-46%
7	24%	42%	29-47%
11	19%	33%	28-46%

One idea is that due to the cloudiness in the UK the diffuse share of the hemispherical irradiation is higher in this country than in the climates used in the tests that established and validated the FSC method in the Task26. Indeed with the calculations done in TRNSYS using TMY2 average weather data to investigate this issue here, it was shown that at a monthly basis the rate of the diffuse to the total incident energy at a South-facing 45° tilted surface in Carpentras, Stockholm, Zurich and Cardiff is 40%, 43%, 51% and 54% respectively. In the FSC approach the exact share of the diffuse energy harvested by the system was determined by the detailed system modelling or by measurements and this information was then 'passed' on the solar combisystem characteristic values. Considering all those mentioned above it is unclear whether the method can return accurate predictions for other locations -or even weather data other- than those tested in Task 26 and it could be that a location correction factor should be introduced in the FSC calculation to account for this issue. One further limitation of the FSC approach is that the collector type used in all 9 solar combisystems is a FP. Therefore any comparisons between the two methods applied here should be done with care, acknowledging the difference in the testing boundary conditions.

It is beyond the scope of this work to analyse the performance of the ST systems tested under Task 26. Nevertheless a few aspects will be discussed here. Considering the systems' comparison done in Task 26 and as shown in Figure 46, Figure 47 and Figure 48, the best performing systems are systems #15 and #3a. System #15 brings higher thermal energy savings than system #3a but when the parasitic energy consumption is taken into account and for FSC values higher than 0.5, #3a is slightly better than #15. Next is system #8 with #4 and #11gas being of similar effectiveness. This comparison ignores the penalty that occurs for using the same reference (predicted) heating load for low and high-temperature heat delivering systems. It is appreciated that comparison between systems using radiators or heating floors is a complicated task, as for example in a heating floor case a lower inside air temperature would be required but also increased energy losses are anticipated. Nevertheless the decision was taken to ignore this aspect here, as was also suggested by the Task documentation, where it was assumed that it is not unrealistic to do this comparison, due to the fact that this two phenomena would almost compensate each other (WEISS, W., 2003).

Table 22 shows the auxiliary burners' efficiency used in the simulations. The performance of the systems was found to depend strongly on these efficiencies which vary between 82.2 (oil)-105.1% (gas). For example, the difference between the $f_{sav,therm}$ for #15 and #3a is mainly due to the higher gas efficiency of the burner used in the first compared to the one used in the latter. However this issue is not always straightforward as shown with the systems' comparison (WEISS, W., 2003) e.g. although the oil to gas efficiency improvement in system 11 is at ~10% the fractional energy savings differ only for 7-8% between the two cases. With the condensing gas boilers the effect of using a low-temperature delivering system (exhaust gas condensing more often due to the low return T of the SH loop) is highlighted with the performance of system #3a.

The existence of a store tank is of major importance as shown with the systems' comparison. System #2 is ineffective for the system sizes considered in these houses, bringing significantly lower energy savings than the rest systems. This fact is highlighted especially in comparison to #4, which is very similar to #2 but includes a store. Conclusions regarding the store losses in these 9 systems cannot be easily drawn, as this issue is dependent on both the store characteristics and the overall system design. Nevertheless it is expected that higher insulation of the store e.g. in case #3a would be favourable. Integrated burners within the store can occasionally bring higher store losses (#8) although in general they have their losses counting as gains to the tank, increasing their efficiencies (#15). The effect of poor store stratification mechanisms is highlighted on the performance of system #9b; a high efficiency boiler is used, heat exchanger losses are avoided with the system design, the store is adequately insulated and the existence of a dedicated DHW store could be used advantageously for a potential enhanced stratification effect (floor heating determining set-point Temperature) but the resulting overall system performance is average. This is projected in contrast to system #15 which makes use of a sophisticated stratification approach (Table 5).

5.5.3 LIMITATIONS-FUTURE WORK POTENTIALS

The FSC method was applied to the monthly loads which were presented in 5.4.1-5.4.2. Within Task 26 it was shown that similar results are returned by the method if this is applied at a daily or at a monthly basis and therefore it was concluded that there is no need to calculate the $f_{sav,therm}$ and $f_{sav,ext}$ for every day of the year (LETZ, T., 2002).However it has to be kept in mind that within the simulations conducted in Task 26 the building model is simplified and a smooth load has resulted from the single-zone modelling and, most importantly, from the flat-patterned occupation of the dwellings (both at a daily and a year-around basis). Thus, although the comparison between the two time-steps in Task 26 showed that the monthly application of the FSC method gives the maximum possible accuracy within the scopes of the task, this could be not the case if realistic fluctuating loads were simulated. Nevertheless at the moment it is uncertain whether the use of the FSC method in the predicted loads for the 12x4 case studies at a daily basis is valid, as the curves were built based on monthly values, and the FSC method is recommended for use with constant occupancy. The results of Task 26 were applied here, although this limitation is known, acknowledging that an error occurs with the fact that the predicted loads in this PhD work are simulated in a more realistic way and larger fluctuations occur. Validation of the FSC method against real practice would help clarifying this issue.

One of the initial intentions of this PhD work was to model real ST systems, such as the MaxLean (or the Template solar) system along with the building models of the 12 typical Welsh houses to assess the real systems' performance in this region and in these housing types. This was not performed within the duration of this PhD research for several reasons:

1. The MaxLean is an innovative concept developed within the IEA SHC task 32 and has been proved to be a state-of-the-art solar combisystem but there is little evidence that it is an optimum solution of this type, suitable to any ST residential application for SH and DHW preparation. Assessing this solar combisystem only for the entire Welsh housing stock will not bring reliable conclusions regarding the performance of solar combisystems in general as the results would be tied to the particular system and generalisation of the conclusions would be impossible.

2. The Template solar system TRNSYS files are available in the public from the Task 32 website but the *.deck file is provided in a format which is hard to use. As the co-author of the relevant report and co-developer of the files R. Haller explained (HALLER, M., 2008) the system is entirely built in a text-file format and is not compatible with the Studio environment in TRNSYS 16.1 which was used here. On the other side, a deck file suitable with Studio was provided by S. Kuethe, a researcher from the University of Kassel who has modelled the Template as part of his research work. Nevertheless due to similar reasons as those described above for the Maxlean system it was decided that no work would be done towards this direction. Detailed system modelling applied to the existing building models could be the subject of post-doctoral work.

6 SUMMARIZING THE RESULTS PER HOUSE TYPE

It is advised that the reader unfolds the Appendices C section which is printed at A3 size for this purpose, so that the 3-D images and other information per dwelling type are on hand when reading the text.

Up to this point the research outcomes were presented for all house types collectively, so that an overall picture of the findings was given. In the following paragraphs a short discussion of the results per house type is presented. Analysing the results per dwelling type allows for a better understanding of the findings especially with regards to associating them with each house typology of the corresponding 12 case studies.

Along with the discussion for each one of the 12 house models, the image on the right of the text gives an indication of the water volumes corresponding to the storage capacities presented in Table 20. More analytically the following information is included in these images, to summarise the results for all 4 cases per house type (2 comfort and 2 weather conditions):

- The large cube represents the house volume (also given in m^3).
- The value in % on the left refers to the maximum solar contribution that can be achieved in the (best) case of intermittent comfort maintenance and actual 2007 weather conditions. The medium-size cube represents the TES volume required in that case; that is the volume of water required, ignoring the volume for container and insulation.
- The value in % on the right refers to the maximum solar contribution that can be achieved in the (worst) case of continuous comfort maintenance and average weather conditions. The small cube represents the TES volume required in that case; that is the volume of water required, ignoring the volume for container and insulation.

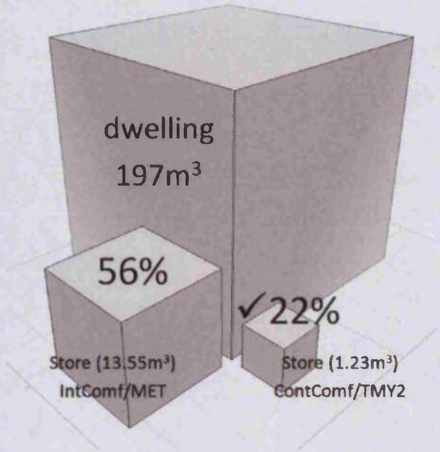
Note that the TES volumes included in the graphs correspond to the 'saturated' TES potential in each case; higher storage capacities than these would not bring higher solar contributions.

6.1 MODEL 1: PRE-1850 DETACHED HOUSE

Model 1 is a detached house built before 1850. It has undergone some refurbishment and has therefore a lower than expected NSH demand at 94kWh/m^2 per annum for intermittent comfort and average weather conditions. Two large South facing (35° tilted) roofs accommodate in total 5 collector units (28% of the roof area remains unused). Annually the energy absorbed by the collectors is between 39-98% of the overall energy requirement, depending on the weather and comfort conditions. Assuming that the collectors' yield (70% efficiency) directly serves the immediate needs for thermal energy and no losses occur, the energy savings due to solar would be between 12-16%.

1. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

72% of roof covered by collectors
NSH: **62-131** kWh/m^{2}a



With an overall system efficiency of 0.4 and an 1100kWh store, a maximum[22] of 56% of the annual thermal energy needs could be met by the solar system during a warmer than average year and for intermittent comfort maintenance. At the lower end of expectations, a 22% solar contribution with a 100kWh store is predicted for average weather conditions and 24/7 comfort maintenance. Therefore if a 1.23m^3 (see volume comparison in the image) water volume was used for TES the savings achieved would be between 22-44%[23] over the 4 studies of this dwelling. In an average year this would translate to 2,814 kilowatt-hours saved if comfort was maintained a few hours a day or 3,017 kilowatt-hours if comfort was maintained 24/7. The savings in 2007 would be 3,397 kWh (IntComf) and 3,814 kWh (ContComf) respectively.

It is the author's opinion that the use of a larger store in order to reach a maximum 56% solar contribution might not be easily justified by the economics and/or the energy savings and could also stumble at space restrictions, as shown by the volume

[22] As the use of a larger store would not increase the solar contribution.
[23] The figure 44% calculated for IntComf/MET is not shown in the image for simplicity reasons.

comparison. However detailed system modelling would be required in order to draw accurate conclusions to this respect.

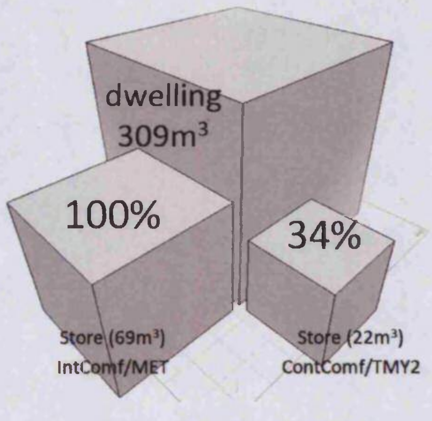
Comparing the results with those from section 5.5.2, it can be seen that the estimated solar system efficiency at 0.40 returns a slightly lower potential than the one resulting from the use of actual systems. The $f_{sav,therm}$ for the continuous comfort and TMY2 case study is around 28% with the use of solar combisystem #11oil. This system has an optimised storage capacity at 1.25m^3 (Table 5) which is very close to the one estimated with the model above. Both methods' limitations and problems have been analysed before, mainly with regards to the way they treat the diffuse part of the available solar energy. It is therefore possible that the actual potential in this scenario (ContComf/TMY2, solar combisystem #11oil with a 1.25m^3 water volume for TES) would be somewhere between 22-28%.

6.2 MODEL 2: PRE-1850 CONVERTED FLAT

Model 2 is a flat on the top floor of a converted semi-detached house built before 1850. The NSH requirement predicted for this house type is the highest among the 12 assessed in this study. 78% of the available roofs is covered by collectors: 6 units facing South (46°), 7 facing East (34°) and 7 facing West (34°). On an annual basis the collectors' yield is estimated around 41-191% of the total energy requirement for SH&C and DHW, for 2 weather and 2 comfort conditions. 13-19% of the demand could be met instantaneously by the absorbed energy (if system losses are ignored).

2. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

78% of roof covered by collectors
NSH: **92-242** kWh/m^{2}a



The calculations show that a solar system with an overall efficiency of 0.4 and a 100kWh store would be able to meet 54% of the total thermal demand in 2007 with intermittent comfort conditions. For this dwelling an inter-seasonal store also appears to look attractive as 'optimisation' of the system sizing (see also Figure 42 Figure 43Error! Reference source not found. and appears to take place at higher store capacities compared to the other models. For the same conditions mentioned before and with a store capacity set at 5600kWh ($69m^3$ of water at a 70°C ΔT gradient, if losses are ignored) 100% solar contribution would be theoretically possible. At the lower end of expectations, 27% and 34% solar contributions is predicted with average weather conditions and for constant comfort maintenance (TMY2/ContComf) with storage capacities at 100kWh and 1900kWh respectively[24].

In more realistic terms, if a TES system with 100kWh storage capacity is used ($1.23m^3$ water volume, losses ignored) the thermal energy that could be saved in 2007 would be 6549kWh for intermittent comfort (54%) and 8513 for continuous comfort (41%), while for average weather conditions the savings would be 5705kWh (36%) and 6769kWh(27%) respectively. That actually shows that the storage size would be dependent on many factors such as the comfort strategy, the space restrictions and the project aims. It is not possible to give a solid suggestion for every possible scheme, but it is shown that for the specific house type considerable savings can be reached even with a very reasonably sized store. On the other hand, for the 100% solar contribution a very large store volume is required. However with the use of innovative TES techniques in the future, such as the one described in 3.6.3.5.2, the storage volume could be significantly reduced.

6.3 MODEL 3: 1850-1919 SEMI DETACHED HOUSE

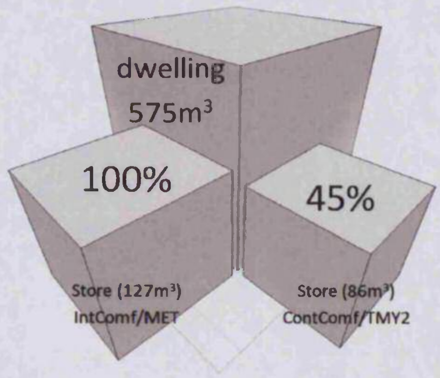
Model 3 is the largest dwelling of this database (1850-1919 era) and it requires between 92-227kWh/m^2 per annum only for SH, depending on comfort and weather conditions. However large roof areas are available for mounting in total 20 South facing and 6 East facing collector units (various tilts), leaving 26% unused roof space. The energy absorbed by the collectors at an annual basis is between 54-137% of the respective thermal energy requirement, predicted for two comfort and two weather conditions. If this energy is used instantaneously to meet the demands, without using a store, a direct solar yield at 10-17% of the demand would be expected (ignoring all system losses).

[24] These capacities are presented here to highlight that for an additional 7% on the solar contribution the store size increases significantly.

For a ST system with an overall efficiency of 0.4, during 2007 and for intermittent comfort maintenance, solar contributions at 58%, 72% and 100% are theoretically possible with store capacities at 200kWh, 3300kWh and 10300kWh respectively. The latter capacity corresponds to a water volume of 127m^3 (storing energy at a 70°C ΔT) almost equal to the volume of the two living rooms found at the ground floor. Keep in mind that in actual conditions, and considering container and insulation volumes and storage duration, this TES capacity would correspond to a much larger volume. The volume comparison in the image beside shows that it is impossible to meet 100% of the needs of this house with ST. The required store capacity at 3300kWh for meeting at maximum 72% of the thermal needs (IntComf/MET) would correspond to a 40m^3 water volume. Considering the scenario of an outdoor pit, the required excavation area would be in reality much larger due to the need for heavy insulation all around (doubling the required volume and increasing the cost significantly) otherwise the stored heat would escape in a few days (HADORN, J., 2005).

3. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

74% of roof covered by collectors
NSH: **92-227** kWh/m^{2}a



With a more realistic scenario, with the use of a 2.5m^3 water volume able to store 200kWh of heat, a solar combisystem would serve between 28-58% of the energy required for SH, SC & DHW depending on comfort and weather conditions. That means that in 2007 such a ST system would have saved 14,205kWh in an intermittent comfort scenario and 14,976 in a continuous comfort scenario. At the lower end of expectations, for average weather conditions the savings would be 9,189kWh (IntComf) and 15,803kWh (ContComf).

In this case a large range of options for the ST system sizing are possible, and the actual store capacity would be determined by the overall ST strategy used. The economics of the system are of significant importance as it is assumed that a very large collector area is used. A direct comparison with the actual systems' approach is not feasible in this case, as the East-facing absorbers were not incorporated in the simulations at that stage.

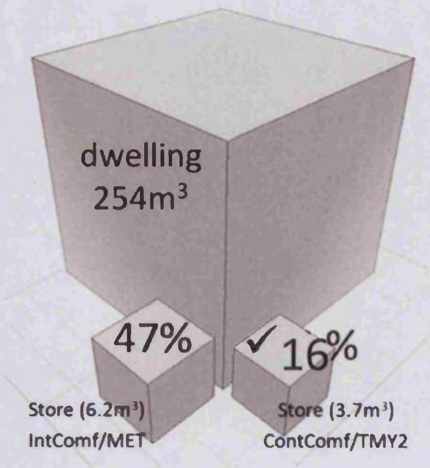
Indeed the $f_{sav,therm}$ for the continuous comfort and TMY2 case study is between 23-41% among the 9 systems used, revealing a lower savings potential if a reduced collector area applies. It is shown that, with a typically-sized water store, solar contributions in the region of 20-60% could be feasible, if the economics permit the use of an adequately large absorber area. Furthermore if other passive measures were used to upgrade the building envelope prior to the solar installation, then a higher ST potential would be anticipated.

6.4 MODEL 4: 1920-1944 SEMI DETACHED HOUSE

Model 4 is a semi-detached house of the period 1920-1944. Three NW and three SE facing (38° tilt) along with four horizontal collector units are mounted on the roofs, absorbing energy equal to 27-82% of the overall demand for DHW, SH&C on an annual basis (for the 4 case studies). A solar contribution of 13-25% could be achieved if the absorbed energy is delivered directly to the demand side, without feeding a store and if system losses are ignored.

4. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

81% of roof covered by collectors
NSH: **88-237** kWh/m²a



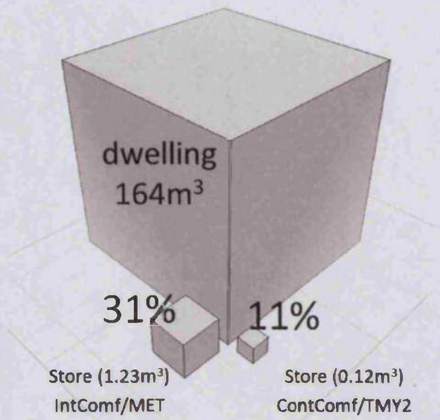
In the example of a 40% efficient ST system with a 500kWh (water volume of 6.2m³) store, a 47% solar contribution would be theoretically possible during 2007 and for intermittent comfort maintenance. For average weather conditions and 24/7 comfort maintenance the maximum solar contribution would be 16% with a 300kWh (water volume of 3.7m³) store. The solar contribution achieved with a 300kWh store is 16-46% among the 4 case studies. That shows that the use of a larger store (6.2m³) in this case would not be justified by the extra savings, as it would bring at maximum only 1% difference in solar contribution.

6.5 MODEL 5: 1945 - 1964 LOW-RISE FLAT

Model 5 is a low-rise flat built in the period 1945-1964. The annual NSH demand is predicted at 98kWh/m^2 for intermittent comfort and average weather conditions. Only 54% of the available roof area is covered by collectors (2 West and 3 East facing, vertical collector units) which absorb energy equal to 20-54% of the overall annual thermal requirement for SH&C and DHW among the 4 case studies. However the West-East orientation of the collectors brings a good matching between energy demand and availability; between 10-18% of the required energy (depending on the comfort and weather conditions) could be provided instantaneously by the collectors' yield if system losses were negligible and with no store used.

5. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

54% of roof covered by collectors
NSH: **65-138** kWh/m^{2}a



With a 40% efficient solar system and a 100kWh (1.23m^3 water volume) store the solar contribution predicted is 31%, for intermittent comfort in 2007. On the lower end, if average weather conditions are modelled and for 24/7 comfort maintenance the maximum predicted solar contribution is only 11% with a very small store requirement at 0.12m^3 of water. The available absorber areas in this house type cannot contribute to higher energy savings and this is due to the fact that the dimensions of the external surfaces allow only 54% of their area to be covered by collectors.

6.6 MODEL 6: 1945-1964 SEMI-DETACHED HOUSE

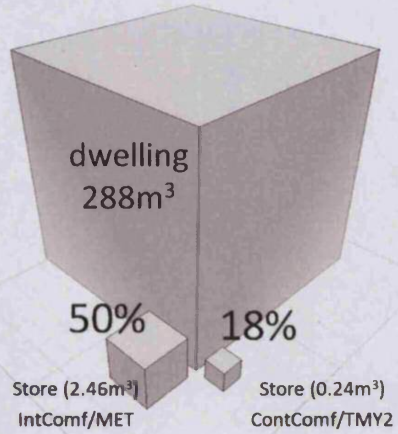
Model 6 is semi-detached house built in the period 1945-1964. Almost 85% of the available, South-facing, roof area is covered by 6 South-facing collector units (40° tilt) which absorb energy equal to 32-87% of the overall thermal requirement annually. The calculations show that 13-24% of the demand could be met instantaneously by the collectors' yield if system losses were negligible and no store was used.

A solar system with an overall efficiency of 0.4 could theoretically achieve a maximum 50% solar contribution if a 200kWh (2.46m^3 water volume) store was used, in 2007 and for intermittent comfort maintenance. For average weather conditions and continuous comfort maintenance the maximum potential solar contribution is predicted at around 18% with a 20kWh (0.24m^3 water volume) store.

Again the results of the FSC method show a higher ST potential for this house type. The predicted $f_{sav,therm}$ for the continuous comfort and average weather data is between 29-46%. As with the other models, it is the author's opinion that the actual potential is somewhere between the values suggested by the two methods.

6. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

85% of roof covered by collectors
NSH: **66-176** kWh/m^{2}a



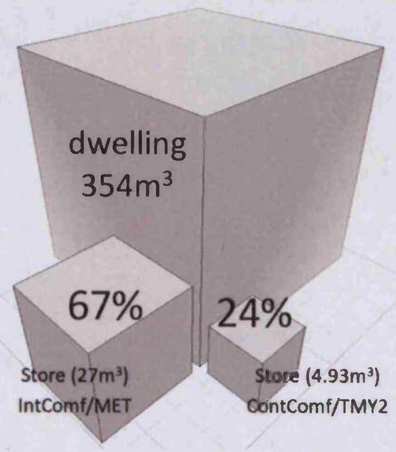
6.7 MODEL 7: 1965-1980 DETACHED HOUSE

Model 7 is a detached dwelling built in the period 1965-1980 with a predicted NSH demand at 61-151 kWh/m^2 per annum, among the 4 case studies. Eight collector units covering almost 90% of the South-facing roof area (29° tilt) absorb energy equal to 42-116% of the overall thermal requirement at an annual basis. The collectors' yield could meet 11-15% of the demand instantaneously if no system losses are considered and with no store used.

With the use of a 40% efficient system, 67% solar contribution could be theoretically achieved, requiring the use of a 2200kWh store, in 2007 and

7. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

89% of roof covered by collectors
NSH: **61-151** kWh/m^{2}a



for intermittent comfort. This storage capacity is translated into a water volume of 27m³ (which would correspond to a much larger store in practice, due to the extra volume required for the container and the heavy insulation) and the image on the right shows how big such a store would be. When comfort is to be maintained 24/7 and with average weather conditions the maximum predicted solar contribution is 24% with around 5m³ of water required to store the heat. With the same store size the solar contribution for intermittent comfort maintenance in 2007 would be 49%.

When the 9 typical solar combisystems are considered then the predicted $f_{sav,therm}$ for the continuous comfort and average weather data is between 29-47%. This in comparison to the results of the simplified approach (max 24%) appears to be unrealistically high. The actual ST potential is expected to be between 24-47% as it is acknowledged that the diffuse part of the solar energy would contribute to the savings, but only moderately.

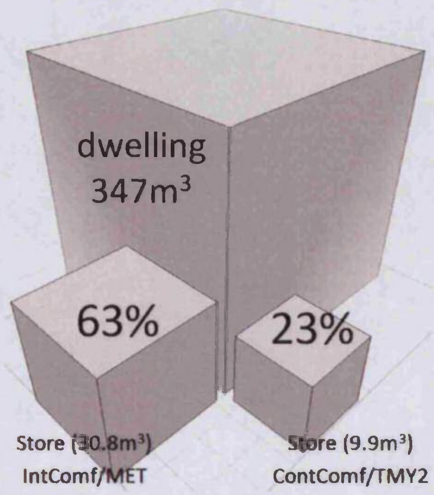
6.8 MODEL 8: 1965-1980 MID-TERRACE HOUSE

Model 8, a mid-terrace of the 1965-1980 era, has only 59% of its roof area covered by collectors. The energy absorbed annually equals to 41-110% of the total thermal energy requirement. If instantaneous use of this energy is considered and if system losses are ignored, 11-19% of the demand can be met by solar.

A 40% efficient system would achieve a maximum 63% solar contribution, with the use of a 2500kWh store, for intermittent comfort maintenance in 2007. That means that a significantly large store would be required, since only the water volume required for a sensible TES in this case is ~31m³, almost 1/3 of the volume of the entire house. Perhaps this would be possible in the future with advanced TES concepts, such as the innovative system described in 3.6.3.5.2. For 24/7 comfort maintenance and with average weather conditions the maximum solar

8. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

59% of roof covered by collectors
NSH: **66-158** kWh/m²a



contribution is predicted at 23% with a $10m^3$ water volume to store the heat. If such a store can be accommodated either indoors or outdoors, then the maximum share in the most favourable situation (IntComf/MET) would be 46%.

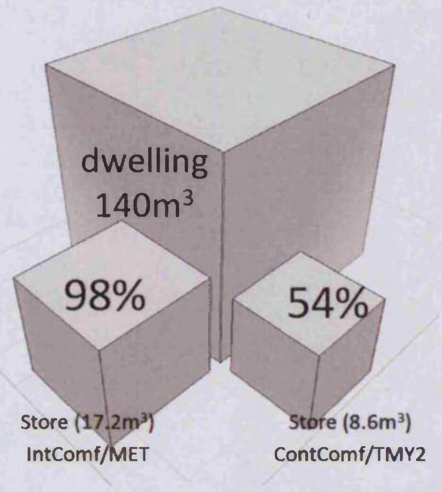
In this case a higher ST potential would apply if more flexible collector sizing would exist, so that a higher share of the available roof could be covered by collectors.

6.9 MODEL 9: 1981-1999 LOW-RISE FLAT

Model 9 which is a 1981-1999 low-rise flat with a NSH requirement of $51kWh/m^2$ per annum for intermittent comfort and average weather conditions. Four West-facing and four East-facing collector units, which cover only 68% of the total roof area, absorb solar energy adequate to deliver 22-34% (depending on weather and comfort conditions) of the total thermal requirement for DHW and SH&C if no store is used.

9. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

68% of roof covered by collectors
NSH: **32-83** kWh/m^2a



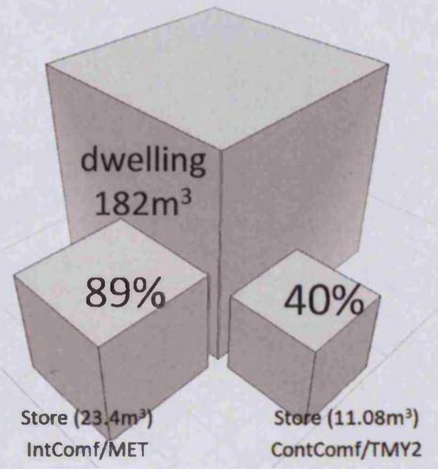
If the overall solar system efficiency is ~0.4 the solar contribution varies from 54% with a 700 kWh store -or $8.6m^3$ water volume at 70°C ΔT gradient- (ContComf/TMY2), up to 98% with a 1400 kWh store -or $17.2m^3$ water volume at 70°C ΔT gradient- (IntComf/MET). The stated storage capacities are on the threshold of the ST system sizing, so that larger capacities would not bring higher energy savings. For such a small flat ($45m^2$) these required water volumes are rather significant and in practice would correspond to even larger store volumes, considering the container and insulation needed. Space for the TES system could be found at the attic above the flat, or smaller systems could be employed, which would be designed for lower solar fractions (e.g. 40-69% with a 20kWh store capacity).

6.10 MODEL 10: 1981-1999 MID-TERRACE HOUSE

Model 10 is a mid-terrace house built between 1981-1999. Four West facing and 4 East facing (29° tilt) collector units, that cover 82% of the overall roof area, absorb solar energy equal to 70-159% of the overall annual demand, among the 4 case studies tested. The direct solar yield i.e. if system losses are ignored and if no store is considered, is 17-28% between the case studies.

10. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

82% of roof covered by collectors
NSH: **46-109** kWh/m^{2}a



With a 40% efficient solar system, up to 89% of the demand can be supplied by solar energy with a 1900kWh store. In that case the water volume required for this capacity is around 23m^3 and although the actual volume of the store would be even bigger, it is a case where a large store would be justified by the solar contribution that can be achieved. With a 900kWh store (2.2m^3 of water) the solar savings for all 4 case studies[25] would be 40-71%. For this house type even a very small storage capacity at 20kWh would bring solar savings between 28-53%.

6.11 MODEL 11: 2000-2006 SEMI-DETACHED HOUSE

Model 11 is a semi-detached house of the period 2000-2006 with 4 South facing collector units mounted on 63% of the overall available roof area. The collector's yield at an annual basis is 33-80% of the overall thermal demand. Between 12-17% of the demand for SH&C and DHW could be met instantaneously (without a store) from solar if system losses were negligible.

In the case of a 40% efficient system a maximum 46% solar contribution appears to be possible with the use of a 300kWh store, for intermittent comfort in 2007. A maximum solar contribution of only 19% is predicted for 24/7 comfort maintenance and average

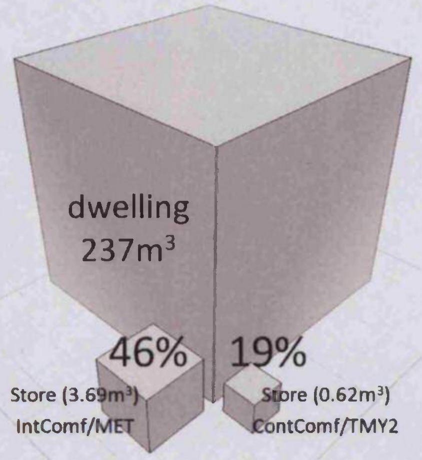
[25] 2 weather and 2 comfort conditions modelled.

weather conditions with a 50kWh store. If a 50kWh store is used (0.62m^3 of water volume) then the solar contribution would be between 19-42% among the 4 case studies tested. In this dwelling only 63% of the roof potential is utilised and so the collectors' yield is very small. Therefore the system could benefit from larger absorber areas if e.g. other external surfaces would be considered as suitable for collector mounting or if more flexible collector sizes were used.

When the 9 typical solar combisystems are considered then the predicted $f_{sav,therm}$ for the continuous comfort and average weather data is between 28-46%. This in comparison to the results of the simplified approach (max 19%) is very high, revealing that the actual potential could be between the range of savings predicted with the 2 methods.

11. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

63% of roof covered by collectors
NSH: **72-145** kWh/m^{2}a

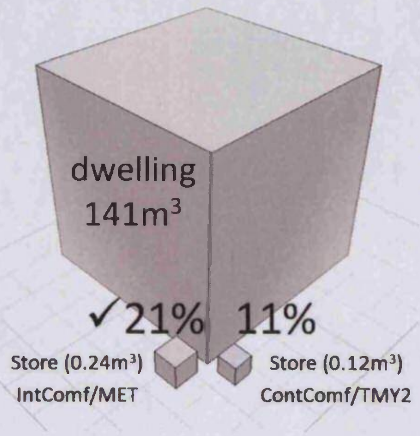


6.12 MODEL 12: POST-2006 HIGH-RISE FLAT

Model 12 is the most recent dwelling of this database, built according to the 2006 UK building regulations at high insulation standards (30kWh/m^2 per annum NSH requirement, for intermittent comfort and average weather conditions). A small flat within a large apartment block, it has only NW and NE facing external surfaces available for collector mounting. This is the worst case within this database, from the solar availability point of view. With this study it was shown that, although only 62% of these vertical

12. Volume comparison between dwelling and required storage material. Maximum ST potential for both minimum and maximum SH demands.

62% of roof covered by collectors
NSH: **16-43** kWh/m^{2}a



surfaces could fit collector units, a 70% efficient solar system would cover 10-19% of the overall demand by instantaneous use of the absorbed energy, among the 4 case studies assessed. A ST system with an overall efficiency of 0.4 could deliver 11-21% of the energy required for SH&C and DHW with the use of a small store (10-20kWh). Use of a larger store would not contribute to higher savings, as in this case the available solar energy is limited and at a 24-hour basis it fluctuates in (reasonable) accordance with the demand, as shown in Figure 49. The flat has a small room (2.6m³) which currently contains a small stainless steel unvented water heater. A 0.24m³ solar store could be easily fitted in this room and the predicted savings in an intermittent comfort maintenance scenario would be 14-21% (587-809 kWh saved annually) depending on the weather conditions.

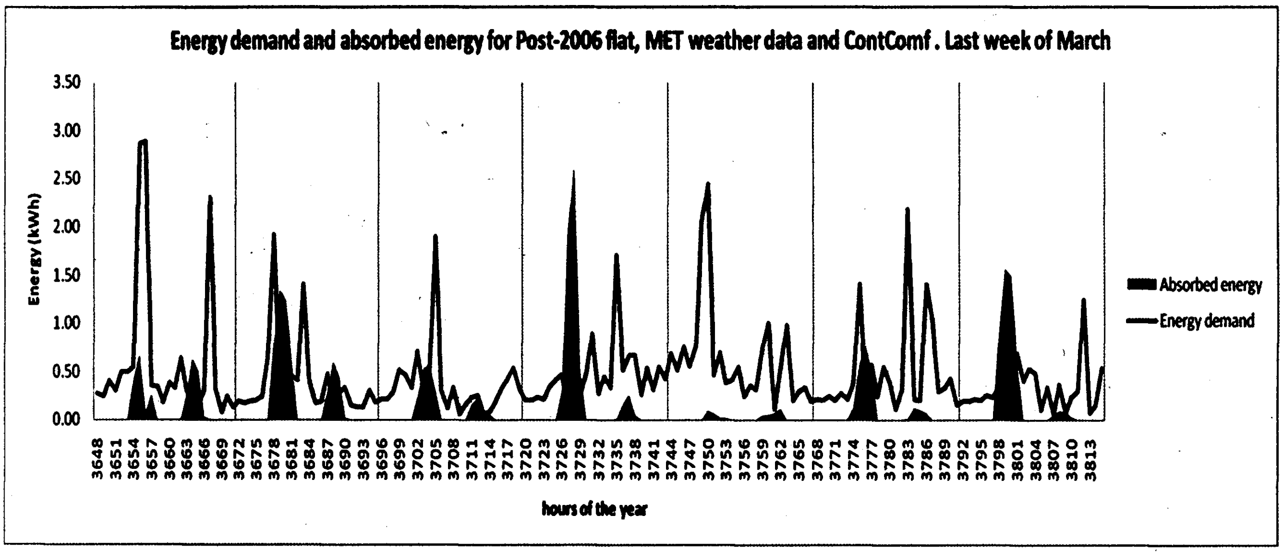


FIGURE 49: THERMAL ENERGY DEMAND PROFILE AND ABSORBED SOLAR ENERGY (NW AND NE FACING VERTICAL COLLECTORS) FOR THE POST 2006 FLAT DURING THE LAST WEEK OF MARCH; WITH ACTUAL WEATHER CONDITIONS AND FOR CONTINUOUS COMFORT MAINTENANCE.

7 CONCLUSIONS

In this last Chapter an overview of the findings of this PhD work is presented and possible future work potentials are suggested.

7.1.1 BUILDING SIMULATIONS AND THERMAL ENERGY DEMAND PROFILES

In this study the modelling approach chosen was found to be significantly time-consuming, as there is currently no user-friendly interface for the building input in TRNSYS. This fact explains why the building model suffers from major simplifications in current practice of solar system simulations and highlights that there is a need for better and more suitable modelling methods, or that the existing tools have to be extended to incorporate comprehensive, building focused,3D interfaces for this reason. Nevertheless it was shown here with the sensitivity analyses that the results vary greatly when a range of potential input values is tested. For example, it was revealed that the internal gains from appliances and lighting have an effect on the predicted heating and cooling demands across all house ages and types, and this is more marked in more recent heavily insulated housing. In such cases the internal gains themselves could constitute a large part of the thermal requirement for SH and even introduce a small cooling demand. It was also highlighted that the variation of internal gains actually found in practice can in itself be problematic when trying to decide which one is appropriate for use. Further to this, a large variation in the predicted thermal demand profiles was caused also by the desirable thermal comfort conditions indoors and a slightly lower variation by the use of actual and average weather data.

As a result of the simulations a range of possible thermal demands for SH and SC in welsh dwellings was predicted. The NSH demands highlighted why the carbon emissions per person in Wales were the 12th highest in the world in 2004:

- The NSH requirement as calculated with average weather data for 24/7 use of the SH system ranges between 43kWh/[m^2.a] and 242 kWh/[m^2.a].
- The NSH requirement for intermittent and constant thermal comfort in the case of actual 2007 weather conditions ranges between 16-92 kWh/ [m^2.a] and 24-172 kWh/ [m^2.a] respectively.

- For the predictions of the year 2007, a maximum cooling demand of 49kWh/m^2 is calculated for the continuous comfort scenario.

It was not possible to draw conclusions relating the building construction date and the thermal behaviour of these dwellings, possibly due to the fact that these buildings do not represent anymore the era in which they were built as they have all undergone some alterations since construction.

7.1.2 THE SOLAR THERMAL POTENTIAL

The results presented in chapters 5 and 6 revealed that solar energy has a role to play on reducing the amount of conventional energy currently consumed for heating and domestic hot water preparation in the UK dwellings. The novel approach that was used in this assessment was accurate enough, with regards to the building part of the system, to reveal the characteristics specific to the dwellings of this region, mainly related to the construction (insulation) and the variations in space volume. The methodology followed in this work allowed also for understanding of the climatic potential, associated with the overcast sky conditions that are dominant in the UK and the amount of useful solar energy available.

The general outcome of this research is that ST is a feasible technology for Wales and that all house types are possible candidates for effective solar thermal applications, serving both DHW and SH needs. That is if we assume that economies of scale could be possible in the near future, as due to the climatic conditions in the UK a larger absorber area is required, compared to ST applications in South Europe. However, albeit the dominant cloudy conditions of its sky, Wales can benefit from the extensive roof area available in its housing stock in order to produce a significant part of its energy requirement for domestic use and can do so with using a range of available orientations and tilts.

The first part of this analysis, that took into account the contribution of the beam radiation only, revealed that there is inarguably a significant amount of useful energy at an individual house approach. More specifically, the ST systems were shown to contribute to thermal savings between 9%- 34% among the case studies (Figure 39) solely with direct utilisation of the collected solar energy. This finding is very important, as it brings out the potential that exists for ST systems in existing houses that are not upgraded nor designed for low carbon, and without the need for sacrificing indoor space for the ST system. The annual incident solar energy between the 12x4 case studies was predicted to be as much as 24,129-33,482kWh (tmy2-met) for the larger dwelling of this database or as little as 1,000-1,392kWh (tmy2-met) when only 6m^2 NW-facing and 12m^2 NE-facing absorber areas are available in a newly built flat. When looking at the ratio of annual solar availability to the annual demand for the 12 houses it was found that the lower was at 27% and the highest at 191%. At a step further the analysis showed that with the use of thermal energy storage technologies the energy savings with a 40% efficient ST system could be up to 54% for average weather conditions, or up to 100% in warmer than usual years. As expected, among the case studies assessed, there were also less optimistic examples, with savings being as low as 11-21% of the required energy for DHW and SH, for the range of weather conditions assessed. However the low potential in these cases was not due to poor sky conditions but was rather related to the particular house characteristics that can vary even between identical house types, e.g. roof orientation.

The findings of this research probably represent a modest prediction, as the actual potential for these case studies might be higher for a number of reasons. Firstly, due to advances in collector performance, a part of the diffuse radiation would be harvested in reality, increasing significantly the collectors' yield. That was not taken into account at the first part of this study due to lack of reliable supporting data but the effect of it was shown with the results of the FSC method. Secondly, more flexible collector sizing (which seems possible with the tubular structure of the contemporary collectors) would allow utilisation of the odd-sized roof area that has not been utilised in this study, accounting for 11-46% of the overall roof surface of the houses. The same applies to the external walls of the dwellings, which have not been taken into account either. Further to these, the overall system efficiency in practice could be higher than the one assumed here, allowing for an extra 20% of the incident energy to find its way to the demand side (efficiency ranging between 30-60%). Next to the highest potential arising from the solar availability itself, if the house performance is improved prior to application of any solar thermal system, the results would be even more positive, possibly also allowing for reduction of the required absorber area. This can be done by simply upgrading the house (insulation, air tightness, new glazing) or indirectly by tolerating the thermal comfort conditions indoors.

In parallel to the modelling approach that used an average efficiency at 0.4, the FSC method was used to reveal the potential that arises if 9 actual solar combisystems tested by the participants of Task 26 of the IEA SH&C program are applied to the housing stock and climate of Wales. The FSC method was only applied to the 5 dwellings which have South facing collectors and the results are only reliable for the continuous comfort maintenance and average weather conditions scenario, as the method is validated only for these conditions. For all 5 models the use of solar energy would bring -at maximum- thermal energy savings of around 41-47% (ContComf/tmy2) if the best system (among the 9 considered in the Task 26 study) is employed, compared to a conventional SH, SC and DHW system. If the parasitic (electric) energy consumption of these systems is of interest (e.g. if no PV modules are installed for this reason) the energy savings can be as low as 10% or as high as 44% for these house types. That shows that within this selection of ST systems, which were considered as typical for Europe, a large variation of system qualities exists and highlights that the energy savings with solar thermal applications are strongly dependent on the choice of the system while the maximum potential is limited only by the building and climate characteristics. With the FSC method, the contribution of the diffuse solar energy to the system yield was included in the results, although the method is not able to accurately weight what share of the diffuse energy would be actually harvested by the systems if locations and weather data other than those used in the Task apply. The approach taken here was to use both methods so that a safe estimation of the actual demand is made, taking into account the limitations and advantages of both approaches.

An additional important outcome of this study is the fact that results were also obtained for off-South orientations. A good matching between the collectors' orientation and the operational schedule for the SH system is important in these cases so that the system benefits from the solar energy when this is still 'fresh' in the system. A flat that had collectors oriented towards East and West (house 5) and another with only South-facing collectors (house 7) were compared and the results showed that although less solar energy was available in the first case (due to smaller collector areas and a lower ratio of annual collector yield to annual overall demand) a good agreement between energy demand and availability was achieved, as 10-18% of the demand could be served by solar energy instantly depending on weather conditions, while the respective range for the case with the South facing collectors was 11-15%. Within the case studies used in this research a range of potential collector tilts that was also assessed. As a general conclusion regarding the collectors considered in this study was that a steep collector tilt of around 75° from horizontal is a good option, as in this case the particular collector's efficiency is very close to the maximum, the winter availability is slightly higher than the one achieved with a 45° tilt and in summer the reduced solar availability would also mean reduced stagnation risk.

Essential information regarding the solar thermal potential in this region is also returned by the sensitivity analyses. In general when warmer than average actual weather conditions were tested the ST potential predicted was found to be significantly larger than that of average weather conditions. Note that this effect was not visible in the results of the FSC method, as the latter does not allow for inclusion of the excess solar energy. It was also found that although at an annual basis the potential appears to be greater for intermittent than continuous comfort system strategies, the direct solar utilisation in an 24/7 comfort maintenance scenario might be higher than that of an intermittent usage, depending on the thermostat settings and schedule (determined by the occupants' presence) and of course on the absorbers' orientation. Both the comfort strategy implemented and the orientation of the available roofs are two important aspects of the overall system design to consider in practice. It is thus highlighted that due to the fluctuating nature of the solar availability in this climate, a solar system has to work as a receptor of the 'free' energy at any time of the day, and be able to utilise it with an effective way; a strategy designed to feed the house with the available energy when this becomes available without being tied to a scheduled demand, could be the preferable choice. Therefore, although in South Europe a small scale solar thermal domestic hot water system can benefit from the constant sunny conditions, in the welsh climate a less 'focused' approach might be required, where solar energy can feed the DHW needs or part of the SH needs, depending on what is required the most, or by charging a store, when the sun is out. This also coincides with the current practice in Central and North Europe, where ST space heating and DHW systems are developed and become popular.

Furthermore, the modelling approach, that used an average 0.4 efficiency, revealed the relation between absorber area and store size tied to the case studies. Among the 12 houses assessed in this work, a great variety of energy demands and solar thermal potentials are predicted (see also Table 20). For most of the case studies, if reasonable sized stores would be used (up to 300kWh TES capacity) then the solar contribution to the overall thermal energy consumption in the most favourable conditions would be around 42-58%. Only a couple of models appear to have a much lower potential, mainly due to the lack of sufficient collector areas. However, even in the example of the Post-2006 high rise flat, where only 2 NW and 2NE facing vertical collector units are used, the system would be able to cover up to 21% of the overall needs with the use of a very small water store (10-20kWh). The same applies to the 1945-1964 flat where energy savings from a solar system would be between 11-31% with a store requirement between 10-100kWh. For model 9 the solar thermal potential appears to be very promising, as with only 20kWh storage capacity requirement ($0.24m^3$ water volume at 70°ΔT) a solar contribution up to 69% appears to be feasible. It was further shown that a clear threshold on the required collector capacities exists for each house type and this effect follows the "law of diminishing returns" (Figure 39); absorber areas larger than a certain size would not contribute to higher energy savings or smaller TES sizes. These findings combined reveal that for the specific climate the solar thermal system would more likely require a large collector area, while the store size would be quite reasonable. However for reaching the highest end of expectations for certain house types -up to 54% with average and up to 100% with warmer weather conditions- inter-seasonal storage would be required. In this case, the maximum justifiable storage capacities predicted were around 5600-10300kWh, which correspond to very large store volumes; up to $123m^3$ of water are required in this case in order to store heat at a 70°C ΔT, and that volume excludes the container and the essential insulation volume. It became clear with the analysis that these inter-seasonal solar systems are currently not feasible options, considering that sensible heat storage is still the state-of-the-art and the only economically justifiable solution for thermal energy storage. Use of innovative storage types that would only be available in the future, such as those revealed with the literature survey, including latent, and thermo-chemical heat storage, would be required in order to achieve high solar fractions in most of these dwellings, as space is limited in the Welsh dwellings.

Based on the above arguments the main conclusion of this work is that it is now worthwhile discussing about solar thermal systems in the UK and thus attention has to be drawn on the solar thermal technologies, especially with regards to the current targets for energy savings and carbon reduction in the built environment. This work has managed to show that there is sufficient solar energy in this region for effective ST applications and has also identified further work potentials. The focus of further research in the area has to be on the particular characteristics of the appropriate solar thermal system(s) per house type, including the thermal energy storage component of the installation. Solar thermal applications could be compared against other technologies using solar or other types of renewable energy sources such as PV. Obtaining more accurate estimates of the potential for each house type would only be possible if detailed solar thermal system simulations would be conducted and compared with real measurements. Critical to this respect is also the development of improved modelling and prediction mechanisms that allow for a holistic design approach of the system, treating with similar detail and accuracy both the building component and the solar thermal system.

As was mentioned at the beginning of this dissertation the author's research is a long-term study of which the PhD is the start. Some of the above mentioned research topics will be, hopefully, the subject of future, post-doctoral work.

TABLE 20: SUMMARY OF THE RESULTS PER HOUSE TYPE.

No	House type/era	N# of collector units, tilts and azimuths	Roof % covered	Range of results for 2 comfort (intermittent and continuous maintenance) and 2 weather (actual 2007 and average) conditions. System losses ignored.			Maximum solar contribution and respective store requirement predicted for a ST system with overall efficiency at 0.4			
				NSH demand (kWh/m². a)	$\frac{\text{annual collectors' yield}}{\text{annual overall demand}}$ %	Direct use of collectors' yield (hourly intervals)	Interm. Comf. met		Cont.comf. tmy2	
1	Pre-1850 Detached	5 S (35° tilt)	72%	62-131	39-98%	12-16%	56%	1100kWh	22%	100kWh
2	Pre-1850 Converted Flat	6 S (46° tilt) 7 E & 7W (34° tilt)	78%	91-242	41-191%	13-19%	100%	5600kWh	34%	1800kWh
3	1850-1919 Semi Detached	2 E (28° tilt), 2 S (28° tilt), 4 E (26° tilt), 12 S (50° tilt), 6 S (31° tilt)	74%	92-227	54-137%	10-17%	100%	10300kWh	45%	7000kWh
4	1920-1944 Semi Detached	3 NW & 3 SE (38° tilt), 4 horizontal	81%	88-237	27-82%	13-25%	47%	500kWh	16%	300kWh
5	1945 - 1964 Low-rise Flat	2 W & 3E -10° (90° tilt)	54%	65-138	20-54%	10-18%	31%	100kWh	11%	10kWh
6	1945-1964 Semi-detached	6 S (40° tilt)	85%	66-176	32-87%	13-24%	50%	200kWh	18%	20kWh
7	1965-1980 Detached	8 S (29° tilt)	89%	61-151	42-116%	11-15%	67%	2200kWh	24%	400kWh
8	1965-1980 Mid-terrace	4 W & 4E +5° (26°tilt), 3 horizontal	59%	66-158	41-110%	11-19%	63%	2500kWh	23%	800kWh
9	1981-1999 Low-rise Flat	4 W & 4E (14° tilt)	68%	32-83	70-180%	22-34%	98%	1400kWh	54%	700kWh
10	1981-1999 Mid-terrace	4 W & 4E+5° (29° tilt)	82%	46-109	70-159%	17-28%	89%	1900kWh	40%	900kWh
11	2000-6 Semi-detached	4 S (46° tilt)	63%	72-145	33-80%	12-17%	46%	300kWh	19%	50kWh
12	Post-2006 High-rise Flat	2NW& 2NE (90° tilt)	62%	16-43	20-32%	10-19%	21%	10kWh	11%	20kWh

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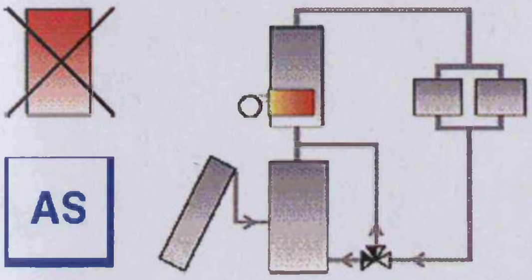
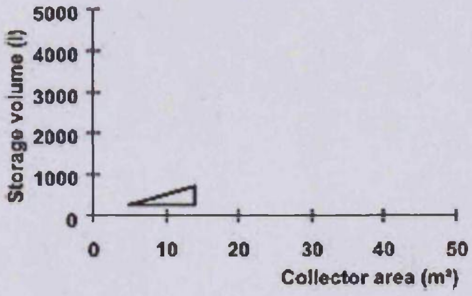
APPENDICES

APPENDICES-A

This section includes supporting information for 3.5.3 'The outcomes of the IEA SHC Tasks 26 and 32'; a detailed description with the hydraulic scheme for each system modelled in Task 26 is provided (source: http://www.iea-shc.org/task26/index.html). At the end of this section, Table 5 printed in an A3 page to facilitate reading of the 5.5.2 'Use of the 9 generic systems tested in Task 26' is presented.

#2: Heat Exchanger between Collector Loop and Space-Heating Loop / DENMARK



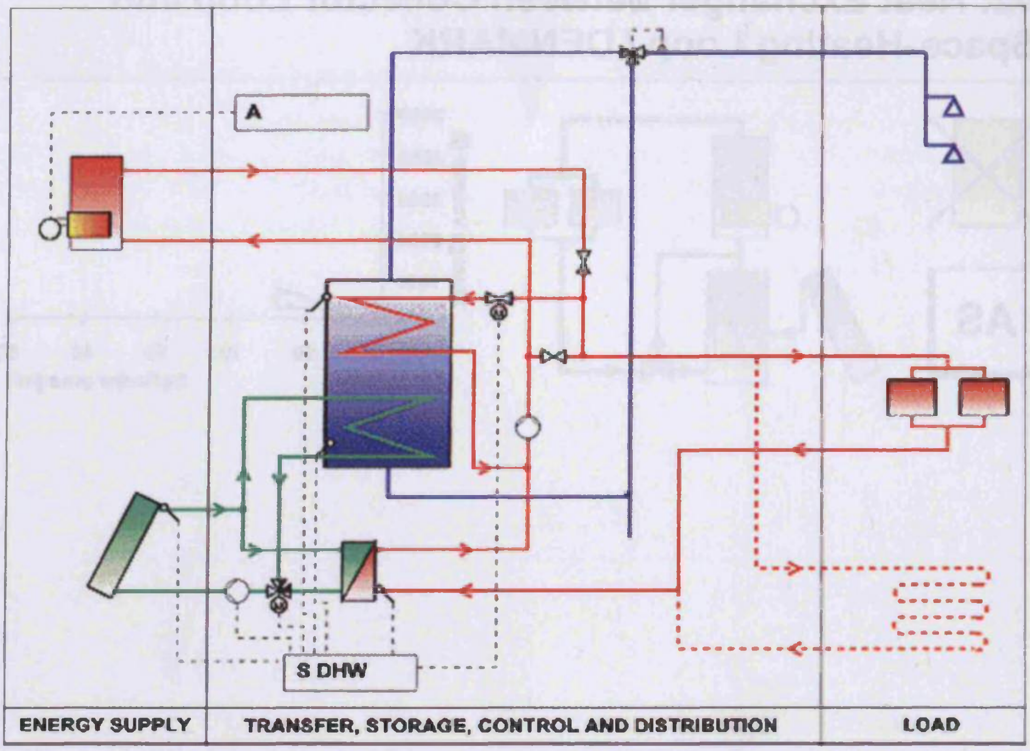


Main features

This system is derived from a standard solar domestic-hot-water system, but the collector area has been oversized in order to deliver energy to an existing space heating system. The connection between the solar and the existing system is made through a heat exchanger included in the return pipe of the space-heating loop. The store is only devoted to DHW preparation, with two immersed heat exchangers: the solar one in the bottom of the tank, and the auxiliary one at the top. A three-way valve directs the antifreeze fluid coming from the collector either to the DHW heat exchanger, or to the space-heating heat exchanger.

Heat management philosophy

The controller doesn't manage the auxiliary part of the system. As long as the temperature at the collector outlet is higher than either the return temperature from the space-heating loop or the temperature at the bottom of the tank, the pump of the collector loop operates. The three-way valve is managed so as to deliver solar energy to the space-heating loop, i.e. when the temperature at the collector outlet is lower than the temperature at the bottom of the tank, or when the storage is warm enough (temperature at the top of the store higher than the set-point temperature). When the domestic-hot-water temperature is too low, auxiliary heat is delivered to the tank through the two-way valve.



Specific aspects

Due to the lack of store for space heating, the solar gain will be increased the more variations of indoor temperature the inhabitants tolerate. In this system, the building itself plays the role of space heating store. Therefore, the system will work better with a high-capacitance heat emission system, like heating floors. Solar-induced variations in the indoor temperature are only possible when the boiler is turned off (i.e. in summer). The system could be controlled so that it delivers heat to the space-heating loop independently of any space heating needs if there is a risk of overheating in the system.

Influence of the auxiliary energy source on system design and dimensioning

This system can work with any auxiliary energy source (gas, fuel, wood, district heating). It could be also used with separated electric radiators.

Cost (range)

A typical system with 7 m² of solar collectors and a 280 litre store costs about 5 200 EUR. This amount only includes the solar part (collectors, storage device, controller and heat exchanger, installation), since the auxiliary part (boiler, radiator circuit) already exists. Total cost for complete heating system with solar is 13 800 EUR, and reference cost for complete heating system without solar is 9 300 EUR.

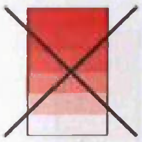
Market distribution

This system is the most common in Denmark. Prior to 2000, about 100 000 m² of solar collectors have been installed by 12 manufacturers and 400 to 800 installers all over Denmark.

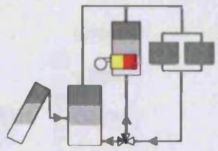
Manufacturer: Batec A/S, others

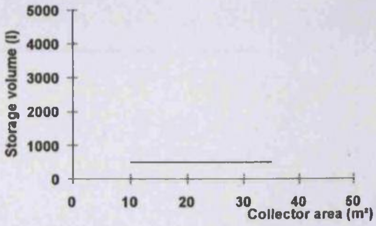
Data Sheet #1 PREVIOUS NEXT Data Sheet #3

#3a Advanced Direct Solar Floor (France)



AP





Main features

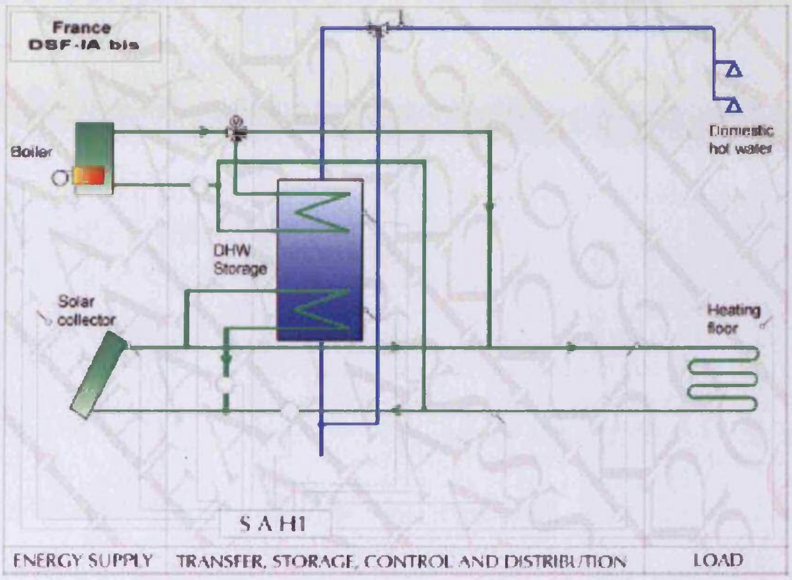
This combisystem has been elaborated from the previous Advanced Direct Solar Floor concept, in order to simplify the hydraulic scheme and to reduce the price. A specific heat management philosophy is used to optimise the solar heat sharing between DHW production and space heating.

Heat management philosophy

The floor heating loop is under control of a heating curve elaborated from a predicted outside temperature and the inside temperature. When solar energy is delivered to the floor, the inlet temperature in the floor can rise so that the room temperature doesn't exceed the auxiliary set-point room temperature more than 4 °C. When auxiliary energy is delivered to the floor, the space heating loop pump is shut down when the inside temperature exceeds the auxiliary set-point room temperature more than 0,5 °C.

The auxiliary boiler is controlled by the solar controller, in such a way that the heat losses are reduced when no auxiliary energy is needed.

In summer, all the volume of the DHW tank is used for solar energy storage.



Specific aspects

All the components drawn in the central box of the hydraulic scheme are factory assembled in compact technical units, which makes the work of the installer in the house easier.

As a strong interaction exists between the auxiliary boiler and the solar system, the system is delivered with the boiler.

Because of the heating floor, this system suits well in new houses, or in retrofits where the floors are rebuild.

Monitoring possibilities are included in the controller, which is able to compute energy balances, and to send them to a remote computer trough a integrated modem. So it is easy to detect failures.

Influence of auxiliary energy source on system design and dimensioning

Gas, fuel or electricity boiler can be easily connected to the technical unit. It is also possible to use a wood boiler, with use of an additional buffer tank.

Cost (range)

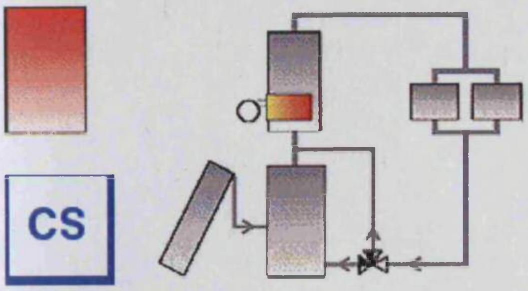
A typical system with 15 m² of solar collectors costs about 17 000 EUR, which can be divided approximately in two halves : the auxiliary part (boiler, pipes of the heating floor, auxiliary DHW tank, control,...) corresponding to the reference system (8 500 EUR), and the solar-related additional investment (solar collectors, solar DHW tank, control,...). Installation costs are reduced through the high level of components integration, and the possibility of partial self-installation.

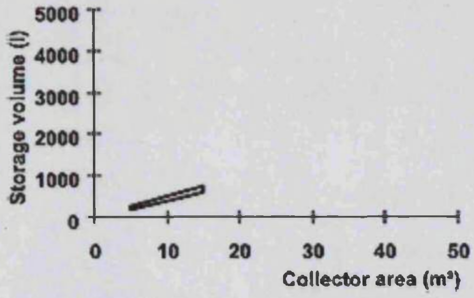
Market distribution

Like Advanced Direct Solar Floor and Basic Direct Solar Floor, this system is only spread in France. Only one company is manufacturing it. More than 300 units have been sold since 1999, that is more than 4500 m² of solar collectors.

Manufacturers : CLIPSOL.

#4: DHW Tank as a Space-Heating Storage Device / DENMARK



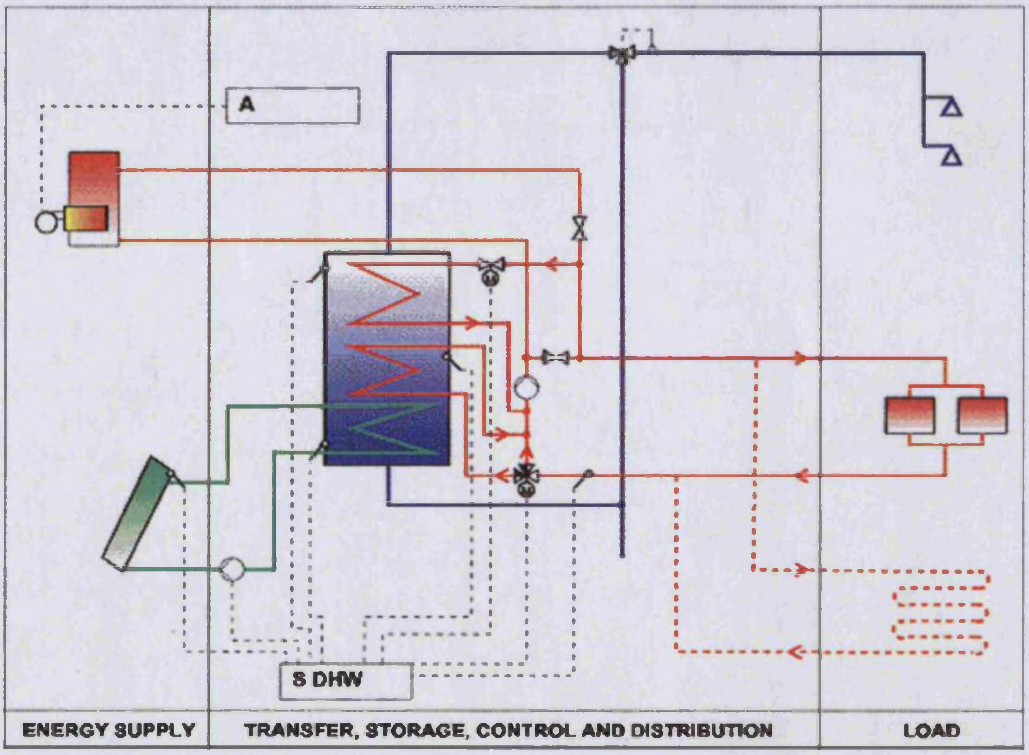


Main features

As is the case for System #2 this system can be added to an existing space heating system. Heat coming from the solar collector is delivered to a DHW tank, which acts also as a small buffer tank for space heating. The DHW store is equipped with three immersed heat exchangers: the solar one in the bottom of the tank, the auxiliary one at the top, and an intermediate one connected to the return line of the space-heating loop. A three-way switching valve directs the fluid from the space-heating loop either to the intermediate heat exchanger, or directly to the auxiliary boiler.

Heat management philosophy

If the temperature at the collector outlet is higher than the temperature at the bottom of the tank, the pump of the collector loop is on. The three-way valve is controlled so as to deliver solar energy to the space-heating loop, i.e. water flows through the intermediate heat exchanger only when the temperature in the middle of the tank is higher than the return temperature of the space-heating loop. When the DHW temperature is too low, auxiliary heat is delivered to the tank through the two-way valve. The auxiliary part of the system is under control of a separate control unit.



Specific aspects

Solar heat used for space heating is stored in the domestic hot water tank.

Influence of the auxiliary energy source on system design and dimensioning

This system can work with any auxiliary energy source (gas, oil, wood, or district heating). It could be also used with separated electric radiators.

Cost (range)

A typical system with 15 m² of solar collectors and a 800 litre storage unit costs about 7 000 EUR. This amount only includes the solar part (collectors, storage tank, controller and heat exchanger, installation), since the auxiliary part (boiler, radiator circuit) already exists. Total cost for complete heating system with solar is 15 600 EUR, and reference cost for complete heating system without solar is 9 300 EUR.

Market distribution

This system is quite new in Denmark. Only one company markets this system, with a total collector area in operation of 100 m². The system is marketed by the manufacturer and is available anywhere in Denmark from the nearest installer (400-800 potential installers).

Manufacturer: Batec A/S

Data Sheet #3 PREVIOUS NEXT Data Sheet #5

#8: Space Heating Store with Double Load-Side Heat Exchanger for DHW / SWITZERLAND

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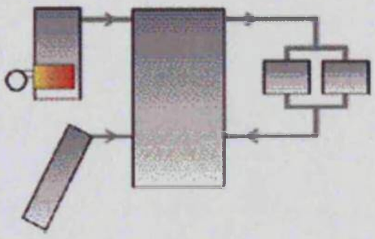
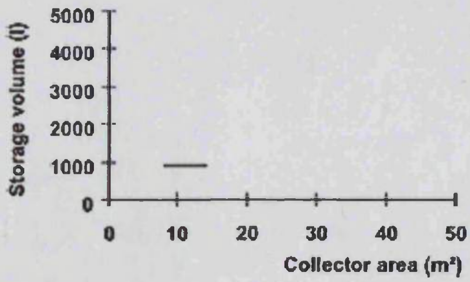




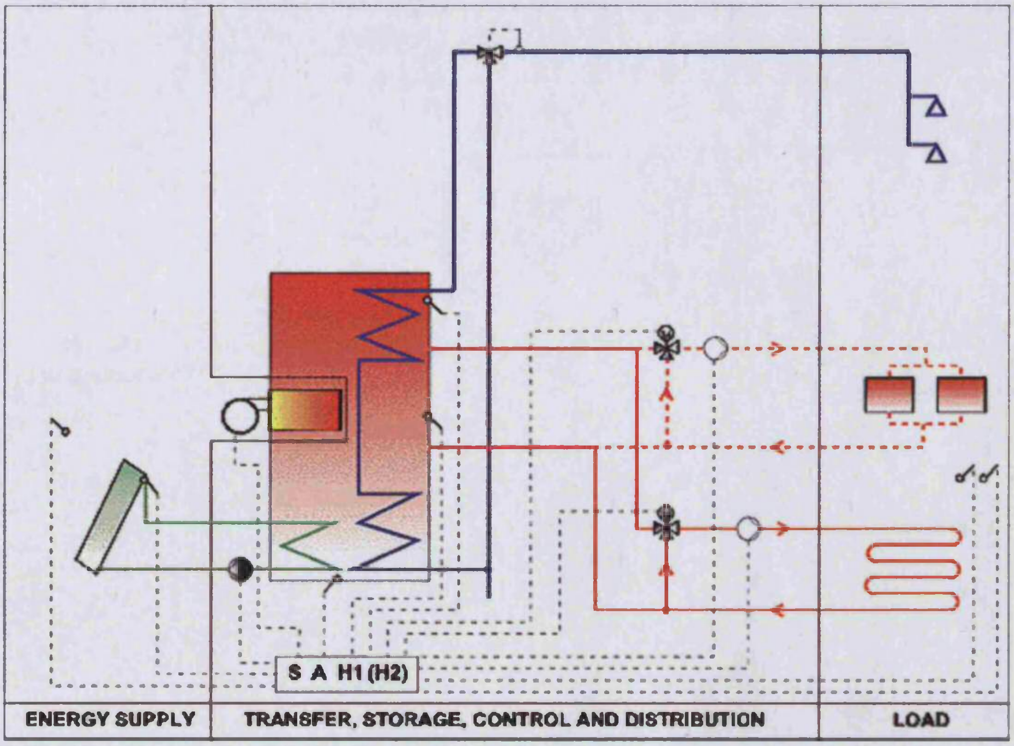
Main features

This system is a compact unit for space heating and DHW, with an integrated gas or oil burner. The storage tank is fitted out with two immersed horizontal finned-coil heat exchangers (one in the upper and one in the lower part) for DHW preparation and a third one in the bottom for the collector loop.

Heat management philosophy

The speed of the collector loop pump is varied in accordance with the temperature in the middle of the tank and the temperature difference between the collector outlet and the bottom of the storage tank. The storage tank set-point temperature, which controls the auxiliary burner, is automatically adjusted to the space heating needs.

The controller is able to anticipate when solar heat is available from the collector and switch off the burner.
Space heating is managed by the controller, taking into account solar passive gains detected by a second room temperature sensor. In the case of heating floors, a storage tank discharge can be forced in order to store heat in the building structure. In such a case, the room temperature may deviate from its set-point value by as much as 5°C. The control strategy is designed to adjust the start time to improve thermal comfort.



Specific aspects

One single controller is in charge of the whole system (collector loop, DHW, space heating and auxiliary burner), with a display that indicates proper operation. Overheating is prevented by cooling the lower part of the storage tank after the sun has set by using the collector as a heat sink. There is no legionella risk because DHW doesn't stagnate in the storage tank.

Influence of the auxiliary energy source on system design and dimensioning

This system can be used with a gas or oil auxiliary burner. Alternately, a wood boiler can be connected directly to the lower part of the storage tank. In such a case, the boiler should be used cautiously to avoid competition between solar and auxiliary energies in the commonly used, lower section of the storage tank.

Cost (range)

The total cost of the whole system with a gas or oil burner is about 20 000 to 23 000 EUR, for a collector area of 8 to 16 m². Installation costs and a heating floor are included in these figures. A similar reference system without solar heating costs about 11 000 EUR.

Market distribution

This system is rather new in Switzerland (1998). At the end of 1999 25 systems have been installed with a total collector area of about 300 m². Two companies are marketing this system.

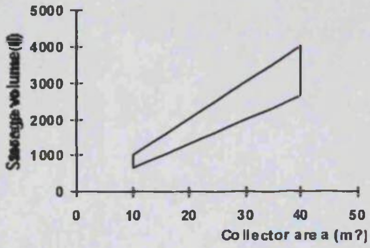
This system is presented thanks to the Swiss Federal Office of Energy

Bundesamt für Energie
Office fédéral de l'énergie
Ufficio federale dell'energia
Swiss federal office of energy

Data Sheet #7 PREVIOUS NEXT Data Sheet #9

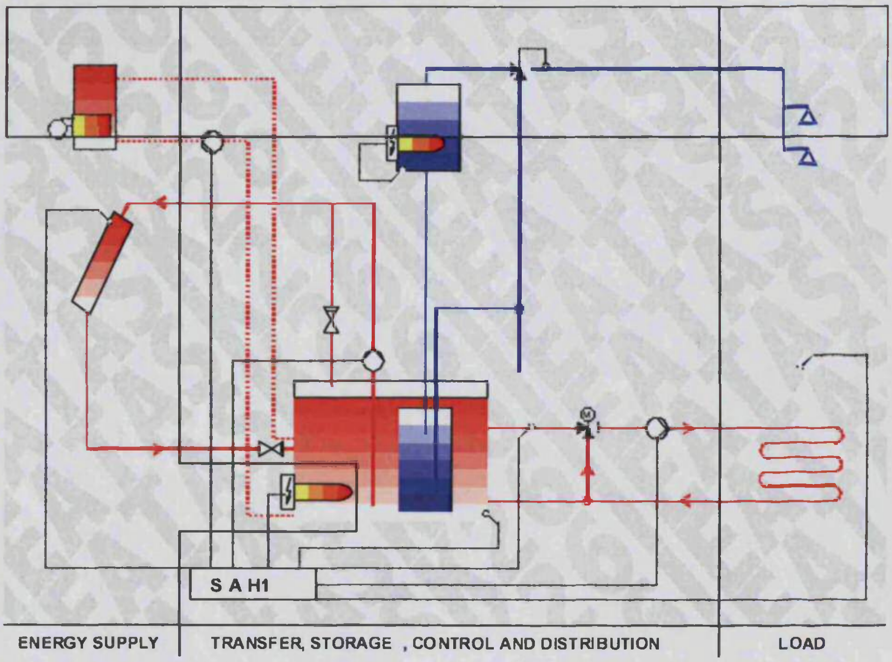
CM*d(i)l*

NORWAY



Main specific features

Water is used as the common heat transfer fluid in the solar collector loop, the space heating tank and the heat distribution loop, without any intermediate heat exchanger. Accordingly, all components are made of stainless steel, copper or plastics. The tank operates at atmospheric pressure. A special polymer flat-plate collector is used, filled with ceramic/clay granulates. Filling with granulates helps keep the water level stable in the space heating tank, independently from the collector loop pump status (operation or standstill), and secures a turbulent flow in the collector channels. The DHW tank located inside the space heating tank is operated at the usual domestic water pressure.



Heat management philosophy

All system functions except DHW auxiliary heating are controlled by a single control unit.

The pump of the collector loop is controlled according to the temperature difference between the collector sensor and the storage tank bottom sensor. For the start-up phase, a special control feature is provided to remove the air present during standstill from the collector.

The supply of auxiliary heat for space heating is basically under control of a thermostat. Optionally, a dynamic thermostat function can be provided (thermostat setting dependent on the outdoor temperature). In the case of electricity, as the auxiliary energy source, adjustment to use off-peak electricity at night time can be done.

The heat transport to the space heating loop is controlled by an 'on/off' operation of the floor circulation pump and/or thermostat valves at the manifold of the floor distribution lines. The control parameters are the outdoor temperature, the solar irradiance (through the windows) and optionally the wind speed (in coastal regions).

The auxiliary heater for DHW is controlled by a separate thermostat.

Specific aspects

Overheating and freeze protection are provided by the drainback principle.

Influence of the auxiliary energy source on system design and dimensioning

This system can be used either with a gas or oil auxiliary boiler, or with a long-running-time boiler (e.g., wood in the form of logs). Alternatively, an auxiliary electrical heater can be installed into the space heating storage tank.

Cost (range)

The total cost of the whole system in Norway is about 11 000 EUR, with a 20 m^2 collector, a 2 000 litre storage tank, a gas or oil boiler and a heating floor. Installation costs are included in these figures. A similar reference system without solar heating costs about 8 000 EUR.

Market distribution

This system was launched on the Norwegian market in 1997. About 4 000 m^2 collectors have been installed. Manufacturer: SolarNor AS

11: Space Heating Store with DHW Load-Side Heat Exchanger(s) and External Auxiliary Boiler

Sweden (Finland)

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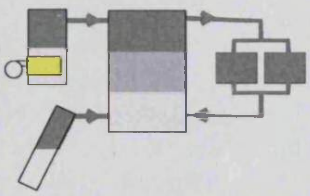
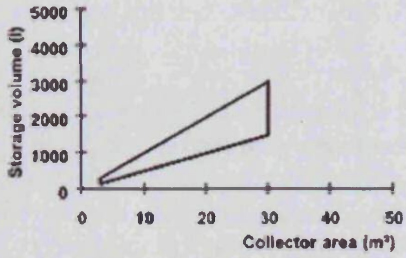




Simulated System – Differences from Market Versions

The version of system #11 that is used with CombiSun is a cost optimised version that was not on the market at the end of 2002. It is different in the following ways from those that are normally sold in Sweden, the main differences being with the store which costs approx. €250 more than the standard version:

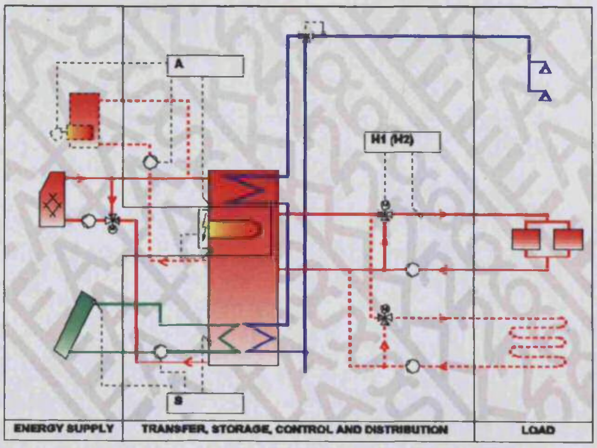
- The upper heat exchanger from preparation of hot water is much larger. This allows a lower set temperature for the auxiliary heated part of the store while still maintaining high thermal comfort.
- Insulation for the store is thicker.
- The two heat exchangers at the bottom of the store are "stretched" from the bottom to the middle of the store, and the flow in the collector is smaller than for usual "high-flow" systems but greater than for "low-flow" systems.
- The auxiliary heater is either a gas or an oil boiler, with an average annual efficiency of 90% and 80% respectively for a non-solar heating system. In Sweden the auxiliary heater is usually a boiler for solid wood, oil or pellets.

Main features

The tank in this system is fitted with an immersed horizontal finned-coil heat exchanger for DHW preparation and another heat exchanger in the bottom for the collector loop. An electric heater, operating on demand, heats the upper third of the tank. The optional use of a wood boiler or a pellet burner is very common in these systems. In Sweden an optional heat exchanger is generally used for DHW preheating as this significantly improves the thermal performance of the system. In Finland, this system is usually designed with a smaller collector area and a smaller storage tank (750 l) than in Sweden.

Heat management philosophy

The pump of the collector loop is under control of a simple differential controller. The pump is switched off when the temperature at the collector outlet reaches 95°C. No control for space heating and auxiliary boiler is included in the system. The electric heater is under control of a separate thermostat.



Specific aspects
Overheating is prevented by using a relatively small expansion vessel (10 - 30% of collector loop volume), and by allowing a high pressure of up to 6 or 9 bar. This ensures that the fluid in the collector does not boil. Due to the way DHW is prepared, there are no legionella risk.

Influence of auxiliary energy source on system design and dimensioning
Depending on the type of auxiliary boiler used, the outlet connection is located at the bottom of the tank (wood logs boiler) or in the middle of it (pellet burner). In the first case, the whole tank is heated up when the boiler is used. In the second case, only the upper part is heated up. One or more buffer tanks can be added in conjunction with a wood boiler. In this way, the boiler's requirement for a large volume is satisfied and the collector loop can still use a part of the whole volume by manually or automatically connecting or disconnecting the buffer tanks. An electric auxiliary heater is always included in the tank.

Cost (range)
Sweden: A typical system with 10 m² of solar collectors and a 1 500 litre storage with a wood boiler as auxiliary, costs about 12 300 EUR. A similar reference system without solar heating costs about 8 600 EUR.

Finland: A typical system with 7 m² of solar collectors and a 700 litre storage without boiler (all auxiliary energy with electricity) costs about 9 100 EUR. A similar reference system without solar heating costs about 6 100 EUR.

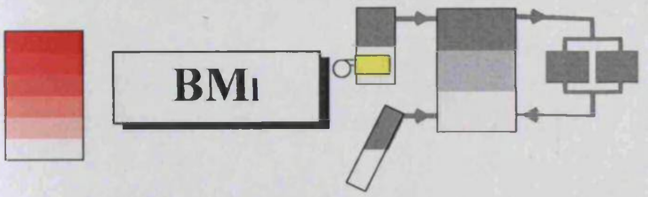
Market distribution
This system has been marketed in Sweden since 1990. About 5 companies have installed 10 000 to 20 000 m² of solar collectors. In Finland this system is quite new. About 80 systems, with 800 m² of solar collectors have been installed, from Helsinki to beyond the Arctic Circle.

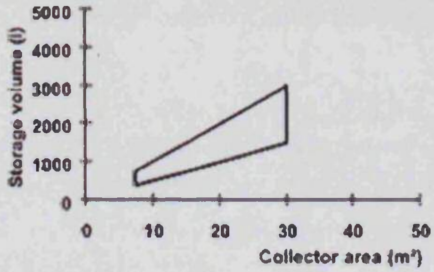
Manufacturers in Sweden: Three or four companies are manufacturing these storage tanks and about the same number of manufacturers produce the collectors. Marketing is by several companies. It is the preferred system among selfbuilders in Sweden involving some 20 small companies. (BoRö pannan AB - industry participant, manufactures and sells the system).

Manufacturers in Finland: Two companies are manufacturing and four companies are selling these systems in Finland. (FORTUM - industry participant, manufactures and sells the system).

12: Space Heating Store with DHW Load-Side Heat Exchanger(s) and External Auxiliary Boiler (Advanced Version)

Sweden





Simulated System – Differences from Marketed System

The version of system #12 that is used with CombiSun is an optimised version that was not on the market at the end of 2002. It is different in the following ways from those that are normally sold, the main differences being with the store and costs approx. €150 more than the standard version:

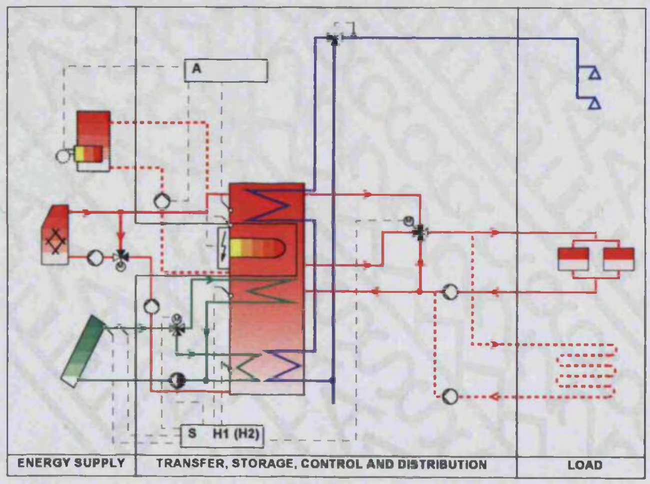
- The upper heat exchanger from preparation of hot water is much larger. This allows a lower set temperature for the auxiliary heated part of the store while still maintaining high thermal comfort.
- The two heat exchangers at the bottom of the store are "stretched" from the bottom to the middle of the store, and the flow in the collector is smaller than for usual "high-flow" systems but greater than for "low-flow" systems.
- There is a larger volume heated by the auxiliary heater.
- The auxiliary heater is a gas boiler, with an average annual efficiency of 90% for a non-solar heating system. In Sweden the auxiliary heater is usually a boiler for solid wood, oil or pellets.

Main features

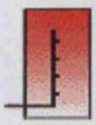
This system is very similar to the previous system but with more sophistication in the collector loop, in the space-heating loop and in the controller. Two immersed heat exchangers are connected to the collector loop to increase the thermal stratification in the storage tank.

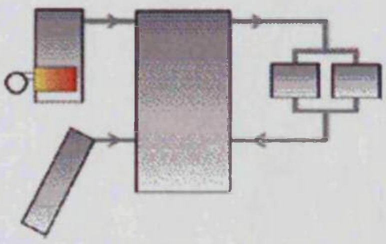
Heat management philosophy

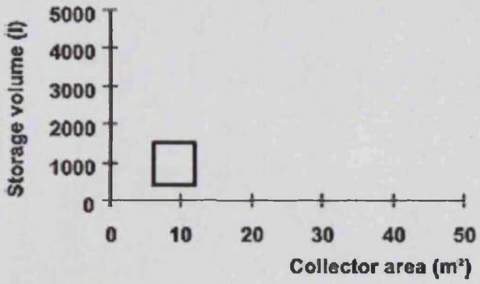
The collector loop pump is turned on under control of the absorber plate temperature. The speed of this pump is then controlled by the temperature difference between the collector outlet and either the temperature of the top or bottom tank sensor, depending upon whether the domestic-hot-water section or space heating section of the tank is to be heated. The space-heating loop is connected to the tank with a 4-way valve enabling heat delivery from the central part of the tank.



#15: Two Stratifiers in a Space Heating Storage Tank with an External Load-Side Heat Exchanger for DHW / GERMANY





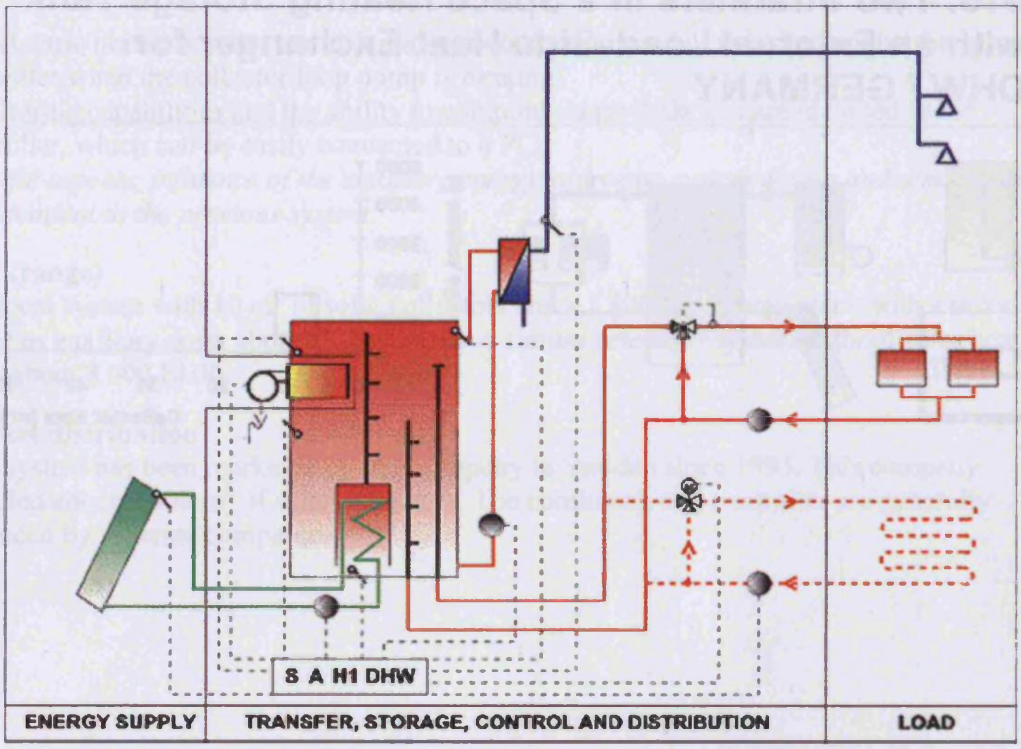


Main features

This system is constructed as a compact unit, in which all components (auxiliary gas condensing burner, DHW flat-plate heat exchanger with its primary pump) are integrated. Consequently, the installation time is reduced because of the reduction in the number of connections needed. The solar storage tank works as an optimised energy manager for all types of incoming energy (from the solar collectors, a gas burner, etc.) and outgoing energy (domestic hot water, space heating water).

Heat management philosophy

The speed of the collector loop pump is controlled to reach an optimal loading temperature in the storage tank and also to maintain a minimum flow rate in the collector to ensure good heat transfer. The DHW temperature is brought up to the set-point temperature by controlling the speed of the pump located in the primary loop of the heat exchanger. Heat delivered to the space heating loop is controlled by a variable-flow-rate pump under selfcontrol of the thermostatic valves of the radiators (to save pump energy and to make sure there is no noise produced by the radiator valves). The power of the gas burner can be modulated between 5 and 20 kW, depending on the temperature in the tank and the requested temperature of the space heating loop (calculated from the outside air temperature, the room temperature and the time of the day).



Specific aspects

Solar energy input to the storage tank is provided by an immersed low-flow heat exchanger in co-operation with stratifying tubes (low-flow technology). The system must be checked once a year, due to the condensing gas boiler and its burner.

Influence of the auxiliary energy source on system design and dimensioning

This system is designed with a gas condensing burner integrated in the storage tank. All other auxiliary energy boilers (e.g. wood or pellet burners) can be easily connected to the storage tank without additional heat exchangers.

Cost (range)

The total cost of the system (space heating emission loop and installation included) is between 13 040 EUR for a 5-m²-collector with a 400-litre-storage-tank system and 16 850 EUR for a 12-m²-collector with a 750-litre-storage-tank system. A similar reference system without solar heating costs about 9 000 EUR.

Market distribution

This system has been marketed in Germany since 1997. About 22 sale offices in Germany are marketing this system directly to 800 to 1000 plumbers, with more than 1300 units and 10 000 m² of solar collectors sold to date.

Manufacturer: SOLVIS Solarsysteme GmbH, distribution by SOLVIS Energiesysteme GmbH & Co. KG

Data Sheet #14 PREVIOUS NEXT **Data Sheet #16**

Table:5 Characteristics of the solar combisystems modelled within Task 26 (source: http://www.iea-shc.org/publications/task26/index.html).

Characteristics / Generic system (description)	Solar loop connection	SH connection	Store	Heat delivery system	Auxiliary sources	Coll. areas (m^2)
System **2** (HX between collector and SH loops. Typical DHW solar system with oversized collectors to deliver energy to an existing SH system). Proved not suitable for low-energy houses (e.g. 30SFH) Denmark (most popular system for the period of the Task)	Immersed HX at the bottom of the tank	Solar loop with external flat plate HX in the return pipe of the SH loop.	No controlled store for SH. DHW only store. 0.28-0.6m^3	Heating floor preferable (building to work as store, due to lack of SH store)	Immersed HX at the top of tank. Not managed by the controller. All types of auxiliary source suitable. Even electric radiators for SH. SH loop may be fed by the auxiliary or by both solar collectors and auxiliary source connected in series.	5- 14
System **3a** (Advanced direct solar floor with improved strategy for solar heat sharing between DHW and SH. Made of compact-factory assembled units.) France: CLIPSOL (only). Marketed as a whole	Immersed HX at the bottom of the tank	Direct connection between solar and SH loops.	No store for SH. DHW only store: 0.5m^3. stores larger than 0.2m^3 required	Heating floor	Immersed HX at the top of tank. Managed by the controller. Gas, oil, electric boilers suitable. If wood boiler, then a buffer store required.	10-35
System **4** (DHW tank as a SH storage device. Typical DHW solar system with oversized collectors to deliver energy to an existing SH system.) Denmark (Batec A/S), The Netherlands (drainback version)	Immersed HX at the bottom of the tank	SH connected with a HX with the store	DHW&SH combined. Fixed spec. volume 0.05m^3/m^2	Radiators or heating floor. Intermediate immersed HX in store for SH return	Immersed HX at the top of tank. Not managed by the controller. All types of auxiliary source suitable. Even electric radiators for SH.	5- 15
System **8** (SH store with double-load side HX for DHW. Compact unit) Switzerland	Immersed HX at the bottom of the tank	Direct connection between SH loop and store	DHW&SH combined. 0.83m^3. 2 immersed HX for DHW (top & bottom)	Heating floor or radiators. Sophisticated control strategy for all components.	Integrated gas or oil burner. Managed by controller	8- 16

System **9b** (SH store with immersed DHW tank and external DHW store with auxiliary) Norway (SolarNor AS)	Direct with store	Direct with store (on/off operation & control parameters: outdoor T, incoming solar irradiance and wind speed)	SH store (1-4m^3) with immersed DHW store (0.2 m^3). At atmospheric pressure. Additional external DHW store (0.08-0.15 m^3)	Preferable heating floor or wall heating	Oil, gas or biomass burners suitable. In Norway electricity. Single control unit for entire system except the external DHW vessel's auxiliary.	10- 40
System **11** (SH store with DHW load side HX(s) and external auxiliary boiler. Finland, Sweden (in Finland systems smaller than in Sweden)	Immersed HX at the bottom of the tank	Direct with store (mixing valve delivering heat from the centre). No control	DHW&SH combined. 0.3-3m^3 (with optimum at 1.25 m^3).	Radiators (heating floor)	Electric heater integrated in the tank (controlled by a thermostat). External: boiler for solid wood, oil or pellets in Sweden, but an oil or gas boiler used in the simulations.	5- 30
System **12** – an optimised version of System **11** (Advanced version of SH store with DHW load-side HX(s) and external auxiliary boiler) Sweden	Two immersed HX at the bottom and centre of the tank (stratification)	Direct. A four-way valve delivering heat from the centre and top of the tank.	Store 0.3-3m^3	Radiators (heating floor)	Electric heater integrated in the tank (controlled by a thermostat, but locked out by the solar controller when collector pump in operation). External: boiler for solid wood, oil or pellets in Sweden, but a gas boiler used in the simulations	8- 30
System **15** (Two stratifiers in a SH storage tank with an external load-side HX for DHW. (Compact unit, all components integrated. The store works as an energy manager for all in-out energy flows) Germany (Solvis GMbH & Co KG)	Indirect: stratifying tube (low-flow)combined with an immersed HX	Direct. Stratified tube for the return of SH loop. Variable flow rate pump controlled from thermostatic valves	DHW&SH combined. 0.377- 1.423 m^3	Radiators (heated floor or wall heating) External HX for DHW preparation	Integrated condensing gas burner. All other auxiliary boilers can be connected with additional HX. Power 5-20kW, controlled by store temperature and demand of the SH loop	4-12
* The same FP collector used in all systems. System #19 designed for multi-family houses not included.						

APPENDICES-B

This section includes supporting information for 3.6.3 'Latent heat storage".

From (STREICHER, W. et al., 2007) pp11-15:

Table 1: Inorganic substances with potential use as PCM

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m·K)	Density (kg/m3)
$Na_2CrO_4 \cdot 10\,H_2O$	18 [51]	n.a.	n.a.	n.a.
$KF \cdot 4\,H_2O$	18.5 [3,8,49,52,53]	231 [3,8,49,52]	n.a.	1447 (liquid, 20°C) [49] 1455 (solid, 18°C) [49] 1480 [52]
$Mn(NO_3)_2 \cdot 6\,H_2O$	25.8 [54]	125.9 [54]	n.a.	1738 (liquid, 20°C) [54] 1728 (liquid, 40°C) [54] 1795 (solid, 5°C) [54]
$CaCl_2 \cdot 6\,H_2O$	29 [1,55] 29.2 [53] 29.6 [52] 29.7 [3,8,49] 30 [51] 29-39 [5]	190.8 [1,55] 171 [3,8,49] 174,4 [5] 192 [52]	0.540 (liquid, 38.7°C) [1,55] 0.561 (liquid, 61.2°C) [55] 1.088 (solid, 23°C) [1,55]	1562 (liquid, 32°C) [1,55]1496 (liquid) [49] 1802 (solid, 24°C) [1,55] 1710 (solid, 25°C) [49] 1634 [5] 1620 [52]
$LiNO_3 \cdot 3\,H_2O$	30 [52]	296 [52]	n.a.	n.a.
$K_3PO_4 \cdot 7\,H_2O$	45 [51]	n.a.	n.a.	n.a.
$Zn(NO_3)_2 \cdot 4\,H_2O$	45.5 [51]	n.a.	n.a.	n.a.
$Ca(NO_3)_2 \cdot 4\,H_2O$	42.7 [53] 47 [51]	n.a.	n.a.	n.a.
$Na_2HPO_4 \cdot 7\,H_2O$	48 [53]	n.a.	n.a.	n.a.
$Na_2S_2O_3 \cdot 5\,H_2O$	48 [49,51-53] 48-49 [5]	201 [49] 209,3 [5] 187 [52]	n.a.	1600 (solid) [49] 1666 [5]
$Zn(NO_3)_2 \cdot 2\,H_2O$	54 [51]	n.a.	n.a.	n.a.
$NaOH \cdot H_2O$	58.0 [53]	n.a.	n.a.	n.a.
$Na(CH_3COO) \cdot 3\,H_2O$	58 [52,56] 58.4 [53,57-63]	264 [57-63] 226 [52]	n.a.	1450 [52]
$Cd(NO_3)_2 \cdot 4\,H_2O$	59.5 [53]	n.a.	n.a.	n.a.
$Fe(NO_3)_2 \cdot 6\,H_2O$	60 [51]	n.a.	n.a.	n.a.
$NaOH$	64.3 [52]	227.6 [52]	n.a.	1690 [52]
$Na_2B_4O_7 \cdot 10\,H_2O$	68.1 [53]	n.a.	n.a.	n.a.
$Na_3PO_4 \cdot 12\,H_2O$	69 [53]	n.a.	n.a.	n.a.
$Na_2P_2O_7 \cdot 10\,H_2O$	70 [52]	184 [52]	n.a.	

n.a.: not available or not known at the time of writing

Table 2: Inorganic eutectics with potential use as PCM

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m·K)	Density (kg/m3)
51-55% $Cu(NO_3)_3 \cdot 6H_2O$ + 45-49% $LiNO_3 \cdot 3H_2O$	16.5 [36]	250 [36]	n.a.	n.a.
45-52% $LiNO_3 \cdot 3H_2O$ + 48-55% $Zn(NO_3)_2 \cdot 6H_2O$	17.2 [36]	220 [36]	n.a.	n.a.
55-65% $LiNO_3 \cdot 3H_2O$ + 35-45% $Ni(NO_3)_2 \cdot 6H_2O$	24.2 [36]	230 [36]	n.a.	n.a.
66.6% $CaCl_2 \cdot 6\ H_2O$ + 33.3% $MgCl_2 \cdot 6\ H_2O$	25 [52]	127 [52]	n.a.	1590 [52]
45% $Ca(NO_3)_2 \cdot 6H_2O$ + 55% $Zn(NO_3)_2 \cdot 6H_2O$	25 [36,49]	130 [36,49]	n.a.	1930 [36,49]
48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% H_2O	26,8 [49,52]	188,0 [52]	n.a.	1640 [52]
67% $Ca(NO_3)_2 \cdot 4\ H_2O$ + 33% $Mg(NO_3)_2 \cdot 6\ H_2O$	30 [36,49]	136 [36,49]	n.a.	1670 [36]
60% $Na(CH_3COO) \cdot 3\ H_2O$ + 40% $CO(NH_2)_2$	31.5 [36,64] 30 [65]	226 [36,64] 200.5 [65]	n.a.	n.a.
61.5% $Mg(NO_3)_2 \cdot 6\ H_2O$ + 38.5% NH_4NO_3	52 [55]	125.5 [55]	0.494 (liquid, 65.0°C) [55] 0.515 (liquid, 88.0°C) [55] 0.552 (solid, 36.0°C) [55]	1515 (liquid, 65°C) [55] 1596 (solid, 20°C) [55]
58.7% $Mg(NO_3) \cdot 6\ H_2O$ + 41.3% $MgCl_2 \cdot 6\ H_2O$	59 [55] 58 [52] 59.1 [36,49]	132.2 [55] 132 [52] 144 [36,49]	0.510 (liquid, 65.0°C) [55] 0.565 (liquid, 85.0°C) [55] 0.678 (solid, 38.0°C) [55] 0.678 (solid, 53.0°C) [55]	1550 (liquid, 50°C) [55] 1630 (solid, 24°C) [55] 1680 (solid) [36,49]
53% $Mg(NO_3)_2 \cdot 6\ H_2O$ + 47% $Al(NO_3)_2 \cdot 9\ H_2O$	61 [36,49]	148 [36,49]	n.a.	1850 [36]

Table 3: Non-eutectic mixtures of inorganic substances with potential use as PCM

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m·K)	Density (kg/m3)
$Mg(NO_3)_2 \cdot 6\ H_2O$ / $Mg(NO_3)_2 \cdot 2\ H_2O$	55.5 [51]	n.a.	n.a.	n.a.
80% $Mg(NO_3) \cdot 6\ H_2O$ + 20% $MgCl_2 \cdot 6\ H_2O$	60 [66]	150 [66]	n.a.	n.a.

% in weight

n.a.: not available or not known at the time of writing

Table 4: Organic eutectics with potential use as PCM

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m·K)	Density (kg/m3)
37.5% urea + 63.5% Acetamide	53 [49]	n.a.	n.a.	n.a.
67.1% naphthalene + 32.9% benzoic acid	67 [55]	123.4 [55]	0.136 (liquid, 78.5°C) [55] 0.130 (liquid, 100°C) [55] 0.282 (solid, 38°C) [55]	n.a.
			0.257 (solid, 52°C) [55]	

% in weight
n.a.: not available or not known at the time of writing

Table 5: Organic substances with potential use as PCM

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m·K)	Density (kg/m3)
Dimethyl-sulfoxide (DMS)	16,5 [67]	85.7 [67]	n.a.	1009 (solid and liquid) [67]
Paraffin C_{16}-C_{18}	20-22 [9]	152 [9]	n.a.	n.a.

Polyglycol E600	22 [1,55]	127.2 [1,55]	0.189 (liquid, 38.6°C) [1,55] 0.187 (liquid, 67.0°C) [55]	1126 (liquid, 25°C) [1,55] 1232 (solid, 4°C) [1,55]
Paraffin C_{13}-C_{24}	22-24 [49]	189 [49]	0.21 (solid) [49]	760 (liquid, 70°C) [49] 900 (solid, 20°C) [49]
1-dodecanol	26 [8] 17.5-23.3 [3]	200 [8] 188.8 [3]	n.a.	n.a.
Paraffin C_{18}	28 [49] 27.5 [68] 22.5-26.2 [3]	244 [49] 243.5 [68] 205.1 [3]	0.148 (liquid, 40°C) [68] 0.15 (solid) [49] 0.358 (solid, 25°C) [68]	774 (liquid, 70°C) [49] 814 (solid, 20°C) [49]
Paraffin C_{20}-C_{33}	48-50 [49]	189 [49]	0.21 (solid) [49]	769 (liquid, 70°C) [49] 912 (solid, 20°C) [49]
Paraffin C_{22}-C_{45}	58-60 [49]	189 [49]	0.21 (solid) [49]	795 (liquid, 70°C) [49] 920 (solid, 20°C) [49]
Paraffin wax	64 [1,55]	173.6 [1,55] 266 [52]	0.167 (liquid, 63.5°C) [1,55] 0.346 (solid, 33.6°C) [1,55] 0.339 (solid, 45.7°C) [55]	790 (liquid, 65°C) [1,55] 916 (solid, 24°C) [1,55]
Polyglycol E6000	66 [1,55]	190.0 [1,55]	n.a.	1085 (liquid, 70°C) [1,55] 1212 (solid, 25°C) [1,55]
Paraffin C_{21}-C_{50}	66-68 [49]	189 [49]	0.21 (solid) [49]	830 (liquid, 70°C) [49] 930 (solid, 20°C) [49]

n.a.: not available or not known at the time of writing

Table 6: Fatty acids with potential use as PCM

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m·K)	Density (kg/m3)
Propyl palmiate	10 [8] 16-19 [3]	186 [8]	n.a.	n.a.
Caprylic acid	16 [1,55] 16.3 [49]	148.5 [1,55] 149 [49]	0.149 (liquid, 38.6°C) [1,55] 0.145 (liquid, 67.7°C) [55] 0.148 (liquid, 20°C) [49]	901 (liquid, 30°C) [1,55] 862 (liquid, 80°C) [49] 981 (solid, 13°C) [1,55] 1033 (solid, 10°C) [49]
Capric-lauric acid (65 mol%-35 mol%)	18.0 [69] 17-21 [3]	148 [69] 143 [3]	n.a.	n.a.
Butil stearate	19 [8,36] 18-23 [3]	140 [3,8] 123-200 [70] 200 [36]	n.a.	n.a.
Capric-lauric acid (45%-55%)	21 [8]	143 [8]	n.a.	n.a.
Dimethyl sabacate	21 [36,70]	120-135 [70] 135 [36]	n.a.	n.a.
Octadecyl 3-mencaptopropylate	21 [36]	143 [36]	n.a.	n.a.
34% Mistiric acid + 66% Capric acid	24 [55]	147.7 [55]	0.164 (liquid, 39.1°C) [55] 0.154 (liquid, 61.2°C) [55]	888 (liquid, 25°C) [55] 1018 (solid, 1°C) [55]
Octadecyl thioglycate	26 [36]	90 [36]	n.a.	n.a.
Vinyl stearate	27-29 [70] 27 [36]	122 [36,70]	n.a.	n.a.
Myristic acid	49-51 [71] 54 [49]	204.5 [71] 187 [49]	n.a.	861 (liquid, 55°C) [55] 844 (liquid,

	58 [55]	186.6 [55]		80°C) [49] 990 (solid, 24°C) [55]
Palmitic acid	64 [1,55] 61 [72,73] 63 [49]	185.4 [1,55] 203.4 [72,73] 187 [49]	0.162 (liquid, 68.4°C) [1,55] 0.159 (liquid, 80.1°C) [55] 0.165 (liquid, 80°C) [49]	850 (liquid, 65°C) [1,55] 847 (liquid, 80°C) [49] 989 (solid, 24°C) [1,55]
Stearic acid	69 [1,55] 60-61 [73,74] 70 [49]	202.5 [1,55] 186.5 [73,74] 203 [49]	0.172 (liquid, 70°C) [49]	848 (liquid, 70°C) [1,55] 965 (solid, 24°C) [1,55]

% in weight
n.a.: not available or not known at the time of writing

Table 7: Commercial PCMs available in the market

PCM name	Type of product	Melting temperature (°C)	Heat of fusion (kJ/kg)	Density (kg/L)	Source
RT20	Paraffin	22	172	0.88	Rubitherm GmbH [75]
ClimSel C 24	n.a.	24	108	1.48	Climator [76]
RT26	Paraffin	25	131	0.88	Rubitherm GmbH [75]
STL27	Salt hydrate	27	213	1.09	Mitsubishi Chemical [77]
AC27	Salt hydrate	27	207	1.47	Cristopia [78]
RT27	Paraffin	28	179	0.87	Rubitherm GmbH [75]
TH29	Salt hydrate	29	188	n.a.	TEAP [79]
STL47	Salt hydrate	47	221	1.34	Mitsubishi Chemical [77]
ClimSel C 48	n.a.	48	227	1.36	Climator [76]
STL52	Salt hydrate	52	201	1,3	Mitsubishi

					Chemical [77]
RT54	Paraffin	55	179	0,90	Rubitherm GmbH [75]
STL55	Salt hydrate	55	242	1,29	Mitsubishi Chemical [77]
TH58	n.a.	58	226	n.a.	TEAP [79]
ClimSel C 58	n.a.	58	259	1,46	Climator [76]
RT65	Paraffin	64	173	0,91	Rubitherm GmbH [75]
ClimSel C 70	n.a.	70	194	1,7	Climator [76]

n.a.: not available or not known at the time of writing

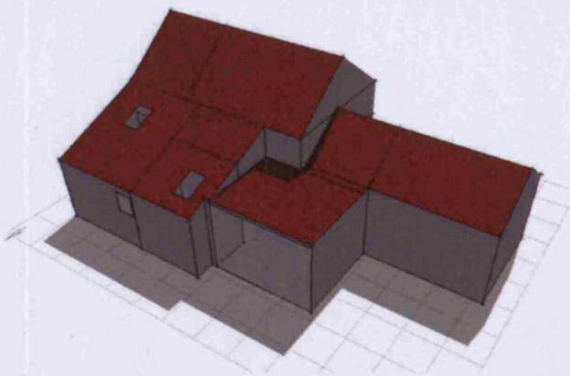
APPENDICES-C

This section includes specific data per house type for the 12 houses used in this work. It is advised that the reader unfolds the pages which are printed at A3 size when reading 6.1 'Discussion: Summarizing the results per house type' so that the 3-D images and other information per dwelling type are on hand.

TABLE 1: SOLAR ABSORPTANCE COEFFICIENTS PER HOUSE TYPE (STACS). (INTERNAL AND EXTERNAL CONVECTIVE HEAT TRANSFER COEFFICIENTS ARE 11 KJ/H M² K AND 64 KJ/H M² K RESPECTIVELY).

Welsh House type		Exterior Walls	Exterior Roof	Interior Walls	Interior Floor
Pre-1850	Converted Flat	White [0.25-0.30]	Slate (dark) [0.70-0.75]	White [0.25-0.30]	Light Carpet [0.30-0.35]
	Detached House	Stone [0.60-0.65]	Slate (dark) [0.70-0.75]	White [0.25-0.30]	Dark Stone [0.70-0.75]
1850-1919	Semi-detached House	Red Brick [0.65-0.70]	Slate (dark) [0.70-0.75]	White [0.25-0.30]	Light Carpet [0.30-0.35]
1920-1944	Semi-detached House	White [0.30-0.35]	Red Clay Tiles [0.75-0.80]	White [0.25-0.30]	Light Carpet [0.30-0.35]
1945-1964	Low-rise Flat	Yellow Brick [0.65-0.70]	n/a (grey tile) [0.75-0.80]	White [0.25-0.30]	Light Carpet [0.30-0.35]
	Semi-detached House	Grey Pebbledash [0.65-0.70]	Dark Brown Tile [0.75-0.80]	White [0.25-0.30]	Light Carpet [0.30-0.35]
1965-1980	Detached House	Yellow Brick [0.65-0.70]	Red Clay Tile [0.70-0.75]	White [0.25-0.30]	Light Carpet [0.30-0.35]
	Mid-terrace House	Grey Pebbledash [0.65-0.70]	Dark Brown Tile [0.75-0.80]	White [0.25-0.30]	Light Carpet [0.30-0.35]
1981-1999	Low-rise Flat	Yellow Brick [0.65-0.70]	Dark Grey Tile [0.75-0.80]	White [0.25-0.30]	Dark Blue Carpet [0.65-0.70]
	Mid-terrace House	Red Brick [0.65-0.70]	Dark Grey Tile [0.75-0.80]	White [0.25-0.30]	Light Carpet / Laminate [0.30-0.35]
2000-2006	Semi-detached House	Grey / Brown Brick [0.60-0.65]	Red Tile [0.75-0.80]	White [0.25-0.30]	Light Carpet / Laminate [0.30-0.35]
Post-2006	High-rise Flat	Light Render / Cladding [0.60-0.65]	n/a	White [0.25-0.30]	Light Carpet / Laminate [0.30-0.35]
	Passivhaus	Yellow Plaster [0.60-0.65]	Zinc (light grey) [0.35-0.40]	Light Timber [0.25-0.30]	Black Rubber [0.70-0.75]

1 PRE 1850 DETACHED HOUSE



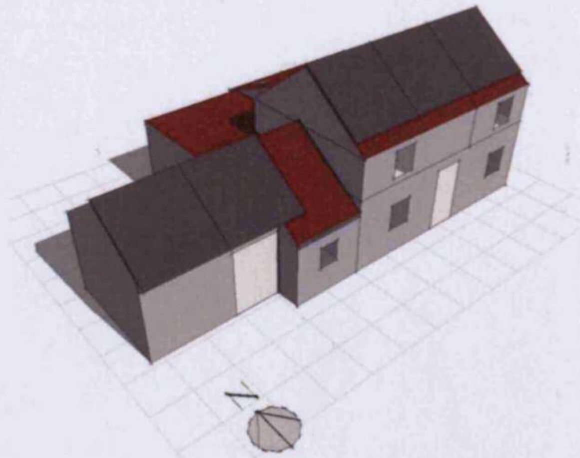


TABLE 1: THERMAL ZONES' VOLUME AND AREA DATA

Zone name	Volume (m^3)	Volume based factors (%)	Area (m^2)	Area based factors (%)
Kitchen	19.884	11.08	7.73	0.09
Lounge	49.501	27.58	23.52	0.27
Hall	23.766	13.24	9.66	0.11
Bathroom	23.075	12.86	8.85	0.10
Bedroom1	28.562	15.91	10.28	0.12
Bedroom2	16.529	9.21	15.01	0.17
Office	9.378	5.22	8.51	0.10
Utility	8.803	4.90	3.72	0.04
Total	179.498	100.00	87.27	1.00

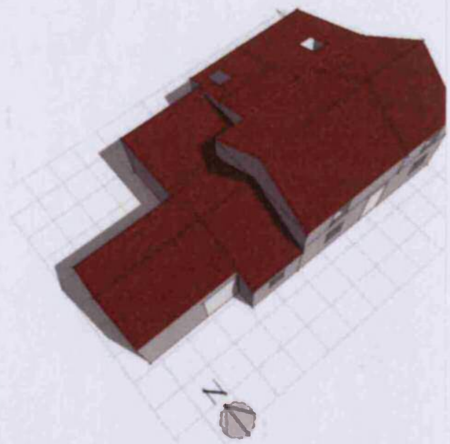


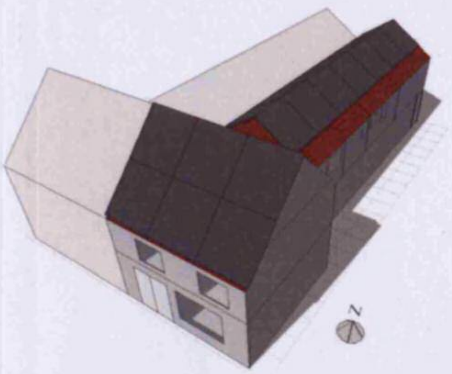
TABLE 2: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

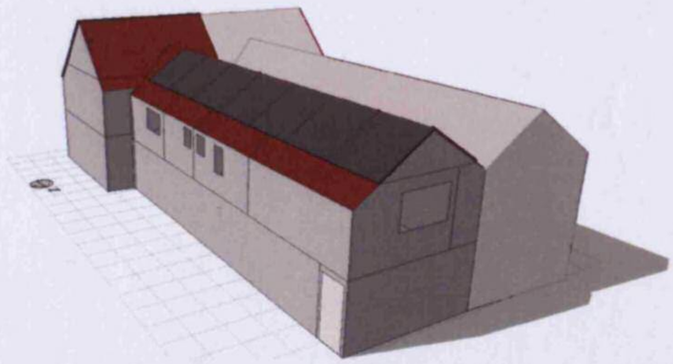
TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
295 TESS Lib	LIMESTONE	2.52	1	1400	-
231 TESS Lib	3/4_INCH_SOFTWOOD	0.42	1.38	512.6	-
Non Standard	THERMAFLEECE_100MM	-	-	-	0.7083
Non Standard	THERMAFLEECE_150MM	-	-	-	1.055
Non Standard	THERMAFLEECE_50MM	-	-	-	0.3472
463 TESS Lib	BEECH OAK LATHS	0.72	2	800	-
104 Basic Lib	LIMEMORTAR	3.13	0.84	1800	-
2 TESS Lib	PERPENDICULAR AIRGAP	-	-	-	0.047
410 TESS Lib	STYROFOAM	0.16	0.84	32	
86 Basic Lib	NATURAL SOIL	5.4	1.8	1500	
Non Standard	RIVEN_SLATES	-	-	-	0.0512
398 TESS Lib	1.75" SOLID DOOR	-	-	-	0.079
Non Standard	LIGHTWEIGHT EXPANDED CLAY	-	-	-	0.79365

TABLE 3: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS Survey	width (mm)	layer name: TRNSYS
2_STOREY_WALL	lime mortar (in)	15	104 Basic Lib
	limestone inner leaf (var thickness)	250	295 Tess Lib
	air gap	*100*	2 TESS Lib
	limestone outer leaf (var thickness)	250	295 Tess Lib
	lime mortar (out)	25	104 Basic Lib
1_STOREY_WALL	lime mortar (in)	15	104 Basic Lib
	limestone inner leaf (var thickness)	200	295 Tess Lib
	air gap	*20*	2 TESS Lib
	limestone outer leaf (var thickness)	200	295 Tess Lib
PARTITION BATHROOM	softwood boards	18	231 TESS Lib
	air gap	*210*	2 TESS Lib
	softwood boards	18	231 TESS Lib
GFLOOR	blue lias (stone) flagstone	25	295 Tess Lib
	limecrete screed	50	104 Basic Lib
	limecrete slab	150	*As above*
	lightweight expanded clay aggregate	200	Non standard
2_STOREY_CEILING	Thermafleece (sheep wool)	150	Non standard
	oak laths	8	463 TESS Lib
	lime plaster	20	104 Basic Lib
2_STOREY_INTWALL	softwood boards	18	231 TESS Lib
	Thermafleece (sheep wool)	100	Non standard
	softwood boards	18	231 TESS Lib
2_STOREY_FFLOOR	softwood boards	18	231 TESS Lib
	Thermafleece (sheep wool)	50	Non standard
	softwood boards	20	231 TESS Lib
2_STOREY_ROOF	riven slates	-	Non standard
1_STOREY_FLATROOF	soil (green roof)	100	86 Basic Lib
	solitex membrane		*ignored*
	Pavatherm insulation board	25	410 TESS (styrofoam)
	Thermafleece (sheep wool)	100	Non standard
	Pavatherm insulation board	60	410 TESS (styrofoam)
	lime plaster	15	104 Basic Lib
1_STOREY_ROOF	riven slates	10	295 Tess Lib (Limestone)
	solitex membrane	-	*ignored*
	Pavatherm insulation board	25	410 TESS (styrofoam)
	Thermafleece (sheep wool)	100	Non standard
	Pavatherm insulation board	60	410 TESS (styrofoam)
	lime plaster	15	104 Basic Lib
EXTERNAL DOOR	solid door		398 Tess Lib
ROOF_WINDOW	24mm sealed argon filled double glazed units (low-E glass) in metal frame	N/A	ASH_A17.23a
GLAZING OF THE 2 STOREY PART	4mm single glazed units in softwood timber frame	N/A	ASH_A17.1C
GLAZING OF THE 1 STOREY PART (including sliding door)	24mm sealed argon filled double glazed units (low-E glass) in hardwood timber frame	N/A	ASH_A17.23c

2 PRE 1850 CONVERTED FLAT





Ground floor is occupied by a store. This was simulated with boundary conditions, assuming that identical to the house comfort conditions were maintained. (no interzonal heat exchange).

TABLE 4: THERMAL ZONES' VOLUME AND AREA DATA

Zone name	Volume (m^3)	Volume based factors (%)	Area (m^2)	Area based factors (%)
Kitchen	41.606	16.51	17.02	16.44
Lounge	75.831	30.09	32.35	31.25
Corridor	51.578	20.47	20.26	19.57
Bathroom	21.768	8.64	8.90	8.60
Bedroom1	32.141	12.75	13.18	12.73
Bedroom2	29.104	11.55	11.81	11.41
Total	252.028	100.00	103.522	100.00

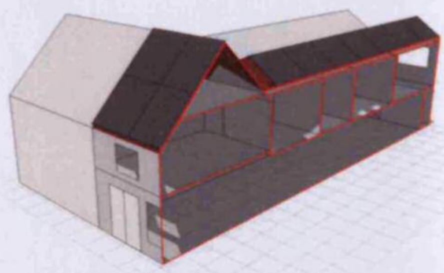


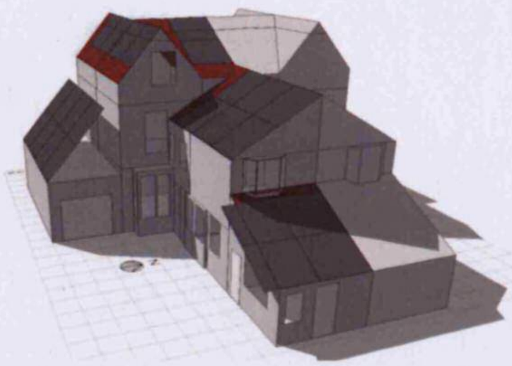
TABLE 5: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m^3)	Resistance
103 Basic Lib	GYPSUM PLASTER	1.5	0.84	1200	
295 Tess Lib	LIMESTONE	2.52	1	1400	
151 TESS Lib	1"CEMENT MORTAR	2.596	0.837	1858.1	
65 Basic Lib	BRICKS	1.8	0.84	1250	
106 Basic Lib	PLASTERBOARD	1.26	0.84	1000	
2 TESS Lib	PERPENDICULAR VOID				0.047
402 TESS Lib	RUBBERBACKED CARPET				0.06
231 TESS Lib	3/4_INCH SOFTBOARD	0.42	1.38	512.6	
3 TESS Lib	HORIZONTAL VOID				0.047
Non Standard	RIVEN SLATES MASSLESS				0.051
257 TESS Lib	MINERAL WOOL INSULATION	0.16	0.9	80	
Non Standard	PLASTERBOARD MASSLESS				0.0567
237 TESS Lib	3/4INCH_PLYWOOD	0.42	1.21	544.6	
398 Tess Lib	1.75"SOLID DOOR				0.079
9 Basic Lib	CONCRETE SLAB	4.07	1	1400	

TABLE 6: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS survey	width (mm)	layer name: TRNSYS
PRE1850FLAT_SS500	gypsum plaster (internal surface)	10	103 Basic Lib
	stone / lime masonry	470	295 Tess Lib
	cement mortar (external surface)	20	151 TESS Lib (1 inch)
PRE1850FLAT_SS530	gypsum plaster (internal surface)	10	103 Basic Lib
	stone / lime masonry	500	295 Tess Lib
	cement mortar (external surface)	20	151 TESS Lib (1 inch)
PRE1850FLAT_SS600	gypsum plaster (internal surface)	10	103 Basic Lib
	stone / lime masonry	570	295 Tess Lib
	cement mortar (external surface)	20	151 TESS Lib (1 inch)
PRE1850FLAT_SB115	gypsum plaster (internal surface)	10	103 Basic Lib
	brick (assumed no cavity)	250	65 Basic Lib
	gypsum plaster (external surface)	20	103 Basic Lib
PRE1850FLAT_SB250	gypsum plaster (internal surface)	10	103 Basic Lib
	brick (assumed no cavity)	250	65 Basic Lib
	cement mortar (external surface)	20	151 TESS Lib (1 inch)
PRE1850FLAT_SB300	gypsum plaster (internal surface)	10	103 Basic Lib
	brick (assumed no cavity)	300	65 Basic Lib
	cement mortar (external surface)	20	151 TESS Lib (1 inch)
PRE1850FLAT_INTWALL	plasterboard	12	106 Basic Lib
	Timber stud frame with 80mm void	-	2 TESS Lib
	plasterboard	12	106 Basic Lib
PRE1850FLAT_FFLOOR	wool / polyester carpet	*10*	402 TESS Lib (rubber backed carpeting)
	rubber underlay	*10*	see above
	softwood floor boards	18	231 TESS Lib (3/4 inch)
	void	*150*	3 TESS Lib
	plasterboard	12	106 Basic Lib
PRE1850FLAT_ROOF (ventilated):	riven slates	-	Non Standard
PRE1850FLAT_CEIL1 except over lounge	mineral wool insulation	50	257 TESS Lib
	Plasterboard	12	106 Basic Lib
PRE1850FLAT_CEIL2	Plasterboard	*12*	Non Standard
PRE1850FLAT_LADDER	carpet	10	402 TESS Lib (rubber backed carpeting)
	rubber	5	see above
	timber	25	237 TESS Lib (1 inch)
PRE1850FLAT_EXTDOOR	solid door		398 Tess Lib
PRE1850FLAT_GFLOOR	concrete slab	200	9 Basic Lib
Glazing:	4mm single glazed units in softwood timber frame (except Lounge)	N/A	ASH_A17.1C
Lounge Glazing:	24mm double glazed units in softwood timber frame	N/A	ASH_A17.23c
Roof Windows:	20mm sealed double glazed units in cast iron frame	18	ASH_A15.5b

3 1850-1919 SEMI-DETACHED HOUSE



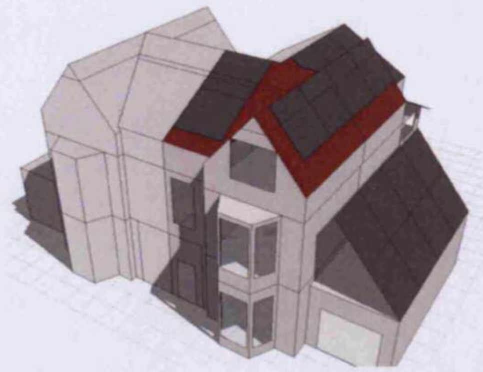


TABLE 7: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

Zone name	Volume (m3)	Volume based factors (%)	Area (m2)	Area based factors (%)
Lounge1	71.443	10.85	21.64	9.83
Lounge2	61.882	9.40	18.77	8.53
WC1	10.036	1.52	3.74	1.70
Hall	178.067	27.04	57.52	26.13
Store	49.045	7.45	N/A	N/A
Kitchen	4.989	0.76	14.91	6.78
Bed 1	60.988	9.26	19.96	9.07
Bed 2	53.568	8.13	17.51	7.95
Bed 3	44.467	6.75	15.66	7.12
Bed 4	16.664	2.53	5.43	2.47
Bathroom	19.014	2.89	3.52	1.60
Loftroom1	39.899	6.06	18.74	8.51
Loftroom2	35.838	5.44	16.83	7.65
WC2	12.652	1.92	5.86	2.66
Total	658.552	100.00	220.087	100.00

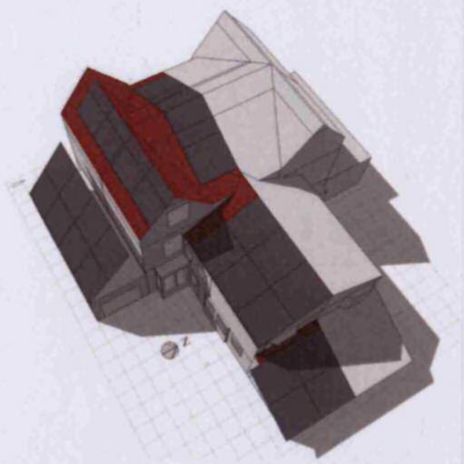


TABLE 8: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m^3)	Resistance
106 Basic Lib	PLASTERBOARD	1.26	0.84	1000	
Non Standard	CELOTEX INSULATION	0.1	1.65	30	
392 TESS Lib	FELT MEMBRANE	0.69	1.67	1121.3	
257 TESS Lib	MINERAL WOOL INSULATION	0.16	0.9	80	
102 Basic Lib	COMMON PLASTER	1.26	0.84	1200	
65 Basic Lib	BRICKS	1.8	0.84	1250	
103 Basic Lib	GYPSUM PLASTER	1.5	0.84	1200	
2 TESS	PERPENDICULAR VOID				0.047

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
402 TESS Lib	RUBBERBACKED CARPET				0.06
231 TESS Lib	3/4" SOFTWOOD	0.42	1.38	512.6	
3 TESS	HORIZONTAL VOID				0.047
86 Basic Lib	CLAY	5.4	1.8	1500	
161 TESS Lib	12_3_CELL CLAYTILES	2.49	0.84	1121.3	
9 Basic Lib	CONCRETE SLAB	4.07	1	1400	
398 TESS Lib	1.75" SOLID DOOR				0.079
400 TESS Lib	WOOD GLASS DOOR	0.58	2.67	1174.2	
94 basic Lib	SLATES	7.58	0.75	2700	
2 Basic Lib	FIBREGLASS	0.144	0.84	12	
231 TESS Lib	3/4" PLYWOOD	0.42	1.21	544.6	
7 Basic Lib	CONCRETE BLOCK	1.836	1	1400	
399 TESS Lib	STEEL DOOR				0.086

TABLE 9: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
1850_SEMIDET_EXTWALL For Front	gypsum plaster (internal surface)	15	103 Basic Lib
	standard bricks (double brick skin)	206	65 Basic Lib
	cavity void (no insulation)	50	2 TESS
	standard bricks	103	65 Basic Lib
1850_SEMIDETR_EXTWALL for Rear	gypsum plaster (internal surface)	15	103 Basic Lib
	standard bricks (double brick skin)	103	65 Basic Lib
	cavity void (no insulation)	50	2 TESS
	standard bricks	103	65 Basic Lib
1850_SEMIDET_INTWALL for Front	plaster skim	5	102 Basic Lib
	standard bricks	103	65 Basic Lib
	plaster skim	5	102 Basic Lib
1850_SEMIDET_INTWALL2	single leaf concrete breezeblock	150	7 Basic Lib
1850_SEMIDETR_INTWALL for Rear	Plasterboard	12	106 Basic Lib
	cavity void (no insulation)	75	2 TESS
	Plasterboard	12	106 Basic Lib
1850_SEMIDETR_INTWALL2 For Rear: Kitchen/Dining	solid brick/masonry	206	65 Basic Lib
1850_SEMIDET_GFLOOR1 for Front: Hall for Rear: Dining	clay tiles	20	161 TESS Lib
	Compacted earth	300	86 Basic Lib (clay)
	no insulation		
1850_SEMIDETR_GFLOOR1 for Rear: Kitchen	clay tiles	15	161 TESS Lib
	concrete slab	150	9 Basic Lib

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
	no insulation		
1850_SEMIDET_GFLOOR2 for Front: Lounge1	softwood timber boards	18	231 TESS Lib (3/4 inch)
	ventilated air void	1000	3 TESS Lib
	to simulate 1000mm two layers used	-	3 TESS Lib
1850_SEMIDET_GFLOOR3 for Front: Lounge2	softwood timber boards	18	231 TESS Lib (3/4 inch)
	ventilated air void	200	3 TESS Lib
1850_SEMIDET_GFLOOR4	solid concrete slab	150	9 Basic Lib
1850_SEMIDET_FFLOOR for Front: Ground and First Floor	wool/polyester carpet	10	402 TESS Lib (rubber backed carpeting)
	rubber underlay	10	see above
	timber floor boards	18	231 TESS Lib (3/4 inch)
	void	150	3 TESS
	Plasterboard	12	106 Basic Lib
1850_SEMIDET_LADDER	wool/polyester carpet	10	402 TESS Lib (rubber backed carpeting)
	rubber underlay	10	see above
	18mm timber floor boards	18	231 TESS Lib (3/4 inch)
1850_SEMIDET_CEILING for Front	Rockwool	150	257 TESS Lib (mineral wool)
	Plasterboard	12	106 Basic Lib
1850_SEMIDETR_CEILING for Rear: Dining	Plasterboard	12	106 Basic Lib
	cavity void	150	3 TESS
	timber boards	18	231 TESS Lib
1850_SEMIDET_ROOF for Front	Slates	6	94 basic Lib
	Felt Underlay	-	392 TESS Lib
	Mineral wool insulation	200	257 TESS Lib
	Plasterboard	12	106 Basic Lib
1850_SEMIDET_GROOF for garage	fibreglass	5	2 Basic Lib
	marine plywood	18	237 TESS Lib
1850_SEMIDET_FLATROOF for the sill of bay window	asbestos slate	6	94 basic Lib
	breathable membrane	-	ignored
	airgap	-	3 TESS
	Plasterboard	20	106 Basic Lib
1850_SEMIDETR_ROOF for Rear	Slates	6	94 basic Lib
	Felt Underlay	-	392 TESS Lib
	rigid foam insulation	50	Celotex Non Standard
	Plasterboard	12	106 Basic Lib
1850_SEMIDET_EXTDOOR	solid wooden door	-	398 TESS Lib
1850_SEMIDET_GARDOOR	steel door	-	399 TESS Lib
1850_SEMIDET_INTDOOR	glass and wood door	-	400 TESS Lib
GLAZING for Front: all windows for Rear: Dining	4mm single glazed units in timber frame	-	1st in Basic Lib
GLAZING for Rear: Kitchen	24mm sealed double glazed units in uPVC frame	-	ASH_A17.23c
SKYLIGHTS	24mm sealed double glazed units in timber frame	-	ASH-A17.5c

4 1920-1944 SEMI-DETACHED HOUSE

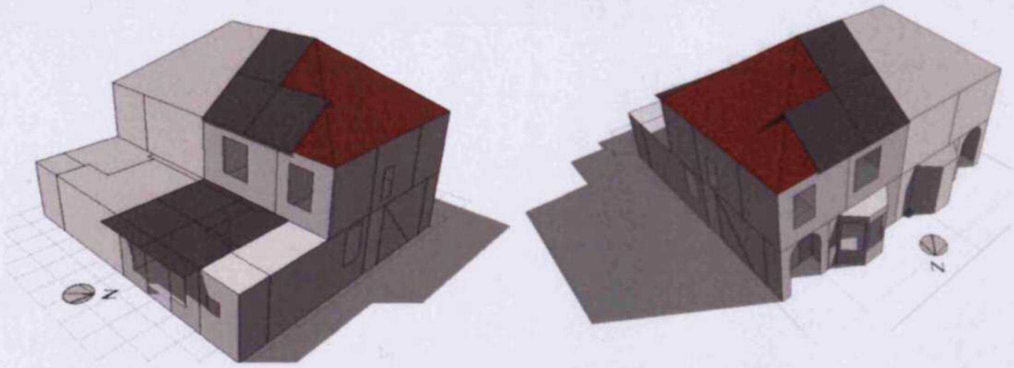


TABLE 10: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

Zone name	Volume (m3)	Volume based factors (%)	Area (m2)	Area based factors (%)
Kitchen	55.98	25.75	27.20	0.29
Dining	25.58	11.77	10.65	0.11
Lounge	56.58	26.03	23.52	0.25
Bathroom	10.90	5.01	4.53	0.05
WC	4.42	2.03	1.84	0.02
Bedroom1	27.54	12.67	11.46	0.12
Bedroom2	21.46	9.87	8.86	0.09
Bedroom3	12.64	5.81	5.26	0.06
Store	2.28	1.05	N/A	N/A
Total	217.37	100.00	93.32	1.00

TABLE 11: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
65 Basic Lib	BRICKS	1.8	0.84	1250	
103 Basic Lib	GYPSUM PLASTER	1.5	0.84	1200	
2 TESS Lib	PERPENDICULAR VOID				0.047
104 Basic Lib	LIME MORTAR	3.13	0.84	1800	
102 Basic Lib	COMMON PLASTER	1.26	0.84	1200	
257 TESS Lib	MINERAL WOOL	0.16	0.9	80	
392 TESS Lib	FELT MEMBRANE	0.69	1.67	1121.3	
106 Basic Lib	PLASTERBOARD	1.26	0.84	1000	
231 TESS Lib	¾" SOFTWOOD	0.416	1.382	512.6	
3 TESS Lib	HORIZONTAL VOID				0.047
402 TESS Lib	RUBBERBACKED CARPET				0.06
231 TESS Lib	1" HARDWOOD	0.571	1.256	720.8	
222 TESS Lib	¾" PLYWOOD	0.416	1.214	544.6	
161 TESS	12" 3-CELL HOLLOW CLAY TILE	2.492	0.837	1121.3	
399 TESS Lib	1.75" STEEL DOOR				0.086

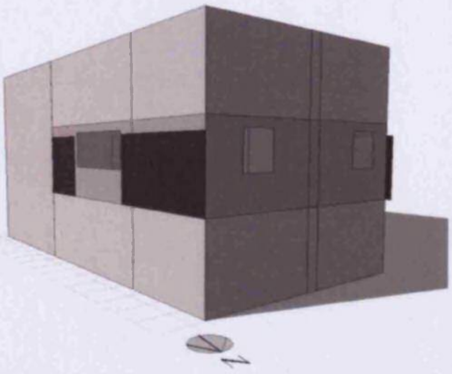
TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
Non Standard	INTWALL THIN				0.1133
41 TESS Lib	BITUMEN	0.61	1	1200	

Table 12: Materials used in TRNBUILD

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
20_44_SEMIDET_EXTWALL600	standard bricks	103	65 Basic Lib
	cavity void	212	2 TESS Lib
	standard bricks	103	65 Basic Lib
	cavity void (no insulation)	80	2 TESS Lib
	concrete "pebbledash" render (ext)	20	104 Basic Lib (lime mortar)
20_44_SEMIDET_EXTWALL300	gypsum plaster (int)	15	103 Basic Lib
	standard bricks	103	65 Basic Lib
	cavity void (no insulation)	80	2 TESS Lib
	20mm concrete "pebbledash" render (ext)	20	104 Basic Lib (lime mortar)
20_44_SEMIDET_COLUMN	standard bricks	103	65 Basic Lib
	standard bricks	103	65 Basic Lib
	standard bricks	103	65 Basic Lib
20_44_SEMIDET_ROOF	Clay tiles	20	161 TESS
	Felt Underlay	-	392 TESS Lib
20_44_SEMIDET_CEILING	Rockwool (mineral wool) insulation	150	257 TESS Lib
	Plasterboard	12	106 Basic Lib
20_44_SEMIDET_GFLOOR	Softwood timber boards	18	231 TESS Lib (3/4")
	ventilated air void	*300*	3 TESS Lib
20_44_SEMIDET_FFLOOR	wool/polyester carpet	*10*	402 TESS Lib (rubber backed carpet)
	10mm rubber underlay	-	see above
	Softwood timber boards	18	231 TESS Lib (3/4")
	ventilated air void	*150*	3 TESS Lib (air gap horizontal)
	Plasterboard	12	106 Basic Lib
20_44_SEMIDET_INTWALL_150	plaster skim	5	102 Basic Lib (common plaster)
	standard bricks	103	65 Basic Lib
	plaster skim	5	102 Basic Lib (common plaster)
20_44_SEMIDET_INTWALL_075	Plasterboard both sides with air gap (massless)	75	Non Standard
20_44_SEMIDET_INTWALL_100	Plasterboard both sides with air gap (massless)	75	Non Standard
20_44_SEMIDET_LADDER	carpet	*10*	402 TESS Lib (rubber backed carpet)
	rubber	*5*	*see above*
	timber	25	237 TESS Lib (1" inch)
20_44_FLATROOF	Plasterboard	12	106 Basic Lib
	150mm mineral wool	150	257 TESS Lib
	plywood sheet	18	222 TESS Lib
	bitumen felt	4	41 TESS Lib

FOR GLAZING OF THE 2 STOREY PART:	4mm single glazed units in timber frame		ASH_A17.1C
FOR GLAZING OF THE 2 STOREY PART:	4mm single glazed units in softwood timber frame		ASH_A17.1C
20_44_EXTDOOR	steel door		399 TESS Lib

5 1945-1964 LOW RISE FLAT



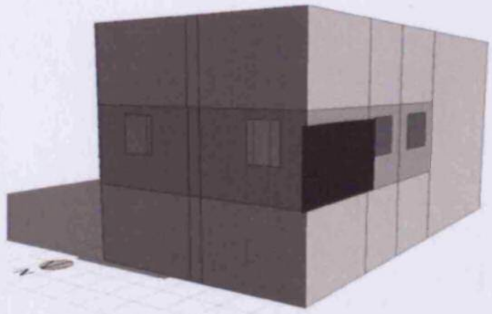


TABLE 13: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

Zone name	Volume (m3)	Volume based factors (%)	Area (m2)	Area based factors (%)
Kitchen	17.87	10.89	7.12	10.83
Lounge	51.98	31.68	21.01	31.96
Bedroom1	31.85	19.42	12.72	19.34
Bedroom2	29.29	17.86	11.71	17.80
Hall	17.49	10.66	6.97	10.61
Bathroom	15.58	9.50	6.22	9.46
Total	164.06	100.00	65.74	100.00

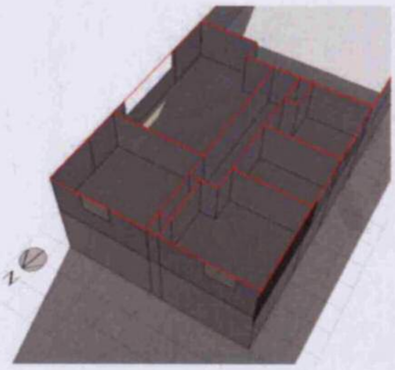


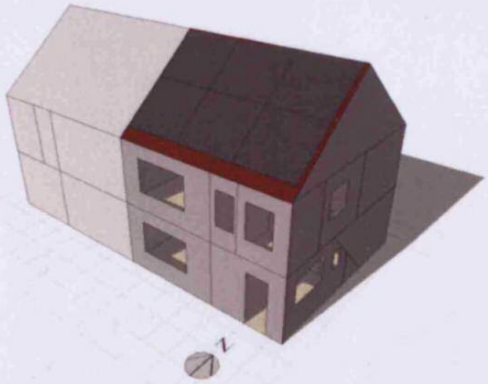
TABLE 14: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
9 basic Lib	CONCRETE SLAB	4.068	1	1400	-
106 Basic Lib	PLASTER BOARD	0.576	0.84	950	
103 Basic Lib	GYPSUMP LASTER	1.5	0.8	1200	
65 Basic Lib	POLYURETHANE	0.11	1	40	
65 Basic Lib	BRICKS	1.8	0.84	1250	
2 TESS Lib	PERPENDICULAR VOID				0.047
102 Basic Lib	COMMONPLASTER	1.26	0.84	1200	
11 TESS Lib	TIMBERFLOOR	0.5	1.2	650	

TABLE 15: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
45_64_FLAT_EXTWALL	gypsum plaster (internal)	10	103 Basic Lib
	standard brick	103	65 Basic Lib
	ventilated cavity	-	2 TESS Lib
	standard brick	103	65 Basic Lib
45_64_FLAT_INTPART	plaster skim	5	102 Basic Lib (common plaster)
	brick	103	65 Basic Lib
	plaster skim	5	102 Basic Lib (common plaster)
45_64_FLAT_CEILING	R/C concrete slab	150	9 basic Lib (concrete slab)
	Plasterboard	12	106 Basic Lib
45_64_FLAT_FLOOR	wood block (parquet)	25	11 TESS Lib
	R/C concrete slab	150	9 basic Lib
glazing	20mm Double glazed sealed in timber frame	-	ASH_A15.4

6 1945-1964 SEMI-DETACHED HOUSE



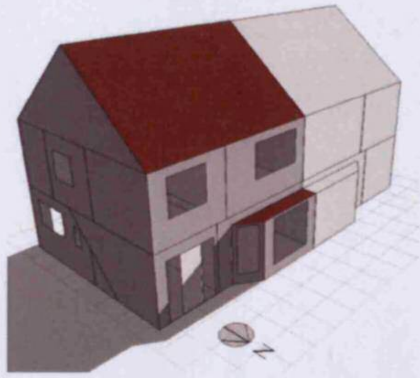


TABLE 16: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

Zone name	Volume (m3)	Volume based factors (%)	Area (m2)	Area based factors (%)
Kitchen	21.40	9.56	8.75	9.82
Dining	31.70	14.17	12.85	14.41
Lounge	39.36	17.59	15.71	17.62
Hall	38.23	17.08	12.72	14.27
Bathroom	7.11	3.18	2.98	3.35
WC	3.98	1.78	1.60	1.79
Bedroom1	29.28	13.08	12.10	13.57
Bedroom2	32.82	14.67	13.53	15.18
Bedroom3	19.17	8.57	8.92	10.01
Store	0.75	0.34	N/A	N/A
Total	223.80	100.00	89.17	100.00

TABLE 17: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density [kg/m³]	Resistance
257 TESS Lib	MINERAL WOOL INSULATION	0.16	0.9	80	
106 Basic Lib	PLASTERBOARD	1.26	0.84	1000	
102 Basic Lib	COMMON PLASTER	1.26	0.8	1200	
65 Basic Lib	BRICKS	1.8	0.84	1250	
104 Basic Lib	LIME MORTAR	3.13	0.8	1800	
9 Basic Lib	CONCRETE SLAB	4.07	1	1400	
402 TESS Lib	RUBBERBACKED CARPET				0.06
231 TESS Lib	3/4" SOFTWOOD BOARD	0.42	1.38	512.6	
3 TESS Lib	HORIZONTAL VOID				0.047
392 TESS Lib	FELT MEMBRANE	0.69	1.67	1121.3	
399 TESS Lib	1.75" STEEL DOOR				0.086
161 TESS Lib	12" 3 CELL CLAY TILES	2.49	0.8	1121.3	

TABLE 18: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
45_64_SEMIDET_EXTWALL	Plasterboard	12	106 Basic Lib
out	Rockwool insulation	40	257 TESS Lib (mineral wool)
	standard bricks	103	65 Basic Lib
	concrete 'pebbledash' render	20	104 Basic Lib (lime mortar)
45_64_SEMIDET_INTWALL	plaster skim	5	102 Basic Lib (common plaster)
	standard bricks	103	65 Basic Lib
	plaster skim	5	102 Basic Lib (common plaster)
45_64_SEMIDET_GFLOOR	wool/polyester carpet	*10*	402 TESS Lib (rubber backed carpet)
	rubber underlay	*10*	*see above*
	softwood timber boards	18	231 TESS Lib (3/4")
	ventilated air void *to complete the 900mm I put two layers*	*900*	- Simulated as external element with view fac to sky =0
45_64_SEMIDET_LADDER	wool/polyester carpet	*10*	402 TESS Lib (rubber backed carpet)
	rubber underlay	*10*	*see above*
	softwood timber boards	18	231 TESS Lib
45_64_SEMIDET_FFLOOR	wool/polyester carpet	*10*	402 TESS Lib (rubber backed carpeting)
	rubber underlay	*10*	*see above*
	softwood timber boards	18	231 TESS Lib (3/4")
	void	*150*	3 TESS
	Plasterboard	12	106 Basic Lib
45_64_SEMIDET_CEILING	Rockwool insulation	150	257 TESS Lib (mineral wool)
	Plasterboard	12	106 Basic Lib
45_64_SEMIDET_ROOF	clay tiles	20	161 TESS Lib
	Felt Underlay	2	392 TESS Lib
45_64_SEMIDET_FLATROOF	solid concrete	100	9 Basic Lib
45_64_SEMIDET_EXTDOOR	steel door	-	399 TESS Lib
45_64_SEMIDET_GLAZING	sealed double glazed units in metal frame	-	ASH_A17.5b

7 1965-1980 DETACHED HOUSE

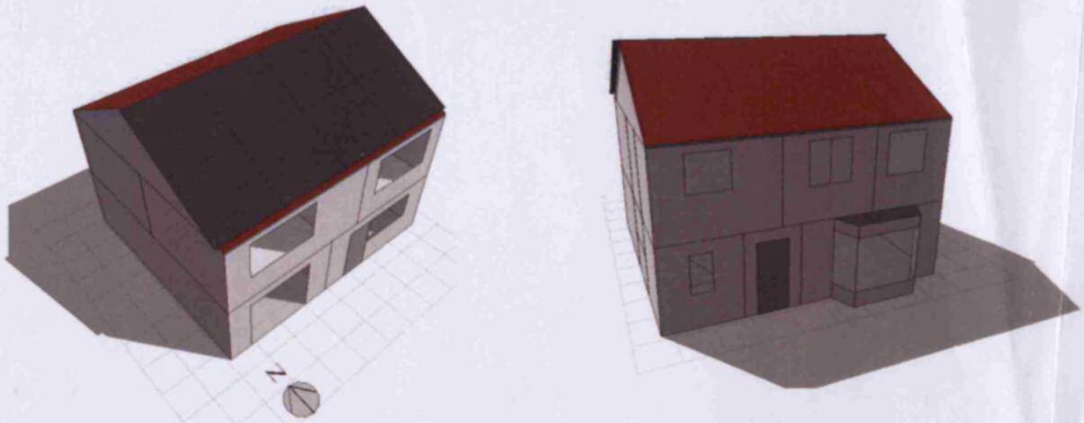


TABLE 19: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

Zone name	Volume (m^3)	Volume based factors (%)	Area (m^2)	Area based factors (%)
Kitchen	35.90	12.39	14.96	12.91
Dining	75.73	26.13	31.64	27.31
WC	10.37	3.58	4.32	3.73
Hall	46.61	16.08	15.31	13.21
Bathroom	15.44	5.33	6.43	5.55
Bedroom1	39.94	13.78	16.66	14.38
Bedroom2	27.34	9.43	11.39	9.83
Bedroom3	15.68	5.41	6.52	5.63
Bedroom4	20.78	7.17	8.64	7.46
Cylinder	2.02	0.70	N/A	N/A
Total	289.80	100.00	115.86	100.00

TABLE 20: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

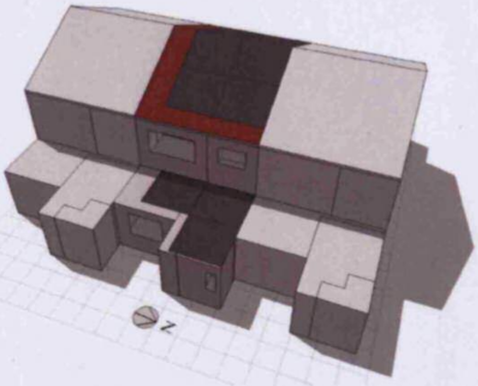
TRNSYS layer	description	Conductivity [Kj/hmK]	Capacity [Kj/KgK]	Density [kg/m³]	Resistance
106 Basic Lib	PLASTERBOARD	0.576	0.84	950	
394 TESS Lib	BLOW IN INSULATION	0.155	0.83	16	
402 TESS Lib	RUBBERBACKED CARPET				0.06
170 TESS Lib	3/4'' HARDBOARD	0.339	1.172	640.7	
3 TESS Lib	HORIZONTAL VOID				0.047
9 basic Lib	CONCRETE SLAB	4.068	1	1400	
372 TESS Lib	SAND/GRAVEL MIX	2.52	1	1800	
392 TESS Lib	FELTF MEMBRANE	0.69	1.67	1121.3	
371 TESS Lib	PUMICE GRAVEL	0.68	1	1000	
7 Basic Lib	BRICKS	1.8	0.84	1250	
2 TESS Lib	PERPENDICULAR VOID				0.047

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
231 TESS Lib	¾'' SOFTWOOD	0.42	1.38	512.6	
399 TESS Lib	1.75" STEEL DOOR	0.086			
161 TESS Lib	12'' 3 CELL CLAY TILES	2.49	0.84	1121.3	

TABLE 21: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
65-80_DET_EXTWALL	Plasterboard	12	106 Basic Lib
	dense concrete bricks	100	7 Basic Lib
	Verniculite (blown-in) insulation	55	394 TESS Lib
out	brick (external surface)	100	7 Basic Lib
65-80_DET_INTWALL	Plasterboard	12	106 Basic Lib
	softwood timber stud	80	2 TESS Lib (air gap)
	Plasterboard	12	106 Basic Lib
65-80_DET_GFLOOR	wool/polyester carpet	*10*	402 TESS Lib (rubber backed carpet)
	rubber underlay	*10*	*see above*
	concrete screed	-	*See below*
	concrete slab	150	9 basic Lib
	Celotex (rigid foam insulation)	25	Non Standard
	DPM	-	*ignored*
	sand blinding	25	372 TESS Lib (sand gravel)
	Compacted hardcore	150	371 TESS Lib (pumice gravel)
65-80_DET_FFLOOR	wool/polyester carpet	*10*	402 TESS Lib (rubber backed carpet)
	rubber underlay	*10*	*see above*
	chipboard	18	170 TESS Lib (3/4 " hard board)
	void	*150*	3 TESS
	Plasterboard	12	106 Basic Lib
65-80_DET_CEILING	Verniculite (blown-in) insulation	200	394 TESS Lib
	Plasterboard	12	106 Basic Lib
65-80_DET_ROOF	clay tiles	20	161 TESS Lib
	Felt Underlay	2	392 TESS Lib
65-80_DET_EXTDOOR	steel door	-	399 TESS Lib
GLAZING	24mm sealed double glazed units in uPVC frame		ASH_A17.5c
65-80_DET_LADDER	wool/polyester carpet	*10*	402 TESS Lib (rubber backed carpet)
	rubber underlay	*10*	*see above*
	softwood timber boards	18	231 TESS Lib (3/4")

8 1965-1980 MID-TERRACE HOUSE



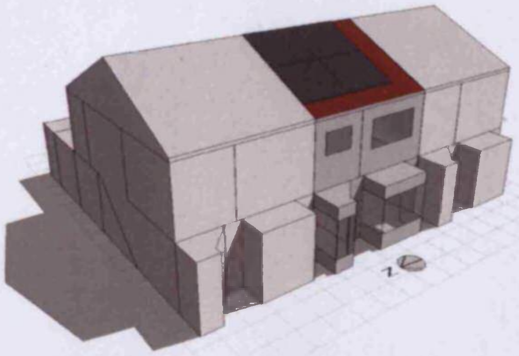


TABLE 22: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

Zone name	Volume (m3)	Volume based factors (%)	Area (m2)	Area based factors (%)
Kitchen	52.54	17.94	19.99	18.96
Lounge	64.32	21.97	24.27	23.02
Bathroom	9.89	3.38	3.73	3.54
Utility	20.74	7.08	7.86	7.46
Hall	47.14	16.10	14.00	13.28
Bedroom1	38.49	13.15	14.53	13.78
Bedroom2	31.28	10.68	11.82	11.22
Bedroom3	19.18	6.55	7.23	6.86
Store	3.99	1.36	N/A	N/A
WC	5.24	1.79	1.98	1.88
Total	292.81	100.00	105.42	100.00

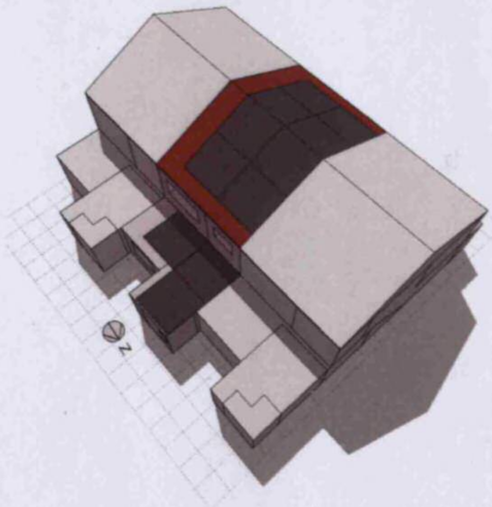


TABLE 23: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
9 basic Lib	CONCRETE SLAB	4.07	1	1400	
392 TESS Lib	FELT MEMBRANE	0.69	1.67	1121.3	
106 Basic Lib	PLASTERBOARD	1.26	0.84	1000	
65 Basic Lib	BRICKS	1.8	0.84	1250	
394 TESS Lib	BLOWIN INSULATION	0.16	0.83	16	
104 Basic Lib	LIME MORTAR	3.13	0.84	1800	
11 TESS Lib	TIMBER FLOORING	0.5	1.2	650	
372 TESS Lib	SAND/GRAVEL	2.52	1	1800	
371 TESS Lib	PUMICE GRAVEL	0.68	1	1000	
402 TESS Lib	RUBBERBACKED CARPET				0.06
231 TESS Lib	3/4" SOFTWOOD BOARDS	0.42	1.38	512.6	

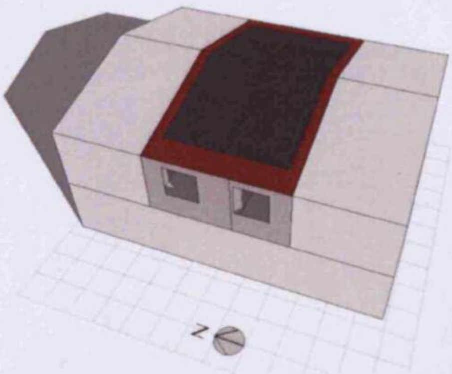
TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m^3)	Resistance
3 TESS	HORIZONTAL VOID				0.047
2 TESS	PERPENDICULAR VOID				0.047
102 Basic Lib	COMMON PLASTER	1.26	0.84	1200	
257 TESS Lib	MINERAL WOOL INSULATION	0.16	0.9	80	
41 TESS Lib	BITUMEN	0.61	1	1200	
237 TESS Lib	3/4" PLYWOOD	0.42	1.21	544.6	
399 TESS Lib	1.75" STEEL DOOR				0.086
161 TESS Lib	12" 3-CELL CLAY TILES	2.49	0.84	1121.3	

TABLE 24: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
65-80_MIDTER_EXTWALL	Plasterboard	12	106 Basic Lib
	standard bricks	103	65 Basic Lib
	Cellulose (blow in insulation)	60	394 TESS Lib
	standard bricks	103	65 Basic Lib
out	concrete 'pebbledash' render	20	104 Basic Lib (lime mortar)
65-80_MIDTER_INTWALL	Plasterboard	12	106 Basic Lib
	Timber stud frame with 80mm void	80	2 TESS (only void)
	Plasterboard	12	106 Basic Lib
65-80_MIDTER_INTWALL2	plaster skim	5	102 Basic Lib (common plaster)
	standard bricks	103	65 Basic Lib
	plaster skim	5	102 Basic Lib (common plaster)
65-80_MIDTER_GFLOOR	wood laminate	5	11 TESS Lib (timber flooring)
	polyurethane foam sheet	-	*Ignored, only for soundproofing and levelling*
	concrete screed	50	*As below*
	concrete slab	150	9 basic Lib
	DPM	-	*ignored*
	sand blinding	25	372 TESS Lib (sand gravel)
	Compacted hardcore	150	371 TESS Lib (pumice gravel)
65-80_MIDTER_FFLOOR	wool/polyester carpet	*10*	402 TESS Lib (rubber backed carpeting)
	rubber underlay	*10*	*see above*
	softwood timber boards	18	231 TESS Lib (3/4")
	void	*150*	3 TESS
	Plasterboard	12	106 Basic Lib
65-80_MIDTER_CEILING	Rockwool (mineral wool) insulation	150	257 TESS Lib
	Plasterboard	12	106 Basic Lib
65-80_MIDTER_LADDER	wool/polyester carpet	*10*	402 TESS Lib (rubber backed carpeting)
	rubber underlay	*10*	*see above*
	softwood timber boards	18	231 TESS Lib (3/4")
65-80_MIDTER_FLATROOF	Bitumen felt	3	41 TESS Lib
	Marine Plywood	18	237 TESS Lib
	Rockwool (mineral wool) insulation	150	257 TESS Lib

	Plasterboard	12	106 Basic Lib
65-80_MIDTER_ROOF	clay tiles	20	161 TESS Lib
	Felt Underlay	2	392 TESS Lib
65-80_MIDTER_EXTDOOR	steel door	-	399 TESS Lib
GLAZING	24mm sealed double glazed units in uPVC frame	-	ASH_A17.5c

9 1981-1999 LOW RISE FLAT



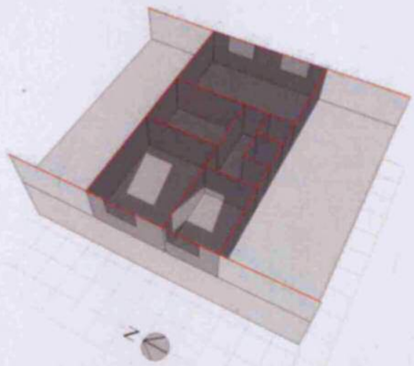


TABLE 25: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

Zone name	Volume (m3)	Volume based factors (%)	Area (m2)	Area based factors (%)
Kitchen	13.71	12.17	5.70	12.75
Lounge	39.04	34.66	16.25	36.35
Hall	10.38	9.22	4.30	9.62
Bedroom	27.72	24.61	11.55	25.84
Bathroom	16.60	14.73	6.90	15.44
Store1	2.88	2.56	N/A	N/A
Store2	2.33	2.06	N/A	N/A
Total	112.66	100.00	44.70	100.00

TABLE 26: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
106 Basic Lib	PLASTER BOARD	1.26	0.84	1000	
257 TESS	MINERAL WOOL	0.16	0.9	80	
402 TESS Lib	RUBBERBACKED CARPET				0.06
7 Basic Lib	CONCRETE BLOCKS	1.84	1	1400	
Non Standard	CELOTEX INSULATION	0.1	1.65	30	
392 TESS Lib	FELT MEMBRANE	0.69	1.67	1121.3	
170 TESS Lib	CHIPBOARD	0.339	1.172	640.7	
mer3 TESS	HORIZONTAL VOID				0.047
2 TESS	PERPENDICULAR VOID				0.047
161 TESS Lib	12" 3-CELL CLAY TILES	2.49	0.84	1121.3	

TABLE 27: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
1981-1999_F_EXTWALL	Plasterboard	12	106 Basic Lib
	dense concrete bricks	100	7 Basic Lib
out	Celotex	50	Non Standard
	brick (external surface)	100	7 Basic Lib
1981-1999_F_INTWALL	Plasterboard	12	106 Basic Lib
	Timber stud frame with 80mm void	*80*	2 TESS (only void)
	Plasterboard	12	106 Basic Lib
1981-1999_F_FFLOOR	wool/polyester carpet	*5*	402 TESS Lib (rubber backed carpet)
	rubber underlay	*10*	*see above*
	chipboard	18	170 TESS Lib (3/4 I" hard board)
	void	*150*	3 TESS
	Plasterboard	12	106 Basic Lib
1981-1999_F_CEILING	Mineral Wool	150	257 TESS
	Plasterboard	12	106 Basic Lib
1981-1999_F_ROOF	clay tiles	20	161 TESS Lib
	Felt Underlay	2	392 TESS Lib
GLAZING	24mm sealed double glazed units in uPVC frame	-	ASH_A17.5c

10 1981-1999 MID-TERRACE HOUSE

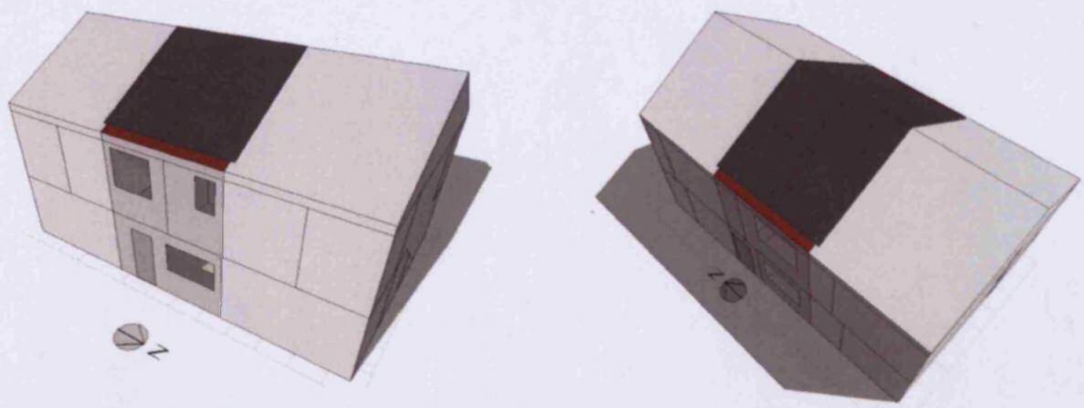


TABLE 28: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

Zone name	Volume (m^3)	Volume based factors (%)	Area (m^2)	Area based factors (%)
Kitchen	21.12	14.68	8.80	15.76
Lounge	41.28	28.70	17.40	31.16
Hall	20.59	14.31	5.75	10.30
Bedroom1	32.28	22.44	13.42	24.04
Bedroom2	16.03	11.15	6.67	11.94
Bathroom	9.10	6.33	3.79	6.80
Store	3.42	2.38	N/A	N/A
Total	143.82	100.00	55.82	100.00

TABLE 29: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

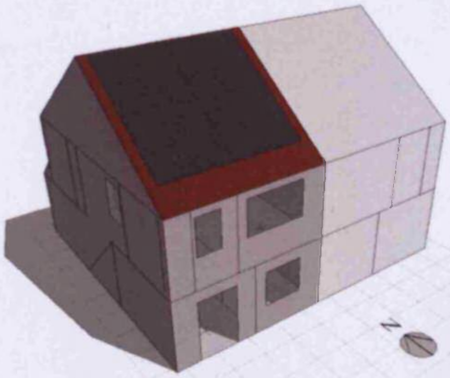
TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m^3)	Resistance
106 Basic Lib	PLASTERBOARD	1.26	0.84	1000	
257 TESS	MINERAL WOOL INSULATION	0.16	0.9	80	
7 Basic Lib	CONCRETE BLOCK	1.836	1	1400	
9 basic Lib	CONCRETE SLAB	4.07	1	1400	
Non Standard	CELOTEX INSULATION	0.1	1.65	30	
372 TESS Lib	SAND/GRAVEL	2.52	1	1800	
371 TESS Lib	PUMICE GRAVEL	0.68	1	1000	
11 TESS Lib	TIMBER FLOORING	0.504	1.2	650	
402 TESS Lib	RUBBERBACKED CARPET				0.06
170 TESS Lib	CHIPBOARD	0.34	1.17	640.7	
3 TESS	HORIZONTAL VOID				0.047
2 TESS	PERPENDICULAR VOID				0.047
392 TESS Lib	FELT MEMBRANE	0.69	1.67	1121.3	
399 TESS Lib	1.75" STEEL DOOR				0.086

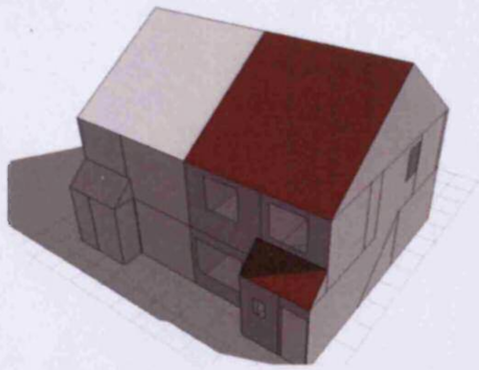
TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
231 TESS Lib	¾" SOFTWOOD	0.42	1.38	512.6	
65 Basic Lib	BRICKS	1.8	0.84	1250	
161 TESS Lib	12" 3-CELLCLAY TILES	2.49	0.84	1121.3	

TABLE 30: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
1981-1999_EXTWALL	Plasterboard	12	106 Basic Lib
	dense concrete bricks	100	7 Basic Lib
	Mineral wool	50	257 TESS
out	brick (external surface)	100	65 Basic Lib
1981-1999_INTWALL	Plasterboard	12	106 Basic Lib
	Timber stud frame with 80mm void	*80*	2 TESS (only void)
	Plasterboard	12	106 Basic Lib
1981-1999_GFLOOR	wood laminate	5	11 TESS Lib (timber flooring)
	polyurethane foam sheet	-	*Ignored, only for soundproofing and levelling*
	concrete screed	50	*9 basic Lib (concrete slab)*
	concrete slab	150	9 basic Lib (concrete slab)
	Celotex (rigid foam insulation)	25	Non Standard
	DPM	-	*ignored*
	sand blinding	25	372 TESS Lib (sand gravel)
	Compacted hardcore	150	371 TESS Lib (pumice gravel)
1981-1999_FFLOOR	wool/polyester carpet	*5*	402 TESS Lib (rubber backed carpet)
	rubber underlay	10	*see above*
	chipboard	18	170 TESS Lib (3/4 " hard board)
	void	-	3 TESS
	Plasterboard	12	106 Basic Lib
1981-1999_LADDER	wool/polyester carpet	*5*	402 TESS Lib (rubber backed carpet)
	rubber underlay	10	*see above*
	softwood timber boards	18	231 TESS Lib (they got 3/4")
1981-1999_CEILING	Mineral Wool	150	257 TESS
	Plasterboard	12	106 Basic Lib
1981-1999_ROOF	clay tiles	20	161 TESS Lib
	Felt Underlay	2	392 TESS Lib
1981-1999_EXTDOOR	steel door	-	399 TESS Lib
GLAZING	24mm sealed double glazed units in uPVC frame	-	ASH_A17.5c

11 2000-2006 SEMI-DETACHED HOUSE





This model was fully modelled in Ecotect first to get some preliminary results on the thermal demand and the ST with TES potential. This study was presented in a paper at the PALENC 2007 conference[1]. For this model only and to allow for comparisons between the ECOTECT and TRNSYS models, the layers from the Ecotect library were introduced as new layers in TRNSYS. Therefore the materials' data is presented with a different way than in the other models, as no layers from the TRNSYS libraries were used.

TABLE 31: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

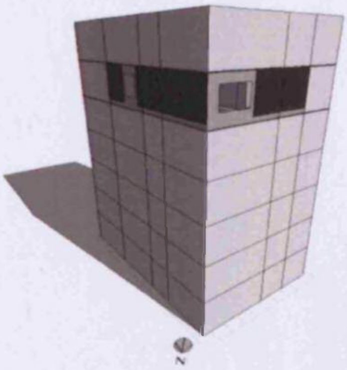
Zone name	Volume (m3)	Volume based factors (%)	Area (m2)	Area based factors (%)
Kitchen	18.03	9.94	7.59	10.13
Dining	19.79	10.91	8.33	11.12
Lounge	37.95	20.92	15.96	21.30
WC	5.22	2.88	2.18	2.91
Bed 1	26.51	14.61	11.17	14.91
Bathroom	10.27	5.66	4.33	5.78
Bed 3	11.74	6.47	4.93	6.58
Bed 2	24.93	13.74	10.47	13.97
Entrance	22.74	12.54	9.96	13.29
Store Ground	2.66	1.47	N/A	N/A
Store Floor	1.57	0.87	N/A	N/A
Total	181.41	100.00	74.92	100.00

[1] E. Ampatzi, I. Knight. The potential application of residential solar thermal cooling in the UK and the role of thermal energy storage technologies. *AIVC 28th Conference and Palenc 2nd Conference: Building Low Energy Cooling and Ventilation Technologies in the 21st Century*. Crete island, Greece (27-29 September 2007)

TABLE 32: LIST OF MATERIALS USED IN TRNBUILD WITH LAYERS AND THEIR PHYSICAL PROPERTIES AS TAKEN FROM ECOTECT'S LIBRARY.

Wall name	layer name: STACS survey	width (mm)	conductivity (KJ/hmK)	capacity (KJ/KgK)	density (Kg/m3)
Yarrow_external_wall	Brick Masonry Medium	100	2.56	0.84	2000
	Air Gap	50	20.02	1.00	1.3
	Celotex	50	0.10	1.65	30
	Concrete 1-4 Dry	100	2.71	0.66	2300
	Plasterboard	12	0.58	0.84	950
Yarrow_int_partitions	Plasterboard	12	0.58	0.84	950
	Air Gap	40	20.02	1.00	1.3
	Rock Wool	30	0.12	0.71	200
	Plasterboard	12	0.58	0.84	950
Yarrow_first_floor	Carpet, Simulated Wool	5	0.22	1.36	200
	Rubber Neoprene	2	0.69	2.18	1250
	Chipboard	18	0.24	1.26	430
	Air Gap	150	20.02	1.00	1.3
	Plasterboard	12	0.58	0.84	950
Yarrow_ground	Hard Stone	45	10.44	0.84	2750
	Aggregate (Sand Gravel Or Stone_	25	4.68	0.92	2240
	Celotex	50	0.09	1.65	30
	Concrete Cinder	100	1.21	0.66	1600
	Cement Screed	50	5.04	0.65	2100
	Polyurethane Foam Flexible	5	0.15	1.76	60
	Wood Chip Board Cement Bonded	5	0.54	1.47	530
Yarrow_roof	Clay Tiles	50	67.78	0.84	2760
Yarrow_ceiling	Cellulosic Insulation	125	0.15	0.84	43
	Plasterboard	12	0.58	0.84	950
glazing	ASH_A17.5c	N/A	N/A	N/A	N/A

12 POST 2006 HIGH RISE FLAT



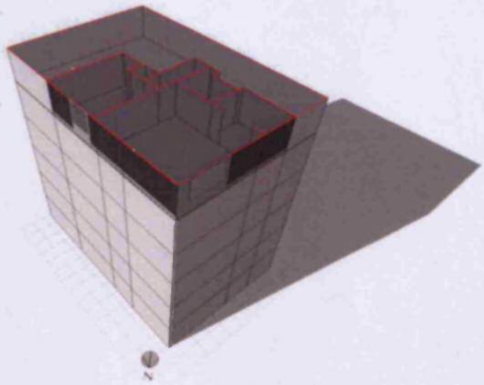


TABLE 33: THERMAL ZONES' VOLUME AND AREA DATA (STORE'S AREA BASED FACTOR NOT CALCULATED AS THIS IS USED ONLY FOR OCCUPANTS DISTRIBUTION)

Zone name	Volume (m3)	Volume based factors (%)	Area (m2)	Area based factors (%)
Kitchen/Lounge	78.97	56.15	32.86	57.17
Hall	9.35	6.65	3.90	6.78
Bedroom	38.59	27.44	16.07	27.97
Bathroom	11.16	7.94	4.64	8.08
Store	2.56	1.82	-	-
Total	140.63	100.00	57.47	100.00

TABLE 34: LIST OF LAYERS AND THEIR PHYSICAL PROPERTIES (RESISTANCE ONLY FOR LAYERS WITH NEGLIGIBLE THERMAL MASS -SEE WIDTH IN ITALICS IN NEXT TABLE) USED IN TRNBUILD.

TRNSYS layer	description	Conductivity (Kj/hmK)	Capacity (Kj/KgK)	Density (kg/m³)	Resistance
9 basic Lib	CONCRETE SLAB	4.07	1	1400	-
Non Standard	CELOTEX INSULATION	0.1	1.65	30	-
106 Basic Lib	PLASTERBOARD	1.26	0.84	1000	-
151 TESS Lib	1" CEMENT MORTAR	2.6	0.84	1858.1	-
2 TESS Lib	PERPENDICULAR VOID	-	-	-	0.047
11 TESS Lib	TIMBER FLOORING	0.5	1.2	650	-
402 TESS Lib	RUBBERBACKED CARPET	-	-	-	0.06
405 TESS Lib	CERAMIC TILE	-	-	-	0.002

TABLE 35: MATERIALS USED IN TRNBUILD

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
POST_2006_EXTWALL	Plasterboard	12	106 Basic Lib
	Insulated cladding panel (rigid foam insulation)	100	Non Standard
	cast reinforced concrete	150	9 basic Lib
out	cement render (external surface)	10	151 TESS Lib

Wall name	layer name: STACS survey	Width (mm)	layer name: TRNSYS
POST_2006_INTWALL	Plasterboard	12	106 Basic Lib
	Steel stud frame with 80mm void	80	2 TESS Lib
	Plasterboard	12	106 Basic Lib
POST_2006_FLOORLAMIN	wood laminate	5	11 TESS Lib (timber flooring)
	polyurethane foam sheet	5	*ignore*
	concrete screed	50	*As below*
	concrete slab	100	9 basic Lib
POST_2006_FLOORCARPET	wool/polyester carpet	10	402 TESS Lib (rubber backed carpet)
	polyurethane foam sheet	5	*ignore*
	concrete screed	50	*As below*
	concrete slab	100	9 basic Lib
POST_2006_FLOORTILE	tiles	8	405 TESS Lib
	polyurethane foam sheet	5	*ignore*
	concrete screed	50	*As below*
	concrete slab	100	9 basic Lib
POST_2006_FLOOR	concrete screed	50	*As below*
	concrete slab	100	9 basic Lib
POST_2006_CEILING	cast concrete on steel deck	150	9 basic Lib
	rigid foam insulation	100	Non Standard
	Plasterboard	12	106 Basic Lib
POST_2006_GLAZING	24mm sealed argon filled double glazed units (low-E glass) in PVC frame	-	ASH_A17.23b