Department of Mechanical and Aerospace Engineering

**Project: Individual Thesis**

# Title:

# Investigating the Potentials of Glazing as External House Protection on Energy Saving and Thermal Comfort in Cold Climates using Simulation Modelling:

# Scottish Greenhouse Residences

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## Copyright Declaration

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Signed: Georgia-Charoula Anagnostou Date: 31st August 2016

## Abstract

In Scotland, space heating accounts for about 73% of a household's energy consumption, with thermal comfort and fuel poverty being among the country's chronic building-related problems. This study arose from the need to put forward passive solutions involving the use of glass as insulation means in Scottish residential buildings, aiming at reducing heating demands, while maintaining acceptable thermal conditions.

Greenhouse residences are pointed out in several locations around the world as a new form of sustainable building design for reducing the total energy requirements, while creating additional living areas with pleasant indoor conditions. This thesis aimed to evaluate the effectiveness of greenhouse residences in Scotland based on the potentials for heating reduction and thermal comfort, using simulation modelling techniques.

An extensive literature review was carried out around the energy use and the building-related problems in the Scottish housing, the use of glass as a protection and insulation means in buildings, and the concept of greenhouse residences. A reference building model of a single-storey detached dwelling in Aberdeen was created, using the IES VE modelling and dynamic simulation software. The study examined the effect of several design variations on the energy saving potentials as well as ventilation strategies as a way to address the overheating problem.

The study showed that a greenhouse residence can be successfully applied in detached properties in Scotland, giving an overall 25% reduction in heating demands, while the problem with overheating is manageable. Increasing the ventilation through the greenhouse facades reduced the peak temperatures and the hours of discomfort in all zones. Results indicated that the most influential parameters regarding the potential in demand reduction are the building's thermal insulation level and the glazing type of the greenhouse. Poorly insulated houses benefited the most from the greenhouse presence, while using a double-glazed glass cover gave higher savings. The effect of changing the distance between the glass cover and the building envelope was moderate, with smaller greenhouse sizes leading to greater energy savings but also higher temperatures. The greenhouse orientation in relation to the main building had practically no influence in the total annual demands, while results for all locations examined across Scotland were consistent. Finally, the application of a glass shelter in multi-storey dwellings gave the same percentage reduction in the total heating demands as in the baseline house.

## Acknowledgements

First of all, I would like to express my deep sense of gratitude and appreciation to my project supervisor, Dr Daniel Cóstola, for sharing his insight and expertise and providing me with technical knowledge and valuable building modelling tips throughout the course of the project work. But most importantly, I would like to thank him for his inspiring guidance, the moral support, confidence and trust he showed me during the tough times.

A big thank you to my Mum and Dad for always supporting me in everything I do, and all my family and friends back home for making me feel loved and supported.

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# 1 Introduction

This study arose from the need to put forward relatively unexplored passive solutions involving the use of glass as insulation means in residential buildings in cold climates, aiming at reducing the energy use for heating and at the same time maintaining acceptable indoor thermal conditions.

## 1.1 Background

***World energy use and consumption trends in the building sector***

World energy consumption is rapidly growing. Global warming, supply difficulties and energy resources depletion are the cause of much debate in international forums. Buildings are a key player in these trends, accounting for 40% for the world's energy use and about one-third of global $CO_2$ emissions. Therefore, a major contribution to the objective of tackling the world energy crisis could be made from energy savings in the buildings sector. To make things more daunting, the projected expansion of the built area driven by economic growth, along with the growing desire for better indoor built environment are anticipated to further increase the associated energy needs in buildings. In this regard, the impetus for more energy efficient buildings is becoming ever intense, with the challenge being not only to create energy sustainable buildings but at the same time to provide occupants with a healthy and comfortable indoor environment.

Space heating is the most energy intense end-use in homes, particularly in extremely cold climates. Namely, in Scotland heating accounts for more than the half of total energy use and 73% of household energy consumption. Among others, the building envelope and poor insulation level have a detrimental effect on the dwellings heating requirements, thus underpinning the problems with thermal comfort and fuel poverty.

***Passive solutions and greenhouse residences***

Ways to alleviate the above issues normally focus on technical measures such as improving the insulation or using high energy efficient generation equipment. However, passive measures are also becoming increasingly popular as alternative solutions. By best taking advantage of the sun's energy, passive solar strategies reduce the heating load, and in turn the environmental impact of dwellings, aiming at the same time at maintaining comfortable and healthy conditions inside the buildings.

Among the passive and sustainable building solutions explored, various versions of greenhouse residences have been developed over the last years in several locations around the world (e.g. in the Netherlands, France, Germany, Sweden, Japan), under different climate conditions, uses, configurations and materials. However, due to the novelty of the "building-in-a-glass house" concept, the limited experience, the small number of existing examples and research carried out on the field, little information is currently available on the energy performance and thermal comfort of this dwelling type.

In general, experience over these pilot developments have identified great potentials in reducing the heating load of a building. One of the problems, however, associated with glass-covered residences is the overheating during summer months due to the stronger solar radiation. Therefore, additional cooling devices would be necessary to mitigate the high temperatures, thus adding a considerable cooling load and reducing the overall energy savings. Hence, a greenhouse dwelling would better be used in cooler climates.

***The favourable Scottish climate***

In this respect, the generally cool and wet Scottish climate seems to well-match with the potentials of "house-within-a-greenhouse" concept, so the location chosen for this study was Scotland. Cold winter temperatures (with an average mean of 3 ℃) indicate that if a dwelling is surrounded by an insulating glass it can have significant savings in heating demands. On the other hand, summer temperatures are moderate, with an average high of 15-17 ℃, which means that that glass shell would -probably- not undermine occupants comfort in summer. For example, other areas, although of similar latitude, many have also cold winters but experience hotter summers (e.g. Glasgow vs. Stockholm) and in turn indoor overheating when using a glass cover. In addition, the weather in Scotland is highly and unpredictably changeable and, as it is often said, there are four seasons in a day. With respect to this, and particularly the high levels of rainfall and wind speed, using a glazed envelope around a house diminishes the weather impact on occupants' activities – and mood – offering a more "uniform" indoor climate and smaller temperature fluctuations.

***Why detached houses***

The Scottish housing stock is diverse, both in terms of dwelling type and age. In his project, detached houses were selected as a case study for a number of reasons. According to the Scottish Housing Condition Survey (Scottish Government, 2015a), detached houses are the second most prevalent model of households in Scotland. In fact, they account for 22% (or 532,000) of the overall housing stock and more than half of them were pre-1982 properties, meaning that they have to comply with less strict energy efficiency and airtightness standards. Across all age bands, due to larger areas and heat losses caused by greater exposure to wind and weather, it is the type of dwelling which uses the most energy - and therefore emits the most $CO_2$ - and has notably lower energy efficiency ratings compared to the other types. Another important problem experiencing tenants in detached houses is fuel poverty, affecting more than one third of them. Finally, given the scale of the buildings and its practicability to accommodate a glass envelope, this type has been chosen as the study case.

***Lack of data***

Based on the above data and trends, there is a clear need for more energy efficient buildings both from an environmental and an occupants' perspective. So far, there has not been any development or research on greenhouse residences in the Scottish climate and housing stock. Therefore, any potentials of such a building design for addressing the energy and indoor comfort problems in the Scottish territory are currently unknown. An investigation on that subject could provide a number of useful findings and make suggestions for future developments and designs.

## 1.2 Aim

This thesis deals with investigating the applicability of the "greenhouse residence" concept as a sustainable building strategy in cold climates.

More specifically, the aim of this study is to evaluate and compare the effectiveness of implementing greenhouse envelopes in residential buildings under Scotland's climate conditions, based on their energy saving potentials and indoor thermal comfort conditions, using building modelling and simulation techniques.

## 1.3 Objectives

The objectives given below express a breakdown of the above aim and help towards its achievement:

- Provide an overview of the current status of the **Scottish housing stock** and identify energy-related issues.
- Literature investigation and understanding of the concept and current status of **greenhouse residences**.
- Creation of a validated reference **building model** for the studied housing type (detached house) using a modelling tool for building performance simulation. The corresponding greenhouse residence will also be modelled using the same tool.
- Determine the changes in **energy demands and thermal comfort** levels associated with the presence of the greenhouse cover around a typical detached Scottish dwelling under a number of design variations, aiming at the evaluation of energy saving potentials and desirable thermal comfort levels by the use of greenhouse residences.

## 1.4 Approach overview

In order to achieve the aim and objectives described in paragraphs 1.2 and 1.3, the thesis work involved an extensive **literature review** to gain knowledge about the all the aspects involved in the problem and the project, and also the **simulation part** in order to obtain the necessary information to investigate the influence of greenhouse envelopes in the case study residence.

The procedure for the investigation is schematically presented in Figure 1. The overall approach to the project's objectives follows three stages: pre-processing (green), modelling/calculations (blue), post-processing (red).

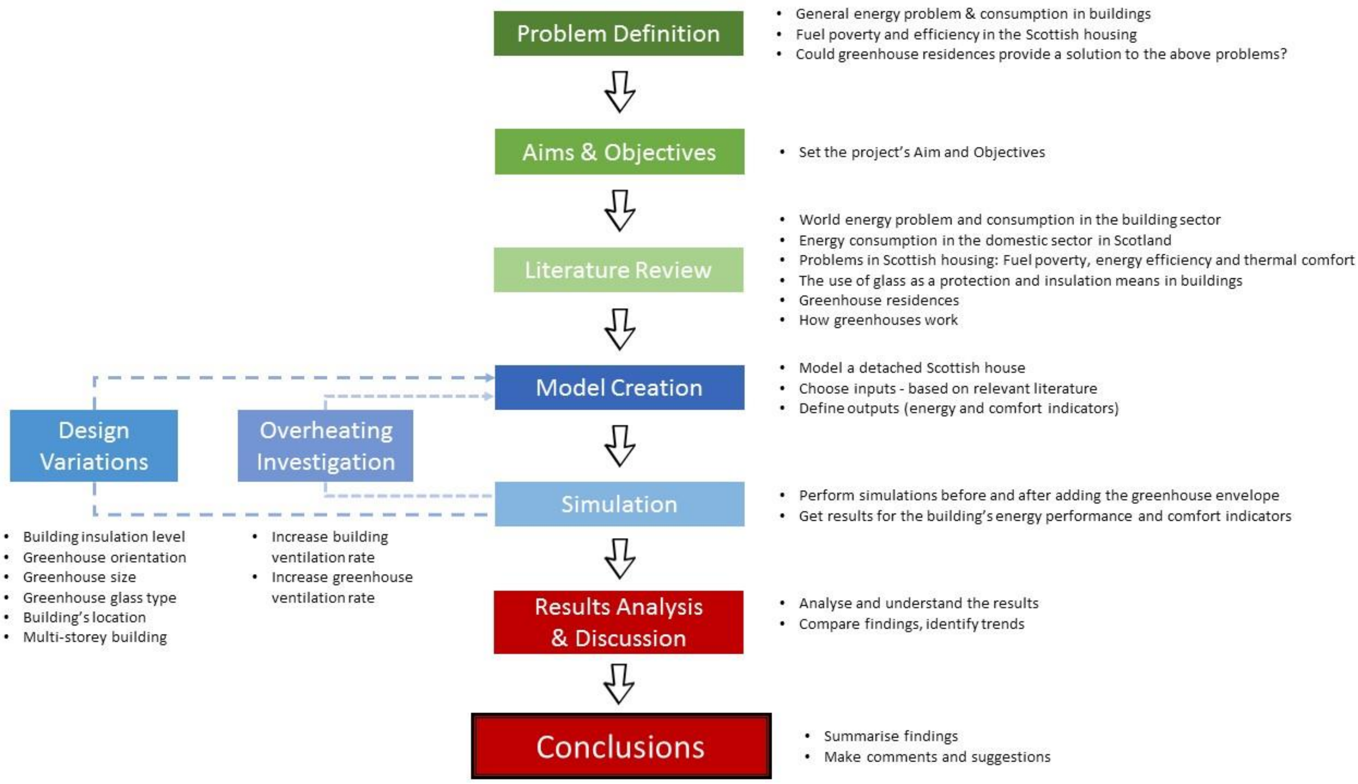


*Figure 1: Project schematic approach*

The explanatory text below summarizes and describes the most important aspects of each stage of the investigation procedure that are displayed in the scheme:

***Problem Definition***: The first thing to do before start working on this thesis was, obviously, to understand and define the problem that this study was asked to investigate. This study arose from the wider need to put forward passive solutions for reducing energy use for heating and at the same time maintaining acceptable indoor thermal conditions in residential buildings in cold climates. More specifically, this thesis tried to provide information about the potentials of using greenhouse dwellings in Scotland against its energy efficiency and thermal comfort issues.

An essential part of the project was to gather real information from the building stock to ensure that the approach taken and the outcomes provide a practitioner-focused outcome, not just a thesis for academic purposes.

***Aims and Objectives***: After identifying the problem, the general aim and objectives for this research were set. As mentioned in the "Aim" section, the overall aim of this project was to examine the applicability of the "greenhouse residence" concept as a sustainable building strategy in cold climates.

The objectives presented previously correspond to the aim of the thesis. In other words, they demonstrate how the aim will be approached and achieved.

***Literature review*:** Literature was used for multiple reasons.

Firstly, it was necessary in order to have a deeper understanding on the energy problem in buildings - and particularly in cool climates - and describe it using actual data from the Scottish housing stock.

Furthermore, before introducing the concept of greenhouse dwellings as an option of using glass as a protection and insulation means in houses, a review on other, more widespread uses of glazing in buildings was carried out. Then, in order to describe the idea of greenhouse dwellings, a literature research around its concept (definition, principles of operation, current status, energy and comfort performance, potential benefits and limitations, shapes, technologies, materials used, etc.) was essential. In fact, a large part of the literature research was conducted on interesting existing projects that incorporate greenhouses. As mentioned, due to the novelty of "greenhouse residences", there are not currently any generic predefined methodologies for their energy performance and comfort level evaluation. For this reason, knowledge about the performance and the design of greenhouse residences was largely based on information on already built cases that could be found online (on the architects' and the design team own websites or in relevant publications).

Note that literature research was conducted throughout the progress of the project, based on the needs, knowledge and data required at each stage.

***Model Creation*:** An essential part of this study was the creation of a validated reference building model. A detached house in Scotland was selected as a case study. The core building, and then the corresponding glass box, were modelled using the IES VE software, a dynamic building simulation tool.

An analytical report on the parameters used in for the baseline dwelling and the other design versions is provided in Chapter 3.

After the model was constructed, it was also vital to examine the outcomes obtained from the simulations in order to make sure they are reasonable and to verify the accuracy of the model. This was done by comparing the energy demands obtained from the software simulation analysis with the energy consumption measured in similar houses in the area and also by reviewing the graphs from the thermal controls.

***Simulation*****:** After creating the building model, the research continued with computational simulations, and more specifically, using the dynamic simulation option provided by the IES-VE software. Dynamic simulation was necessary in order to investigate and understand the effect of the time varying behaviour of several parameters that influence the energy and thermal performance of the structure. These parameters include, inter alia, weather patterns, occupancy regimes, fabric and materials, indoor temperatures, casual gains from occupants and equipment, heating controls and ventilation rates.

***Overheating Investigation***: The way a greenhouse dwelling operates and benefits from natural energy sources (i.e. the sun) is analogous to that of a typical greenhouse. Consequently, a major issue associated with greenhouse residences is the risk of overheating during warm periods. It was therefore essential to examine the impact of the glass envelope on the thermal conditions created in the structure’s living areas. The fluctuations in air temperature both inside the building and in the garden area under the greenhouse were studied, in order to identify any unacceptable levels. This was followed by the application of natural ventilation strategies in order to evaluate their effectiveness against the overheating problem.

***Design Variations*****:** In order to obtain a wider picture of the applicability of the “greenhouse residence” concept in Scottish houses, this thesis analysed various design options and their correlation on the annual energy demand and, if necessary, thermal comfort. The design variations modelled and simulated in this study involved both the core dwelling (thermal insulation, number of floors) and the greenhouse encasement (orientation, size, glass type), as well as different geographical locations within Scotland. Results identified the level of influence of each of these design parameters on the overall greenhouse effectiveness.

***Results Analysis & Discussion*:** This stage involved presenting, understanding, analysing and interpreting the results drawn from the simulation process. Key energy and comfort indicators that were examined are: a) the dwelling's annual heating requirements, in terms of total annual demands, specific heating requirements and saving potentials, and b) the thermal conditions inside the dwelling and in the greenhouse area, in terms of temperature levels and hours of overheating. Any trends were identified and the level of influence of each parameter were graphically presented and discussed.

***Conclusions*:** Findings were summarized and the applicability of greenhouse envelopes in Scottish detached dwellings were pointed out. Any important observations, potentials and limitations were highlighted, complemented with design proposals and recommendations for future work.

## 1.5 Report structure

The thesis work is organized in five chapters as follows:

**Chapter 1** outlines the background to the problem in hand and sets out the aims, objectives and approach of the study.

**Chapter 2** includes a literature review on the various aspects associated with the subject of this project, namely, energy in buildings, the Scottish climate and housing stock, the use of glass in buildings, and the greenhouse dwelling concept.

**Chapter 3** introduces the software used in this thesis and describes all the inputs and assumptions made in the in modelling and simulation parts of the study. In addition, all the design variations that will be applied in the model are explained.

**Chapter 4** presents the results from the simulations. This Chapter is organized in two main parts: a) an analysis around the energy and thermal condition performance of the baseline dwelling, and b) an investigation on several design variations of the baseline greenhouse residence evaluating their influence in the dwelling's heating requirements.

**Chapter 5 s**ummarises the work of this thesis. Main results, conclusions and suggestions for further work are provided.

# 2 Literature review

## 2.1 Energy use in buildings

The rapidly growing world energy use has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts (ozone layer depletion, global warming, climate change, etc.) (Pérez-Lombard, *et al.*, 2008). A significant portion of the total primary energy is consumed by today's buildings in developed countries (Robert, *et al.*, 2011). More specifically, buildings account for 40% of the world's primary energy consumption and are responsible for about one-third of global $CO_2$ emissions (Hernández-Pérez *et al*., 2014).

With rapid economic growth, demands for thermal comfort, in terms of space heating in winter and cooling during the hot/humid summer months, have also increased remarkably (Lam *et al*., 2008). Wan *et al*. (2011) suggest that this growing desire for more comfortable indoor build environment has contributed to a significant proportion of this continuously rising energy demands in buildings. On top of that, according to Pérez-Lombard *et al*. (2008), population growth and increasing demand for building services together with the rise in time spent inside buildings (normally, a person will spend over 70% of his lifetime inside buildings (Huang and Niu, 2015)), assure the upward trend in energy demand will continue in the future. For this reason, effective energy management and efficiency in building design is today a prime objective for a sustainable future at regional, national and international levels (Pérez-Lombard *et al*., 2008; Huang and Niu, 2015).

## 2.2 Scotland's climate

Scottish climate is diverse and different to the rest of the United Kingdom in many aspects. The North of Scotland often suffers from harsh and extreme weather conditions. On the East and West weather is milder, however the east experiences cold North Sea winds and the west part can be very wet. Due to these patterns, the ability to provide heat to Scottish households adequately and effectively becomes vitally important (Scottish Government, 2002).

Due to the difference between climate in Scotland and the rest of the UK, according to Stevenson and Williams (2000) the heating season in Scotland is much longer. They also state that a house in north Scotland can have up to 68% higher spending on fuel compared to one in the south of England, which is largely due to the lengthened heating season.

## 2.3 Current status of the Scottish housing stock

Scotland has set targets to reduce final energy consumption by 12% by 2020 against the 2005-07 baseline, decrease $CO_2$ emissions by 80% by 2050 (Scottish Government, 2012) and ensure that by November 2016, fuel poverty in Scottish households will have been eradicated, so far as is practically possible (Gov.scot, 2014). Improving the energy efficiency of Scotland's housing stock can contribute drastically in achieving these ambitious targets.

The Scottish housing stock is diverse; key characteristics such as age of construction, dwelling type, size, insulation, fuel type, household type, tenure vary significantly across the Scottish territory. Energy efficiency, emissions, operational costs of a property, as well as occupants' comfort levels, depend directly upon these characteristics and therefore also vary within the country.

This chapter describes the current state of Scottish housing with regard to technical characteristics and energy and comfort performance.

### 2.3.1 Dwelling types, age and size

The age and the built form of a dwelling are key drivers for its energy performance, potentials for improvement, affordability and living conditions it provides. Scotland's housing stock is divided into two broad categories: houses including detached, semi-detached, and terraced, and flats including tenements, 4-in-a-block, towers, and slabs. The majority of occupied dwellings in Scotland are houses (62%) rather than flats (38%) (Scottish Government, 2015a).

As can be seen in Table 1, in 2014, there proportions detached, semi-detached and terraced housed were similar, each accounting for approximately one fifth of the Scotland's housing stock.

The Scottish House Condition Survey (SHCS - 2014) also estimated that 75% of Scottish occupied properties were built before 1982 (Table 1), meaning that they did not have to comply with high energy efficiency and airtightness standards (Scottish Government, 2015).

*Table 1: Proportion of Occupied Dwellings by Age and Type, 2014 (Percentage of Whole Stock), (Scottish Government, 2015a)*

| | Type of Dwelling | | | | | |
|---|---|---|---|---|---|---|
| Age of dwelling | Detached | Semi-detached | Terraced | Tenement | Other flats | Total |
| pre-1919 | 4% | 3% | 2% | 9% | 2% | 20% |
| 1919-1944 | 2% | 3% | 1% | 2% | 5% | 12% |
| 1945-1964 | 1% | 6% | 8% | 4% | 3% | 22% |
| 1965-1982 | 5% | 4% | 8% | 3% | 2% | 22% |
| post-1982 | 10% | 4% | 3% | 6% | 2% | 25% |
| Total | 22% | 19% | 21% | 24% | 14% | 100% |

Dwelling types can also differ significantly in terms of their size. The internal floor area as well as the total size of exposed areas have impact on the heating needs of a house and in turn on the energy efficiency and the risk of occupants experiencing fuel poverty (see Chapters 2.3.3 and 2.3.4, respectively).

Scottish data from the SHCS indicates that older buildings are overall larger compared to the corresponding types built after 1919, with detached houses being by far the largest across all age bands (Figure 2). Moreover, dwellings in Scottish rural areas were found to be 40% larger than in urban areas, on an internal floor area basis with over half of them being detached (Figure 3).

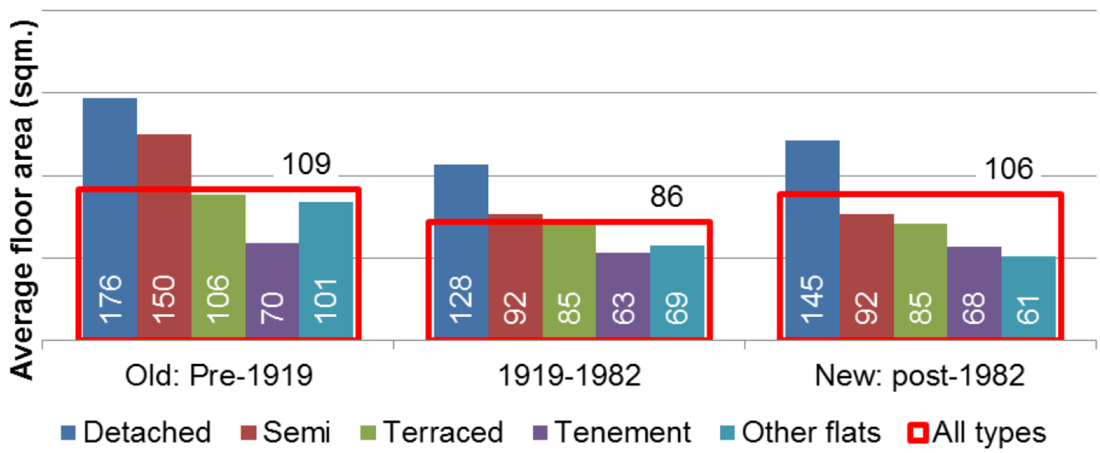


*Figure 2: Average Floor Area ($m^2$) by Dwelling Type and Age (Scottish Government, 2015a)*

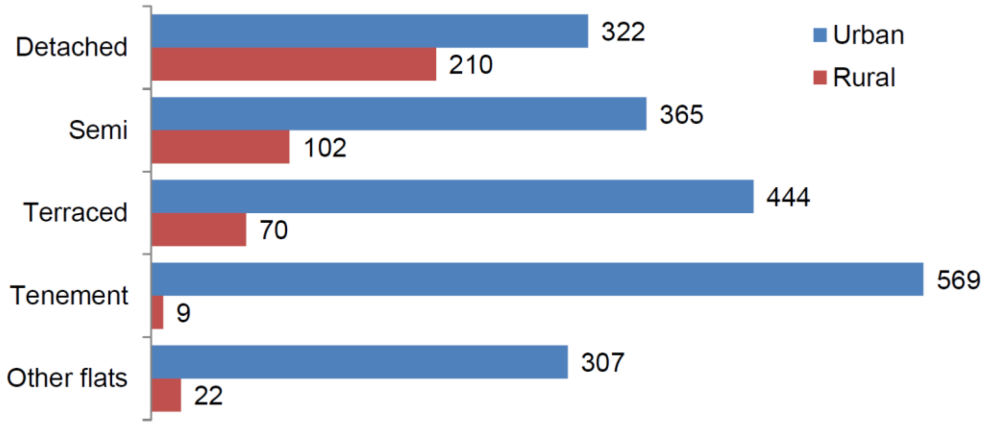


*Figure 3: Dwelling Types in Rural and Urban Areas (000s), 2014 (Scottish Government, 2015)*

### 2.3.2 Domestic heating demand

At this point, it is worth mentioning that according to Scottish Government statistical publication for Energy in Scotland (Scottish Government, 2016), in 2013 non-electrical heat demand accounted for over half of Scotland's energy use (Figure 4) of which approximately 41% was consumed domestically. Moreover, 13% of households in Scotland use electricity as their primary heating fuel. Figure 5 shows that between 2005 and 2013 heat demand in Scotland has fallen by 22% for the domestic sector, most likely due to more energy efficient boilers and improved insulation.

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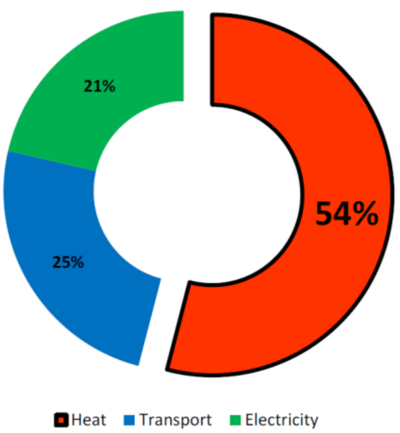
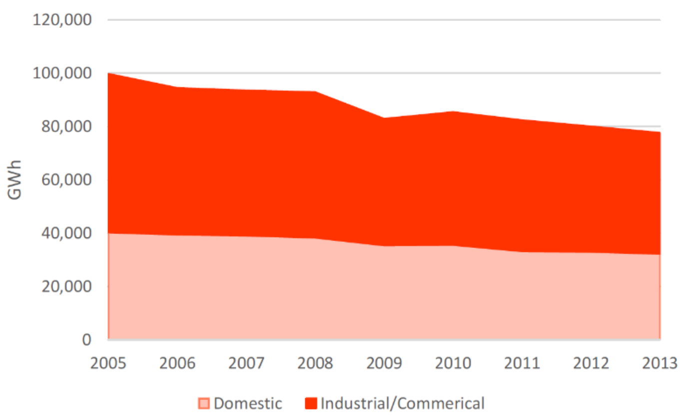



*Source: DECC, Scottish Government*

*Figure 4: Total final energy consumption in Scotland by sector, Scotland, 2013 (Scottish Government, 2016)*




*Source: DECC, Scottish Government*

*Figure 5: Non-electrical heat demand by sector, Scotland, 2005-2013 (Scottish Government, 2016)*

However, space heating still remains by far the largest component of energy spend in Scottish households, which is estimated at 17.7 MWh per year for an average Scottish dwelling. In fact, based on the SHCS (Scottish Government, 2015a), around 73% of the total household energy demand was from space heating (Figure 6). On the one hand, this fact underpins fuel poverty but one the other hand it suggests that appropriate measures to curtail domestic heating load can make a substantial contribution to reduce Scotland's overall energy demands.

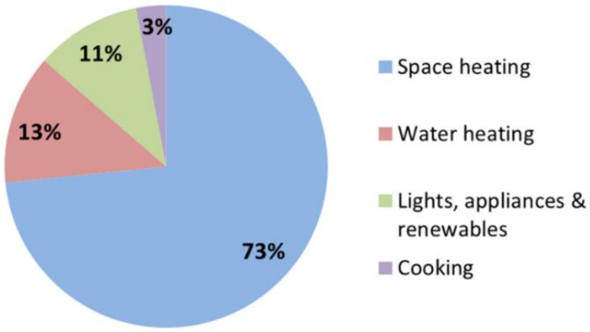



*Figure 6: Average household energy consumption by end use, 2014 (Scottish Government, 2015)*

Primary heating fuel varies within age and type, location of dwelling. According to the Scottish House Condition Survey (Scottish Government, 2015a), overwhelmingly the most common heating fuel in Scotland's housing stock is mains gas: 78% of households (around 1.9 million) rely on mains gas for heating, 13% use electricity and 6% use oil. Older properties are least likely to use main gas, while households living in detached houses have the highest usage of electricity or other fuels for heating (nearly one third of them), which is highly attributed to their being located in off the gas grid areas.

### 2.3.3 Energy Efficiency

Energy efficiency and heating demands are highly determined by the dwelling's physical attributes: design, age, insulation and heating system the major drivers of energy consumption. According to Satin *et all*. (2009), occupant behaviour and household characteristics such as household size, age and income also influence energy use.

***Insulation***

A key determinant for the energy efficiency of a house is its level of insulation. In 2014, the proportions of un-insulated walls were 29% for cavity walls and 86% for solid and other wall types, making a high total 48% of uninsulated dwellings in Scotland. Considering that in an un-insulated dwelling a third of its heat escapes through the walls (Energy Saving Trust, 2016), the consequences of the above statistics in energy wasted, indoor thermal comfort and heating bills is non-trivial. On the other hand, the proportion of dwellings without loft insulation had fallen below 1% of all dwellings with lofts in 2014, and since has been reported significant increase in the thickness of loft insulation (Scottish Government, 2015a).

On top of that, some Scottish constructions are defined as Hard-to-Treat, which means that for some technical (e.g. difficulties with installing insulation, off the gas grid, etc.) or economic reasons, upgrading them using conventional measures is difficult or inadvisable (Dowson *et al.*, 2012). In 2010, the SCHS estimated that across Scotland approximately 704,000 (or 30%) dwellings were Hard-to-Treat (Scottish Government, 2012).

***Energy Efficiency Ratings***

With respect to the Energy Efficiency Ratings (EER) reported in the latest Scottish House Condition Survey, which are calculated under the Standard Assessment Procedure (SAP 2009), half of the Scottish dwellings had an EER of 67 or higher, falling into energy band D or better of the Energy Performance Certificates (EPCs). Although there is a continuous improvement trend in the mean EERs in Scottish homes, standing at 64.1 points in 2014, there is still 16% of total housing stock that is rated E or lower.

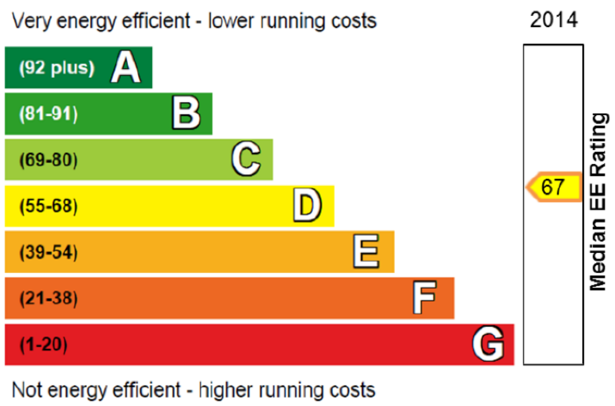



*Figure 7: Median EERs relative to EPC bands, SAP 2009, 2014, (Scottish Government, 2015a)*

*Table 2: EPC Ratings of the Scottish Housing Stock 2014, SAP 2009 (Scottish Government, 2015a)*

| EPC Rating | SAP 2009 000s | % |
|---|---|---|
| A (92-100) | - | - |
| B (81-91) | 42 | 2% |
| C (69-80) | 939 | 39% |
| D (55-68) | 1,037 | 43% |
| E (39-54) | 321 | 13% |
| F (21-38) | 68 | 3% |
| G (1-20) | 14 | 0% |
| Total | 2,420 | 100% |
| Sample | | 2,682 |

No A-rated properties were sampled in 2014.

Table 3 shows how energy efficiency strongly correlates with dwelling type and construction age. Older properties tend to receive lower EPC ratings, with 12% of pre-1919 Scottish housing stock being rated F or G. Detached houses are found to be the worst dwelling type in terms of overall energy performance, with barely one in three receiving C or better rating and the highest concentration of ratings falling in the lowest EPR bands. Moreover, properties in rural areas tend to be significantly less energy efficient, due to high proportion of old, detached or non-gas heated properties.

*Table 3: Mean EER and broad EPC Band by Dwelling Characteristics, SAP 2009, 2014, (Scottish Government, 2015a)*

| | **EE Rating Mean** | **Band** BC | DE | FG |
|---|---|---|---|---|
| **Dwelling Type** | | | | |
| Detached | 60.5 | 32% | 60% | 9% |
| Semi | 62.2 | 29% | 68% | 3% |
| Terraced | 64.1 | 35% | 63% | 2% |
| Tenement | 67.2 | 55% | 43% | 1% |
| Other flats | 66.9 | 53% | 45% | 1% |
| **Age of dwelling** | | | | |
| pre-1919 | 54.8 | 17% | 71% | 12% |
| 1919-1944 | 62.6 | 30% | 68% | 2% |
| 1945-1964 | 64.8 | 39% | 60% | 2% |
| 1965-1982 | 64.3 | 35% | 63% | 1% |
| post-1982 | 71.3 | 71% | 29% | 1% |

### *$CO_2$ emissions*

Energy consumption and $CO_2$ emissions are closely related. As shown in Figure 8, dwellings with larger floor areas or older constructions generally have higher carbon emissions. Across all age bands, detached houses have the highest carbon emissions in the Scottish housing stock, due to the greater proportion of exposed surfaces and the higher usage of carbon intensity fuels for heating. Namely, a pre-1919 detached house is estimated to emit up to 120kg $CO_2/m^2$/year, which is more than twice that of a new tenement, at 54 kg/$m^2$ per year.

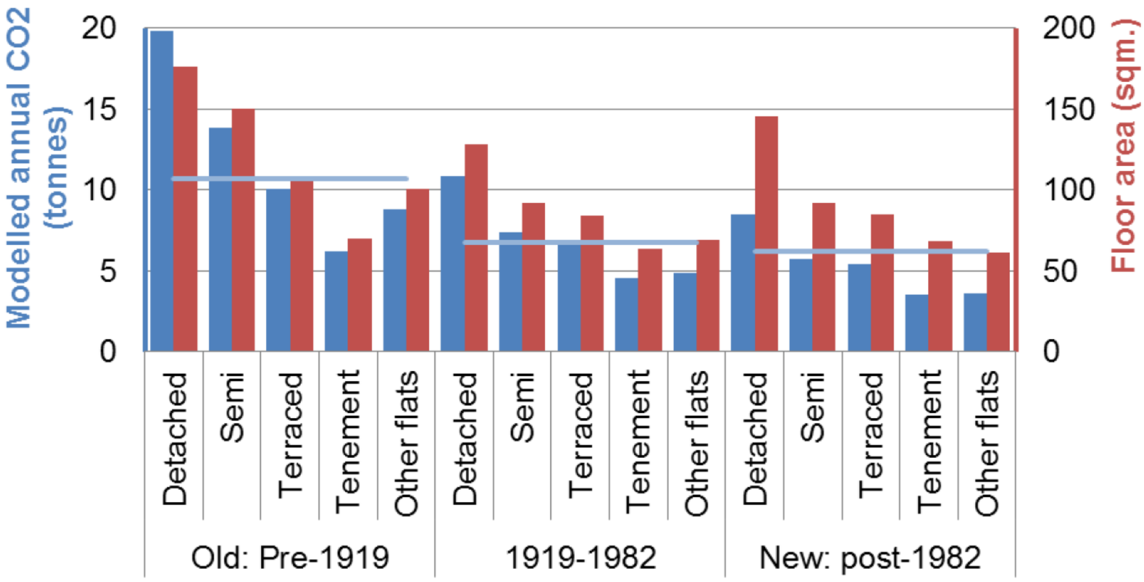



*Figure 8: Average Floor Area and Average Modelled Annual Emissions by Age and Type of Dwelling, (Scottish Government, 2015a)*

### 2.3.4 Fuel poverty and heating satisfaction

***What is Fuel Poverty?***

In broad terms, fuel poverty means not being able to heat a home to a satisfactory standard at a reasonable cost. More specifically, a definition adopted for fuel poverty in Scotland considers that "a household is in fuel poverty if, in order to maintain a satisfactory heating regime, it would be required to spend more than 10% of its income (including Housing Benefit or Income Support for Mortgage Interest) on all household fuel use" (Scottish Government, 2002).

Fuel poverty is one of Scotland's chronic building-related problems (Kelly, 2006). Despite the overall better energy efficiency of the Scottish housing stock, fuel poverty in Scotland is more prevalent than in England, and also more common than income poverty (Scottish Government, 2008). This difference is partly due to structural and demographic factors, such as Scotland's cooler and windier climate, income levels, high rurality and also greater proportion of older or long term sick people.

According to the Scottish Fuel Poverty Statement (Scottish Government, 2002), fuel poverty can result from a host of factors and their combination. Among these, the three major factors that determine whether a household is fuel poor, as well as the level and number of people suffering from fuel poverty, are household income, fuel cost, and the house's energy efficiency.

Using the definition of fuel poverty stated above, the Scottish House Condition Survey tells us that in 2014 there were around 845,000 fuel poor households in Scotland representing 34.9% of the population, while 229,000 households (or 9.5%) could be described as suffering extreme fuel poverty, requiring to spend over 20% of their income on fuel use. The Survey also reported that older dwellings in general have higher fuel poverty rates; in fact, 34% of households in pre-1919 dwellings are fuel poor. As expected, low efficiency ratings also lead to higher fuel poverty rates, with 73% of Scotland's households rated F or G being fuel poor. Furthermore, fuel poverty is particularly high in rural areas due to an interplay of factors, such as older houses, more detached or hard to insulate homes and infrastructure (e.g. properties off the gas grid) (Scottish Government, 2008).

With regards to detached houses, in 2014, 37% were classified as fuel poor. This is mainly attributed to the greater size and surface area to volume ratio, and in turn the higher exposure to wind and weather.

On top of that, rising fuel prices further exacerbate Scotland's fuel poverty problem, particularly among low-income households. Indeed, although energy efficiency and median household income (two key drivers of fuel poverty) have improved since 2003, fuel prices have risen much faster (nearly three times) resulting in a similar increase in fuel poverty rates (Figure 9).

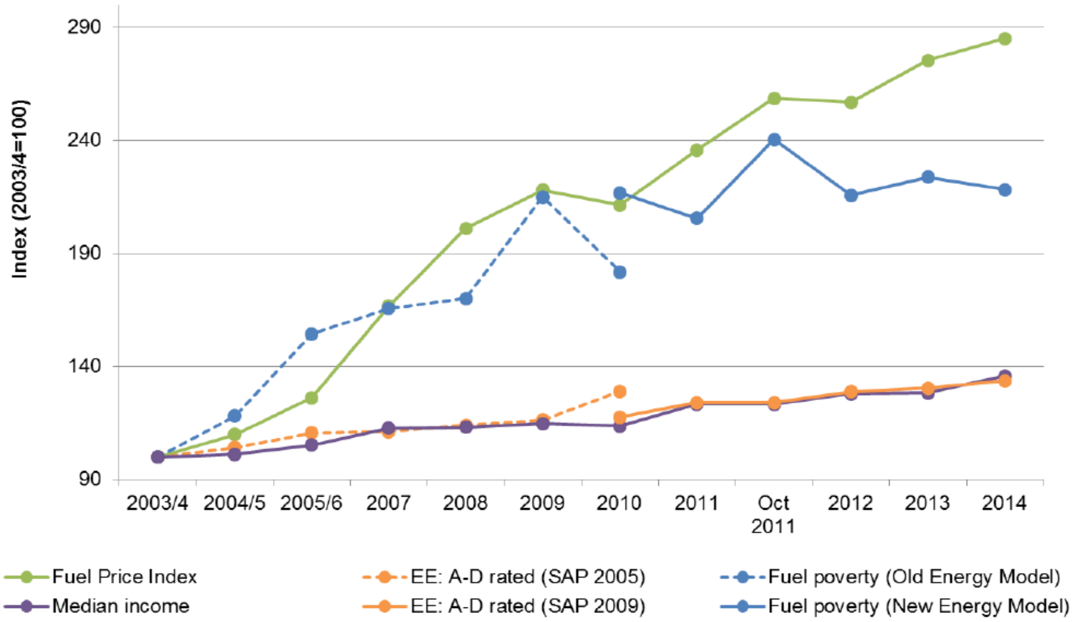



*Figure 9: Trends in Fuel Price, Energy Efficiency and Median Income, 2003/4 – 2014 (Scottish Government, 2016)*

### *Effects of fuel poverty in occupants and households*

According to the Scottish Fuel Poverty Statement published by the Scottish Government (2002), fuel poverty can detrimentally influence the quality of life and health of the occupants, both directly and indirectly. Direct effects include exacerbating illnesses, such as influenza, heart disease and strokes, due to cold indoor temperatures. Additionally, cold, damp homes are a breeding ground for the growth of fungi and dust mites, which are associated with asthma and other chronic conditions. A less direct, albeit important, effect is that households that are forced to spend greater share of their income on heating purposes have to compensate in other aspects of their family budget, such as social and leisure activities, nutrition, education or medication.

As expected, the impact of fuel poverty is more intense among vulnerable groups. Older people are less resistant to the effect of cold, as it can cause raised blood pressure and even deaths from coronary thrombosis. Older householders tend to spend more time indoors and therefore they are more largely affected by fuel poor dwelling. People with a disability or a long-term illness are particularly vulnerable to fuel poverty as it can worsen existing problems or lengthen time taken to recover. Cold and dump indoor conditions are often linked to respiratory conditions in children (e.g. asthma) and also impact on their education due to longer recovery times and overcrowding caused by families in heated areas.

Considering the above trends and implications, identifying and implementing strategies to combat fuel poverty should be a primary target of the Scottish Government in collaboration with related bodies and householders.

***Heating Satisfaction***

With respect to the occupants' heating satisfaction, nearly a quarter of Scotland's households find that their heating keeps them warm in winter only "sometimes" (17%) or "never" (6%). Fuel poor households are more likely to report that their heating does not keep them warm in winter, with 13% of them attributing it to affordability problems. (Scottish Government, 2015). Other major reasons reported to lead to difficulties in heating homes are draughty, inadequate heating poor insulation and old windows. As previously mentioned, experiencing cold indoor temperatures can be detrimental to health in the "vulnerable" population groups (elderly and very young), exacerbating any respiratory or cardiovascular problems.

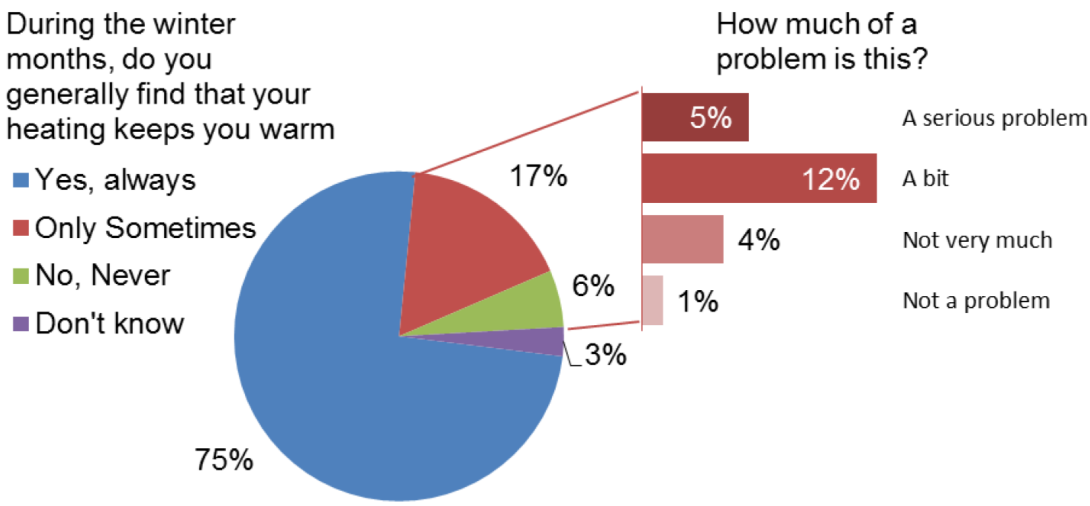



*Figure 10: Winter warmth, (Scottish Government, 2015)*

As shown in Figure 10, of those reporting dissatisfied by the warmth in their house during winter, about three quarters consider this to be "a bit of a problem" or "a serious problem".

## 2.4 The use of glazing in buildings as a protection and insulation means

The use of glazing as protection means is common place in modern buildings. However, there is a range of potential glazing applications that can be utilised and some are more commonly implemented than others. The reasons for the different extents of implementation are a function of cost vs benefits and the age of the technology. In the following sections some typical applications of glazing will be reviewed including an examination of energy performance, thermal comfort, cost and usability.

### 2.4.1 Windows

The use of glazing in windows has become increasingly common. Nearly all modern buildings are constructed with windows that are at least double glazed and many older buildings have been retrofitted with double glazing instead of the original single glazing. In Figure 11, depictions of double and triple window glazing can be seen.

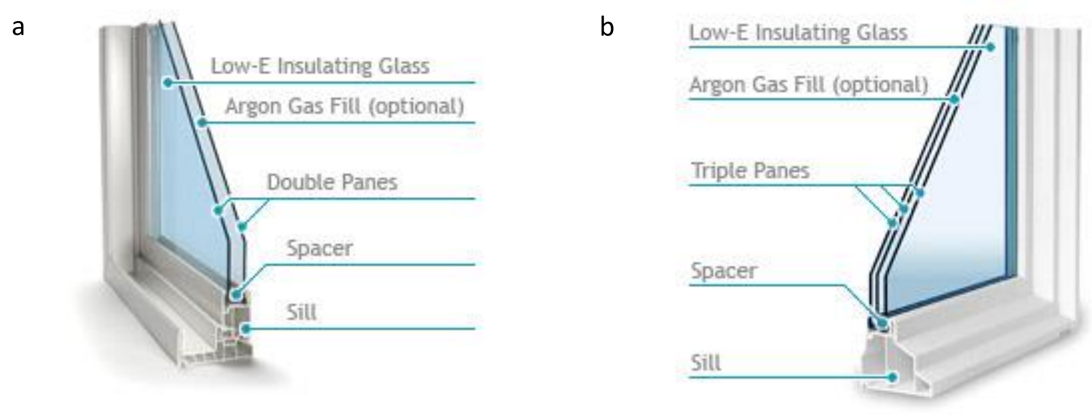



*Figure 11: Depictions of a) double glazing and b) triple glazing windows (Milgard, 2016).*

There are differences in the energy performance of double and triple glazed windows. For example, a study conducted by Wall (2006) on different window types in Swedish housing found that in terms of space heating, the use of double glazing was more energy intensive than triple glazing requiring 14.2 kWh per m$^2$ per year as opposed to space heating requirements of 10.7 kWh per m$^2$ per year for triple glazing. This is due to the greater heat retention inside buildings with triple glazing.

It is costlier to install triple glazing windows, approximately double the price of double glazing (Brinkley, 2015). However, tripled glazed windows have a substantially lower U-value of around 0.5 W/m$^2$K compared to U-values of between 1.0 and 3.5 W/m$^2$K for double glazing (depending on whether the glazing is coated or not, higher U-values are found in uncoated double glazing; Eicker *et al*., 2008; Jelle *et al*., 2011).

In colder climates triple glazing offers greater thermal comfort as more heat is retained inside the building in comparison to double glazing (Brinkley, 2015).

One other type of glazing which is most commonly utilised when single glazing in a residence needs upgrading is the use of secondary glazing. Secondary glazing involves the installation of a second glazing panel behind the existing window. This method can be cheaper than the installation of double glazing as the window fitting does not need to be exact, however it is not as effective at the provision of a thermal barrier as is double glazing (Thegreenage, 2016).

### 2.4.2 Building façades

The addition of facades on a building can have a significant influence over the internal environment of the building. In the following sections two types of façade, curtain walls and double skin facades are reviewed.

***Curtain walls***

Curtain walls are architectural features which are comprised of an outer (non-load bearing) wall typically comprised of glass with a metal framework (see Figure 12).

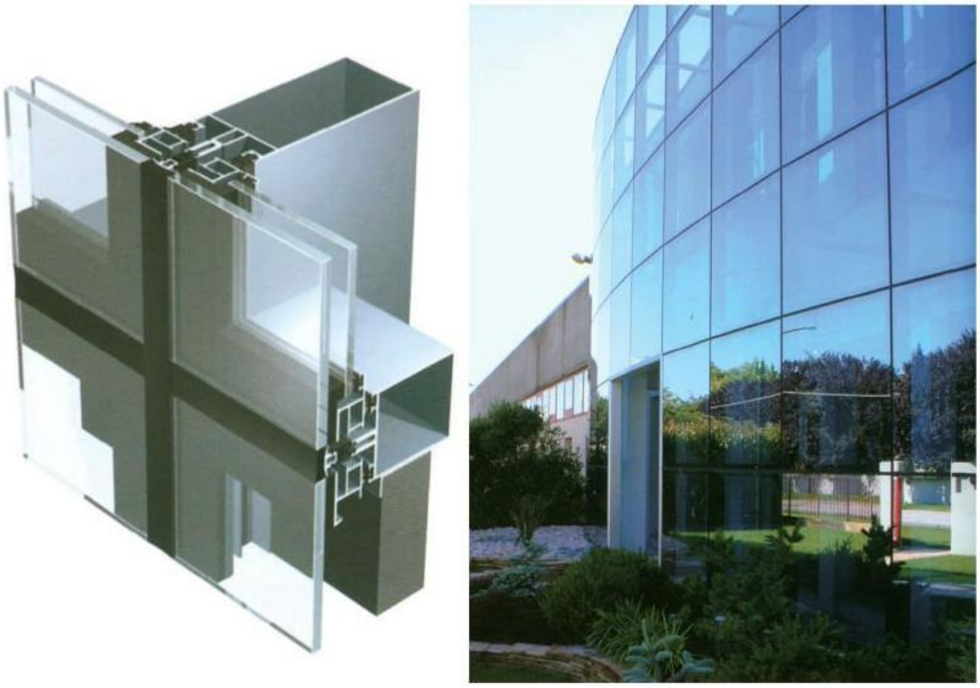


*Figure 12: A typical structure and image of a glass curtain wall (Alibaba, 2016).*

There are usually two layers of glass to aid in improving the thermal properties of the curtain wall by reducing heat gains and losses (Kim *et al*., 2012). Curtain walls can be comprised of either triple of double glazing which will impact the U-value of the curtain wall (see previous section for details).

Whilst curtain walls can provide substantial quantities of light in a building, this can potentially be a disadvantage in terms of the comfort of occupants. The excess light can impact visibility and can also result in uncomfortable temperatures. This has led to the development of curtain wall systems which incorporate blinds to reduce the infiltration of sunlight (Kim *et al*., 2012).

***Double skin façades***

Double skin facades are a newer type of glazing application than curtain walls. It has been suggested that the use of double skin facades is preferential to the use of curtain walls, not only because of the greater design flexibility, but also of the greater potential for creating energy efficiency savings (Shameri *et al*., 2011). In essence a double skin façade is placing two curtain walls one behind the other (see Figure 13).

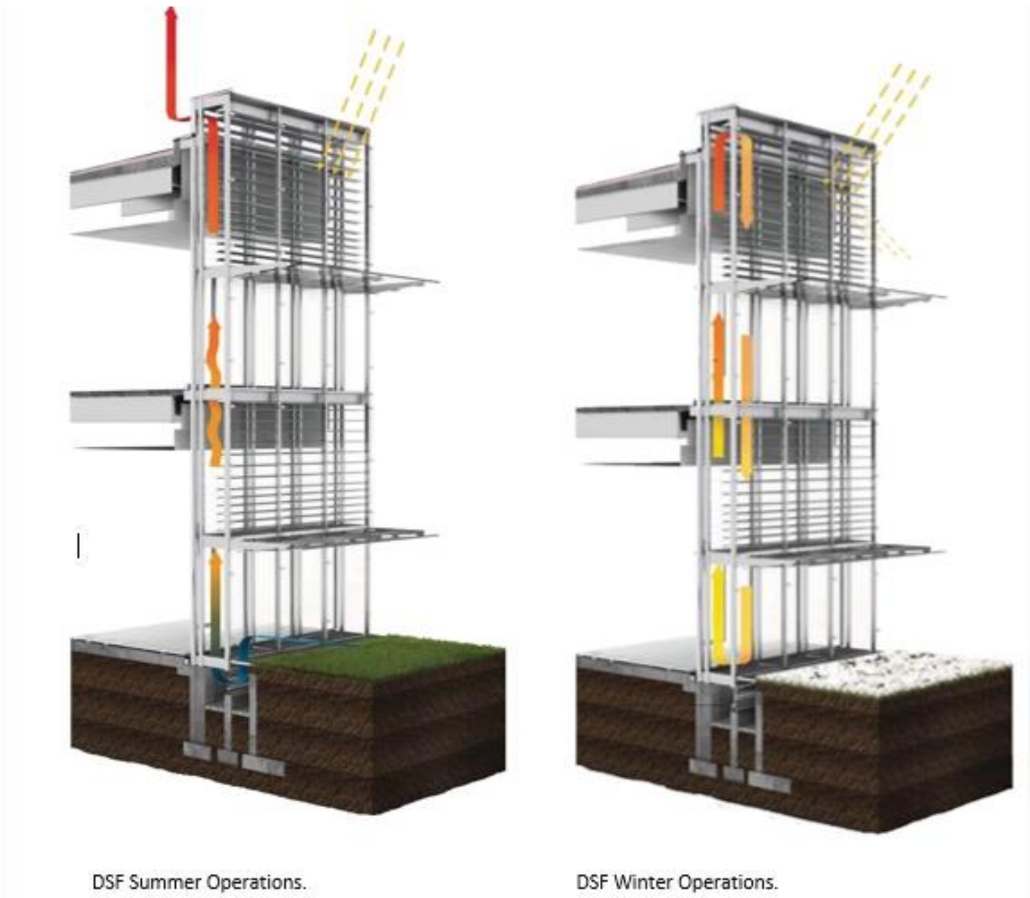



*Figure 13: General design layout for double skin facades (Fenestrapro, 2016).*

Air flows between the two skins can be altered depending on the season, so that in the summer the warm air trapped between the two skins is released to the atmosphere rather than heating the building and in the winter the warm air is trapped between the two skin layers to contribute towards the heating of the building (see Figure 13). In this manner the use of double skin facades can improve the thermal comfort of the buildings occupants and improve the energy efficiency of the building. The use of a curtain wall cannot perform in this manner. The cost of double skin facades exceeds that of curtain walls, due to the greater quantity of materials required for construction, but over the lifetime of the building the costs are likely to be recouped and additional savings made in terms of heating and cooling the building. A study conducted by Shameri *et al*. (2011) found that the inclusion of double skin facades can result in energy savings of 12 -26% with regards to heating and cooling costs.

### 2.4.3 Sunspaces

Sunspaces can be added on to residential buildings (see Figure 14).

*Figure 14: A potential sunspace design (Sunspacessunrooms, 2016).*

Typically, the purpose of this room is to create extra space which is light. The heat flow theory of a sunspace is shown in Figure 15. The basic principle is that the double glazing in the sunspace allows substantial quantities of thermal radiation into the sunspace which heats up the air and is also absorbed by the interior surfaces. This warm air is then circulated into the residence. The use of sunspaces can aid in the reduction of heating costs in the residential setting.

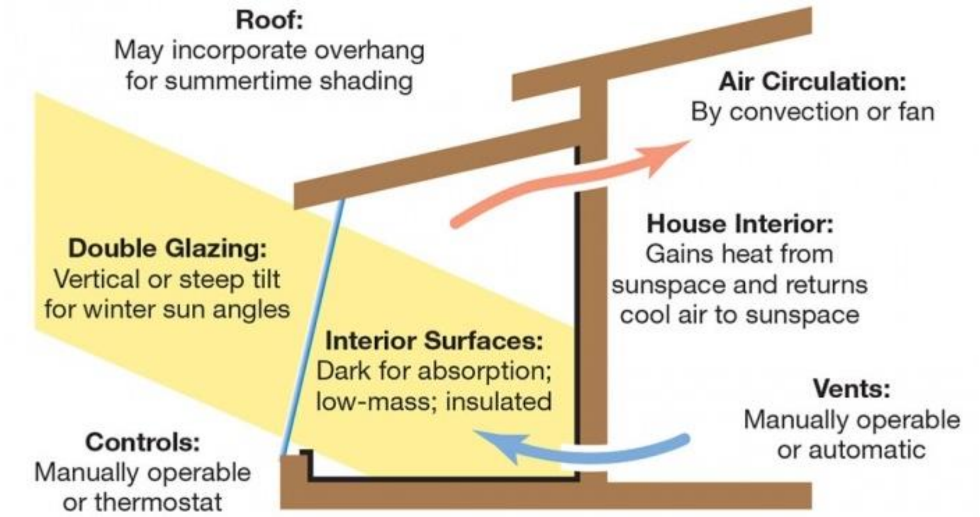



*Figure 15: A general design for a typical sunspace on a residential building (Homepower, 2014).*

The placement of windows can also be on the roof of a sunspace, although this is not as common due to potential issues with leakages (NCSU, 1998).

The addition of a sunspace to a property is typically to increase the area of living space and enjoyment of a property as there are limited energy savings which can be made from the addition of a sunspace, especially when the cost of construction is taken into consideration.

### 2.4.4 Glazed canopies

Glazed canopies are additions which can be made externally to a residential property (see Figure 16). Whilst glazed canopies increase the usability of a residences for the occupants by increasing their ability to utilise outside space during inclement weather. Glazed canopies do not have a significant impact in terms of the


*Figure 16: An example of an external glazed canopy (The garage door, 2016).*

potential for energy savings within the residential building. This is due to glazed canopies being outside structures. They will increase the thermal comfort of occupants when they are in the outside area, but the cost of installing a glazed canopy is not recouped in terms of energy savings.

### 2.4.5 Skylights

Skylights can increase the infiltration of solar radiation into the building. This is because, unlike regular windows in the walls of a building, skylights will allow light into a building for a greater period of sunlight hours; however, this is dependent on the layout of the building and the orientation of the building's roof.

*Figure 17: An example of a typical skylight (lumenrooflight, 2016).*

Increasing the proliferation of sunlight within a residential building can increase the thermal comfort of the occupants during colder periods without the need for additional heating. However, the energy savings of these glazing installations is limited as it is typically during colder periods when sunlight is weakest that additional heating is required.

### 2.4.6 Conservatories

*Figure 18: An example of a conservatory (Adglass, 2016).*

Conservatories are based on similar principle to those of sunspaces. The primary difference between sunspaces and conservatories is that whilst sunspaces typically have on angled wall of glass and an opaque roof, conservatories typically have predominantly glass walls and a glass roof (see Figure 18). Conservatories are in a similar price bracket to those of sunspaces. However, the extra glazing in conservatories will allow a greater infiltration of sunlight, and thus a greater thermal penetration, due to the increase area of glazing. Conversely, the increased glazing will also present a greater opportunity for heat loss during colder months.

### 2.4.7 Overview

In summary, there are several methods by which glazing can be used in buildings as productive methods to increase the energy efficiency of the building and improve the thermal comfort of the occupants. The different glazing options offer different benefits. It is suggested that double and triple glazing, curtain walls and double skin facades are the most beneficial in terms of energy savings. Although there is some speculation with regards to whether the cost of these types of glazing installations is reflected in energy savings to the building occupants.

The use of double glazing is arguably the most common glazing use in residential buildings. This is primarily due to the use of double glazing providing the best cost to benefit ratio in terms of the cost of purchasing and installing the double glazing and the energy savings which can be made.

The idea of using glass in order to shelter the whole building – like a greenhouse – is described in the next section. Apart from providing protection to the building materials and serving as an external insulation, this “greenhouse house” concept offers a number of other benefits which will be presented in Chapter 2.7.

## 2.5 Greenhouse Residences

### 2.5.1 The concept

Compared to the uses of glass described in Chapter 2.4, a "Greenhouse Residence" is considered as a fairly new concept with significantly less existing practical applications in dwellings.

There is not an official or fixed definition for this type of sustainable building design. It has been generally described as a combination of a normal building and a greenhouse like those used in agriculture. Moreover, the greenhouse can shelter either the entire building or a part of it (Van Ree, 2010) (Van Velzen, 2010).

*Figure 19: The makeup of a typical Greenhouse Residence (EFFEKT, 2016)*

In her research paper, Vester (2015) defines the greenhouse dwelling as "a dwelling (volume) connected, sheltered or bordered by a glass façade which can cover (a part of) the volume and its surroundings". This cover serves as a shelter to the building from weather conditions, and provides extra living spaces, as the areas outside the volume can still be used for the occupants' activities, irrespective of ambient weather influences such as rain, wind, snow and cold.

Sayigh (2013) also notes that the size of the transparent envelope covering the core residence is the same order of magnitude of the dwelling. This scale means that the greenhouse implementation emphasizes on the residential character of the concept and therefore is not used for commercial horticultural activities (Van Ree, 2010), but mostly for its benefits on a technical, architectural, climatological and energy consumption level.

With respect to the energy saving potentials for heating, since the dwelling is ventilated with the air from the greenhouse, it actually "benefits" from this preheated air (the temperature inside the greenhouse is 3-5℃ higher that the outside temperature (Sayigh, 2013)) and in turn reduces its heating requirements. Furthermore, greenhouses usually feature openable windows in the upper part and/or the vertical surfaces of the greenhouse for natural ventilation (Van Velzen, 2010).

### 2.5.2 How greenhouses work

During the day, radiation emitted by the sun (the visible and adjacent parts of the infrared and ultraviolet ranges of the spectrum) is able to pass through the transparent greenhouse cover and is absorbed by the materials within (Ucar.edu). Consequently, these materials are heated and re-emit the energy absorbed, warming in this way the interior of the greenhouse. But this energy is emitted as infrared radiation - also called “heat” radiation because although it cannot be seen, it can be felt as heat - which is a long-wavelength radiation form (Ucar.edu). Glass (and other materials) used for greenhouse constructions do not transmit infrared radiation, so the thermal energy cannot escape the greenhouse shell via the radiation mechanism and is reflected back into the interior, where the air has been warmed.

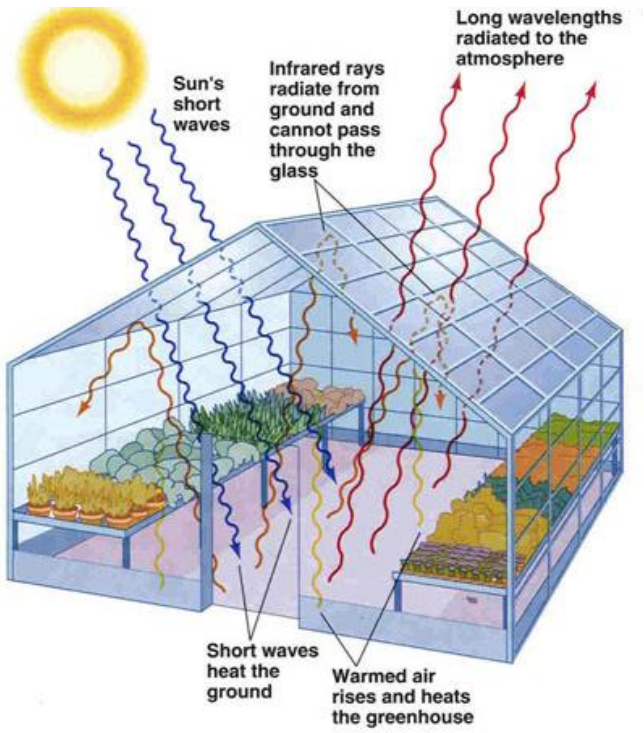



*Figure 20: How a typical greenhouse works (Greenhousesonline.com.au)*

Moreover, as the glass is a border between the space inside the greenhouse construction and the external atmosphere, heat from the inside is prevented from escaping directly to the outside via convection. The warm air is hence trapped inside the greenhouse and since the sun’s radiation continues to stream into the greenhouse, the indoor temperature continues to rise gradually.

A greenhouse residence benefits from the glass presence in an analogous way with respect to the heat gains from the sun; the building absorbs the solar energy entering the glass structure and when this energy is released back, it is eventually trapped within the greenhouse zone. In addition to that, without the greenhouse enclosure there would be severe losses of heat generated inside the dwelling towards the cooler external air. Instead, as explained above, the greenhouse captures the heat that leaves the dwelling by not allowing it to escape via the mechanisms of radiation and natural convection.

Heat can be transferred through the glass via conduction, in which case the heat transfer is proportional to the temperature difference and to the material's thermal conductivity. Therefore, by using materials with a low conductivity (or overall U-value) heat losses through conduction can be minimised.

### 2.5.3 Examples of the building-within-a-greenhouse concept

#### *2.5.3.1 The Netherlands*

In recent years there has been increased interest in greenhouse architecture in buildings in the Netherlands which applies sustainable design principles. As a result, good examples of innovative design have emerged in several locations across the country.

##### *2.5.3.1.1 Greenhouse residences | Culemborg*

| **Project/Building name:** | **Kaswoningen** |
|---|---|
| **Construction year:** | 2002 (first series), 2005 (second series) |
| **Location:** | Culemborg, The Netherlands |
| **Client:** | Aeres Group |
| **Architects:** | KWSA studio |
| **Size:** | 500-900 $m^2$ (each greenhouse) |

Figure 21: Greenhouse residence in Culemborg (kwsa.nl)

The architectural firm KWSA is behind the design of one of Netherlands' largest greenhouse residence developments in the Dutch town of Culemborg. In line with the area's eco-friendly character, the architects proposed an innovative, yet sustainable way of living in urban environments (Van Velzen, 2010). Two series of six greenhouse residences have been built so far; one in 2002 and the other in 2005 (Filique and Nijenmanting, 2010). The greenhouses cover completely the buildings of the first series, while in the second one, the houses have adjacent greenhouse parts (Van Velzen, 2010). Besides their advantages in energy consumption, these dwellings promoted as well a more active participation of the inhabitants during the design process which is reflected in the buildings' diversity in space planning (Filique and Nijenmanting, 2010).

The floor area of the houses ranges from 500 $m^2$ to almost 900 $m^2$ and some units even feature a separate office space (Filique and Nijenmanting, 2010). What they all have in common, is a ground level living room that can be integrated with the outdoor garden space through flexible apertures and a first level terrace; both spaces can be used throughout most of the year, thanks to the outer greenhouse structure. This feature not only urges the residents to adjust their behaviour and daily routine to the weather conditions, but also allows for a broader range of materials to be used for the inner construction, since they are not exposed to weather elements (Van Velzen, 2010), (Filique and Nijenmanting, 2010). The greenhouse features a typical structure of glass and aluminium, albeit a little heavier than most greenhouses (Vester, 2015). The main building is made of sand bricks, concrete slabs and wooden beams, and acrylic paint or mineral stucco are used only for finishing purposes (Filique and Nijenmanting, 2010).

Figure 22:Greenhouse residence in Culemborg - view from inside (kwsa.nl)

The greenhouse, which acts as a buffer between the outside and the inside, substantially reduces the houses' energy demands. In winter, the temperature inside the greenhouse is constantly higher than the outside, whereas in summer the temperature is roughly the same (Van Velzen, 2010). Ventilation is controlled both automatically and manually, thus allowing for an optimal temperature regulation according to the weather conditions and the users' needs. Overheating is prevented by both sun shadings and large windows on the top that can be regulated even when the residents are away (Filique and Nijenmanting, 2010). PV panels and solar collectors were installed in the first series of dwellings to provide heat and hot water, whereas the second series houses featured high efficiency solar-gas combination heaters and a heat pump boiler for hot water (Van Velzen, 2010). Finally, water consumption is regulated through efficient toilets (Filique and Nijenmanting, 2010), and waste water is carefully categorized in black, grey and rain water in order to be effectively processed by the district's natural purification systems. Sewage systems and water filtering and drainage areas ensure that the area's ground water is protected against pollution (Filique and Nijenmanting, 2010).

#### 2.5.3.1.2 The SHIBB House | Rotterdam

| **Project/Building name:** | **CHIBB (Concept House Institute of Building and Business)** |
|---|---|
| **Construction year:** | 2014 |
| **Location:** | Rotterdam, The Netherlands |
| **Project leader:** | Arjan Karssenberg |
| **Size:** | 300 $m^2$ |

Figure 23: View of the CHIBB House (Laylin, 2016)

The CHIBB House is located close to Rotterdam's city centre and it follows the outline of Concept House Village, a local initiative that focuses on sustainable building practices through innovative housing concepts. Designed by students from the Sustainable Building Technology program at the University of Rotterdam, this experimental prototype house sets out to explore the limits of sustainable living (Williams, 2016). CHIBB not only offers its users the opportunity to grow their own food, but also provides solutions for cost and energy effective heating and cooling (Foster, 2016). The family of four that was selected to inhabit it for a testing period of three years, until 2018, lives off-grid in this oversized greenhouse that is sustainable in every aspect; from energy usage and water management to its commitment to the Cradle to Cradle concept, an approach to resource management wherein nothing goes to waste (Concepthousevillage.nl, 2016), (Laylin, 2016).

The house features three bedrooms and one home office, with an area of 120 and 45 square meters, respectively. Moreover, the roof is covered by a 135-square-meter vegetable garden that supplies the inhabitants with all the necessary vegetables. Public spaces, such as the living room and the kitchen, are located on the ground floor and are linked through a covered terrace. The first-floor bathroom and bedrooms all have access to a covered courtyard. The house has a timber frame structure, covered by large glazed areas that allow ample natural light to penetrate into the building. The glazed areas are partially clad with vegetation, mainly on the outside, forming a vertical garden that further reduces the amount of excessive heat entering the building (Foster, 2016).

*Figure 24: Occupant in CHIBB House inside the greenhouse area (Laylin, 2016)*

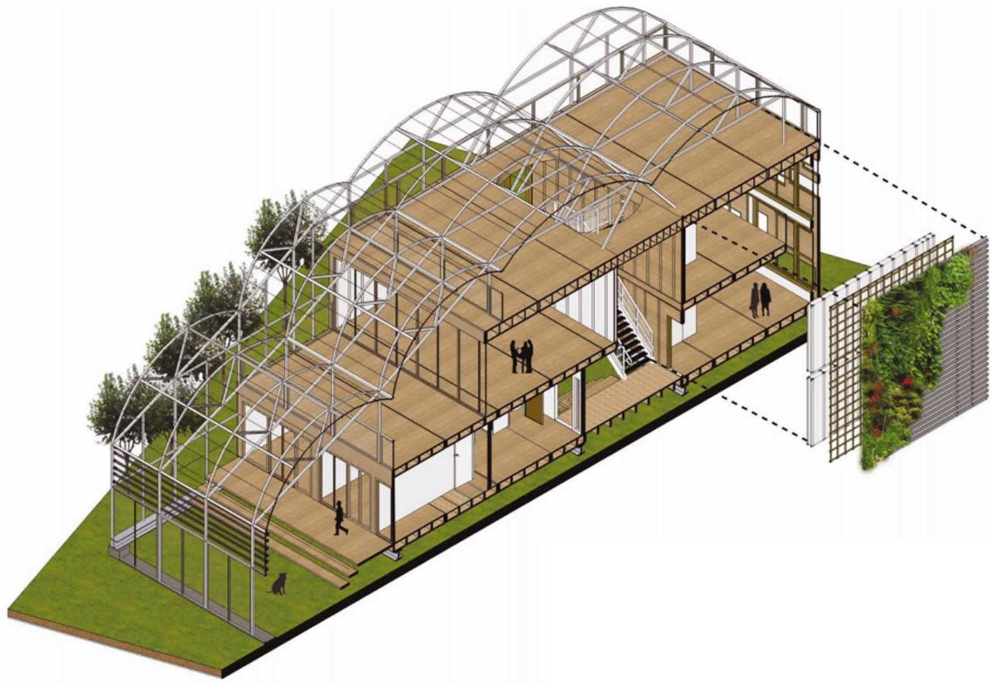


*Figure 25: CHIBB House design (Concepthousevillage.nl, 2016)*

The interior walls are coated with loam stucco to a depth of 45 millimetres. This heat-absorbing material prevents overheating during cooling seasons and releases the accumulated heat in the evening, when the temperature is relatively lower. Besides, the only way for the residents to manually adjust the house's temperature is by opening or closing the windows. The windows on the roof in particular, can also be tilted towards the sun in order to satisfy the greenhouse's increased needs for heat (Foster, 2016). The design team also placed pipes underneath the house to provide ambient air for the dwelling while taking advantage of the earth's steady thermal properties; the earth cools the air during cooling seasons and heats it up during heating seasons (Laylin, 2016). Moreover, there are six water tanks on the roof that collect and store rainwater to be later used to hydrate the crops and flush the toilets. The house features no solar panels and relies on a solar-heated pipe system for hot water. A pallet stove is also installed in case the demand for hot water outweighs the supply (Laylin, 2016).

In general, the CHIBB house aims to minimize transmission losses and achieve optimal ventilation by efficiently using materials that can be used for biomass, reused or recycled. It is an altogether sustainable house, able to provide both thermal and acoustic comfort (Concepthousevillage.nl, 2016).

###### *2.5.3.1.3 CAH Dronten | Dronten*

| **Project/Building name:** | **CAH Dronten** |
|---|---|
| **Construction year:** | (May) 2012 |
| **Location:** | Dronten, The Netherlands |
| **Client:** | Aeres Group |
| **Architects:** | BDG Architects Zwolle |
| **Size:** | 8,450 $m^2$ |
| **Construction costs:** | € 8,650,000 |

Source: (CAH Dronten, 2012)

Figure 26: View of the CAH Dronten campus (ArchDaily, 2012)

The Christelijke Agrarische Hogeschool (CAH) Dronten is a school for advanced education that focuses on agricultural studies. What is unique about it, is that the entire school is enclosed within a massive glasshouse (ArchDaily, 2012). The result is a new type of greenhouse wherein, besides vegetation, people can thrive too. The qualities of this school though are not limited only to its architectural concept; committed to their sustainable approach in buildings, the architects have produced a design with emphasis on reduced energy consumption and systematic exploitation of sunlight, rainwater and air flow (Publishers, 2012).

The external structure, which rises at a height of 16 meters, consists of steel trusses and large glass panels (Cargocollective.com, 2016). On the inside, there are two timber clad volumes wherein all classrooms and offices are enclosed (Publishers, 2012). Besides ground level, the two buildings are linked via a first floor inner plaza and a narrow bridge on the second floor (ArchDaily, 2012). Each building has its own wooden staircase that leads to the first floor, located at the opposite long sides of the glasshouse. The inner plaza, the wide steps of the staircases and the bridge, are all spaces that encourage a more informal interaction between students and teaching staff (ArchDaily, 2012).

*Figure 27: CAH Dronten –space between the building and the glass cover (Vosjan, 2016)*

The gap between the two volumes and the glasshouse serves as a natural air duct that improves the quality of indoor air. Although the 'greenhouse' features a smart climate system that regulates ventilation through spaces, the existence of vegetation at parts of the façade allows for an even greater flow of fresh air. Additional passive cooling techniques, such as solar blinds and printed glass panels, are applied in order to reduce the risk of overheating during cooling periods and thus minimize the building's energy demands. Finally, due to the often rainfalls of the region, the building has also a system that collects and reuses rainwater for diverse tasks, from flushing the toilets to cleaning the entire structure (ArchDaily, 2012), (Publishers, 2012).

#### *2.5.3.1.4 Pyjama Garden | Veldhoven*

| **Project/Building name:** | **Pyjama Garden** |
|---|---|
| **Construction year:** | 2001-2003 |
| **Location:** | Veldhoven, The Netherlands |
| **Client:** | Maxima Medical Centre |
| **Architects:** | MVRDV |
| **Program:** | 1,500 $m^2$, visitors centre |
| **Construction costs/Budget:** | € 1,900,000 |

*Figure 28: View of the Pyjama Garden Medical Centre (Mvrdv.nl)*

In the early 2000's the Dutch architecture studio MVRDV designed a proposal for the public spaces of Maxima Medical Centre, namely a conference centre, a restaurant and a library. In an effort to avoid creating enclosed spaces, which are typical of hospital architecture, they placed the four buildings in the middle of the existing campus and covered them with a giant glasshouse. The proposed design serves as a roofed garden, a greenhouse essentially, that contrasts with the introverted and sterile environment of a classic medical centre (Mvrdv.nl).

The outer structure consists of steel trusses and modular glass panels. The various functions are housed in separate small white buildings, scattered within the glasshouse. Some of them are equipped with their own staircase that leads to the roof, where people can read or relax (Mvrdv.nl). Weather permitting, the greenhouse can be connected with its surroundings; the construction of the glasshouse allows for the doors to be completely opened, forming a large atrium that is accessible to both visitors and patients (Vester, 2015).

*Figure 29: The Pyjama Garden Medical Centre - open areas under the glass shell (Mvrdv.nl)*

The Pyjama Garden is a space with abundant natural sunlight, teeming with trees and local flora that contribute to the improvement of indoor air quality (Mvrdv.nl). In cooling periods however, great amounts of sunlight are not welcomed since they increase the building's energy demands. For this reason, the glass panels are clad with special materials in order to prevent excessive sunlight to penetrate into the greenhouse (Vester, 2015).

### *2.5.3.2 France*

#### *2.5.3.2.1 La Maison Latapie (Latapie House) | Floirac*

| **Project/Building name:** | **Maison Latapie, Floirac** |
|---|---|
| **Location:** | Floirac, France |
| **Design years:** | Completion 1993 |
| **Client:** | Private |
| **Architects:** | Anne Lacaton & Jean-Philippe Vassal<br>With Sylvain Menaud collaborator |
| **Engineering:** | CESMA (metal structure),<br>Ingérop Sud Ouest (foundation) |
| **Area:** | 185 $m^2$ |
| **Cost:** | 55,275 € net |

Built in 1993 by the French architect couple Anne Lacaton and Jean-Philippe Vassal, Maison Latapie is one of the earliest examples of greenhouse residences. Located on an ordinary street in Floirac, a suburb of Bordeaux, this economical house and was a result of a commission to provide, on a low budget, a residence for a family consisting of a couple and their two children (Lacaton and Vassal, 2009).

*Figure 30: La Maison Latapie - view from the garden side (Lacatonvassal.com)*

*Figure 31: La Maison Latapie - view of the garden from the inside (Lacatonvassal.com)*

It is a simple volume on a rectangular base with two open platforms. On a metal structure, one half, on the street side, is covered with opaque fiber-cement sheeting. The other half, on the garden side, is covered with a transparent polycarbonate coat, forming a greenhouse. A two-level wooden volume behind the opaque sheeting makes up an insulated winter area which opens onto the conservatory and the street. Facing east, the greenhouse gains the morning sunshine. It is an inhabitable area which also features a number of ventilation panels to ensure comfort during summer (Lacatonvassal.com).

The moveable nature of the east and west façades, with opening and folding doors, allows the house to adjust between a very open and very closed configuration, based on the occupants' requirements for light, privacy, protection and ventilation (Figure 32).

Consequently, the size of inhabitable areas in the Latapie House can vary during seasons. The smallest version includes the living room and the bedrooms, whereas by integrating the whole garden in summer significantly extends the home's living areas (Lacatonvassal.com).

Figure 32: La Maison Latapie – view from the street – different opening configurations (Lacatonvassal.com)

#### 2.5.3.3 Sweden

Sweden has also a number of interesting greenhouse residence examples to demonstrate. The inspiration came from a pioneering Swedish eco-architect through his "Naturhus" building concept.

##### 2.5.3.3.1 Naturhus (Nature House) | Stockholm

Sweden's Naturhus, a house-within-a-greenhouse concept, was introduced by the late Bengt Warne in the 1970s, who gave the following personal description for "Naturehousing" (Bengtwarne.malwa.nu):

> "Living in a greenhouse gives architecture a fourth dimension, where time is represented by movements of naturally recycled endless flows of growth, sun, rain, wind and soil in plants, energy, air, water and earth."

Figure 33: Bengt Warne's Naturhus (Bengtwarne.malwa.nu)

In practice, a Naturhus (Natural House) consists of a normal abode of a modest size, which is entirely surrounded by a shell of glass – a greenhouse – that functions as an outer barrier and allows for the growing of plants that wouldn't normally survive in cold climates or year-round (Hickman, 2010).

The first Naturhus was developed in Saltsjöbaden, Stockholm, in 1974-76 (Bengtwarne.malwa.nu). It was initially built as a home for Bengt and his family but until 1981, it also served as a research, development and demonstration hub. The house was then sold and is presently used as a family residence.

The core, a living area, is completely enclosed in a greenhouse. The main principle underpinning its operation is to "return to nature what is taken from it"; the house exploits nature's own flows and elements, such as earth, air, water and fire. The Naturhus naturally collects the heat from the sun to warm the air around the core house and the residual heat from the greenhouse is stored in a bedrock under the house, keeping in warm in the evening. It also features a high efficiency stove to maintain the desirable warmth indoors in times of extreme cold.

*Figure 34: Interior zone of the Nature House (Bengtwarne.malwa.nu)*

Warne's Naturhus concept has garnered following in his native Sweden; several Nature Houses of various designs have been built so far, some of which are presented below.

### *2.5.3.3.2 Family house (Naturhus) | Stockholm*

| **Building name:** | **Family House (Naturhus)** |
|---|---|
| **Location:** | Outside Stockholm, Sweden |
| **Construction year:** | Around 2000 |
| **Client:** | Private |
| **Architects:** | Bengt Warne |
| **Area:** | 185 $m^2$ |
| **Cost:** | € 80,000 (the glass structure) |

Figure 35: Family house (Naturhus) in Stockholm (Mok, 2015)

Inspired by Bengt Warne, another Swedish family decided to transform their home into a greenhouse and lead a sustainable, self-sufficient life. The Nature House is located on an area of summer houses, just outside Stockholm, where winter can make it unbearable to live unless the house features an excellent heating system (Kirsten Dirksen, 2015). Unable to find a plot to build a new house, the Swedish couple covered an existing small tea house with a 4mm security glass structure that enabled them to enjoy a comfortable climate all year round. Using only what nature gives, the family now grows its own fruit and vegetables, and has even managed to substantially reduce its energy demands and shorten the heating period.

The core house is a two level building, which was enlarged after the greenhouse was installed. Since the glass envelope protects from rain and wind, the maintenance of the materials used in the external walls becomes a lot easier and on top of that there is no need for much insulation. The two bedrooms are located on the top floor and the master bedroom has its own balcony. Instead of a roof, there is a terrace next to the living spaces, which provides a very pleasant environment especially in spring and autumn. On top of the terrace, there is a large opening that is controlled automatically depending on the temperature inside the greenhouse, ensuring that heat is driven away during the hottest parts of the year.

*Figure 36: Exposed spaces within the greenhouse - Family house (Naturhus) in Stockholm (Mok, 2015)*

The Nature House is highly dependent on sun, so in cloudy days there is no difference between outside and inside temperature. For this reason, the family also uses wood to keep it warm inside the house in winter. A large underground tank is installed for collecting rainwater, which is later used to water the plants, and another one can be found outside in the garden which is used to compost food waste. Besides energy and water, the family has its own sewage system as well. Specially designed toilets with two compartments for dividing urine from feces lead to a sewage system in the cellar. Without applying any chemicals during the 3-step cleaning process, all waste is carefully separated, processed and reused, mostly for irrigation and fertilizing purposes. A similar system takes care of the rest of the water that comes from the dishwasher or the shower. It is a self-built, sophisticated system that uses centrifugal force, a network of tanks and cisterns, grow beds and garden ponds to filter the water and compost the remains.

##### *2.5.3.3.3 Family house | Sikhall*

| **Building name:** | **Family residence** |
|---|---|
| **Construction year:** | 1998 (core house) |
| **Location:** | Sikhall Dalsland County, Sweden |
| **Client:** | Private |
| **Architects:** | Owners in collaboration with Bengt Warne |
| **Size:** | 300 $m^2$ (greenhouse), 150 $m^2$ (core house) |

Figure 37: View of the Nature House in Sikhall, Sweden (Gjermundrød, 2015)

In 1998, a Norwegian couple built its home in the Sikhall community, on the west coast of the lake Vänern. In compliance with the local traditional architecture, the initial establishment was a 150 $m^2$ timber construction built to house them and their three children (Gjermundrød, 2015). Due to the region's unpredictable weather and harsh winter climate, the family decided to cover their entire house with a large greenhouse a few years later, influenced by the Swedish architect Bengt Warne and his experimental greenhouse residences back in the 1970's. The concept was to build an environmentally friendly house using local materials that would help them lead a self-sufficient life in balance with the area's natural resources. The solution was a greenhouse residence that would provide them with a Mediterranean-like climate, significantly reducing the energy demands.

Figure 38: View of the Nature House in Sikhall, Sweden

The 300 $m^2$ greenhouse offers protection against wind, rain and snow, thus prolonging the life of materials used in the construction of the core house. Heat is stored in the core house during sunny days, but there are also some additional solar collectors to cover the family's energy needs. Besides solar heating, the house also uses fuelwood and features two brick ovens that provides the family with hot water even in cloudy days. The temperature inside the greenhouse is regulated by large automatic windows in the roof that let warm air escape, while a pipe in the ground is responsible for supplying the dwelling with fresh, cool air.

The family grows a broad range of fruit, vegetables and plants, so water management was a priority when designing the greenhouse. In the basement there is a water purification system that processes sewage waste water so it can be reused for irrigation purposes. The plants, in turn, not only provide food almost year round, but also help maintain low levels of humidity and clean the indoor air.

#### 2.5.3.4 Norway

##### 2.5.3.4.1 The Nature House| North Norway

| | |
|---|---|
| **Project/Building name:** | **The Nature House** |
| **Location:** | Sandhornøya island, Arctic Circle, North Norway |
| **Construction year:** | 2013 |
| **Client:** | Benjamin & Ingrid Hjertefolger |
| **Construction company:** | Solardome Industries Ltd |
| **Size:** | Diameter – 15m<br>Height – 7.5m<br>Volume – 919$m^3$<br>Floor area – 177$m^2$ |
| **Dome specification:** | Able to withstand over 4KN/$m^2$ of snow loading and wind speeds exceeding 31m/s<br>6mm single-glazed toughened glass, double doors, 11 windows, 5 of which are digitally controlled, and a large aperture linking the internal house to the outside area<br>Exterior metal components polyester powder coated white |

*Figure 39: The Nature House residence in Norway (Solardome Industries)*

Passionate supporters of sustainability and permaculture, the Norwegian couple wanted to build a house that would reflect these values, even under the harsh conditions of the Arctic Circle (Laylin, 2016). Much like in a glasshouse, the living space and part of the garden are enclosed within a massive glass structure; the robust geodesic dome they used in their project not only provides shelter from low temperatures, high winds, severe snow loadings and ultraviolet radiation, but also features a negligible environmental footprint through efficient energy exploitation and usage, and requires little maintenance. Last but not least, it allows plants, vegetables and fruits to grow all year, despite the site's northerly latitude (Solardome Industries), (Laylin, 2016).

During the first construction phase the dome was erected on site in less than a month. Apart from the ease and speed of construction it offers, the dome is capable of covering wide areas with substantially less building materials compared to conventional rectangular structures (Solardome Industries). Measuring 15m in diameter and 7.5m in height, it covers a floor area of 177m$^2$. This six-frequency geodesic dome consists of 360 single-glazed toughened glass panels, 6mm in thickness, and over 800 meters of recycled aluminum framework. Stainless steel was used in the fittings and a white coating of polyester powder was applied to the exterior metal components. The dome features a set of double doorways, a large aperture that links the internal spaces with the outdoor deck and eleven windows, five of which are digitally operated (Solardome Industries), (Design Build Network, 2016).

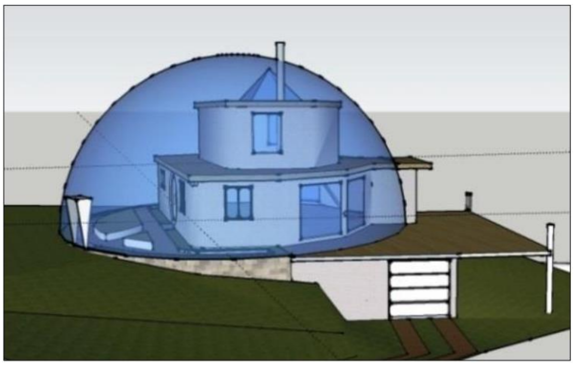


Figure 40: Modelling of the Nature House, Norway (Solardome Industries)

Upon completion of the dome, the house was built within; it is a 200m$^2$ three-level house with an 80m$^2$ adjacent garden and a 100m$^2$ rooftop garden (Design Build Network, 2016). For the needs of the erection and decoration of the house, the couple used only traditional building techniques and recycled materials (Solardome Industries); the second floor walls consist of stacked straw bales finished with clay plaster, the first floor walls are made of cob, namely clay, sand and straw, and finally the basement features lightweight bricks of extruded clay (Laylin, 2016). Since it was built to house a large family, the house has five bedrooms, two bathrooms, a kitchen, a dining room, a lounge and a garage (Solardome Industries).

Figure 41: View of the sky through the transparent glass cover - The Nature House, Norway (Solardome Industries)

Solar panels, supplemented by a wood burning stove, provide warmth and heat the water tank that is installed for non-drinking usage and underfloor heating (Design Build Network, 2016). The electronic windows ensure that the house is naturally ventilated, while at the same time they help maintain a uniform temperature throughout the year. In the basement, the couple has placed a water filtering system as a constant source of fresh water, which is later recycled or reused in the gardens (Solardome Industries). Besides food and a pleasant visual experience, the plants that grow within the dome provide sound absorption and natural insulation. Finally, a network of buried pipes that takes advantage of the Earth's constant temperature brings fresh air from the nearby beach; warm air during heating periods and cool air during cooling periods (Laylin, 2016).

According to its users, the house has drastically reduced its heating requirements and energy consumption, which is reflected in their heating bills (Solardome Industries).

#### *2.5.3.5 Japan*

##### *2.5.3.5.1 Millennium City |Chiba*

| | |
|---|---|
| **Project name:** | **Kurimoto Millennium City I** |
| **Location:** | Katori-shi, Chiba, Japan |
| **Design Team:** | Hiroshi Iguchi + Fifth World Architects |
| **Site area:** | 1,652.33 $m^2$ |
| **Total floor area:** | 583.68 $m^2$ (A-D Building: 138.24 $m^2$, E Building 30.72 $m^2$) |
| **Construction cost:** | $ 470,000 |

(Source: Fifthworld-inc.com)

*Figure 42: Millenium City (Bijlsma, 2009)*

Japanese architect, Hiroshi Iguchi, has long been striving to address Japan's housing problem as well as the socially isolating and environmentally harmful housing stock of the country's big cities (Jewell, 2013). One of his proposals, Millennium City, is an experimental eco-friendly commune which aims not only to achieve a balanced and mutually beneficial coexistence between humans and nature (Jewell, 2013), but also to challenge the idea that people who live in densely populated areas have to make compromises in their private space (Tan, 2013). The commune is located at on open farmland in the region of Chiba and consists of four separate greenhouses (Figure 42). The relatively low cost of this endeavor is explained by the fact that there was a great deal of volunteers involved in the project and that many materials, furniture and even the farmland itself, were either gifted or donated (Bijlsma, 2009). Each greenhouse encases a small number of two-storey wooden cabins which are used as living quarters (Figure 43). Their ground floor is essentially an open platform, slightly above the earthen floor of the greenhouses. Wooden ladders lead to the enclosed spaces on the second floor which is elevated on wooden stilts (Jewell, 2013), (Bijlsma, 2009). The architect's intention was to give residents sufficient freedom and flexibility on how to use the cabins, so the living spaces were not designated for specific use (Jewell, 2013). For practical reasons however, the tenants have to share some facilities and recreational spaces; one of the greenhouses is equipped with a communal kitchen, while the toilet and bathing facilities are located in a separate pavilion (Tan, 2013).

*Figure 43: Millennium City - wooden cabins in greenhouse (Fifthworld-inc.com)*

Figure 44: Millennium City - occupant relaxing in a pavilion inside the greenhouse (Fifthworld-inc.com)

Millennium City does not feature sophisticated instruments and technologies in order to improve its energy performance; it rather relies on minimizing the total area of spaces that require heating and on adjusting people's daily routing according to weather and natural light conditions (Bijlsma, 2009). Although the greenhouses are supplied with electricity, solar panels are also used to generate sufficient power for lighting and heating purposes (Jewell, 2013). Moreover, plastic bottlers are used as additional solar panels to provide residents with hot water. Outside the greenhouses there are carefully planted trees to protect the living spaces from hot, sunny days and mitigate interior temperatures (Tan, 2013).

The project's commitment to environmental conservation and sustainability is also evident in the structures themselves; the cabins' materials can be either reused or recycled and the entire commune can be easily dismantled and relocated without any environmental implications (Bijlsma, 2009).

#### 2.5.3.6 Germany

##### 2.5.3.6.1 Residence in Knoblauchsland | Nuremberg

| | |
|---|---|
| **Building name:** | **Residence in Knoblauchsland** |
| **Location:** | Nuremberg, Germany |
| **Architecture:** | Niederwöhrmeier + Kief |

*Figure 45: View of the greenhouse residence in Knoblauchsland (Niederwöhrmeier + Kief Freie Architekten BDA und Stadtplaner)*

At the edge of the Franconian village, a new open house was developed based on the idea of a typical greenhouse. The number of floors and the roof slope meet the requirements of the authorities. An upstream climate simulation was used to optimize the energy concept and the dimensioning of the whole structure.

*Figure 46: Views of the greenhouse residence in Knoblauchsland (Niederwöhrmeier + Kief Freie Architekten BDA und Stadtplaner)*

On the first floor and the eaves there are automated ventilation flaps at full length. Shading is provided internally in the roof slopes by means of textile sun protection and on the vertical inner walls via metal slats. Fresh air is directly supplied to the living rooms and bedrooms from the each of the gable sides, through specially developed widow constructions. A large glass-covered garden is also formed in the rooftop (Niederwöhrmeier + Kief Freie Architekten BDA und Stadtplaner).

*Figure 47: Gable with specially developed window constructions (Niederwöhrmeier + Kief Freie Architekten BDA und Stadtplaner)*

### 2.5.3.6.2 Mont-Cenis Academy | Herne

| **Project/Building name:** | **Energy Park Mont-Cenis** |
|---|---|
| **Location:** | Herne, Germany |
| **Client:** | EMC GmbH, Land NRW, Stadt Herne, IBA Emscher Park GmbH, Stadtwerke Herne AG |
| **Architecture:** | HHS Planer + Architekten AG in Partnerschaft mit Jourda & Perraudin Architectes, Frankreich, Lyon |
| **Building facility design:** | ARUP, London, HL Technik AG, Frankfurt am Main |
| **Landscape architecture:** | Desvigne & Dalnoky, Frankreich, Versailles Latz, Riehl und Schulz, Kassel |
| **Gross floor area / volume:** | 12,100 $m^2$ / 37,000 $m^3$ |
| **Construction cost:** | € 23,000,000 |

Figure 48: View of the Academy Mont-Cenis building in Herne (Academy Mont-Cenis Herne)

The Education Academy in Herne, initiated in 1990 as part of the international architectural exhibition “IBA Emscher Park”, is found on the 25-hectare site of the former “Mont Cenis” pit which was demolished in 1978 (Werkstatt-stadt.de, 2003). It now makes up both a public space housing urban development (Academy Mont-Cenis Herne) and an impressive example of integrating sustainable energy patterns into buildings (Education Academy Mont-Cenis). The structure consists of two main parts: the outer glass shell and the houses inside it (Academy Mont-Cenis Herne).

Figure 49: Solar panels on the roof of Mont Cenis Academy (Education Academy Mont-Cenis)

The external shell is made up of more than 20,000 $m^2$ of single glazing (Education Academy Mont-Cenis), the loadbearing structure of which is roughly planed spruce timber and timber framing jambs and girders (Werkstatt-stadt.de, 2003). Nearly half of the glass area is covered with solar modules with a total annual yield of 750.000 kWh, a part of which is used to cover the park’s energy demands and the rest - approximately 550.000 kWh - can be exported back to the grid (Werkstatt-stadt.de, 2003).

The modules density varies, providing both optimal the lighting and shading in the internal areas and inside the buildings (Education Academy Mont-Cenis), (Academy Mont-Cenis Herne). Moreover, the windows of the buildings inside the shell feature light reflectors that further increase the daylight supply (Education Academy Mont-Cenis).

An all-year-round Mediterranean climate is created within the shell, the so-called "micro-climatic envelope" (Academy Mont-Cenis Herne) (Werkstatt-stadt.de, 2003). Summer overheating is avoided through openings on the roof and façade elements (Figure 50). There are also seven ground channels that brings air from the outside. During cold periods, a ventilation system with heat recovery is used, the air of which is extra heated through the ground channels (Education Academy Mont-Cenis).

*Figure 50: Natural Ventilation in Mont Cenis Academy (Kuok Hong, Hoi Kiu and Jin Sol, 2013)*

On top of the mild climate created under the glass envelope, the interior space is weather-sheltered which means that all buildings under the glass can be constructed as interior rooms – as simple as steel or wood frame structures (Academy Mont-Cenis Herne) (Werkstatt-stadt.de, 2003). The buildings require reduced floor area, because the open space underneath the shell serves as a circulation area (Academy Mont-Cenis Herne).

Figure 51: Indoor spaces in Mont Cenis Academy (Academy Mont-Cenis Herne)

## 2.6 Future Projects

### 2.6.1 Regen Villages

| | |
|---|---|
| **Project/Building name:** | **ReGen Villages** |
| **Construction year:** | 2016 |
| **Location:** | Aalmeer, The Netherlands |
| **Client:** | ReGen Villages Holding B.V. |
| **Design Team:** | EFFEKT studio |
| **Program:** | 15,500 $m^2$ |
| **Construction costs/Budget:** | - |

*Figure 52: Regen Villages (EFFEKT, 2016).*

ReGen Villages is a pioneering approach to the development of self-sustaining, off-grid communities, which consist of houses that are able to provide clean energy, water and food for a number of self-sufficient families on a daily basis (Dezeen, 2016). The project was initiated as an alternative method to real-estate development, in an attempt to address major contemporary issues, such as increased $CO_2$ emissions, growing population, mass urbanisation, augmented land prices and scarcity of food and other resources (EFFEKT, 2016). Besides greenhouse properties, this eco-village incorporates various existing technologies in its design; from energy positive houses and energy storage to waste-to-resource systems and vertical farming aquaponics. The result is the emergence of a local eco-system where people are tightly connected with nature, keeping sustainable balance between production and consumption (Dezeen, 2016). The first

*Figure 53: Dwelling in ReGen Villages (EFFECT, 2016)*

integrated villages are scheduled to be completed by 2016 and feedback will be gathered constantly so as to improve their performance (EFFEKT, 2016).

The houses of each village are arranged in a circle and enclosed in a glass envelope (Figure 54). The units feature various typologies and sizes, ranging from 80 to 140 square meters for the living spaces (Figure 55). The space for the greenhouse is no more than $25m^2$, whereas the terrace rarely exceeds $40m^2$ (EFFEKT, 2016).

*Figure 54: ReGen Village configuration (EFFECT, 2016)*


*Figure 55: Housing typologies is ReGen Villages (EFFECT, 2016)*

There is enough space for families to grow their vegetables in seasonal gardens or aquaponics systems, and even recycle their waste products. The houses also have built-in solar panels and a water collection system that are sufficient to cover the daily needs of a family. Passive heating and cooling systems as well as natural ventilation are additional key factors that minimize energy consumption and extend the summer season, thus ensuring year round yield (Dezeen, 2016).

Another interesting attribute of ReGen Villages is their well-thought-out waste management. Household waste is sorted into different categories so it can be re-used for multiple purposes. Bio-waste that is not compostable is used in the biogas facility, while compost becomes food for soldier-flies and livestock. The soldier-flies are fed to the fish, and waste from livestock is used to fertilise the seasonal gardens. Finally, the waste from the fish becomes fertilizer for the plants (EFFEKT, 2016).

Besides the housing units, and closer to the community's center, each village has some supplementary food production facilities which are encased in a glasshouse, too. The village's infrastructure consists of eight interconnected public squares that can be also used as electric car charging hubs. In total, ReGen Villages are supposed to create ample space for permaculture and biodiversity by minimizing the footprint of food production and the housing units (EFFEKT, 2016).

### 2.6.2 Flowerbed Hotel |Aalsmeer, The Netherlands

| **Project/Building name:** | **Flowerbed Hotel** |
|---|---|
| **Construction year:** | 2011 |
| **Location:** | Alsmeer, The Netherlands |
| **Client:** | Kloss 2 |
| **Design Team:** | MRDV |
| **Program:** | 19,000 $m^2$ hotel and conference centre |
| **Construction costs/Budget:** | Undisclosed |


*Figure 56: Design of the Flowerbed Hotel (Mvrdv.nl)*

A 19.5000$m^2$ new greenhouse hotel and conference centre, the Flowerbed Hotel, is designed by MVRDV and will be located in the Aalsmeer, Netherlands, next to the future Bloomin' Holland theme park and business centre (Furuto, 2011), (Zimmer, 2011).

The design concept of the project involves a giant glass shell encasement – like a greenhouse – surrounding ta series of structural volumes underneath it. The Flowerbed hotel volume will include 280 floral-themed rooms, 1.600$m^2$ of conference facilities, a 550$m^2$ fitness centre and spa, 2.100 $m^2$ flowerbeds, 1.100$m^2$ services and 140 spaces for parking (Furuto, 2011).


*Figure 57: Structural volumes of the Flowerbed Hotel within the greenhouse encasement (Mvrdv.nl)*

The stacking of volumes amidst the high-ceiling greenhouse envelope offers a diverse and expansive lobby area and also a flower garden accessible to day visitors and hotel guests (Mvrdv.nl).

The roof and terraces will also feature photovoltaic panels to capture solar energy and use it for the needs of the complex. The building will be additionally outfitted with windmills, geothermal hot / cold pump for temperature control, natural ventilation and green walls, leading to an outstanding energy performance despite the glass cover (Mvrdv.nl).

## 2.7 Advantages

Experience over existing greenhouse residences has identified several benefits resulting from the application of this building type. The advantages of the hybridization between a traditional building concept and the use of a greenhouse technique when compared to traditional, uncovered building vary by a number of factors such as building size, location, climate, use, condition, materials etc. By and large, they include the following aspects:

***Usability***

- The glass skin shelters outside areas so they can be used most of the year despite the fact that they are unheated, with a climate protected from rain and wind. (Greenhouseliving.se)
- The extra living area created under the conservatory provides a solution for the very young, the elderly, people with a disability or chronically sick people who would normally be vulnerable if exposed directly to outdoor conditions (cold, wind, rain, etc.).
- The use of glass facilitates the visual and physical connection with the surrounding environment.
- Enhanced flexibility in the type of activities taking place in these locations.

***Indoor Climate***

- A pleasant Mediterranean-like microclimate is created within the shell. (Vester, 2015)
- "Naturally" mitigate cold indoor temperatures that present a significant health risk in the vulnerable groups (elderly, infants, etc.), with respect to causing or exacerbating respiratory, circulatory and other related problems. (Scottish Government, 2002)
- The greenhouse contributes to the climate concept of a building acting as a buffer zone. It captures heat escaping from the dwelling, and at the same time cold ambient air is pre-heated before entering the building volume. (Vester, 2015)
- Fewer temperature fluctuations within the living zones. (Vester, 2015)
- It allows windows and doors to be opened for more frequently and even during cooler seasons, thus allowing for increased ventilation. (Vester, 2015)
- Reduced noise disturbance from outside sources (transport, neighbourhood, industrial, etc.).

***Architectural***

- The greenhouse "brings nature into the home". The buffer between the dwelling volume and the outside results in an interesting architectural area where living and nature merge. (Vester, 2015)

***Technical***

- Increased durability in housing units and the façade due to protection against the weather. (Archdaily, 2012)
- Since the glass shelters the building from wind and rain, it allows for a detailing and materialisation that does not longer need to be water and wind proof. (Vester, 2015) This means that the building can be constructed as simple steel or wood frame structure. (Werkstatt-stadt, 2012)
- Protection and thermal insulation for hard-to-treat buildings.
- Lower heating loads mean reduced size for the heating systems installed.
- Any misgivings relating to circulation, humidity problems, window cleaning, sensitivity to storms etc., can now be dismissed (Hickman, 2010).

***Sustainability***

- A greenhouse residence has overall reduced energy demands and carbon footprint.
- Greenhouse residences can be constructed with simple and more sustainable materials, as they are protected from weather influences.
- It is flexible to integrate solar panels, wind turbines and other forms of renewable energy (Effect, 2016) and also closed-loop water recycling system. (Inhabitat, 2015).
- Facilitates the development of self-reliant residences or neighbourhoods, in terms of energy, food and greywater requirements. (Effect, 2016)

***Cost***

- A greenhouse residence benefits from significant savings in energy bills.

- Reduced heating demands help mitigate the problem of fuel poverty in households and its adverse consequences.
- Since the core building has reduced detailing and material and requirements, as well as lower heating system capacity, that means lower construction and equipment costs for a new dwelling. (Vester, 2015)
- Low maintenance and replacement requirements, both for the core building and the glass shell.

***Greenery***

- Enables growing plant species and greenery that would not normally survive in cold climates.
- Growing season for food production is extended.
- Besides the aesthetical and practical aspect, having greenery provides additional climatological qualities: during summer, in cools warm air by evaporation and they can provide shading from the sun. Note that during winter the absence of leaves allows sun radiation to heat the house. (Vester, 2015)

## 2.8 Disadvantages

Despite the multiple benefits associated with the idea of surrounding a house with a transparent, insulating glass, this concept may involve some risks, particularly if the project location and/or design are inappropriate.

***Comfort***

- The biggest issue associated with greenhouse residences is the risk of summer overheating. (Vester, 2015)
- Risk of condensation on the glass surface.
- Occupants of a greenhouse dwelling would enjoy less a nice day compared to those of a traditional house, as their access/view to the outside will be interrupted by the greenhouse.

***Energy***

- A greenhouse residence can have overall higher energy demands than the respective dwelling without the glass dome, because of higher cooling requirements.

***Cost***

- Installing additional cooling devices is often necessary to ensure acceptable indoor temperatures (Zeiler and Vissers, 2012)

- The operation of mechanical cooling results in increased electricity cost. In a hot (inappropriate for GHR) climate, increased energy cost for cooling may overweigh savings from heating needs.

- Building the glass shell requires a substantial capital cost. It can be very expensive particularly for covering large buildings.

***Dirt***

- The grass cover, especially the horizontal glass, inevitably becomes dirty and requires cleaning, either by cleaning robots or a cleaning company which involve extra cost, or the tenant but that would be a very labour-intensive task.

# 3 Methodology

This Chapter starts by introducing the tool used for creating and simulating the studied building, followed by a description of the assumptions and then the inputs for the simulations. At the end of this section, a validation of the model is made, by comparing its outputs with values from actual residences of the same characteristics.

## 3.1 Simulation program

For the needs of this study, the IES VE software was used.

*Figure 58: The IES VE software*

"Virtual Environment" by Integrated Environmental Solutions (IES VE) is a modern example of dynamic building energy simulation software which allows the design and operation of comfortable and energy efficient buildings. This powerful, in-depth suite of integrated analysis tools (Figure 59), can be used to investigate the performance of a building either retrospectively or in the design stages of the construction of a project. (Iesve.com, 2016)

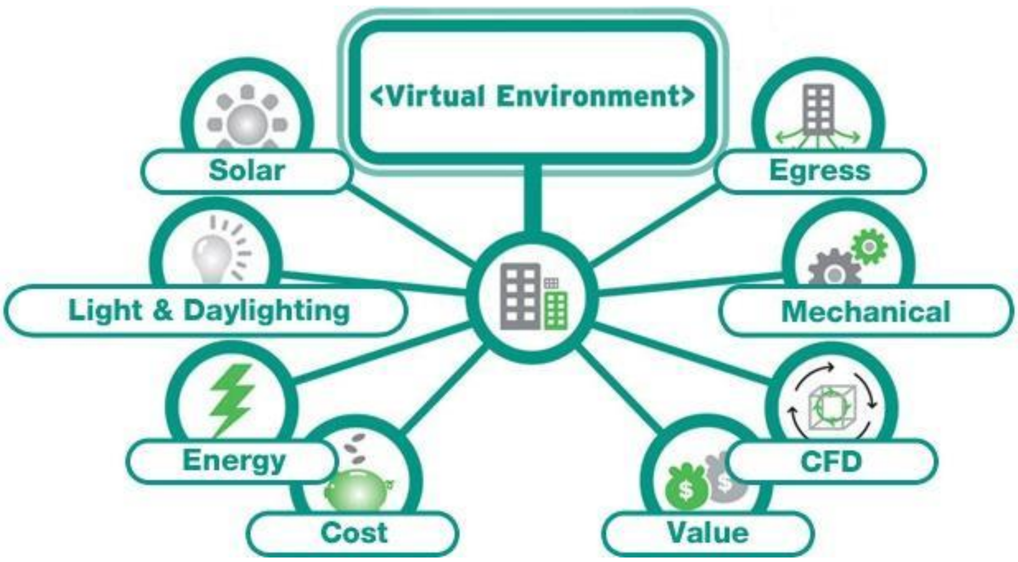



*Figure 59: Modules and analysis tools available in the IES Virtual Environment (Booth, A., 2011)*

IES VE package is formed through a number of modules, and the interaction between the user and the software is done through a common graphical user interface (GUI), on a single integrated data model. The user, therefore, gives the software specific inputs and the results can be displayed graphically, in tables or can be optionally exported to other formats. (Booth, 2011).

For the needs of this project, the modules used were:

- **ModelIT** (geometry creation and editing) – to make the building
- **SunCast** (shading and solar visualisation and analysis) - to run any simulations
- **ApacheSim** (dynamic thermal simulation) – to run the simulations
- **Vista/ VistaPro** (results analysis) – to view the results

A model of a building can be constructed within VE using the ModelIT module. The user can select the orientation and location of the building (among hundreds of locations available across the globe) and thus utilise the relevant real weather data. A key feature of the software is its capability to perform dynamic thermal simulation which provides hour-by-hour results of the air temperature, air flow, and heating loads for each space throughout the year, using the ApacheSim module. Once the simulation has finished, the results are displayed in the Vista module of IES VE, for a single space or a combination of rooms, and variables can also be combined. Hence, users can test different options for building and system designs, compare outcomes and identify best solutions with respect to comfort criteria and energy use.

In this thesis, IES VE was used as key part of the assessment methodology to determine the desirable buildings energy and comfort statistics, as well as to evaluate any energy saving potentials and the microclimate created within the greenhouse shell.

## 3.2 Notes and assumptions

The model creation was based on information about representative characteristics of the dwelling collected through the appropriate relevant literature sources (SHCS, SAP 2012, Building Regulations, etc.). Nonetheless, some standard **assumptions** during the simulations about the make-up and the behaviour of the studied occupying household have been made:

- The total space heating demand was provided by a main heating system. No secondary heaters were assumed.
- Metabolic gains were modelled as the average for all occupants, taking into account their sex and age. In fact, people's heat gains are lower by 15% for female adults and by 25% for children, respectively (Al-Shemmeri, 2011).
- Gains from cooking, water heating, losses, and pumps and fans were neglected.
- Weekly profiles for gains were the same throughout the simulation year.
- In the scenarios where the greenhouse cover was implemented, no heat gains were assumed in the glass-sheltered areas between the external house walls and the glass box.
- Heating set points were constant throughout the year.
- No shading devices have been modelled.
- Construction widths were not modelled; any dimensions mentioned correspond to the internal room/house areas.
- The effect of any physical obstacles (adjacent buildings, trees, etc.) has not been taken into account.
- The external metal components on the greenhouse were modelled only in the edges of the structure.
- When modelling multi-storey constructions, all upper floors were designed as identical to the base floor (reference).
- A flat roof was used to facilitate the modelling of the greenhouse.

The following sections describe the settings and inputs for the reference building configuration. Any changes (materials, location, orientation, size, etc.) that may be applied afterwards for the purposes of each part of the research are analytically described in the relevant sections.

## 3.3 Geometry

### 3.3.1 Core Building

The model house, shown in Figure 60, represents a typical Scottish detached house. It is a single-storey dwelling, consisting of four external walls, 14m in length, 7m in width and 2.5m in height, giving a total rectangular floor area of 98 $m^2$, an external surface of $105m^2$ and a total volume of $245m^3$.

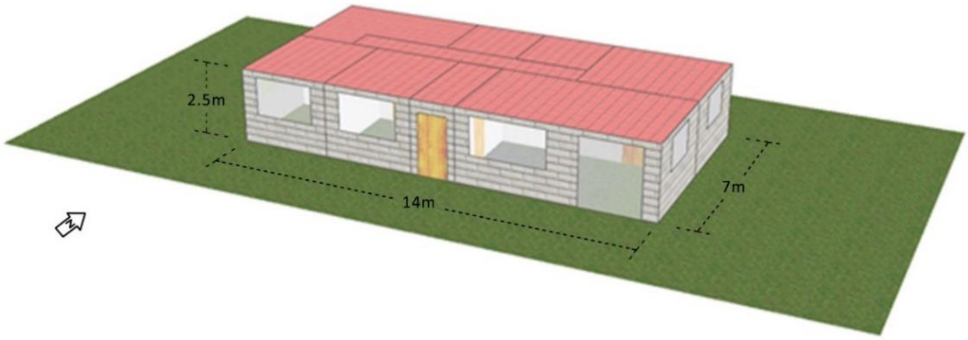



Figure 60: Base case building on IES VE

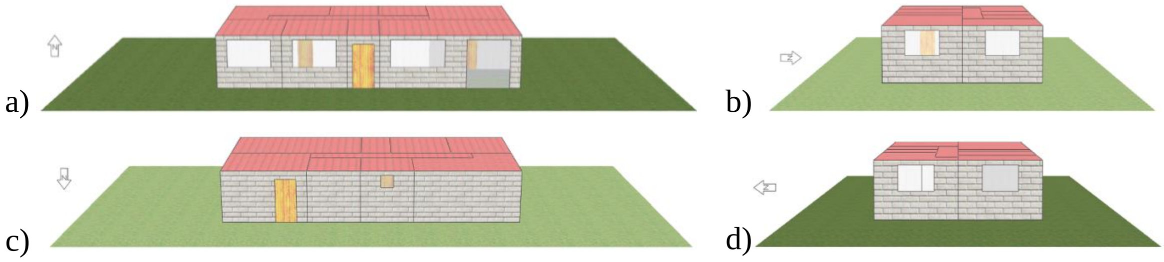



Figure 61: Building facades a) South b) East c) North d) West

The floor area for the case study building represents a typical floor size of a one-storey detached house. Although the average floor areas for detached dwellings indicated by the SHCS (Scottish Government, 2015a) are larger, up to 176m$^2$ for the oldest (pre-1919) ones, these sizes are more likely to correspond to multi-storey buildings.

The model house is divided into nine zones: three bedrooms, a living/dining room, a kitchen, a bathroom, a store/cloakroom and two halls. (Figure 62 - plan).

Table 4: Building rooms characteristics

| Room name | Floor Area ($m^2$) | Volume ($m^3$) | Orientation | Window area ($m^2$) | External surfaces[1] ($m^2$) |
|---|---|---|---|---|---|
| **Hall_1** | 5.25 | 13.125 | S | 0 | 3.75 |
| **Living room** | 22.75 | 56.875 | S/E | 9.5 | 25 |
| **Kitchen** | 14 | 35 | N/E | 1.65 | 18.75 |
| **Store/Cloakroom** | 6.25 | 15.625 | N | 0 | 6.25 |
| **Bathroom** | 6.25 | 15.625 | N | 0.36 | 6.25 |
| **Hall_2** | 8 | 20 | - | 0 | 0 |
| **Bedroom_1** | 14.5 | 36.25 | N/W | 1.65 | 21.25 |
| **Bedroom_2** | 10.5 | 26.25 | S/W | 4.25 | 16.25 |
| **Bedroom_3** | 10.5 | 26.25 | S | 2.6 | 7.5 |
| **Total** | 98 | 245 | - | 20.01 | 105 |

[1] Refers to the gross external surface area, including openings.

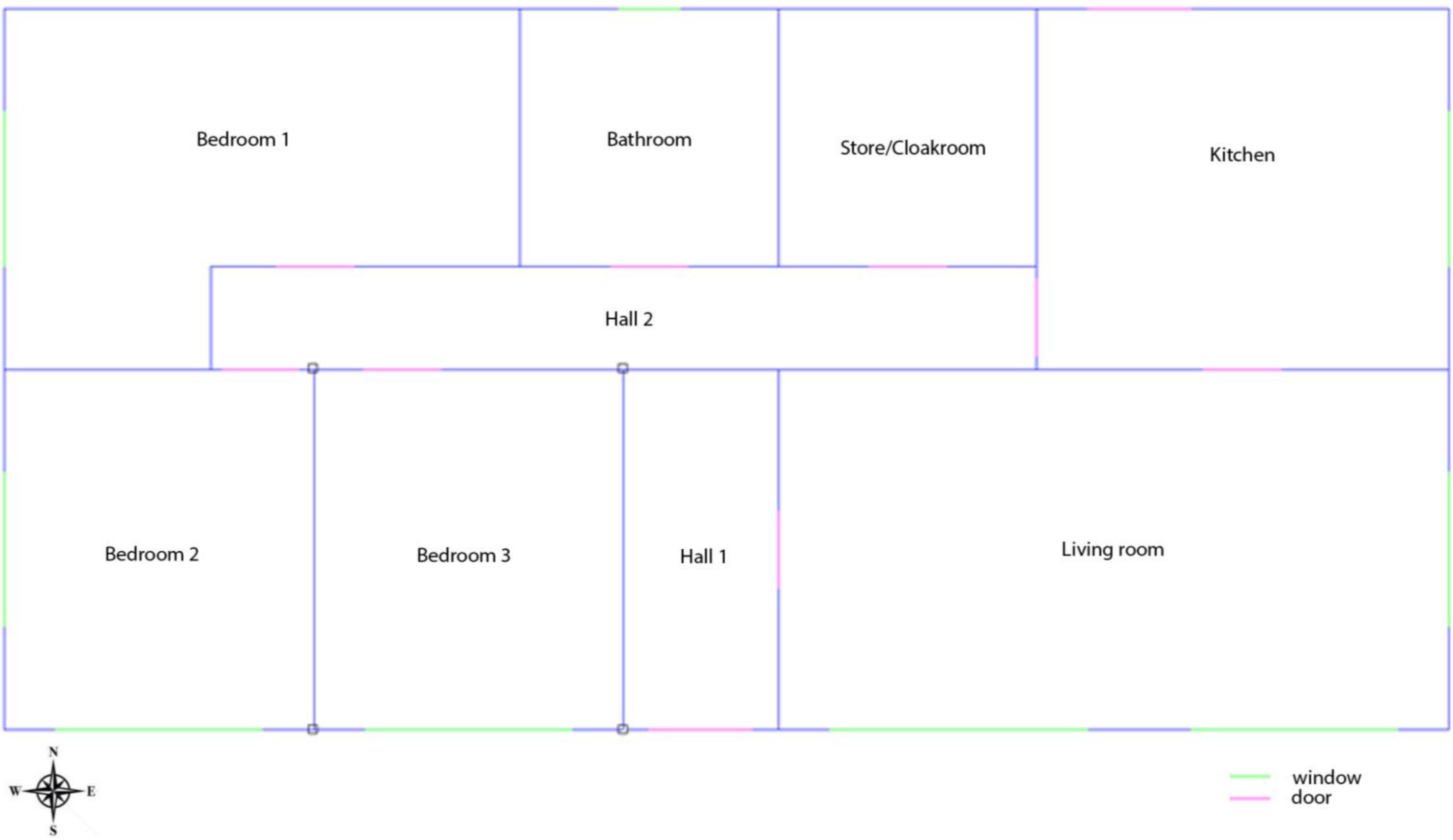



Figure 62: Dwelling floor plan in IES VE

The building has two external door openings of 2.1 m$^2$ each, 1m in width and 2.10m in height. The one makes up the main entrance from the hall on the south façade and the second is in the kitchen, on the north façade.

All zones are separated by internal partition walls. Partition walls have door openings with a total area equal of 1.89m$^2$, 90mm in width and 210mm in height.

A flat roof was implemented as a simplified version of the model.

The same building figure will be used in this study under various configurations, which will be described in the next paragraphs.

### 3.3.2 Greenhouse construction

The baseline greenhouse construction is implemented symmetrically around the core dwelling at a distance of 2.5m in all directions. That means that the base case glass box is 5m tall, 19m in length and 12m in width, as shown in Figure 63.

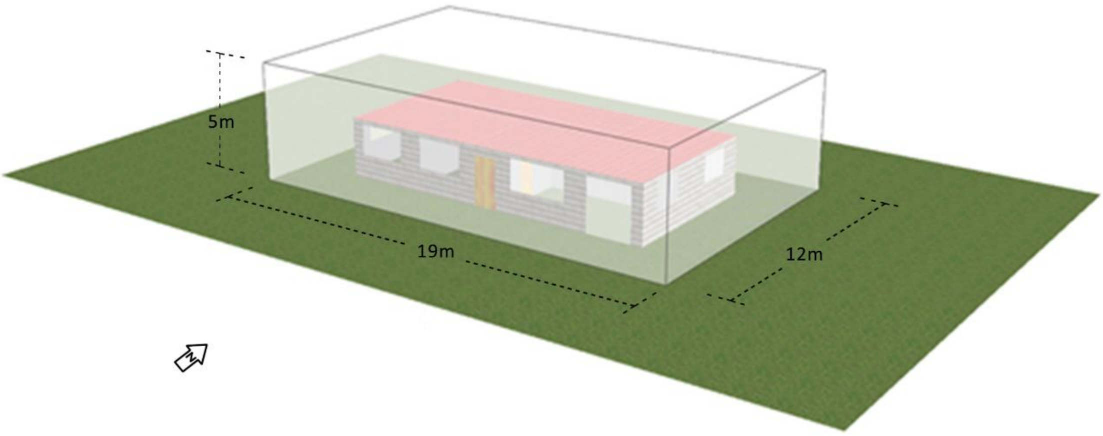



Figure 63: Dwelling with the glass box on IES VE

## 3.4 Orientation

South orientation is considered as the most selected design practice on residential buildings in Scotland. A good practice is to keep the main orientation of the building within 30° of south, and placing the larger windows on the south side of the dwelling (Esru.strath.ac.uk).

In this approach, the house plan was designed as shown in Figure 62. Larger and most of the windows are oriented South (Figure 61.a). One window in the living/dining room and one in the kitchen are facing East (Figure 61.b), and two windows are facing West which are found in bedrooms 1 and 2 (Figure 61.d). Only the bathroom features a small window facing North (Figure 61.c).

## 3.5 Location, climate and simulation calendar

Unless mentioned otherwise, the reference dwelling is assumed to be located in Aberdeen, Scotland's third most populous city, which is statistically the coldest city in the UK. Aberdeen features an oceanic climate (Köppen Cfb) (Wikipedia, 2016).

***Location data***

Aberdeen is located in the north-east part of Scotland (Figure 64). More detailed data about its location[1] are shown in Table 5.

[1] Based on the weather station in Aberdeen/Dyce Airport, located about 7 km to the North West of the city centre.


*Figure 64: Location of the base case residence (Google.co.uk)*

*Table 5: Aberdeen - Location data*

| Aberdeen | | | |
|---|---|---|---|
| **Latitude (º)** | **Longitude (º)** | **Altitude (m)** | **Time zone (hours ahead of GMT)** |
| **57.2 N** | 22.2 W | 69 | 0 |

### *Site data*

In all simulations a ground reflectance value of 0.2 was used for both the general situation and the surroundings, representing a temperate locality and typical crops and woodland respectively (IES VE Software). The terrain type chosen was for "suburbs".

### *Weather data*

The simulations were based on typical meteorological weather data of this location, using the annual climate files from the ASHRAE design weather database. Figure 65 shows the average max and min dry-bulb temperature, and the max wet-bulb temperature for each month of the year, as taken from the IES VE programme.

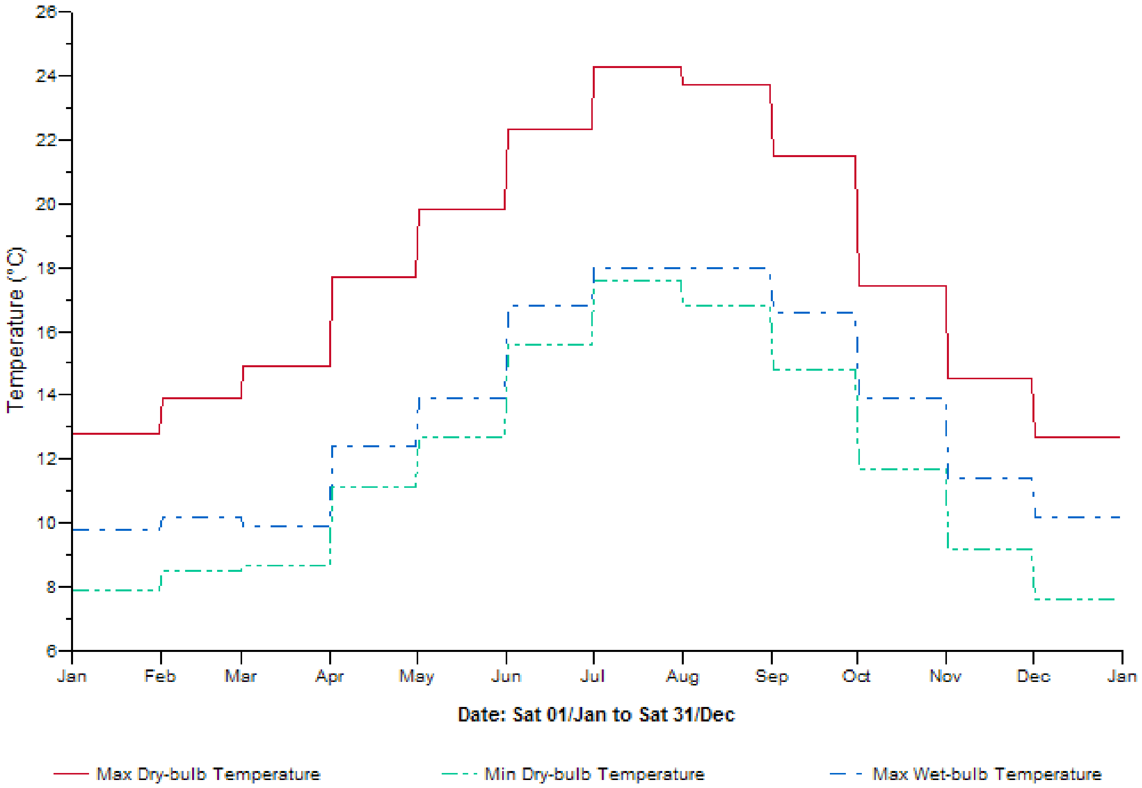



*Figure 65: Extreme monthly temperatures in Aberdeen (IES VE climate file).*

***Simulation Calendar***

Three day-types were used in the simulations: one for the five working days of the week, one for weekends and one for holidays[1]. Weekends and holidays were assumed to have the same daily profiles with respect to the occupancy and the equipment usage patterns.

## 3.6 Occupancy

The house model represents a typical small-family[2] detached dwelling. In this approach, it is considered that four people live in the house, with two of them being adults. According to the Scottish Housing Condition Survey (Scottish, Government, 2015a) households in Scotland containing children are more likely to be found in houses (72%), rather than flats (28%).

In this study, the occupancy patterns were introduced in simulations in terms of fixed weekly and daily schedules, representing a typical family behaviour which differs between weekdays and weekends/holidays, using common sense.

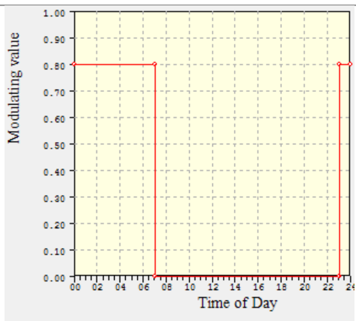
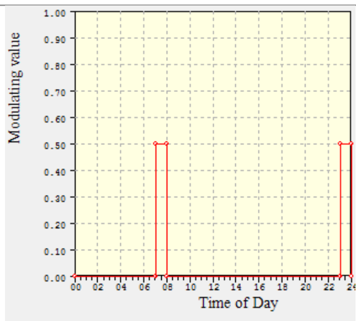
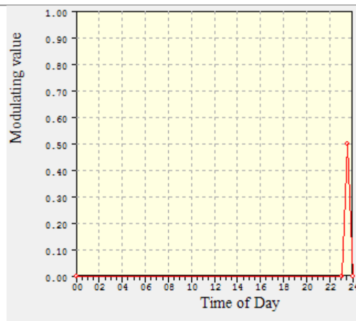
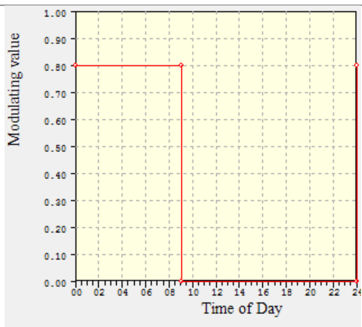
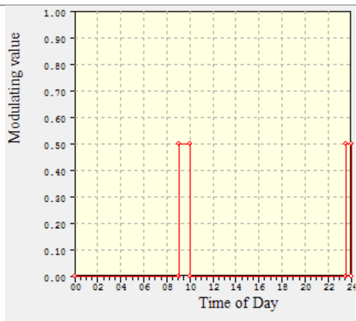
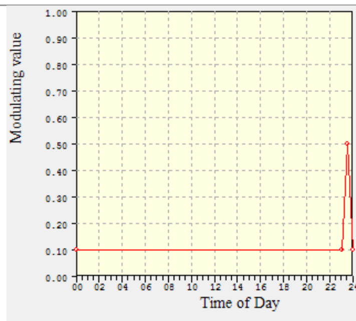
[1] Based on the bank holidays in Scotland.
[2] A "small family" is considered to consist of 2 adults and 1 or 2 children Scottish Housing Condition Survey (Scottish, Government, 2015a)

## 3.7 Internal gains

In this thesis, the internal gains included the heat supplied to the rooms by the people (metabolic), lights and appliances. These gains generally vary according to the purpose of each room, the time of the day and the day of the year. For this reason, the areas of the said house were divided into "sleeping" and "living" zones. Similarly, different occupancy and usage patterns were set for weekdays and weekends/holidays.

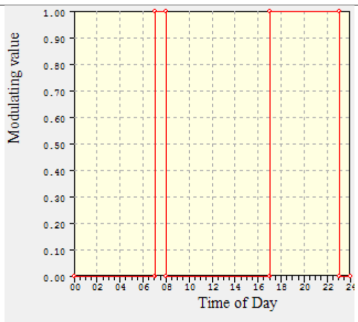
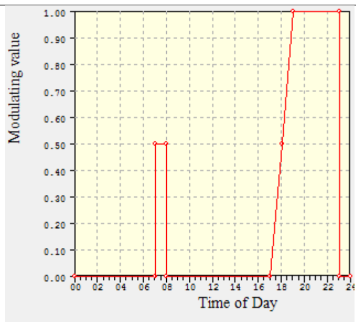
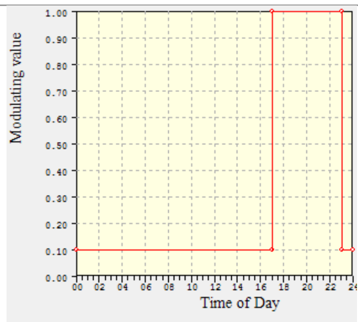
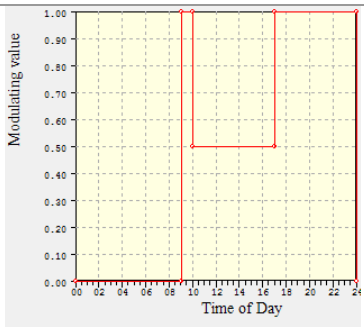
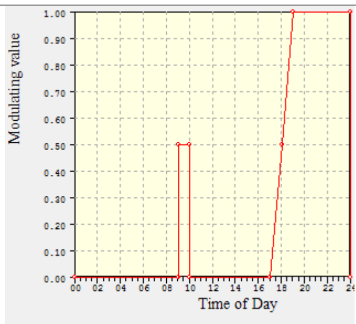
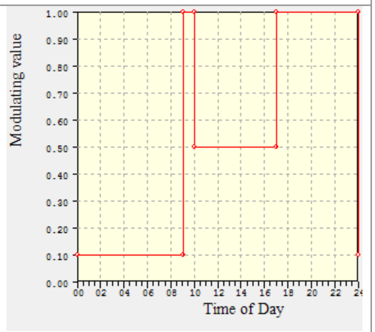
The magnitude and types of these casual gains and their variation throughout the day for each zone type are shown in Table 6 and Table 7 below.

*Table 6: Casual Heat Gains for Sleeping zones*

| **Sleeping zones: Bedrooms** | | | |
|---|---|---|---|
| **Type** | **People** | **Lighting** | **Equipment** |
| **Max Sensible** | 70 W/person | 6 W/m$^2$ | 10 W/m$^2$ |
| **Max Latent** | 40 W/person | - | **0** |
| **Occupancy** | 1 or 2 people[1] | - | - |
| **Max Power Consumption** | - | 6 W/m$^2$ | 10 W/m$^2$ |
| **Radiant Fraction** | - | 0.45 | 0.5 |
| **Fuel** | - | Electricity | Electricity |
| **Variation Profile** | | | |
| **Weekdays** |  |  |  |
| **Weekends/Holidays** |  |  |  |

[1] 1 person in "Bedrooms 2 & 3" and 2 people in "Bedroom 1"

*Table 7: Casual Heat Gains for Living zones*

| **Living zones: Living room, Kitchen, Bathroom, Cloakroom, Halls** | | | |
|---|---|---|---|
| **Type** | **People** | **Lighting** | **Equipment** |
| **Max Sensible** | 70 W/person | 6 $W/m^2$ | 10 $W/m^2$ |
| **Max Latent** | 40 W/person | - | 5 $W/m^2$ |
| **Occupancy** | $16m^2$/person[1] | - | - |
| **Max Power Consumption** | - | 6 $W/m^2$ | 10 $W/m^2$ |
| **Radiant Fraction** | - | 0.45 | 0.5 |
| **Fuel** | - | Electricity | Electricity |
| **Variation Profile** | | | |
| **Weekdays** |  |  |  |
| **Weekends/Holidays** |  |  |  |

## 3.8 Ventilation

***Infiltration***

Infiltration rate for the base case building was set at 0.14 $L/(s{\cdot}m^2)$. According to CIBSE Guide A: Environmental Design, an air permeability of $10m^3/(m^2{\cdot}h)$ at 50Pa represents a building that complies with 2002 regulations and for a single-storey dwelling. According to the Government's Standard Assessment Procedure (SAP), this value is divided by 20 to give an estimate of the air change rate at typical pressure differences – the so called rule-of-20 (Jones, *et al.*, 2012) – resulting in an average infiltration rate of 0.5 $m^3/(h{\cdot}m^2)$ or nearly 0.14 $L/(s{\cdot}m^2)$.

[1] Occupancy density=Total area of all "Living zones"/Number of occupants

The infiltration rate of the greenhouse was set at 1L/(s·m$^2$) based on a precedent relevant study on the Culemborg greenhouse residences (see Chapter 2.5.3.1.1) (Van Ree, 2010).

***Natural Ventilation***

The ventilation rate was set at 21 L/s for all zones. This is the value for the whole building ventilation rate for a dwelling with 3 bedrooms provided by the UK Building Regulations (The Building Regulations 2010. Approved document F. Ventilation, 2015).

***Mechanical Ventilation***

Due to the use and size of the building, and the window to wall ratio that is deemed able to provide adequate natural ventilation, no mechanical ventilation system was assumed to be installed in the building.

## 3.9 Heating/Cooling

The annual modelled energy use for heating for the whole dwelling highly depends on the heating regime that will be enforced as well as on the volume of the spaces that need to be heated.

The total heated floor is 98 m$^2$ (equal to the total building area) and the respective heated volume is 245 m$^3$.

Two setpoints for each zone were set, based on their occupancy patterns (see Table 6 and Table 7 for occupants' casual gains). Heating set points were set at 21℃ for the living zones and 19℃ for the sleeping zones when these rooms were occupied. When the building spaces were assumed to be unoccupied, thermostats were set to a typical unoccupied set point of 13℃ (Heating Policy, 2014) for all rooms. Maintaining this temperature level during unoccupied periods helps avoid condensation and dampness, prevents the building from becoming too cold and thus reduces peak heating requirements and pre-heating time at start-up (Designbuilder.co.uk), (Zhivov).

The capacity of the heating system was defined "unlimited", in order to evaluate the total heating requirements of the house, independently of any system capacity restrictions (Bocanegra-Yáñez, 2014).

There is not space cooling system present, hence no cooling set points have been set.

*Table 8: Heating system settings*

| Zone | Living | | Sleeping | |
|---|---|---|---|---|
| **Heated area** | 62.5 $m^2$ | | 35.5 $m^2$ | |
| **Heated volume** | 156.25 $m^3$ | | 88.75 $m^3$ | |
| | **Heating periods** | **Heating set point** | **Heating periods** | **Heating set point** |
| **Weekdays** | 0:00-7:00<br>7:00-8:00<br>8:00-17:00<br>17:00-23:00<br>23:00-24:00 | 13°C<br>21°C<br>13°C<br>21°C<br>13°C | 0:00-7:00<br>7:00-23:00<br>23:00-24:00 | 19°C<br>13°C<br>19°C |
| **Weekends/Holidays** | 0:00-9:00<br>9:00-24:00 | 13°C<br>21°C | 0:00-9:00<br>9:00-24:00 | 19°C<br>13°C |

## 3.10 Constructions

The construction materials and their properties for the baseline building were chosen in a way to represent a typical detached dwelling in Scotland of an average energy performance. Most values were adopted from the SAP data sheets for an averagely insulated dwelling, built around the late 80's (The Government's Standard Assessment Procedure for Energy Rating of Dwellings, 2014).

### 3.10.1 Opaque constructions

*Table 9: Opaque constructions - base case building*

| Category | U-value ($W/m^2K$) | Description | Source [1][2][3][4] |
|---|---|---|---|
| **External Walls** | 0.25 | Filled cavity wall | [1] |
| **Internal Partitions** | 1.60 | Gypsum-cavity walls | [2] |
| **Ground Floor** | 0.44 | Solid-ground floor | [1], [3] |
| **Roof** | 0.40 | Domestic flat roof – insulated | [1], [3] |
| **Internal Ceiling/Floor** | 0.25 | Glass-fibre quilt, gypsum plasterboard | [4] |
| **Doors** | 3 | 37mm plywood | [1] |

More details about the opaque constructions in the building are found in Appendix A.

[1] SAP-2012
[2] Diyidata.com
[3] Energy Saving Trust, 2004
[4] Assumed

## 3.10.2 Glazed constructions

### 3.10.2.1 Windows

A double glazing unit for windows was assumed for the baseline building of this study. This was based on the fact that most dwellings in Scotland have double glazing units; in 2010, approximately 92% of all dwellings in Scotland had double glazing, with over 95% and 99% for post-1919 and post-1982 buildings respectively (Scottish Government, 2012).

The double glazed windows with an air gap of 12mm, have a PVC frame and a U-value of approximately 2.8 (including frame and glass), representing a typical pre-2003 installed unit (SAP 2012).

### 3.10.2.2 The window-to-wall ratio

The ratio of window to wall area determines the amount of incident solar radiation entering into the interior as well as the heat losses. Consequently, it can dramatically influence indoor thermal comfort and energy consumption (Mirrahimi et al., 2016).

The total window area is about 20m$^2$, equivalent to about 20.5% of the dwelling's total floor area. This value corresponds to the typical total window area obtained from a RdSAP-based calculation for a detached house of 98m$^2$ (The Government's Standard Assessment Procedure for Energy Rating of Dwellings, 2014).

### 3.10.2.3 Greenhouse construction

There are no specific guidelines for the glazing used in greenhouse residences, therefore the values used were taken from existing building practices and relevant studies. More specifically, in this study, the base case glass shelter is made up from single glazing units (Solardome Industries) with a U-value 5.8 W/m$^2$K of and a g-value of 0.8 (Van Ree, 2010). Aluminium frame was used in the structure's edges, with U-value of 5.88 W/m$^2$K.

The ground surface inside the greenhouse and outside the core dwelling was modelled as cultivated clay soil with 12.5% moisture with a depth of 0.4m.

## 3.11 Simulation settings

***Simulation timestep***

Although a time step of 10 minutes is generally suitable for most building simulations (ApacheSim User Guide, 2015), in this project a smaller time step of 2 minutes was necessary from the system in order to capture the detail of control operation.

***Reporting interval***

The reporting interval should be greater than or equal to the time-step. In this study it was set at one hour, which is considered satisfactory for most simulations (ApacheSim User Guide, 2015).

***Preconditioning period and initial temperature***

A preconditioning period of 10 days was accounted in the simulations, with an initial temperature of 18℃. This values approximates the long-term average temperature inside a building and it is the temperature to which the building fabric will be initialized at the start of the preconditioning period (ApacheSim User Guide, 2015).

## 3.12 Verification of the model

Once all model characteristics were defined in IES VE, it was necessary to check if the results were reasonable. In order to verify that the heating system controls were set appropriately and the thermal indoor conditions were reasonable and representative for a dwelling in Scotland, a simulation was run for a weekday in March (when temperatures may become low and hence the heating system operates). Looking at the indoor temperatures in the sleeping and living zones (Figure 66), we see that they are maintained at 19℃ and 21℃, respectively, when the rooms are occupied, and at 13℃ during unoccupied periods, i.e. in accordance with the respective predefined setpoints (Table 8).

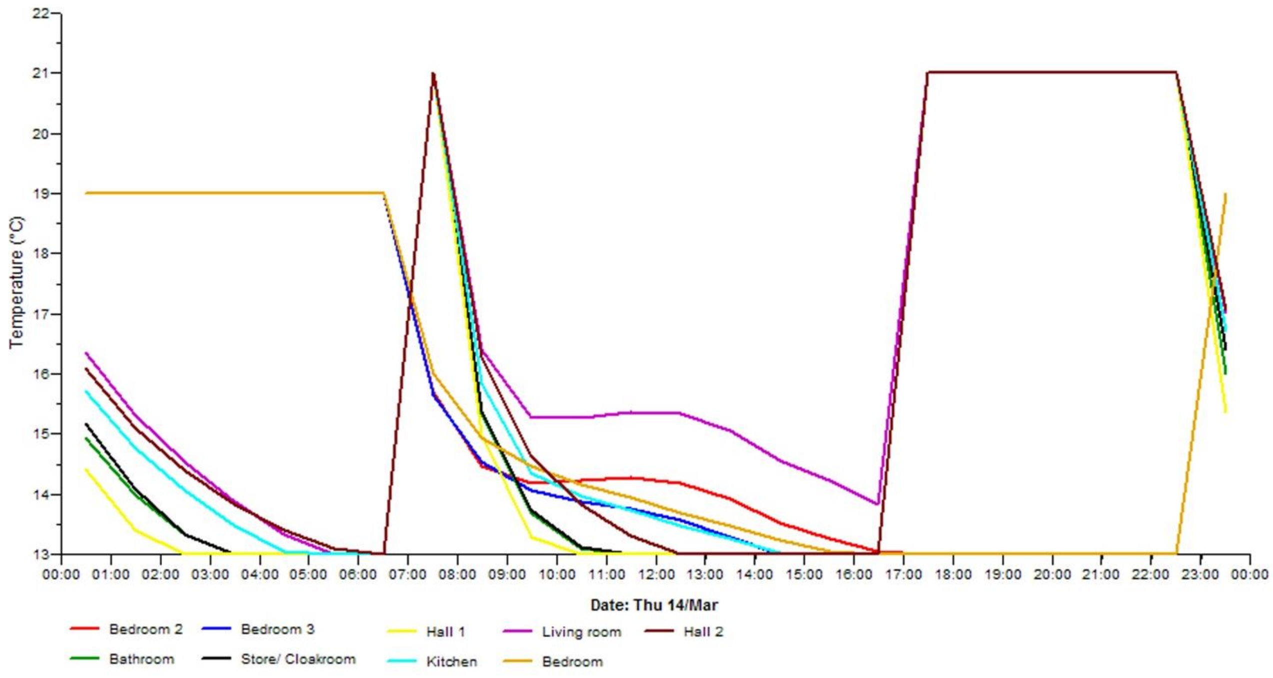



*Figure 66: Air temperature in rooms - base case, no greenhouse*

Next, it was needed to check the appropriateness of the building fabric, with regards to the dwelling's energy consumption for heating. The total annual heating requirements obtained from the software were 23.7MWh or 242kWh/m$^2$, which are overall in good agreement with real energy consumption data.

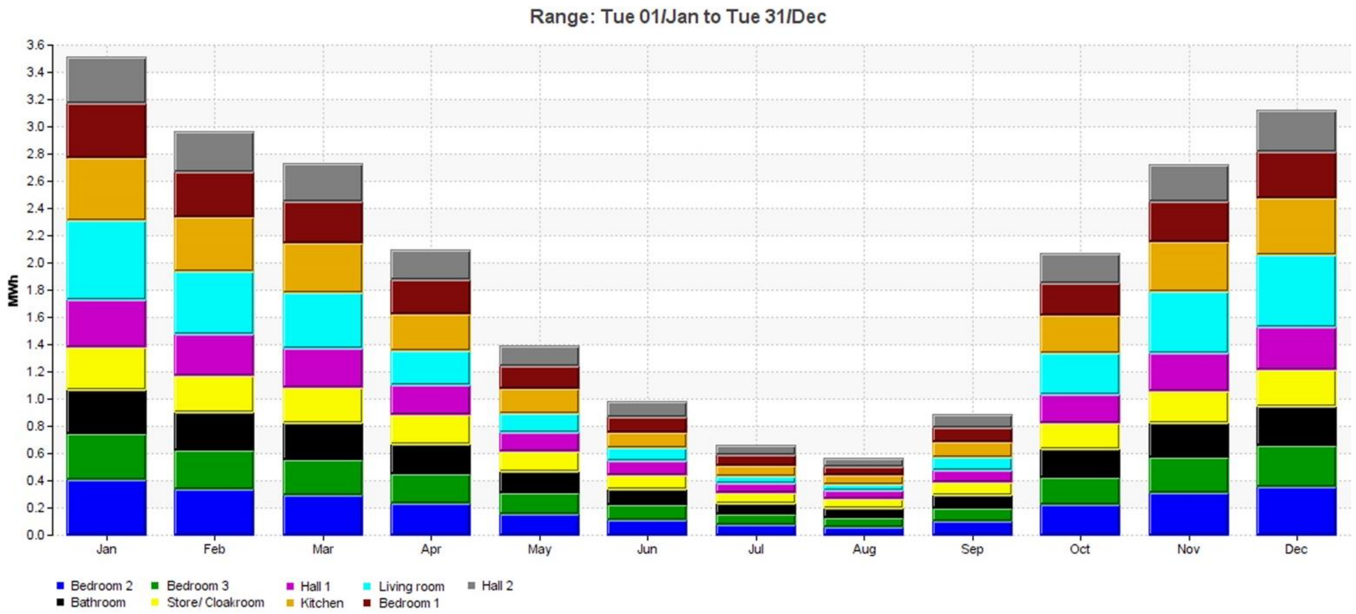



*Figure 67: Monthly and annual heating demands - Base case dwelling (No Greenhouse)*

By comparison, the Passive House Standard (Passivhaus.org.uk), which refers to a low energy building, suggests a specific heating demand of less than 15kWh/m$^2$·year, which is much lower than the one drawn from the programme.

The National Energy Efficiency Data (NEED) report (Department of Energy & Climate Change, 2015) for the domestic consumption in Scotland estimates that the typical consumption for a detached Scottish dwelling is 19.7MWh. The difference between this number and the energy demand found from the IES VE model is attributed to the fixed setpoints used for the whole year (including summer periods) and the fact that the house was assumed to be occupied all-year-round. In real world, the effect of human behaviour who may adjust the setpoints based on his desires and also to the fact that the dwelling may be unoccupied for prolonged periods (e.g. holidays) would lead to a lower total energy consumption.

Therefore, the found heating demand of 23.7MWh/year was acceptable for the base case detached dwelling as described in Chapter 3, and could be used to investigate the impact of a greenhouse shell on its heating load.

## 3.13 Design variations

In order to obtain a wider picture of the applicability of the "greenhouse residence" concept as a sustainable building strategy in Scottish houses, this thesis investigated their applicability under various design variations of both the core dwelling and the greenhouse encasement, as well in different geographical locations within the Scottish territory. The aspects examined are presented more analytically in the next paragraphs.

### 3.13.1 Greenhouse effectiveness in different building thermal envelopes

In this section, the same building configuration was examined under three different scenarios of the building's fabric thermal insulation status and subsequently energy performance. This was done in order to evaluate and also compare how the glass box implementation affects the requirements for heating and the thermal comfort levels for identical buildings configurations of different thermal performance.

More specifically, the three case studies to be compared included:

a) **The base case dwelling** - average insulation and energy performance
b) **Old dwelling** - poor insulation and low energy efficiency
c) **Newly built dwelling** - good insulation and high energy efficiency

Table 10 below gives a summary of the parameters applied for the three construction scenarios: base case, poorly insulated, and well-insulated.

*Table 10: Construction age and U-values for the averagely (base case), poorly (old) and highly insulated (new) dwelling*

| Scenario | **Averagely insulated** | **Poorly insulated** | **Highly insulated** |
|---|---|---|---|
| Construction period[1] | pre-1919 | 1984-1991 | 2012 onwards |
| Constructions U-value ($W/m^2 \cdot K$) | | | |
| External walls [2] | 0.25 | 2.1 | 0.14 |
| Internal walls [3] | 1.9 | 1.6 | 1.6 |
| Internal Ceiling/Floor [4] | 0.25 | 0.35 | 0.21 |
| Ground/Exposed floor [5] | 0.6 | 0.5 | 0.15 |
| Roof [12, 15] | 2.3 | 0.4 | 0.18 |
| Doors [12] | 3 | 3 | 1.6 |
| Windows [12, 15] | 4.8 | 2.8 | 2 |
| Air permeability ($m^3/(h \cdot m^2)$ @50Pa) | | | |
| Infiltration rate [6] | 15 | 10 | 7 |

### 3.13.2 Investigate the impact of different greenhouse typologies

The way the core buildings and the greenhouse enclosures are positioned determines the use of areas that are created between the building and the glass façade (Vester, 2015). Apart from functionality-related issues, the size and the positioning of the glass envelope can play a large role in the solar heat gained and, consequently, the performance of the greenhouse residence. This thesis investigated the effect of the greenhouse orientation and size, in relation to the main building structure.

[1] Where the properties assigned were drawn from the SAP 2012 datasheets (or other sources), they represented a typical property of the chosen size and character. SAP divides dwellings by age of construction in 12 different age bands, from A (oldest) to L (newest), for the purposes of assigning U-values and other data. In this study, the properties assigned to the baseline, the poorly insulated and the well-insulated dwelling were based on the A (pre-1919), G (1984-1991) and L (2012 onwards) age bands, respectively.
[2] SAP
[3] Diydata.com
[4] assumed
[5] Energy Saving Trust, 2004
[6] CIBSE, 2006

#### 3.13.2.1 Greenhouse orientation

This section evaluated how the orientation of the glass cover influences the reduction in energy demands. In addition to the baseline scenario (greenhouse is implemented symmetrically around the core dwelling), the simulations involved the greenhouse oriented towards the four cardinal directions (North, South, West, East).

In all cases examined, the height of the glass shell was maintained at 5m, i.e. 2.5m higher than the core dwelling. The greenhouse gross area and volume were maintained approximately 228m$^2$ and 1,140m$^3$, respectively, i.e. equal to the gross greenhouse area and volume in the baseline scenario. In this regard, the length and width of the greenhouse were adjusted accordingly to give a gross greenhouse area of 228m$^2$. (The structure configurations are shown in Table 14 along with the simulation results.)

#### 3.13.2.2 Greenhouse size

This section evaluated how the volume size of the glass cover influences the reduction in energy demands. As in the base case scenario, the simulations involved the greenhouse surrounding the building symmetrically but now in greater or smaller distances. More specifically, in order to determine the impact of increasing or decreasing the distance between the glass surface and the external building walls/roof, the following scenarios were modelled and simulated:

a) The greenhouse is implemented around the core dwelling at a distance of **2.5m** in all directions (**base case**)
b) The greenhouse is implemented around the core dwelling at a distance of **1.25m** in all directions (**half distance**)
c) The greenhouse is implemented around the core dwelling at a distance of **5m** in all directions (**double distance**)

| Scenario | Distance between building and GH | Greenhouse gross volume | Greenhouse net volume[1] |
|---|---|---|---|
| **"Base case"** | 2.5 m | 1,140 m$^3$ | 895 m$^3$ |
| **"Half distance"** | 1.25 m | 587.8125 m$^3$ | 342.8125 m$^3$ |
| **"Double distance"** | 5 m | 3060 m$^3$ | 2815 m$^3$ |

(The structure configurations are shown in Table 15 along with the simulation results.)

[1] Greenhouse net volume = Greenhouse gross volume - Dwelling volume(245m$^3$)

### 3.13.3 Investigate the impact of using different greenhouse glazing types

In this study, it was assumed that the base case glass shell encasement was made of single glazing. This assumption was based on the relevant literature review on existing greenhouse residences (Chapter 2.5.3). This section of the study additionally examined the potential of using a double-glazed greenhouse cover, with an air gap of 12mm and a U-value of 2.96W/$m^2$·K.

### 3.13.4 Greenhouse effectiveness in three different Scottish regions

The impact of the greenhouse shell was examined and compared for 5 Scottish cities in different geographical locations across Scotland. The weather file formats the VE can read are .fwt (proprietary format) and .epw files. Representing a wide variation of Scotland's climate in different locations was limited by the available weather data file sources. The Scottish regions examined in this part of the study were Aberdeen (base case) in the north-east of Scotland, Leuchars in the east, Eskdalemuir in the south, Oban in the west, and Glasgow in the west central side of Scotland (Figure 68).


*Figure 68: The five Scottish locations involved in the study (Google.co.uk)*

The climatic data for Aberdeen, Glasgow and Eskdalemuir were based on the weather files include in the IES VE package. Weather files for Oban and Leuchars were sourced from the EnergyPlus website (Energyplus.net, 2016). Table 11 shows more detailed data about the location of these regions.

*Table 11: Location data for the 5 Scottish regions investigated*

| City/Region | Latitude (°) | Longitude (°) | Altitude (m) |
|---|---|---|---|
| **Aberdeen** | 57.2 N | 22.2 W | 69 |
| **Glasgow** | 55.87 N | 4.43 W | 8 |
| **Eskdalemuir** | 55.32 N | 3.20 W | 242 |
| **Oban** | 56.42 N | 5.47 W | 4 |
| **Leuchars** | 56.4 N | 2.87 W | 10 |

### 3.13.5 Greenhouse effectiveness in a multi-storey detached dwelling

In this investigation part, two extra dwelling structures were modelled: a two-storey and a three-storey building. The plan and all the modelling inputs (constructions, thermal conditions, etc.) were the same as for the reference building. As in the base case scenario, the simulations involved the glass structure surrounding the building symmetrically at a distance of 2.5m from the external walls/roof.

# 4 Results

As explained in the Approach overview, the variables to be examined for the purpose of this study are:

a) the dwelling's annual heating requirements[1], in terms of total annual demands, specific heating requirements and saving potentials

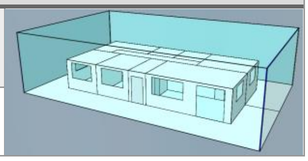
b) the thermal conditions inside the dwelling and in the greenhouse area, in terms of temperature levels and hours of overheating.

## 4.1 Base case dwelling

### 4.1.1 Energy consumption

Simulation results about the total annual heating demands for the base case dwelling, before and after the greenhouse implementation, are presented in Table 12 below.

*Table 12: Total annual heating requirements without and with the greenhouse - Base case dwelling*

| Base case | | | |
|---|---|---|---|
| | **Without Greenhouse** | **With Greenhouse** |  |
| **Annual Heating Requirements (MWh)** | 23.7 | 17.8 | |

The bar chart in Figure 70 indicates that insulating the building with the glass cover led to a considerable reduction in the specific heating demands by approximately 25% or 60 kWh/m$^2$/year. This percentage corresponds to an overall 6 MWh savings for heating for the said household per year (Figure 69).

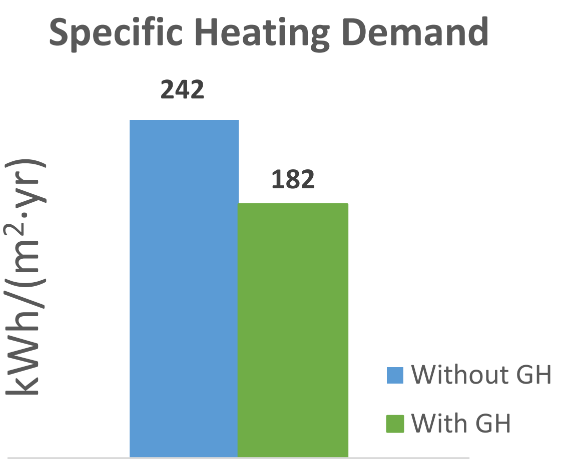



*Figure 70: Specific Heating Demand without and with the greenhouse – Base case dwelling*

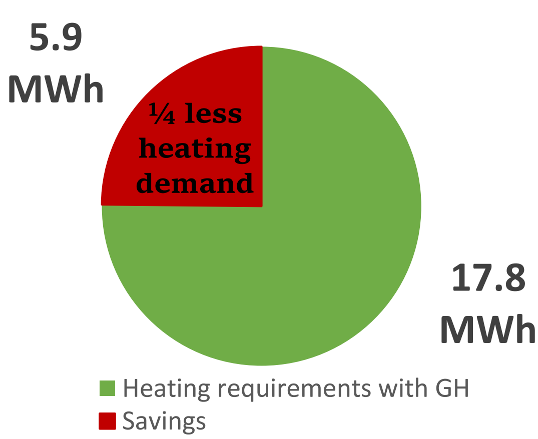



*Figure 69: Reduction in Heating requirements after the greenhouse implementation – Base case dwelling*

[1] Data will be rounded to the nearest integer, unless greater precision is required for results comparison.

As described in Chapter 2.5.2, the reduction in the building's heating demand is attributed on the one hand, to the heat from solar radiation, which is trapped inside the structure causing the air temperature to rise, and on the other hand, to the reduced heat losses from the dwelling to the environment through convection. In details, simulation analysis showed that the annual solar gains in the greenhouse zone were about 124MWh.

### 4.1.2 Overheating risk

#### 4.1.2.1 Base case ventilation rate

In addition to the reduction in the building's heating requirements, the rise in the indoor air temperatures due to the glass cover effect caused significant overheating problems. The bar chart below indicates that the average number of hours per year that temperature in the rooms exceeded the acceptable for the occupants levels went up by over fifteen times. Detailed results about the overheating hours and the maximum temperatures for each zone can be found in Appendix B.

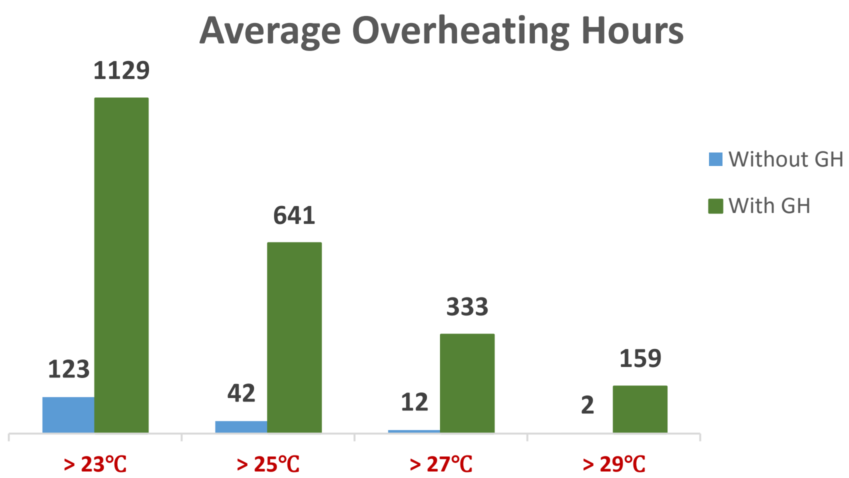



*Figure 71: Average number of overheating hours in the rooms without and with the greenhouse – Base case dwelling (ventilation rate=21L/s)*

Furthermore, Figure 72 below shows the air temperature variations in the rooms for a hot summer day. As can be seen, indoor temperatures reach intolerable levels, exceeding 30°C in all zones, going up to 38°C in the living room.

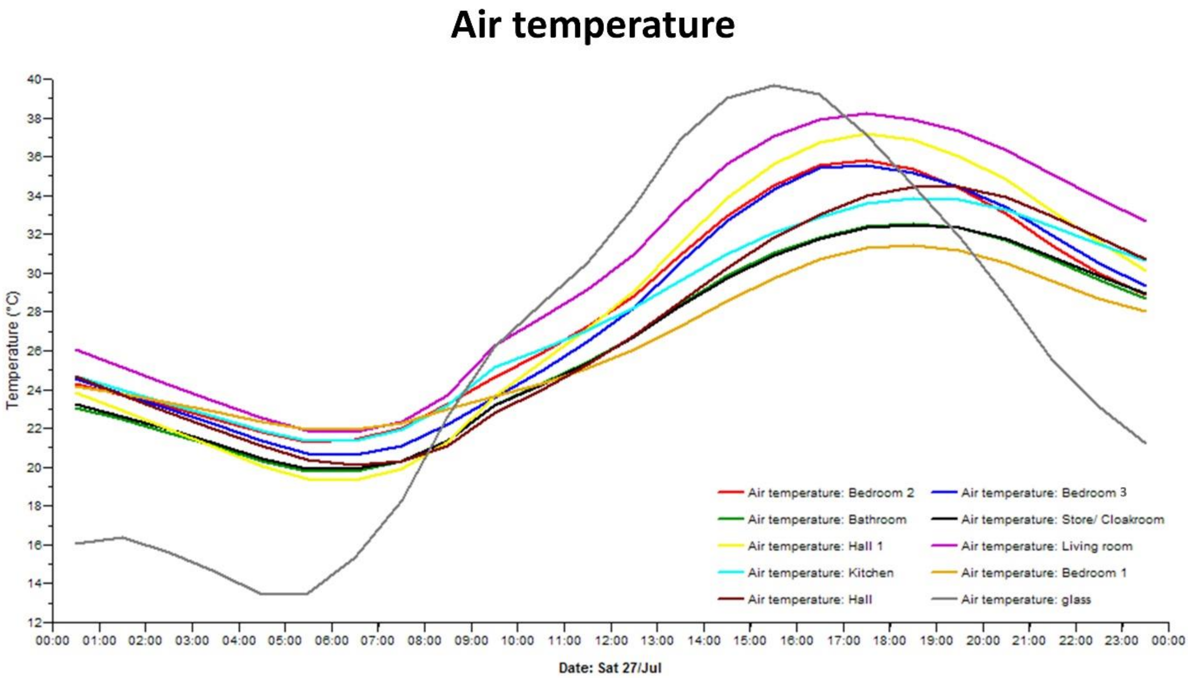



*Figure 72: Air temperatures in the main dwelling and the greenhouse area – Base case conditions applied*

It was also observed that the greatest problem with overheating was found in the rooms facing south (Living room, Hall 1, Bedroom 2, and Bedroom 3), whereas those facing north reported considerably lower temperatures.

Nevertheless, the overall performance of a greenhouse residence with respect to its indoor thermal conditions should not be determined exclusively based on the above findings, as these results were drawn assuming a constant rate for natural ventilation in all building zones, namely 21L/s (Chapter 3.8). In real world, occupants can adjust their behaviour based on their comfort needs, and in turn increase the natural ventilation provided in the spaces, e.g. through open windows and/or doors.

#### *4.1.2.2 Increased natural ventilation in building spaces*

In order to examine if the problem with overheating can be solved with window opening strategies, three extra simulations were run, where the baseline natural ventilation rate was increased by a factor of two, four and eight, i.e. 42L/s, 84L/s, and 168L/s, respectively[1]. Windows in the greenhouse were set to remain closed (zero natural ventilation rate) as in the base case scenario. Below are shown the results for the average overheating hours per year for all the four dwelling natural ventilation rates examined.

[1] When these rates are converted into air changes per hour, their values differ between zones. The mean value in ach calculated for the rooms is approximately 3, 6, 12, and 24 ach, respectively.

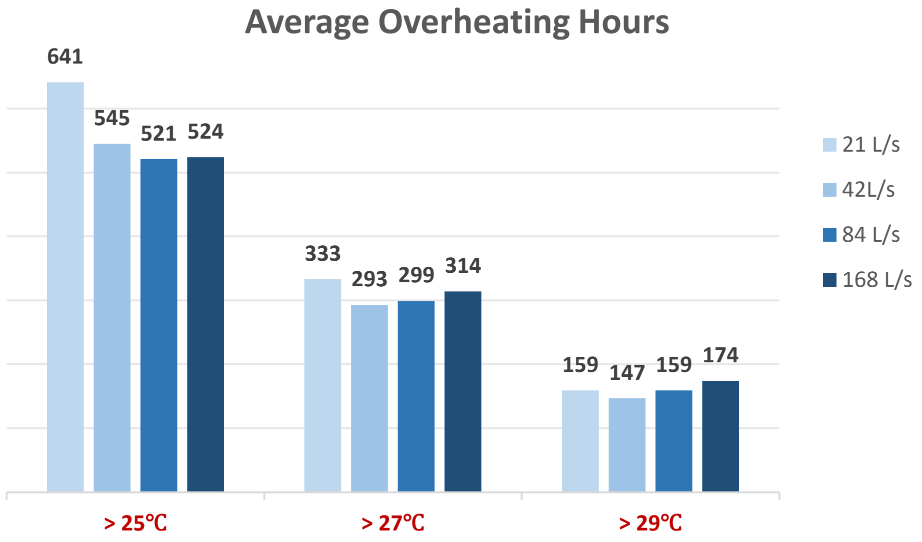



*Figure 73: Average number of overheating hours in the building areas (after the greenhouse implementation) for 21L/s, 42 L/s, 84 L/s, and 168 L/s of dwelling natural ventilation rate – No greenhouse windows opening*

The above data indicate that when the natural ventilation in the building is increased above the initial rate of 21L/s the number of very high indoor temperatures also rises. This is attributed to the greater amount of hot air from the greenhouse entering the building. Consequently, the solution of using higher ventilation rates for the building without any window opening schemes in the greenhouse is inefficient.

### 4.1.2.3 Increased natural ventilation in the greenhouse

In order to examine the effectiveness of window opening strategies in the greenhouse façade as a way to tackle the overheating problem, another group of simulations was run, this time changing the greenhouse ventilation rates. These rates were increased from zero (base case) to 5 ach, 10 ach, and 15 ach. It must be noted that in these simulations the dwelling was ventilated at the baseline rate, i.e. at 21 L/s. The outcomes of these scenarios are illustrated below:

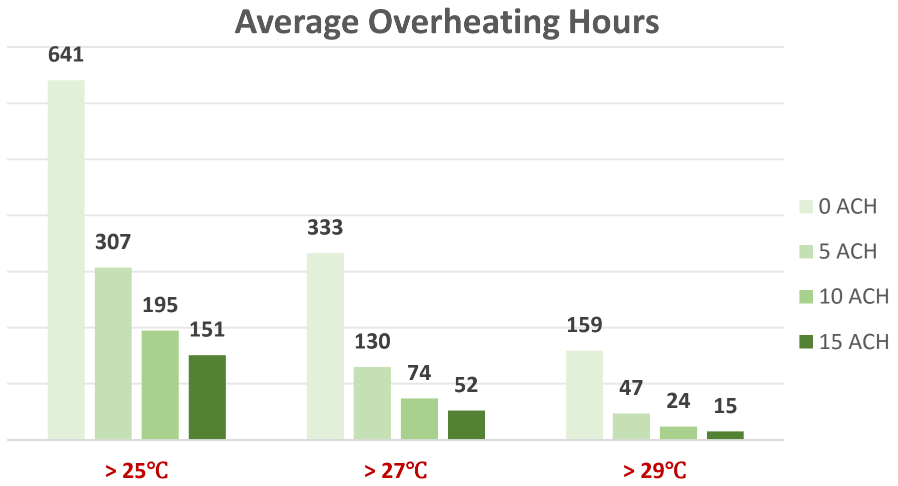



*Figure 74: Average number of overheating hours in the building areas for 0 ach, 5 ach, 10ach, and 15ach of greenhouse natural ventilation rate – Dwelling ventilation rate at 21L/s*

As indicated in Figure 74, providing natural ventilation through the glass façades led to remarkable reductions in the hours of thermal discomfort. Even a rate of 5 air changes per hour in the garden area gave a 50%-70% decrease in hot indoor temperatures. It was also found that - as expected - the more the greenhouse is ventilated the fewer the overheating hours are. This happens because the cooler external air passes in the greenhouse area and hence cools the air temperature in the zone[1]; then this cooler greenhouse air is used to ventilate the dwelling rooms, where the new temperatures are subsequently lower.

At this point, it is worth mentioning that the above temperature levels were achieved without the use of sun control or shading devices which is a large limitation to a justified appraisal of the dwelling's thermal comfort status. Providing shading to the building – or locally to the greenhouse – would reduce solar heat gained through glazing when it is not required, and this would in turn help keep temperatures lower.

### 4.1.3 Thermal comfort conditions in the garden area

A direct impact of the glass encasement is that it creates additional living areas, which are protected from rain and wind. In fact, the Scottish climate is characterised by very strong winds and frequent rainfalls (Figure 75), with an average of 188 days of rainfall

[1] As will be described in Chapter 4.1.3, for every 5 ach of increase in the greenhouse ventilation rate the maximum temperature in the greenhouse zone drops by 2 to 6 degrees.

in Scotland per year[1]. Therefore, the sheltered garden area within the greenhouse can be used all year round, as both the strong winds and the rain are blocked by the cover.

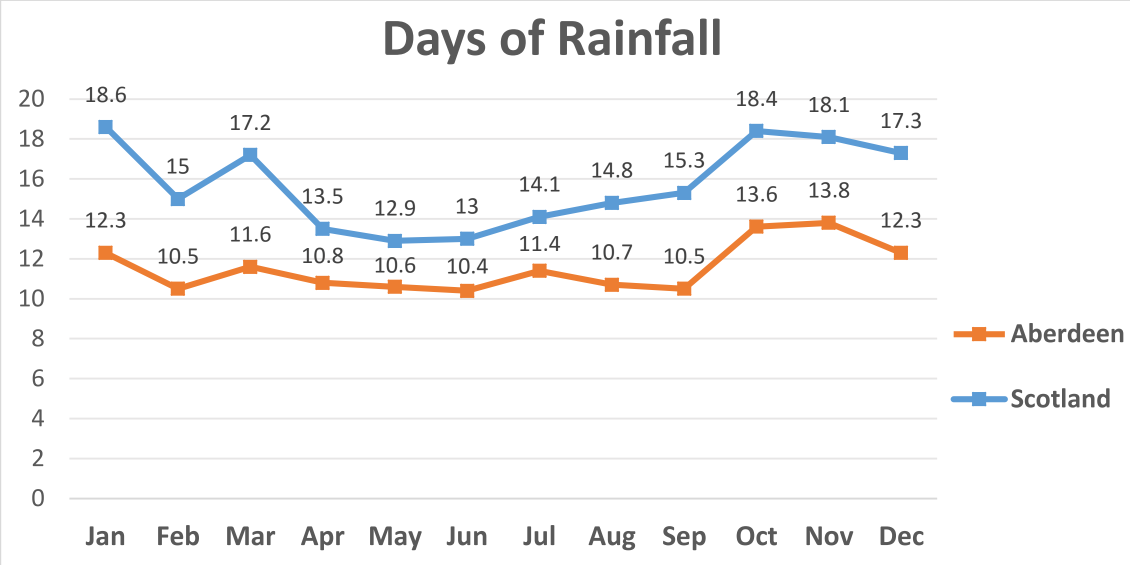



*Figure 75: Average number of days of rainfall in Aberdeen (base case) and in Scotland (Met Office, 2016)*

In addition to providing protection from weather conditions, the glass skin also affected the thermal conditions in the garden area inside the greenhouse. Before the greenhouse implementation, the outdoor temperature in the studied location exceeded 20°C for less than 70 hours per year (Figure 77), which would often discourage occupants to spend their time outside the building.

On the contrary, the glass protection caused the temperatures within the greenhouse to rise considerably, especially during warmer months (see Figure 76 with the annual temperature fluctuations). The graph below also illustrates that during summer months the greenhouse temperature exceeds the desirable limits very often, reaching a high 40°C in July. However, it should be underlined that these results were based on the assumption that <u>the greenhouse ventilation is zero</u>.

[1] The wettest parts of Scotland experience approximately 250 days of rain per year, whereas the driest parts about 150 days of rain per year (Scotland.com).

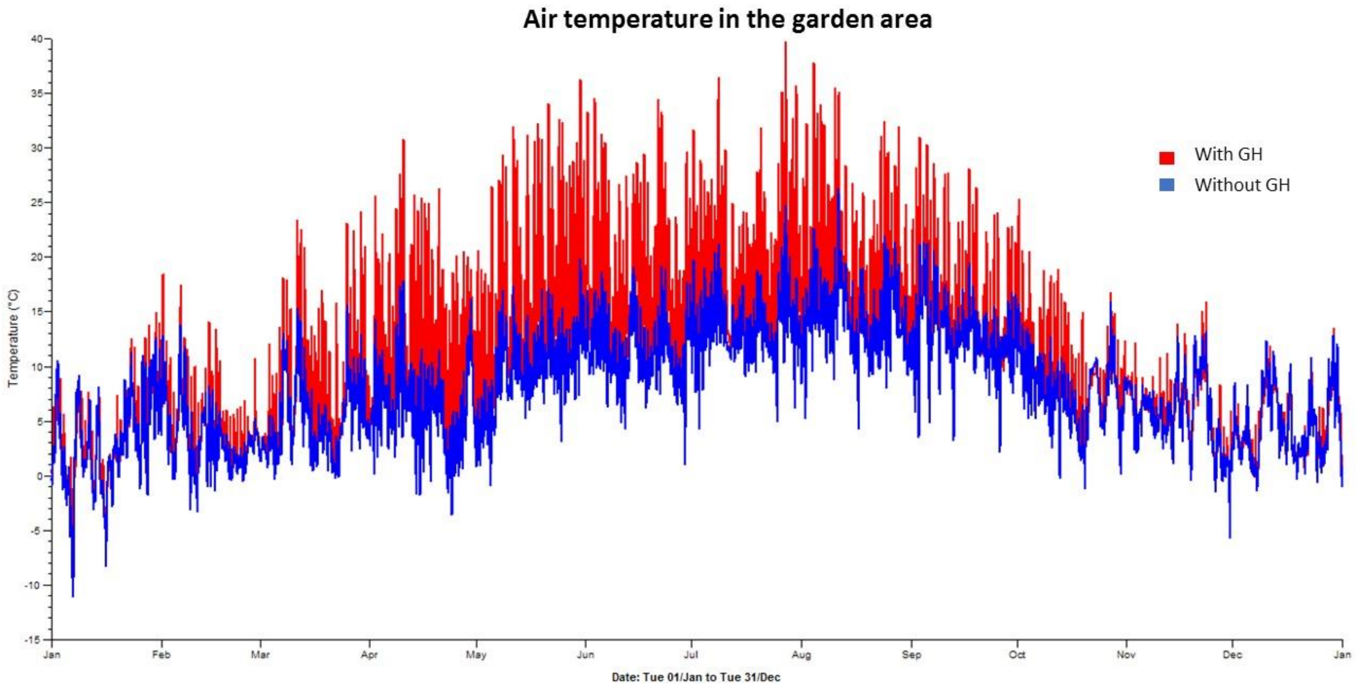



*Figure 76: Annual air temperature fluctuations in the garden area around the house - Base case conditions*

In order to evaluate the thermal conditions in the zone between the glass façades and the building envelope with openable greenhouse windows, a group of simulations was run with greenhouse ventilation rates set at 5 ach, 10 ach, and 15 ach. As can be seen in Figure 77 below, window opening strategies can reduce drastically the peak temperatures occurring in the garden zone, by up to 10°C when applying a ventilation rate of 15 ach.

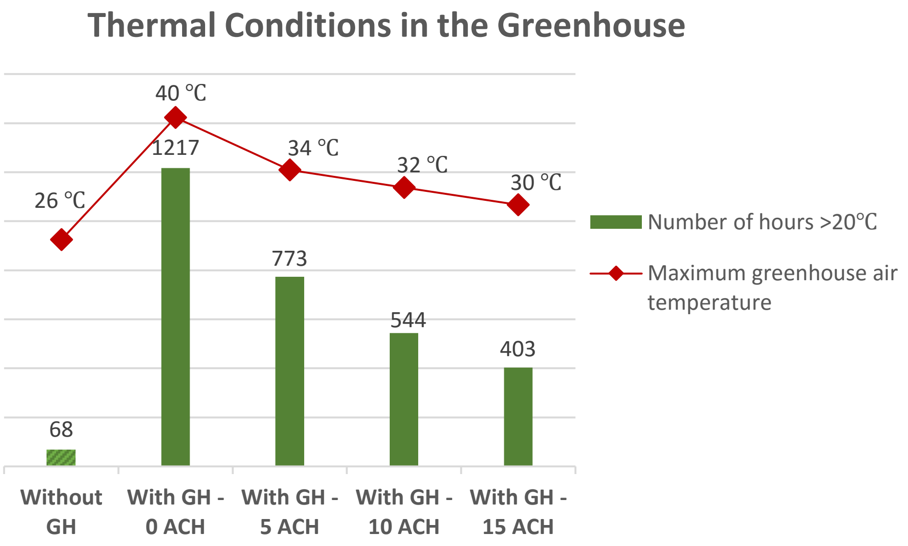



*Figure 77: Thermal conditions in the greenhouse area for different natural ventilation rates*

This strategy also caused a downward trend in the occurrence of external temperatures beyond 20°C (Figure 77). Albeit reduced, the occurrence of desirable temperature levels in the garden area was still satisfactory, allowing the occupants to take advantage of the extra living area underneath the glass shell.

## 4.2 Design variations effect

In Chapter 4.1.3 it was proven that by providing adequate ventilation through the greenhouse shell, the overheating issue can be moderated. Based on that, the following chapters were focused on the effect of the design variations (as described in Chapter 3.13) on the dwelling's heating demands, using the baseline ventilation rates (as determined in Chapter 3.8) both for the core building and for the greenhouse. Detailed results about the overheating hours and the maximum temperatures for each zone and for each design variation examined can be found in Appendix B.

### 4.2.1 Effect of the building's thermal envelope

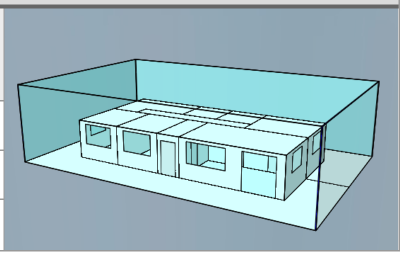
In this section, three identical buildings were examined featuring different thermal characteristics:

a) **The base case dwelling** - average insulation and energy performance
b) **Old dwelling** - poor insulation and low energy efficiency
c) **Newly built dwelling** - good insulation and high energy efficiency

The energy consumption for space heating these three building cases before and after the greenhouse contribution are shown below.

*Table 13: Annual heating requirements without and with the greenhouse – Effect of different building thermal envelopes*

| Annual Heating Demand (MWh) | | |
|---|---|---|
| | **Without Greenhouse** | **With Greenhouse** |
| **Base case** | 23.7 | 17.8 |
| **Old** | 46.4 | 26.3 |
| **New** | 17.6 | 13.5 |



Data in Table 13 and Figure 78 shows that the energy performance of the old dwelling with the glass cover approached the performance of the averagely insulated house and, correspondingly, the baseline dwelling after the greenhouse contribution performed like a conventional well-insulated house of the same size. In other words, the glass encasement acted like an energy upgrade measure for existing buildings.

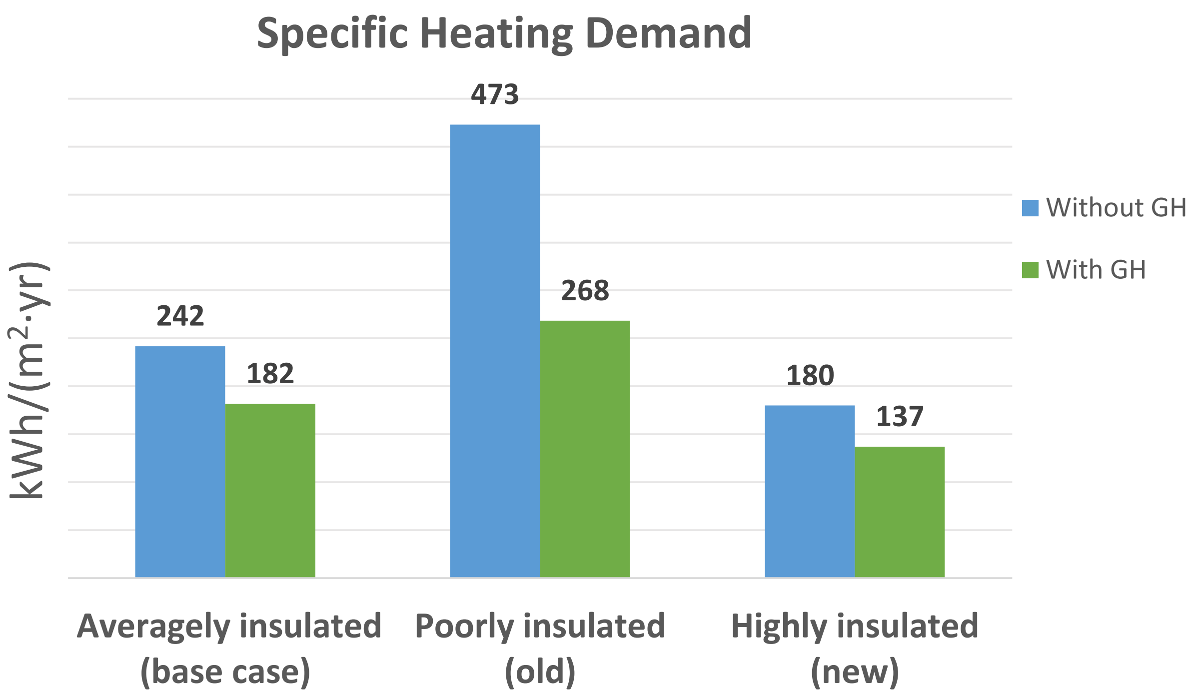



*Figure 78: Specific heating requirements without and with the greenhouse for different building thermal envelopes*

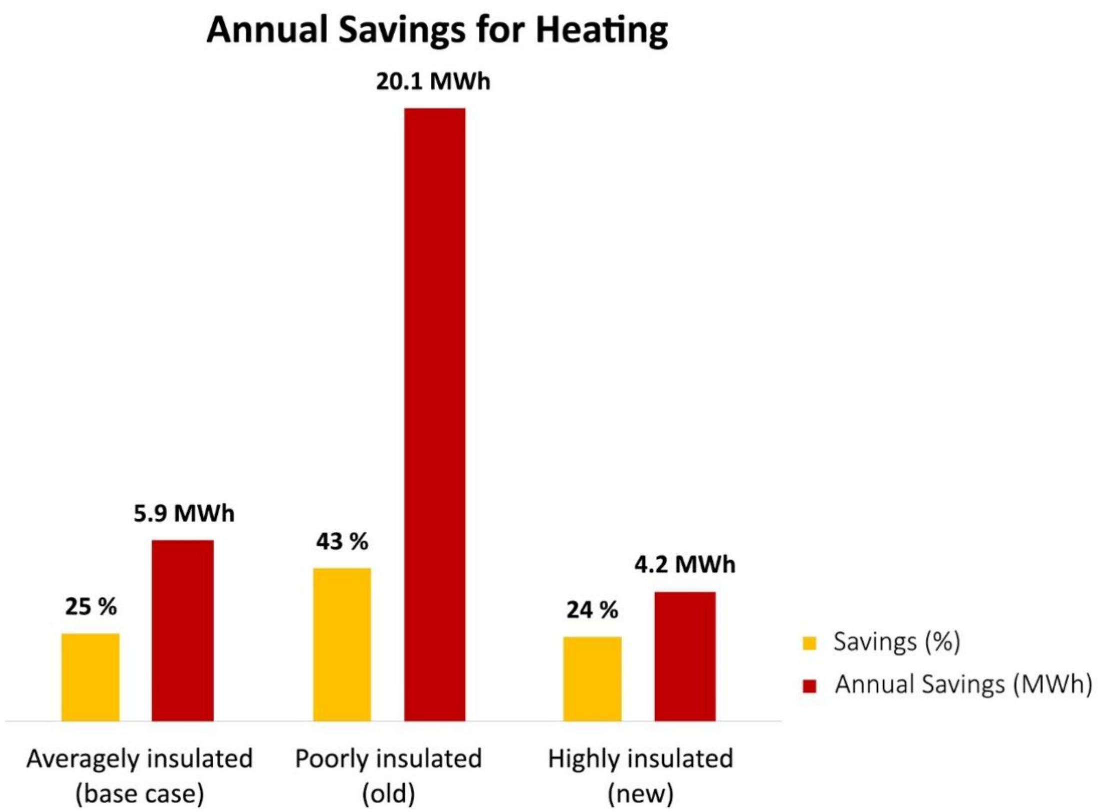



*Figure 79: Annual energy savings for heating in percentage (%) and absolute value (MWh) due to the greenhouse implementation for different building thermal envelopes*

Results also indicated that the effectiveness of a greenhouse cover as a thermal insulation means is significantly affected by the dwelling's thermal characteristics, with the poorly house having the greatest saving potentials compared to the buildings with a better insulation status.

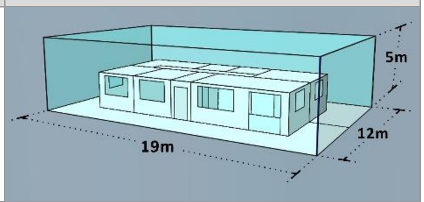
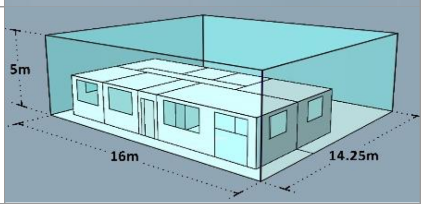
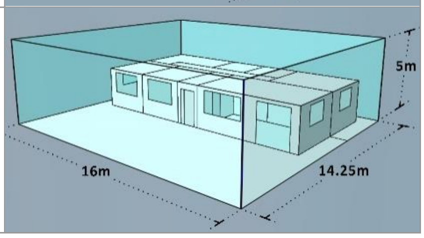
More specifically, an old, very poorly insulated house can save up to 43% of its heating requirements (or 205 kWh/m$^2$ per year) if it is surrounded by a glass cover. This is a very interesting finding for the case of listed buildings across Scotland, where installing insulation is not always easy or advisable (Pickles, 2016). The above result also suggests that new houses can be constructed using simpler materials, since the glass envelope will compensate for the building's bad thermal properties by providing an external form of insulation.

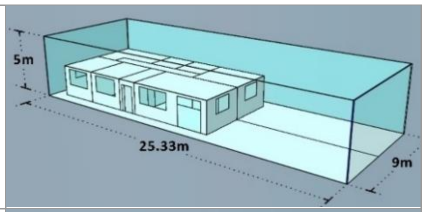
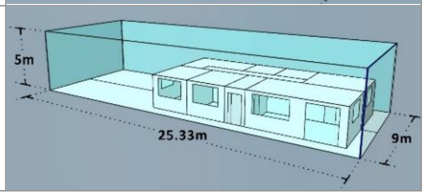
Findings also showed that, although already of a good energy performance, a well-insulated building can still benefit from the presence of a glass cover. In fact, demands for heating fell by nearly one fourth, or equivalently by 43 kWh/m$^2$ per year.

### 4.2.2 Effect of the greenhouse orientation

Simulation results about the energy performance of the base case greenhouse residence typology and the four additional greenhouse orientations that were modelled are shown in Table 14.

*Table 14: Annual heating requirements without and with the greenhouse – Effect of different greenhouse typologies*

<table>
<tr><th colspan="4">Annual Heating Demand (MWh)</th></tr>
<tr><th>GH Orientation</th><th>No Greenhouse</th><th>With Greenhouse</th><th>Greenhouse typology</th></tr>
<tr><td>Centre<br>(base case)</td><td rowspan="3">23.7</td><td>17.8</td><td>
</td></tr>
<tr><td>North</td><td>17.8</td><td>
</td></tr>
<tr><td>South</td><td>17.7</td><td>
</td></tr>
</table>

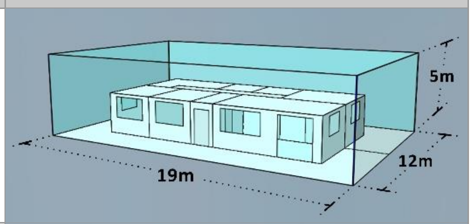
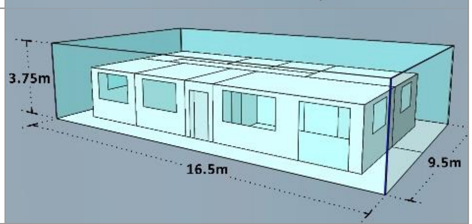
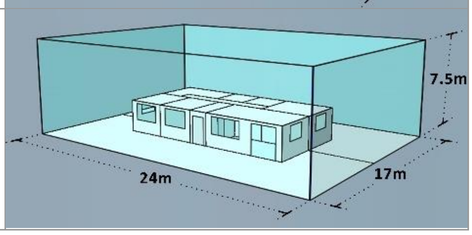
| | | | |
|---|---|---|---|
| **East** | | 17.9 |  |
| **West** | | 17.9 |  |

The above data indicates that for a greenhouse envelope of the same volume, the orientation of the glass construction has practically no impact in the total annual heating requirements. Consequently, the reduction in heating requirements is again reckoned at 25% or, equivalently, at 60 kWh/m$^2$ per year.

### 4.2.3 Effect of the greenhouse size

Simulation results about the energy performance of the base case greenhouse typology and for the two additional greenhouse sizes that were modelled are presented below:

*Table 15: Annual heating requirements without and with the greenhouse – Effect of the greenhouse size*

| **Annual Heating Demand (MWh)** | | | |
|---|---|---|---|
| **Distance between glass facades and ext.walls/roof** | **No Greenhouse** | **With Greenhouse** | **Greenhouse typology** |
| **2.5m (base case)** | | 17.8 |  |
| **1.25m (half)** | 23.7 | 16.9 |  |
| **5m (double)** | | 18.7 |  |

The energy consumption trends shown in the bar charts below indicate that as the distance between the glass cover and the core building decreases, the energy savings for heating increase. More specifically, for the case study dwelling, halving (or doubling) the distance of the greenhouse from the external walls/roof changed the base case annual heating savings by 4%. This is translated as an extra (or less) 1MWh or 10 $kWh/m^2$ energy saved per year.

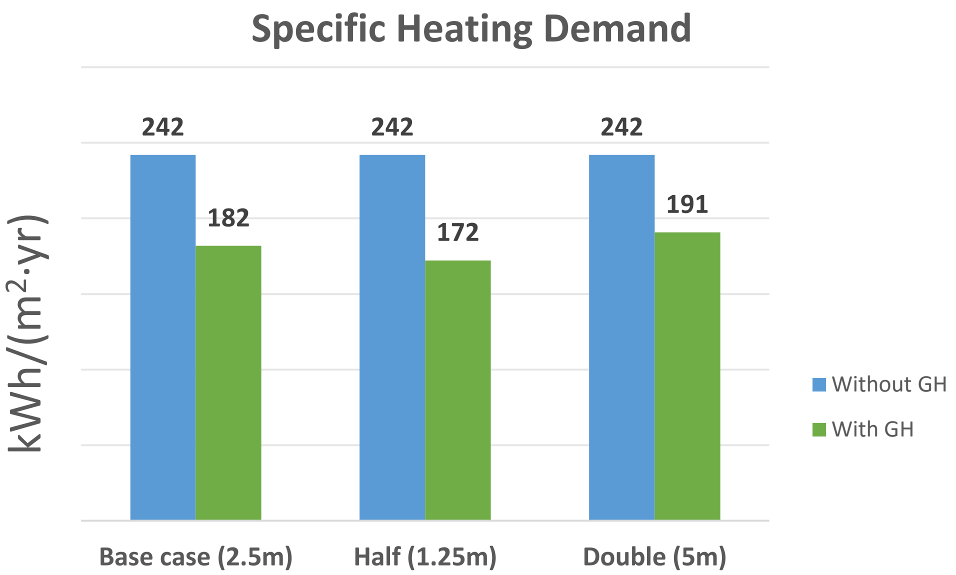



*Figure 80: Specific heating requirements without and with the greenhouse for different greenhouse sizes*

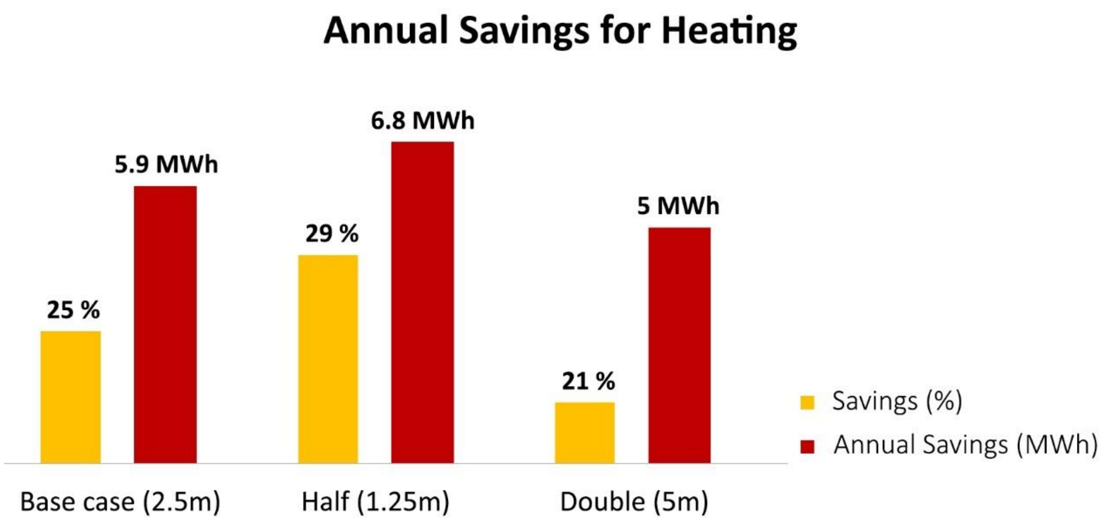



*Figure 81: Annual energy savings for heating in percentage (%) and absolute value (MWh) due to the greenhouse implementation for different greenhouse sizes*

It should be pointed out that these findings are based on the assumption that the natural ventilation rate for the glass cover is zero. The solar gains will warm up more quickly the smaller greenhouse volume, which – since there is no air exchange with the cooler external air – will maintain its risen temperatures and help the dwelling stay warmer, either by the pre-heated air that is exchanged through the ventilation and infiltration mechanisms or by moderating any heat losses from the rooms to the outside. Figure 82 shows that the occurrence of high temperatures in the garden area increases as the greenhouse distance from the building envelope decreases.

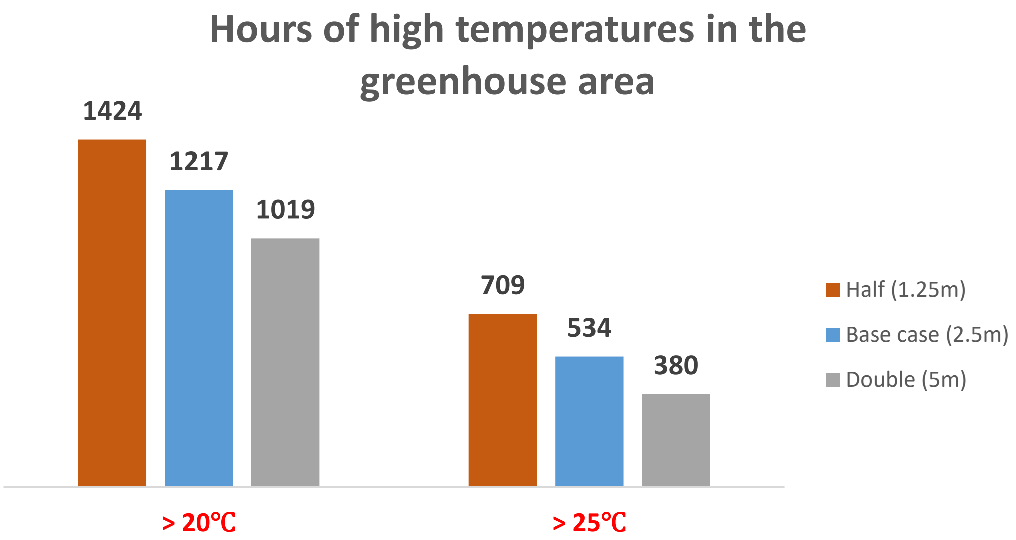
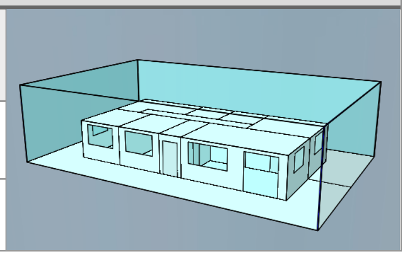



*Figure 82: Annual occurrence of high temperatures in the garden area for different greenhouse sizes*

### 4.2.4 Effect of greenhouse glazing type

Simulation results about the energy performance of the base case greenhouse construction (single glazed with a U-value of 5.8W/m$^2$·K) and for the scenario of using a double-glazed greenhouse encasement (with a U-value of 2.96 W/m$^2$·K) around the baseline dwelling are shown below.

*Table 16: Annual heating requirements without and with the greenhouse – Effect of the greenhouse glazing type*

| Annual Heating Demand (MWh) | | | |
|---|---|---|---|
| | **Without Greenhouse** | **With Greenhouse** |  |
| **Single glazing** **(base case)** | 23.7 | 17.8 | |
| **Double glazing** | | 15.2 | |

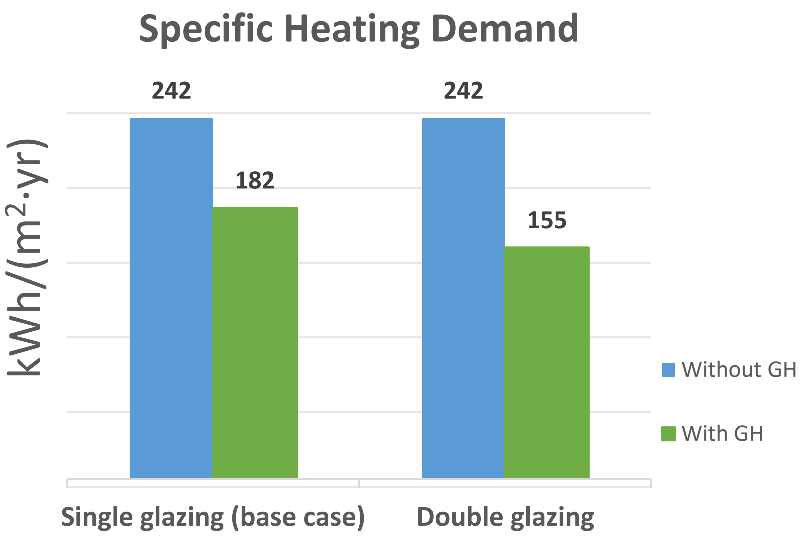



*Figure 83: Specific heating requirements without and with the greenhouse for different greenhouse glazing types*

As described in Chapter 4.1.1, surrounding the case study dwelling with the reference single-glazed cover reduces heating demands by one fourth or equivalently by 60 kWh/m$^2$/year. The greenhouse envelope is dominated by glass; it is hence expected that the type of glass used for the cover will have a critical effect on the inside temperatures (since it will lead to less thermal losses) and in turn on the building's heating demands. In fact, by replacing the single-glazed facade with a double-glazed, the heating savings increased by an extra 30kWh/m$^2$/year compared to the case of using a single-glazed greenhouse. This corresponds to a total reduction in the annual heating demands by about 36% compared to the conventional non-sheltered reference house.

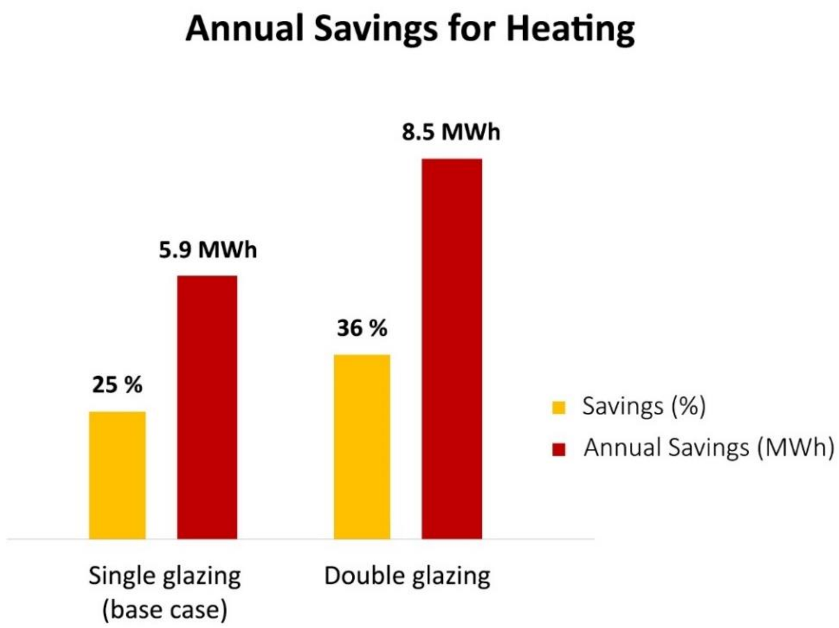



*Figure 84: Annual energy savings for heating in percentage (%) and absolute value (MWh) due to the greenhouse implementation for different greenhouse glazing types*

Although this glazing option appears more effective in terms of energy saving potentials, it involves higher overheating risk both in the greenhouse and the core building areas. Indeed, by comparing the zone temperatures in Figure 85 below with the respective in Figure 72, it can be seen that the use of double glazing instead of single glazing for the greenhouse increased indoor temperatures by 3℃ to 5℃, and the temperature in the garden area by almost 10℃.

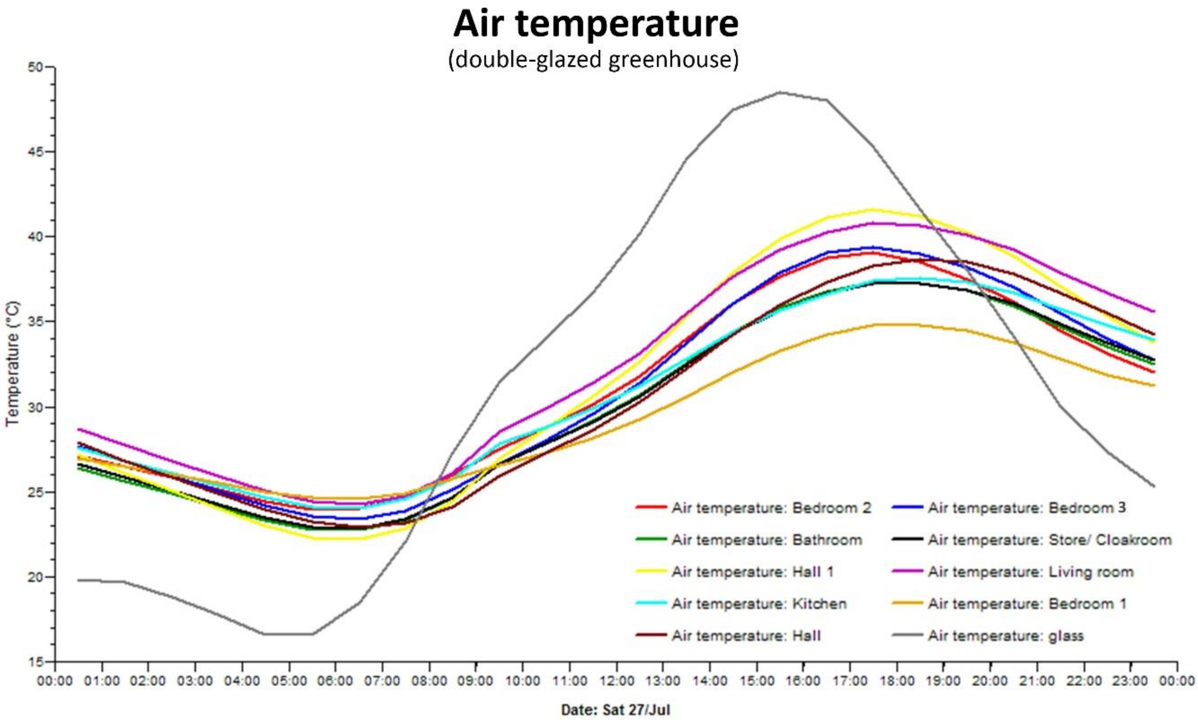



*Figure 85: Air temperatures in the main dwelling and the greenhouse area – Double-glazed greenhouse*

### 4.2.5 Greenhouse effectiveness in different locations in Scotland

Figure 86 below show the greenhouse cover effectiveness in the specific heating requirements of the baseline dwelling in the five Scottish locations studied. It is observed that, due to the different weather conditions, the heating requirements for the baseline dwelling differ by region, ranging from 208 kWh/m$^2$/year in Oban to nearly 270 kWh/m$^2$/year in Eskdalemuir. However, the percentages of energy saved for heating due to the greenhouse cover were similar in all locations examined, namely at about one fourth, or equivalently between 50 and 60 kWh/m$^2$ per year (Figure 86).

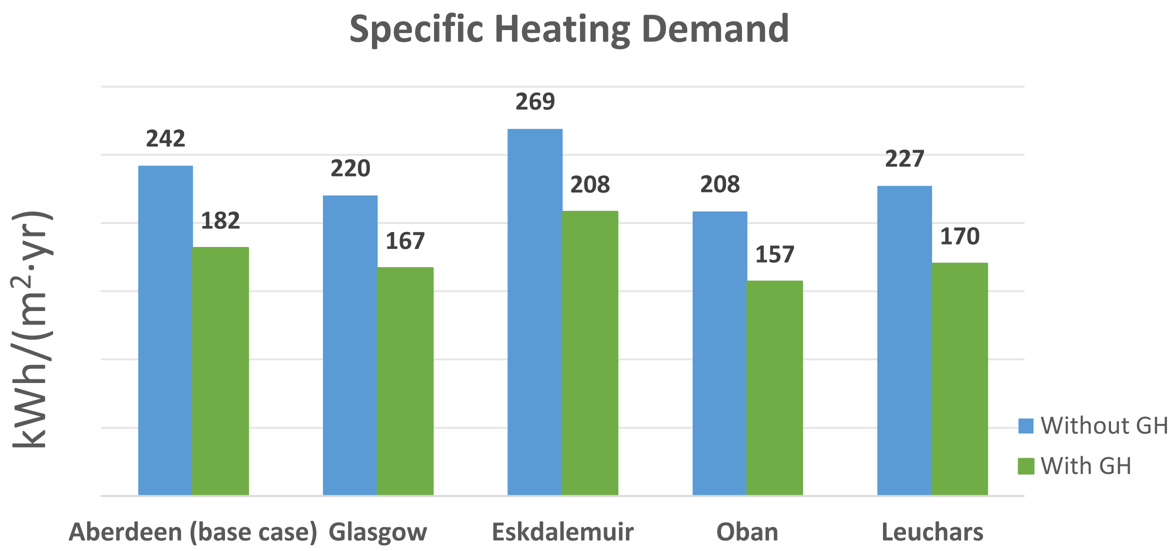



*Figure 86: Specific heating requirements without and with the greenhouse for different locations in Scotland*

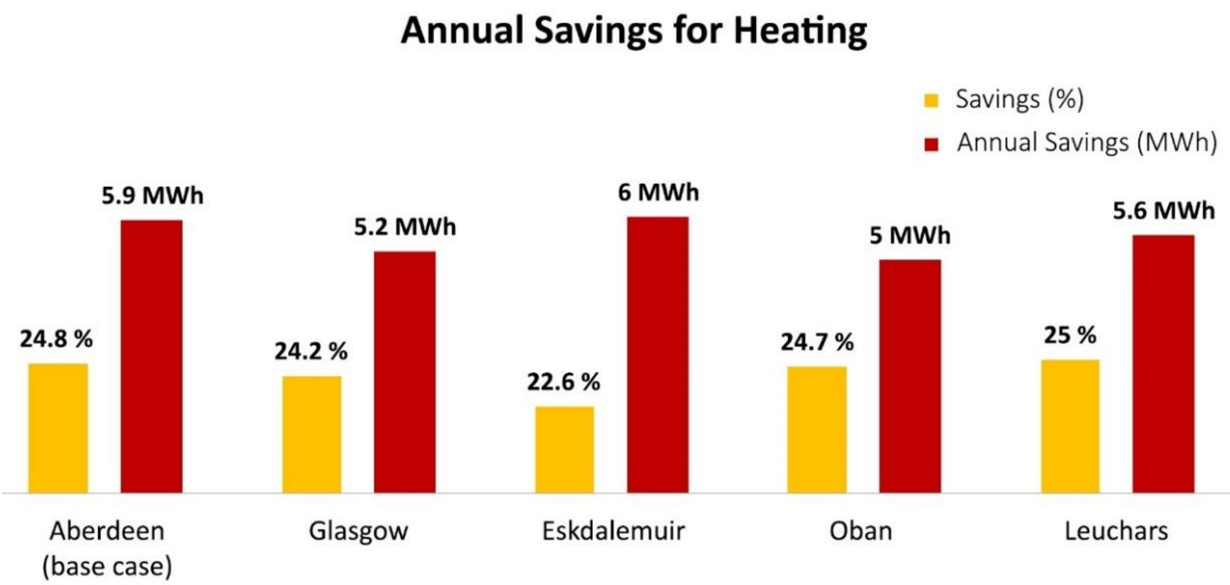
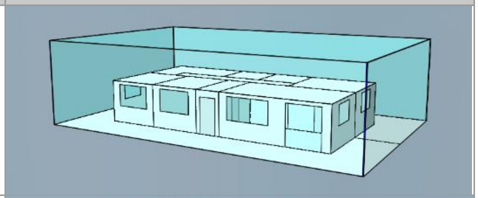
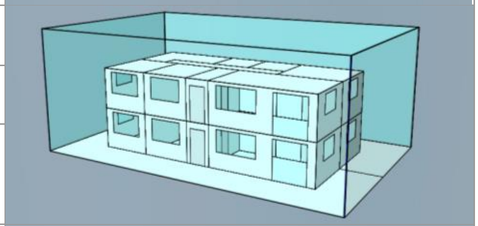
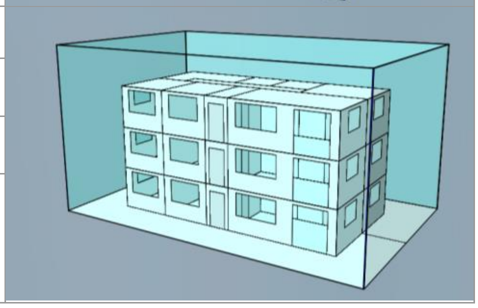



*Figure 87: Annual energy savings for heating in percentage (%) and absolute value (MWh) due to the greenhouse implementation for different locations in Scotland*

### 4.2.6 Greenhouse effectiveness in a multi-storey dwelling.

Simulation results about the energy performance of a single-, two-, and three-storey dwelling, before and after the greenhouse implementation, are presented below:

*Table 17: Annual heating requirements without and with the greenhouse – dwelling with different number of storeys*

| Annual Heating Demand (MWh) | | | |
|---|---|---|---|
| **Number of storeys** | **No Greenhouse** | **With Greenhouse** | **Greenhouse residence typology** |
| **Single-storey (base case)** | 23.7 | 17.8 |  |
| **Two-storey** | **1st:** 19.4 | **1st:** 14.9 |  |
| | **2nd:** 20.7 | **2nd:** 15 | |
| | **Total: 40.1** | **Total: 29.9** | |
| **Thee-storey** | **1st:** 21.2 | **1st:** 14.6 |  |
| | **2nd:** 16.5 | **2nd:** 12.1 | |
| | **3rd:** 18.7 | **3rd:** 14.8 | |
| | **Total: 56.4** | **Total: 41.5** | |

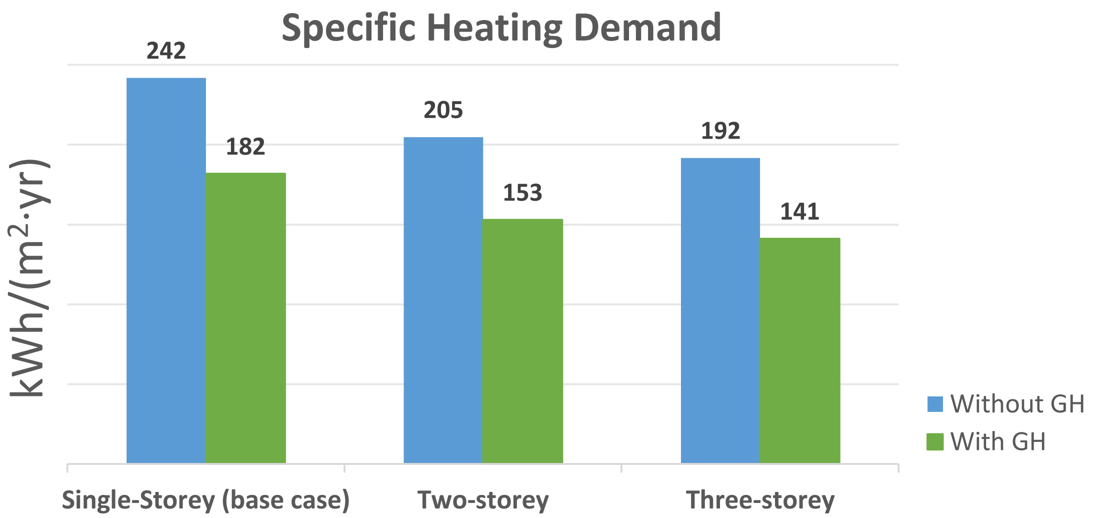



*Figure 88: Specific heating requirements without and with the greenhouse – Effect of number of storeys*

A building's total annual heating consumption normalised by floor area normally decreases as the number of storeys increases, due to the smaller ratio of exposed surfaces to the building volume. This inversely proportional relationship is also observed in Figure 88, with the three-storey dwelling consuming 50 kWh/m$^2$/year less compared to the baseline, single-storey dwelling. Nevertheless, an interesting finding is that in all three cases simulated, the total heating demands of the dwellings fell by the same percentage after the greenhouse addition, namely by one fourth (Figure 89).

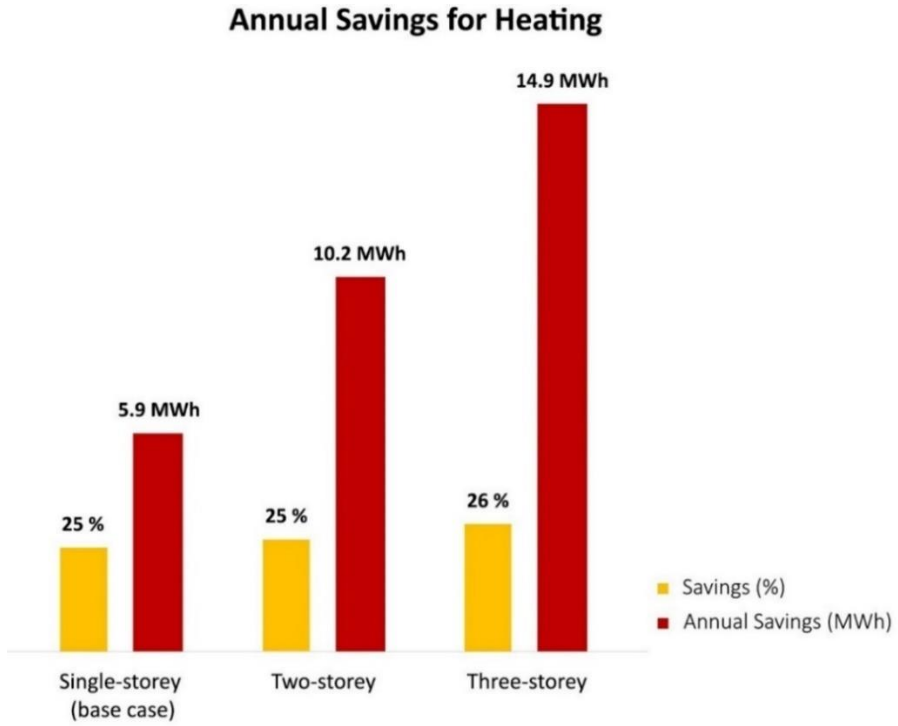



*Figure 89: Annual energy savings for heating in percentage (%) and absolute value (MWh) due to the greenhouse implementation for dwellings with different number of storeys*

Another interesting result is how the saving potentials vary by building level. Figure 90 gives a breakdown of the energy saved in each storey. There is a considerable 10% difference in the energy saving potentials between the base-floor and the third storey of a three-storey dwelling, with the former reporting the biggest reduction in the heating load, by about one third, and the latter by one fifth. On the contrary, both levels of a two-storey building reported similar percentages in savings for space heating, as shown in the blue bars below.

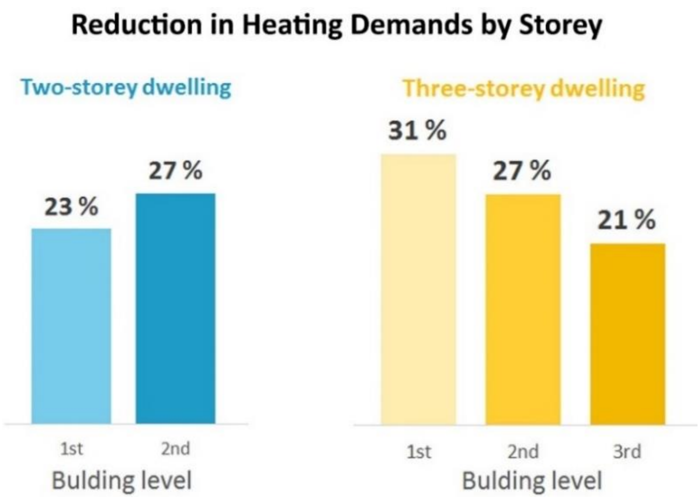



*Figure 90: Comparison of energy saving potentials by building level*

As has been discussed, temperature level is a major parameter to be considered when studying a greenhouse residence. Graphs below illustrate the air temperature fluctuations in the three south-west oriented bedrooms of a three-dwelling house for a summer week, with and without the glass encasement. As expected, the upper floors experienced overall higher temperatures, which must also be considered when applying measures to deal with overheating.

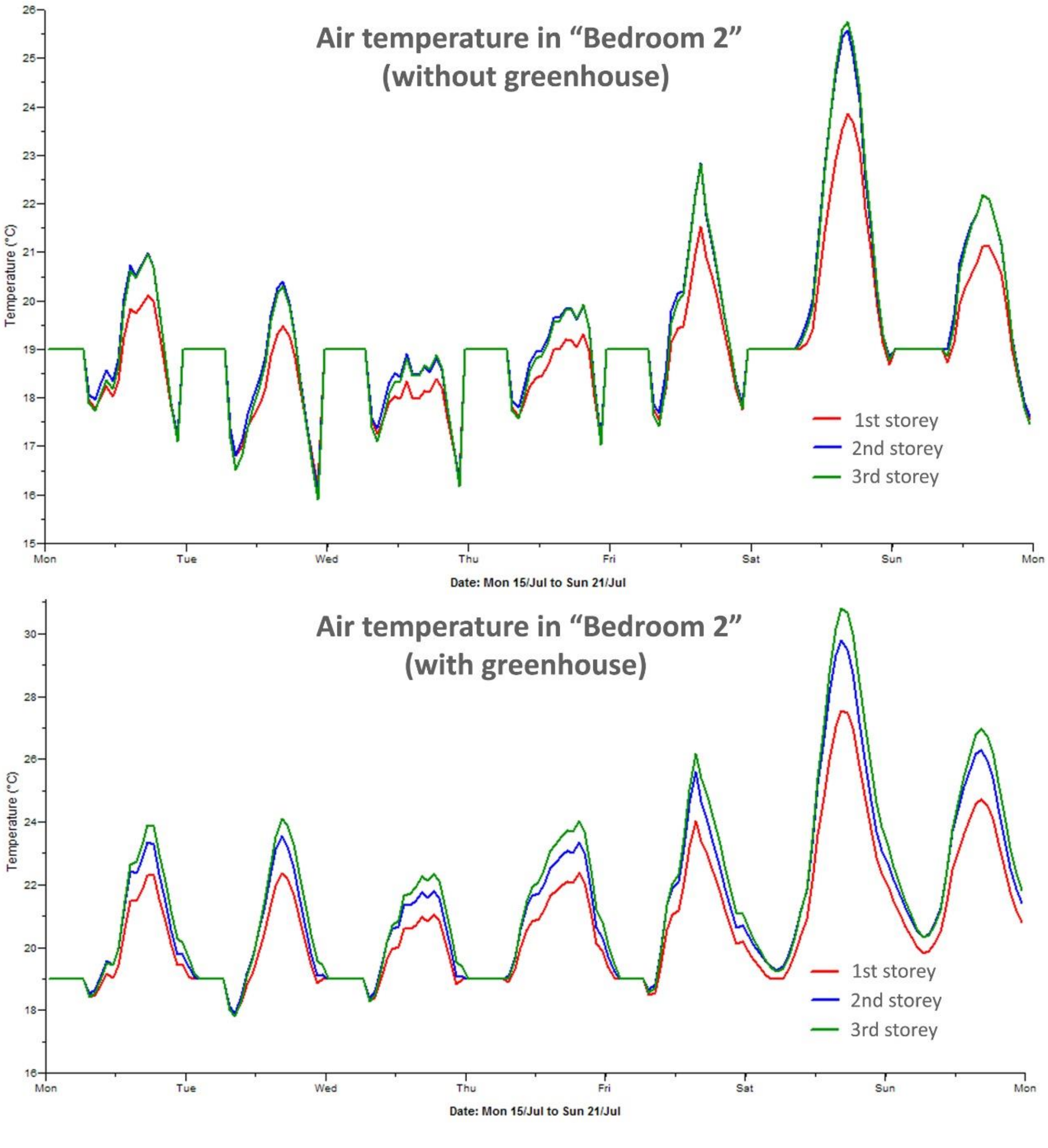



*Figure 91: Temperature fluctuations in "Bedroom 2" (south-west facade) in all three levels of the three-storey case study house for a summer week, without and with the greenhouse*

# 5 Conclusions

## 5.1 Key findings

The energy reduction potentials and thermal comfort conditions in greenhouse residences in Scotland have been investigated by performing dynamic simulations for a number of design variations in a reference detached dwelling. Results showed that the "house-within-a-greenhouse" concept can be successfully applied in detached houses in Scotland.

To begin with, the analysis carried out verified the claim documented in literature that the main drawback associated with the greenhouse residence concept is the overheating risk. Simulations also indicated the imperative need for providing proper ventilation in the structure. Indeed, when the greenhouse was not ventilated, inside temperatures reached intolerable levers, up to 40°C. Opening the windows on the greenhouse façade was proven to be a satisfactory mitigating measure against overheating; it decreased the hours of discomfort and the maximum temperatures both in the garden area and the in building zones, without necessarily a negative impact on the energy saving potentials. On the contrary, increasing the natural ventilation rate of the dwelling while keeping greenhouse windows closed exacerbated the problem with high temperatures.

The analysis indicated, however, that it is hardly possible to fully address the overheating issue based solely on ventilation strategies. In this study, sun shading was ignored, which is likely an important limitation to a justified appraisal of the dwelling's thermal comfort status as it would decrease the solar gains. Based on that, it is reckoned that, the combination of suitable ventilation strategies with shading devices can make the creation of acceptable thermal conditions inside a greenhouse residence achievable.

Furthermore, the fact that the cooling of the spaces highly depends on the air exchanges with the external environment signifies that, as expected, a non-air conditioned greenhouse residence performs better in cool climates.

Investigation on the energy performance of the base case detached dwelling showed that greenhouse residences have the potential to reduce the energy demand by approximately 25% (or equivalently about 60kWh/$m^2$ per year) in comparison to a conventional non-sheltered building, by taking advantage of the increased solar gains (greenhouse effect) and the reduced heat losses. However, the magnitude of this potential is influenced by the various design parameters involved in the whole structure.

Results indicated the most influential parameters regarding the potential in heating demand reduction are the building's thermal insulation level and the glazing type of the greenhouse. More specifically, among the different thermal envelopes tested, by far the greatest saving potentials were achieved for a badly insulated house which consumed 43% less energy for space heating after the greenhouse incorporation. The study also showed that the idea of a glass residence can also be effective in already well-insulated homes. Overall, in all three cases the glass shelter performed similarly to an additional external insulation for existing buildings.

In terms of energy performance, a double-glazed greenhouse performs noticeably better that a single-glazed one, but with respect to thermal comfort, the overheating problem is exacerbated by 3℃ to 5℃ in the main building and almost 10℃ in the garden area.

Calculations of the annual energy demand in a greenhouse residence for various distances between the glass facade and the building envelope (1.25m, 2,5m, and 5m) showed that their overall effect in the results is moderate. However, it was clear that the smaller the greenhouse size is, the higher the saving potentials become. On the other hand, building the greenhouse close to the house facades entails higher overheating risk and also limits the extra living area created under the glass skin.

Simulations were conducted for five locations in Scotland, giving very similar results. It hence seems fair to assume that these findings can be adopted for other locations across Scotland, as well. Results also showed that the positioning (orientation) of the greenhouse in relation to the main building has practically no influence in the total annual heating requirements.

Regarding the investigation on multi-storey greenhouse dwellings (one, two, and three storeys), the important observation was that the percentage decrease in the total heating demands was the same for all cases, namely one fourth. Energy consumption followed similar patterns for both levels of the two-storey dwelling. On the contrary, in the case of a three-storey house, although the base-floor had generally higher heating demands, it proved to benefit considerably more from the greenhouse presence compared to the other floors, which additionally suffered from higher indoor temperatures.

## 5.2 Further considerations

In addition to insulating the building and reducing its heating loads, a direct impact of the glass skin is that it shelters the outside areas, creating additional living spaces that can be used irrespective of transient outdoor conditions and low temperatures. Keeping in mind the characteristics of Scotland's climate, where strong winds are very common and rainfalls occur on average half of the days of the year, the creation of such protected areas that can be used most of the year is a very important benefit. The glass protection also increases the durability of housing units and the building's envelope against weather influences. This means either maintenance savings for the occupants of existing dwellings or the ability to construct a new house with simpler – and cheaper – materials, without having to compromise their indoor thermal comfort.

Adding the reduced construction and maintenance costs to the savings from the lower energy bills, the idea of the glass encasements becomes very appealing for householders. However, the cost of installing the glass units is a factor that should also be accounted and apparently increases with the structure size. In general, capital costs, saving potentials and payback periods are critical parameters to be considered when comparing various energy improvement solutions. In contrast to most house upgrade measures that are limited to energy and cost savings, and often improved indoor conditions, a greenhouse residence involves a wider range of benefits from the creation of living areas with favourable weather conditions to the possibility of growing various plants for extended periods. It is therefore suggested that all these aspects be taken into consideration by a homeowner when deciding for a house upgrade investment.

It is hoped that the findings will be useful for a range of stakeholders, including researchers, building engineers, house designers, owners, and – hopefully – policy makers. It is worth mentioning that, the cost of installing a greenhouse around a residence currently falls entirely on the owner as there are not government subsidies for this type of building upgrade. The results of this study can contribute to the promotion of the use of glass as an external insulation means in the form of a greenhouse residence and their inclusion in future government energy efficiency schemes.

## 5.3 Future suggestions

The objectives and the aim of this project have been met. The results and the analysis carried out revealed a number of useful findings regarding the applicability of the greenhouse residence concept in Scottish detached dwellings. However, this research has also raised a number of questions and areas for further investigation in the future. Suggestions for further work related to this study are organized into three broad areas:

***Building modelling***

A number of assumptions have been made in the modelling stage of this study, as described in Chapter 3.2. Introducing additional aspects in the model that may influence the performance of a greenhouse residence would be of value. Such aspects include but are not limited to:

a) the effect of any trees or casual heat gains within the greenhouse
b) the effect of shading devices
c) use of a Mechanical Ventilation with Heat Recovery system
d) solar panels as part of the greenhouse surface and their contribution in the dwelling's energy balance.

***Comparison with other energy saving measures***

The "house-within-a-greenhouse" concept has proved to offer remarkable reductions in energy demands when applied in cold climates. Nonetheless, its effectiveness as an energy saving strategy should additionally be compared with other energy saving improvements (e.g. installing insulation, heating system upgrade, integrating renewable technologies, etc.), under both an energy and a cost analysis.

***Building types***

The research carried out in this project focused exclusively on detached dwellings. An expansion on this theme would be an analogous investigation on different types of Scottish residences (semi-detached, flats, terraced, tenements). Furthermore, an investigation in covering non-domestic structures (e.g. offices, hotels, shopping centres, restaurants, etc.) with a glass shell could be another interesting research subject, as these buildings feature significantly different occupancy profiles, equipment and heating regimes, and in turn casual heat gains and energy requirements.

Finally, the outcomes of this study could contribute to future investigations in the use of glass a protection and insulation means for buildings, and enhance the existing knowledge on the potential of greenhouse residences.

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# Appendix A – Constructions

## Baseline dwelling

| External wall | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density kg/m³ | Specific Heat Capacity J/(kg·K) | Resistance m²·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| BRICKWORK (OUTER LEAF) | 110 | 0.7 | 1700 | 800 | 0.1571 | 58 |
| DENSE EPS SLAB INSULATON – LIKE STYROFOAM | 85 | 0.025 | 30 | 1400 | 3.4 | 830 |
| CONCRETE BLOCK | 110 | 0.51 | 1400 | 1000 | 0.2157 | 120 |
| GYPSUM PLASTERING | 15 | 0.42 | 1200 | 837 | 0.0357 | 45 |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value (W/m²·K) | **0.2513** |
| Total R-value (m²·K/W) | 3.8085 |

| Internal partition | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density kg/m³ | Specific Heat Capacity J/(kg·K) | Resistance m²·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| GYPSUM PLASTERBOARD | 15 | 0.16 | 950 | 840 | 0.0938 | - |
| CAVITY | 100 | - | - | - | 0.18 | - |
| GYPSUM PLASTERBOARD | 15 | 0.16 | 950 | 840 | 0.0938 | - |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value (W/m²·K) | **1.5936** |
| Total R-value (m²·K/W) | 0.3675 |

| Roof | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density kg/m³ | Specific Heat Capacity J/(kg·K) | Resistance m²·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| CLAY TILE - HF-C1 | 25 | 0.571 | 1121 | 837 | 0.0438 | 200 |
| ASPHALT | 20 | 0.4 | 1700 | 1000 | 0.05 | 5000 |
| FIBREBOARD | 14 | 0.06 | 300 | 1000 | 0.2333 | 263 |
| CAVITY | 25 | - | - | - | 0.18 | - |
| GLASS-FIBRE QUILT | 70 | 0.04 | 12 | 840 | 1.75 | 6 |
| GYPSUM PLASTERBOARD | 15 | 0.16 | 950 | 840 | 0.0938 | 45 |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value (W/m²·K) | **0.4015** |
| Total R-value (m²·K/W) | 2.3509 |

| Ground floor | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density $kg/m^3$ | Specific Heat Capacity J/(kg·K) | Resistance $m^2·K/W$ | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| LONDON CLAY | 750 | 1.41 | 1900 | 1000 | 0.5319 | 250 |
| BRICKWORK (OUTER LEAF) | 250 | 0.840 | 1700 | 800 | 0.2976 | 58 |
| CAST CONCRETE | 100 | 1.13 | 2000 | 1000 | 0.0885 | 500 |
| DENSE EPS SLAB INSULATION – LIKE STYROFOAM | 25 | 0.025 | 30 | 1400 | 1 | 830 |
| CHIPBOARD | 25 | 0.15 | 800 | 2093 | 0.1667 | 450 |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value ($W/m^2·K$) | 0.4358 |
| Total R-value ($m^2·K/W$) | 1.5528 |

| Door | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density $kg/m^3$ | Specific Heat Capacity J/(kg·K) | Resistance $m^2·K/W$ | Vapour Resisitivity GN·/(kg·m) |
| PLYWOOD | 37 | 0.2265 | 500 | 1500 | 0.1633 | - |

| | |
|---|---|
| U -value ($W/m^2·K$) | 3 |
| Total R-value ($m^2·K/W$) | 0.1633 |

| Window | | | | | | | |
|---|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Resistance $m^2·K/W$ | Transmittance | Outside reflectance | Inside reflectance | Refractive Index |
| Outer surface | | | | | | | |
| CLEAR FLOAT 6MM | 6 | 1.06 | 0.0057 | 0.8 | 0.07 | 0.07 | 1.526 |
| CAVITY | 12 | - | 0.1588 | - | - | - | |
| CLEAR FLOAT 6MM | 6 | 1.06 | 0.0057 | 0.8 | 0.07 | 0.07 | 1.526 |
| Inner surface | | | | | | | |

| | |
|---|---|
| Net U -value (including frame) ($W/m^2·K$) | 2.8085 |
| U-value (glass only) | 2.8892 |
| Total R-value ($m^2·K/W$) | 0.3461 |
| g-value | 0.7270 |

## Old, poorly insulated dwelling

| External wall | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density $kg/m^3$ | Specific Heat Capacity J/(kg·K) | Resistance $m^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| BRICKWORK (OUTER LEAF) | 210 | 0.75 | 1700 | 800 | 0.28 | 58 |
| PLASTER (DENSE) | 12 | 0.45 | 1300 | 1000 | 0.0276 | 50 |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value ($W/m^2$·K) | **2.0979** |
| Total R-value ($m^2$·K/W) | 0.3067 |

| Internal partition | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density $kg/m^3$ | Specific Heat Capacity J/(kg·K) | Resistance $m^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| GYPSUM PLASTERBOARD | 14 | 0.2 | 950 | 840 | 0.7 | - |
| BRICKWORK (INNER LEAF) | 100 | 0.8 | 1700 | 800 | 0.125 | - |
| GYPSUM PLASTERBOARD | 14 | 0.2 | 950 | 840 | 0.7 | - |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value ($W/m^2$·K) | **1.9048** |
| Total R-value ($m^2$·K/W) | 0.2650 |

| Roof | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density $kg/m^3$ | Specific Heat Capacity J/(kg·K) | Resistance $m^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| SLATE TILES | 20 | 2 | 2700 | 753 | 0.01 | 250 |
| ASPHALT | 20 | 0.5 | 1700 | 1000 | 0.4 | 5000 |
| SCREED | 60 | 0.41 | 1200 | 840 | 0.1463 | 50 |
| CONCRETE BLOCK (HEAVYWEIGHT) | 160 | 1.63 | 2300 | 1000 | 0.0982 | 150 |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value ($W/m^2$·K) | **2.3015** |
| Total R-value ($m^2$·K/W) | 0.2945 |

| Ground floor | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density $kg/m^3$ | Specific Heat Capacity J/(kg·K) | Resistance $m^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| LONDON CLAY | 750 | 1.41 | 1900 | 1000 | 0.5319 | 250 |
| BRICKWORK (OUTER LEAF) | 250 | 0.840 | 1700 | 800 | 0.2976 | 58 |
| CAVITY | 200 | - | - | - | 0.22 | - |
| CHIPBOARD | 25 | 0.15 | 800 | 2093 | 0.1667 | 450 |
| SYNTHETIC CARPET | 10 | 0.06 | 160 | 2500 | 0.1667 | 25 |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value ($W/m^2$·K) | 0.6278 |
| Total R-value ($m^2$·K/W) | 0.8510 |

| Door | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density $kg/m^3$ | Specific Heat Capacity J/(kg·K) | Resistance $m^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| PLYWOOD | 37 | 0.2265 | 500 | 1500 | 0.1633 | - |

| | |
|---|---|
| U -value ($W/m^2$·K) | 3 |
| Total R-value ($m^2$·K/W) | 0.1633 |

| Window | | | | | | | |
|---|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Resistance $m^2$·K/W | Transmittance | Outside reflectance | Inside reflectance | Refractive Index |
| Outer surface | | | | | | | |
| CLEAR FLOAT 6MM | 7 | 1.06 | 0.0066 | 0.78 | 0.07 | 0.07 | 1.526 |
| Inner surface | | | | | | | |

| | |
|---|---|
| Net U -value (including frame) ($W/m^2$·K) | 4.8089 |
| U-value (glass only) | 5.6624 |
| Total R-value ($m^2$·K/W) | 0.1766 |
| g-value | 0.8201 |

## New, highly insulated dwelling

| External wall | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density kg/m$^3$ | Specific Heat Capacity J/(kg·K) | Resistance m$^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| BRICKWORK (OUTER LEAF) | 120 | 0.75 | 1700 | 800 | 0.16 | 58 |
| DENSE EPS SLAB INSULATON – LIKE STYROFOAM | 100 | 0.02 | 30 | 1400 | 5 | 830 |
| CONCRETE BLOCK (MEDIUM) | 110 | 0.065 | 1400 | 1000 | 1.6923 | 120 |
| GYPSUM PLASTERING | 15 | 0.42 | 1200 | 837 | 0.0357 | - |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value (W/m$^2$·K) | **1.9773** |
| Total R-value (m$^2$·K/W) | 6.8880 |

| Internal partition | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density kg/m$^3$ | Specific Heat Capacity J/(kg·K) | Resistance m$^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| GYPSUM PLASTERBOARD | 15 | 0.16 | 950 | 840 | 0.0938 | - |
| CAVITY | 100 | - | - | - | 0.18 | - |
| GYPSUM PLASTERBOARD | 15 | 0.16 | 950 | 840 | 0.0938 | - |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value (W/m$^2$·K) | **1.5936** |
| Total R-value (m$^2$·K/W) | 0.3675 |

| Roof | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density kg/m$^3$ | Specific Heat Capacity J/(kg·K) | Resistance m$^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| CLAY TILE | 20 | 0.7 | 1900 | 800 | 0.0286 | 200 |
| INSULATION | 120 | 0.023 | 40 | 1450 | 5.2174 | - |
| MEMBRANE | 0.1 | 1 | 1100 | 1000 | 0.0001 | - |
| CONCRETE DECK | 100 | 2 | 2400 | 1000 | 0.05 | - |
| CAVITY | 40 | - | - | - | 0.16 | - |
| PLASTERBOARD | 14 | 0.2 | 700 | 1000 | 0.07 | 0 |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value (W/m$^2$·K) | **0.1765** |
| Total R-value (m$^2$·K/W) | 5.5261 |

| Ground floor | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density kg/m$^3$ | Specific Heat Capacity J/(kg·K) | Resistance m$^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| Outer surface | | | | | | |
| INSULATION | 115 | 0.02 | 700 | 1000 | 5.75 | |
| REINFORCED CONCRETE | 150 | 2.3 | 2300 | 1000 | 0.0652 | |
| CAVITY | 50 | - | - | - | 0.21 | |
| CHIPBOARD FLOORING | 40 | 0.13 | 500 | 1600 | 0.3077 | |
| Inner surface | | | | | | |

| | |
|---|---|
| U -value (W/m$^2$·K) | **0.1528** |
| Total R-value (m$^2$·K/W) | 6.3329 |

| Door | | | | | | |
|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Density kg/m$^3$ | Specific Heat Capacity J/(kg·K) | Resistance m$^2$·K/W | Vapour Resisitivity GN·/(kg·m) |
| PINE (20% MOIST) | 50 | 0.11 | 419 | 2720 | 0.4545 | 200 |

| | |
|---|---|
| U -value (W/m$^2$·K) | 1.6012 |
| Total R-value (m$^2$·K/W) | 0.4545 |

| Window | | | | | | | |
|---|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Resistance m$^2$·K/W | Transmittance | Outside reflectance | Inside reflectance | Refractive Index |
| Outer surface | | | | | | | |
| PILINGTON 6MM | 6 | 1.06 | 0.0057 | 0.69 | 0.09 | 0.09 | 1.526 |
| Cavity | 12 | - | 0.1588 | - | - | - | |
| PILINGTON 6MM | 6 | 1.06 | 0.0057 | 0.69 | 0.09 | 0.09 | 1.526 |
| Inner surface | | | | | | | |

| | |
|---|---|
| Net U -value (including frame) (W/m$^2$·K) | 1.9773 |
| U-value (glass only) | 1.9762 |
| Total R-value (m$^2$·K/W) | 0.5060 |
| g-value | 0.6157 |

## Greenhouse

| Glazing | | | | | | | |
|---|---|---|---|---|---|---|---|
| Material | Thickness mm | Conductivity W/(m·K) | Resistance $m^2·K/W$ | Transmittance | Outside reflectance | Inside reflectance | Refractive Index |
| **Outer surface** | | | | | | | |
| CLEAR FLOAT 12MM | 12 | 1.06 | 0.0113 | 0.8 | 0.06 | 0.06 | 1.526 |
| **Inner surface** | | | | | | | |

| | |
|---|---|
| Net U -value (including frame) ($W/m^2·K$) | 5.79 |
| U-value (glass only) | 5.7696 |
| Total R-value ($m^2·K/W$) | 0.1733 |
| g-value | 0.83 |

## Appendix B – Overheating risk

Tables below give the maximum air temperatures and the number of hours of discomfort in the building rooms and the greenhouse, for each design scenario examined. These results are based on zero ventilation rate for the greenhouse and the baseline rates for the main building, i.e. 21L/s for natural ventilation and 0.14 L/(s·m$^2$) for infiltration.

Unless mentioned otherwise, the data shown in the following Tables assume the following characteristics for the building model:

- **Building thermal envelope:** Average insulation/energy performance
- **Greenhouse positioning:** Symmetrical (2.5m distance between the glass facades and the building external walls/roof)
- **Greenhouse glazing type:** Single glazing
- **Greenhouse size:** 19m x 12m x 5m
- **Building location:** Aberdeen
- **Number of storeys:** One

Any changes made in each design variation have been described in the relevant Chapter with the design variations.

### Base case building

| Base case | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours > 25 °C | Peak Air Temperature | | Hours > 25 °C |
| | Time | (°C) | | Time | (°C) | |
| Bedroom 2 | 16:30, 27/Jul | 28.36 | 39 | 17:30, 27/Jul | 35.84 | 687 |
| Bedroom 3 | 16:30, 27/Jul | 27.47 | 21 | 17:30, 27/Jul | 35.58 | 660 |
| Bathroom | 19:30, 27/Jul | 23.47 | 0 | 18:30, 27/Jul | 32.55 | 377 |
| Store/ Cloakroom | 19:30, 11/Aug | 23.34 | 0 | 18:30, 27/Jul | 32.49 | 383 |
| Hall 1 | 17:30, 27/Jul | 26.33 | 18 | 17:30, 27/Jul | 37.19 | 772 |
| Living room | 15:30, 04/Aug | 31.73 | 300 | 17:30, 27/Jul | 38.22 | 1265 |
| Kitchen | 19:30, 27/Jul | 24.92 | 0 | 18:30, 27/Jul | 33.87 | 720 |
| Bedroom 1 | 18:30, 27/Jul | 23.88 | 0 | 18:30, 27/Jul | 31.43 | 346 |
| Hall 2 | 19:30, 27/Jul | 25.39 | 3 | 18:30, 27/Jul | 34.42 | 555 |
| Greenhouse | - | - | - | 15:30, 27/Jul | 39.67 | 534 |

## Different thermal envelopes

| Old dwelling (poorly insulated) | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| Bedroom 2 | 16:30, 27/Jul | 24.52 | 0 | 17:30,27/Jul | 33.4 | 866 |
| Bedroom 3 | 15:30, 27/Jul | 23.09 | 0 | 16:30,30 Jul | 31.46 | 733 |
| Bathroom | 19:30, 27/Jul | 21.93 | 0 | 18:30,27/Jul | 29.77 | 387 |
| Store/ Cloakroom | 19:30, 11/Aug | 21.97 | 0 | 19:30,27/Jul | 29.74 | 400 |
| Hall 1 | 19:30, 27/Jul | 22.78 | 0 | 17:30,27/Jul | 31.72 | 625 |
| Living room | 15:30, 27/Jul | 25.55 | 8 | 17:30,30/Jul | 34.74 | 1233 |
| Kitchen | 19:30, 27/Jul | 23.11 | 0 | 18:30,30/Jul | 32.1 | 870 |
| Bedroom 1 | 19:30, 27/Jul | 22.18 | 0 | 19:30,27/Jul | 30.64 | 600 |
| Hall 2 | 20:30, 27/Jul | 22.06 | 0 | 18:30,30 Jul | 29.62 | 528 |
| Greenhouse | - | - | - | 15:30,27/Jul | 37.61 | 438 |

| New dwelling (highly insulated) | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| Bedroom 2 | 16:30, 27/Jul | 28.45 | 74 | 16:30, 04/Aug | 35.28 | 869 |
| Bedroom 3 | 15:30, 27/Jul | 26.74 | 20 | 16:30, 04/Aug | 33.79 | 718 |
| Bathroom | 15:30, 11/Aug | 22.96 | 0 | 17:30, 27/Jul | 30.81 | 334 |
| Store/ Cloakroom | 19:30, 11/Aug | 22.94 | 0 | 17:30, 27/Jul | 30.72 | 336 |
| Hall 1 | 16:30, 11/Aug | 25.15 | 5 | 17:30, 27/Jul | 34.42 | 726 |
| Living room | 14:30, 04/Aug | 32.64 | 585 | 15:30, 04/Aug | 38.37 | 1880 |
| Kitchen | 18:30, 11/Aug | 24.78 | 0 | 17:30, 04/Aug | 31.84 | 886 |
| Bedroom 1 | 17:30, 27/Jul | 23.58 | 0 | 17:30, 30/Jul | 30.03 | 347 |
| Hall 2 | 19:30, 27/Jul | 24.11 | 0 | 17:30, 27/Jul | 31.5 | 523 |
| Greenhouse | - | - | - | 15:30, 27/Jul | 40.55 | 576 |

## Different greenhouse orientations

| North GH orientation | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| Bedroom 2 | 16:30, 27/Jul | 28.36 | 39 | 17:30, 27/Jul | 36.04 | 700 |
| Bedroom 3 | 16:30, 27/Jul | 27.47 | 21 | 17:30, 27/Jul | 35.75 | 670 |
| Bathroom | 19:30, 27/Jul | 23.47 | 0 | 18:30, 27/Jul | 32.75 | 389 |
| Store/ Cloakroom | 19:30, 11/Aug | 23.34 | 0 | 18:30, 27/Jul | 32.68 | 398 |
| Hall 1 | 17:30, 27/Jul | 26.33 | 18 | 17:30, 27/Jul | 37.41 | 780 |
| Living room | 15:30, 04/Aug | 31.73 | 300 | 17:30, 27/Jul | 38.37 | 1271 |
| Kitchen | 19:30, 27/Jul | 24.92 | 0 | 18:30, 27/Jul | 34.05 | 733 |
| Bedroom 1 | 18:30, 27/Jul | 23.88 | 0 | 18:30, 27/Jul | 31.59 | 357 |
| Hall 2 | 19:30, 27/Jul | 25.39 | 3 | 19:30, 27/Jul | 34.62 | 570 |
| Greenhouse | - | - | - | 15:30, 27/Jul | 39.83 | 551 |

| South GH orientation | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| Bedroom 2 | 16:30, 27/Jul | 28.36 | 39 | 17:30, 27/Jul | 36.19 | 738 |
| Bedroom 3 | 16:30, 27/Jul | 27.47 | 21 | 17:30, 27/Jul | 35.92 | 706 |
| Bathroom | 19:30, 27/Jul | 23.47 | 0 | 18:30, 27/Jul | 32.83 | 408 |
| Store/ Cloakroom | 19:30, 11/Aug | 23.34 | 0 | 18:30, 27/Jul | 32.77 | 413 |
| Hall 1 | 17:30, 27/Jul | 26.33 | 18 | 17:30, 27/Jul | 37.55 | 805 |
| Living room | 15:30, 04/Aug | 31.73 | 300 | 17:30, 04/Aug | 38.74 | 1290 |
| Kitchen | 19:30, 27/Jul | 24.92 | 0 | 18:30, 27/Jul | 34.14 | 755 |
| Bedroom 1 | 18:30, 27/Jul | 23.88 | 0 | 18:30, 27/Jul | 31.67 | 377 |
| Hall 2 | 19:30, 27/Jul | 25.39 | 3 | 18:30, 27/Jul | 34.72 | 593 |
| Greenhouse | - | - | - | 15:30, 27/Jul | 40.01 | 571 |

| East GH orientation | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| Bedroom 2 | 16:30, 27/Jul | 28.36 | 39 | 17:30,27/Jul | 35.61 | 657 |
| Bedroom 3 | 16:30, 27/Jul | 27.47 | 21 | 17:30,27/Jul | 35.3 | 630 |
| Bathroom | 19:30, 27/Jul | 23.47 | 0 | 18:30,27/Jul | 32.26 | 347 |
| Store/ Cloakroom | 19:30, 11/Aug | 23.34 | 0 | 18:30,27/Jul | 32.2 | 355 |
| Hall 1 | 17:30, 27/Jul | 26.33 | 18 | 17:30,27/Jul | 36.92 | 726 |
| Living room | 15:30, 04/Aug | 31.73 | 300 | 17:30,27/Jul | 37.9 | 1221 |
| Kitchen | 19:30, 27/Jul | 24.92 | 0 | 18:30,27/Jul | 33.58 | 671 |
| Bedroom 1 | 18:30, 27/Jul | 23.88 | 0 | 18:30,27/Jul | 31.22 | 316 |
| Hall 2 | 19:30, 27/Jul | 25.39 | 3 | 18:30,27/Jul | 34.17 | 528 |
| Greenhouse | - | - | - | 15:30,27/Jul | 39.51 | 524 |

| West GH orientation | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| **Room** | **Peak Air Temperature** | | **Hours** | **Peak Air Temperature** | | **Hours** |
| | **Time** | **(°C)** | **T>25°C** | **Time** | **(°C)** | **T>25°C** |
| **Bedroom 2** | 16:30, 27/Jul | 28.36 | 39 | 17:30 27/Jul | 35.51 | 653 |
| **Bedroom 3** | 16:30, 27/Jul | 27.47 | 21 | 17:30 27/Jul | 35.34 | 628 |
| **Bathroom** | 19:30, 27/Jul | 23.47 | 0 | 18:30 27/Jul | 32.29 | 349 |
| **Store/ Cloakroom** | 19:30, 11/Aug | 23.34 | 0 | 18:30 27/Jul | 32.25 | 355 |
| **Hall 1** | 17:30, 27/Jul | 26.33 | 18 | 17:30 27/Jul | 36.97 | 728 |
| **Living room** | 15:30, 04/Aug | 31.73 | 300 | 17:30 27/Jul | 37.97 | 1223 |
| **Kitchen** | 19:30, 27/Jul | 24.92 | 0 | 18:30 27/Jul | 33.66 | 671 |
| **Bedroom 1** | 18:30, 27/Jul | 23.88 | 0 | 18:30 27/Jul | 31.1 | 312 |
| **Hall 2** | 19:30, 27/Jul | 25.39 | 3 | 18:30 27/Jul | 34.2 | 527 |
| **Greenhouse** | - | - | - | 15:30 27/Jul | 39.55 | 520 |

## Different greenhouse sizes

| 1.25m (half distance) | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| **Room** | **Peak Air Temperature** | | **Hours** | **Peak Air Temperature** | | **Hours** |
| | **Time** | **(°C)** | **T>25°C** | **Time** | **(°C)** | **T>25°C** |
| **Bedroom 2** | 16:30, 27/Jul | 28.36 | 39 | 17:30, 27/Jul | 37.16 | 880 |
| **Bedroom 3** | 16:30, 27/Jul | 27.47 | 21 | 17:30, 27/Jul | 36.97 | 842 |
| **Bathroom** | 19:30, 27/Jul | 23.47 | 0 | 18:30, 27/Jul | 34.03 | 560 |
| **Store/ Cloakroom** | 19:30, 11/Aug | 23.34 | 0 | 18:30, 27/Jul | 33.97 | 569 |
| **Hall 1** | 17:30, 27/Jul | 26.33 | 18 | 17:30, 27/Jul | 38.74 | 952 |
| **Living room** | 15:30, 04/Aug | 31.73 | 300 | 17:30, 27/Jul | 39.39 | 1438 |
| **Kitchen** | 19:30, 27/Jul | 24.92 | 0 | 18:30, 27/Jul | 35.14 | 954 |
| **Bedroom 1** | 18:30, 27/Jul | 23.88 | 0 | 18:30, 27/Jul | 32.64 | 545 |
| **Hall 2** | 19:30, 27/Jul | 25.39 | 3 | 18:30, 27/Jul | 35.85 | 758 |
| **Greenhouse** | - | - | - | 15:30, 27/Jul | 42.16 | 709 |

| 5m (double distance) | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| **Room** | **Peak Air Temperature** | | **Hours** | **Peak Air Temperature** | | **Hours** |
| | **Time** | **(°C)** | **T>25°C** | **Time** | **(°C)** | **T>25°C** |
| **Bedroom 2** | 16:30, 27/Jul | 28.36 | 39 | 17:30, 27/Jul | 34.73 | 564 |
| **Bedroom 3** | 16:30, 27/Jul | 27.47 | 21 | 17:30, 27/Jul | 34.41 | 526 |
| **Bathroom** | 19:30, 27/Jul | 23.47 | 0 | 18:30, 27/Jul | 31.27 | 234 |
| **Store/ Cloakroom** | 19:30, 11/Aug | 23.34 | 0 | 18:30, 27/Jul | 31.21 | 242 |
| **Hall 1** | 17:30, 27/Jul | 26.33 | 18 | 17:30, 27/Jul | 35.86 | 603 |
| **Living room** | 15:30, 04/Aug | 31.73 | 300 | 17:30, 27/Jul | 37.25 | 1127 |
| **Kitchen** | 19:30, 27/Jul | 24.92 | 0 | 18:30, 27/Jul | 32.8 | 553 |
| **Bedroom 1** | 18:30, 27/Jul | 23.88 | 0 | 18:30, 27/Jul | 30.38 | 213 |
| **Hall 2** | 19:30, 27/Jul | 25.39 | 3 | 19:30, 27/Jul | 33.2 | 426 |
| **Greenhouse** | - | - | - | 15:30, 27/Jul | 37.4 | 380 |

### Different greenhouse glazing types

| Double glazing | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| **Bedroom 2** | 16:30, 27/Jul | 28.36 | 39 | 17:30, 27/Jul | 39.04 | 1332 |
| **Bedroom 3** | 16:30, 27/Jul | 27.47 | 21 | 17:30, 27/Jul | 39.37 | 1300 |
| **Bathroom** | 19:30, 27/Jul | 23.47 | 0 | 17:30, 27/Jul | 37.33 | 1170 |
| **Store/Cloakroom** | 19:30, 11/Aug | 23.34 | 0 | 17:30, 27/Jul | 37.24 | 1191 |
| **Hall 1** | 17:30, 27/Jul | 26.33 | 18 | 17:30, 27/Jul | 41.64 | 1404 |
| **Living room** | 15:30, 04/Aug | 31.73 | 300 | 17:30, 27/Jul | 40.79 | 1799 |
| **Kitchen** | 19:30, 27/Jul | 24.92 | 0 | 18:30, 27/Jul | 37.57 | 1470 |
| **Bedroom 1** | 18:30, 27/Jul | 23.88 | 0 | 17:30, 30/Jul | 34.91 | 1112 |
| **Hall 2** | 19:30, 27/Jul | 25.39 | 3 | 18:30, 27/Jul | 38.66 | 1300 |
| **Greenhouse** | - | - | - | 15:30, 27/Jul | 48.48 | 1212 |

### Different locations in Scotland

| Glasgow | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| **Bedroom 2** | 16:30, 15/Aug | 29.48 | 105 | 17:30,16/Jul | 37.02 | 815 |
| **Bedroom 3** | 16:30, 13/Aug | 28.98 | 72 | 17:30, 16/Jul | 37.28 | 772 |
| **Bathroom** | 19:30, 15/Aug | 25.05 | 1 | 18:30, 16/Jul | 33.58 | 491 |
| **Store/ Cloakroom** | 19:30, 15/Aug | 25.06 | 1 | 18:30, 16/Jul | 33.54 | 494 |
| **Hall 1** | 18:30, 15/Aug | 28.41 | 41 | 17:30, 16/Jul | 38.99 | 839 |
| **Living room** | 15:30, 13/Aug | 33.54 | 407 | 17:30, 16/Jul | 40.12 | 1360 |
| **Kitchen** | 19:30, 15/Aug | 26.94 | 22 | 17:30, 17/Jul | 35.12 | 816 |
| **Bedroom 1** | 18:30, 15/Aug | 24.71 | 0 | 17:30, 17/Jul | 32.46 | 515 |
| **Hall 2** | 19:30, 15/Aug | 26.91 | 21 | 18:30, 16/Jul | 35.85 | 662 |
| **Greenhouse** | - | - | - | 15:30, 16/Jul | 41 | 566 |

| Eskdalemuir | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| **Bedroom 2** | 16:30, 07/Jul | 28.75 | 74 | 17:30,07/Jul | 39.02 | 582 |
| **Bedroom 3** | 16:30, 07/Jul | 27.81 | 58 | 16:30,07/Jul | 38.81 | 547 |
| **Bathroom** | 19:30, 07/Jul | 23.97 | 0 | 18:30,07/Jul | 35.11 | 318 |
| **Store/ Cloakroom** | 19:30, 07/Jul | 23.9 | 0 | 18:30,07/Jul | 35.09 | 318 |
| **Hall 1** | 17:30, 07/Jul | 27.33 | 30 | 17:30,07/Jul | 40.16 | 606 |
| **Living room** | 15:30, 20/Aug | 32.16 | 266 | 17:30,07/Jul | 41.66 | 945 |
| **Kitchen** | 19:30, 07/Jul | 26.13 | 9 | 18:30,07/Jul | 36.94 | 550 |
| **Bedroom 1** | 18:30, 07/Jul | 24.54 | 0 | 18:30,07/Jul | 34.19 | 318 |
| **Hall 2** | 19:30, 07/Jul | 26.05 | 6 | 18:30,07/Jul | 37.23 | 454 |
| **Greenhouse** | - | - | - | 15:30,07/Jul | 42.08 | 474 |

| Oban | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| Bedroom 2 | 17:30, 18/Jun | 30.03 | 49 | 17:30, 18/Jun | 38.73 | 667 |
| Bedroom 3 | 16:30, 18/Jun | 29.07 | 34 | 17:30, 18/Jun | 38.55 | 644 |
| Bathroom | 18:30, 19/Jun | 25.52 | 8 | 18:30, 18/Jun | 35.04 | 395 |
| Store/ Cloakroom | 18:30, 19/Jun | 25.56 | 8 | 18:30, 19/Jun | 35.08 | 405 |
| Hall 1 | 17:30, 18/Jun | 29.47 | 33 | 17:30, 18/Jun | 40.09 | 732 |
| Living room | 17:30, 19/Jun | 33.14 | 277 | 17:30, 18/Jun | 41.16 | 1178 |
| Kitchen | 18:30, 19/Jun | 28.47 | 25 | 18:30, 19/Jun | 37.14 | 692 |
| Bedroom 1 | 18:30, 18/Jun | 25.88 | 8 | 17:30, 19/Jun | 33.95 | 374 |
| Hall 2 | 18:30, 19/Jun | 27.54 | 18 | 18:30, 18/Jun | 37.05 | 560 |
| Greenhouse | - | - | - | 15:30, 18/Jun | 42.64 | 494 |

| Leuchars | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|
| Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| Bedroom 2 | 18:30,08/Jul | 28.23 | 53 | 17:30,09/Jul | 36.2 | 741 |
| Bedroom 3 | 16:30,08/Jul | 26.75 | 24 | 17:30,09/Jul | 35.77 | 693 |
| Bathroom | 20:30,08/Jul | 24.63 | 0 | 18:30,09/Jul | 32.78 | 435 |
| Store/ Cloakroom | 20:30,08/Jul | 24.45 | 0 | 18:30,09/Jul | 32.75 | 448 |
| Hall 1 | 19:30,08/Jul | 26.98 | 7 | 17:30,09/Jul | 36.72 | 790 |
| Living room | 15:30,24/Jul | 30.93 | 279 | 17:30,09/Jul | 38.57 | 1296 |
| Kitchen | 20:30,08/Jul | 25.55 | 4 | 18:30,09/Jul | 34.51 | 800 |
| Bedroom 1 | 19:30,08/Jul | 24.71 | 0 | 18:30,09/Jul | 32.35 | 428 |
| Hall 2 | 20:30,08/Jul | 26.21 | 5 | 18:30,09/Jul | 34.55 | 607 |
| Greenhouse | - | - | - | 16:30,08/Jul | 39.58 | 536 |

## Different number of storeys

| | 2-storey dwelling | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|---|
| | Room | Peak Air Temperature | | Hours | Peak Air Temperature | | Hours |
| | | Time | (°C) | T>25°C | Time | (°C) | T>25°C |
| 1st Storey | Bedroom 2 | 16:30, 27/Jul | 28.34 | 39 | 17:30, 27/Jul | 33.75 | 498 |
| | Bedroom 3 | 16:30, 27/Jul | 27.39 | 22 | 17:30, 27/Jul | 33.28 | 462 |
| | Bathroom | 19:30, 27/Jul | 23.32 | 0 | 18:30, 27/Jul | 30.38 | 195 |
| | Store/ Cloakroom | 19:30, 11/Aug | 23.3 | 0 | 18:30, 27/Jul | 30.34 | 200 |
| | Hall 1 | 17:30, 27/Jul | 26.28 | 18 | 17:30, 27/Jul | 35.08 | 576 |
| | Living room | 15:30, 04/Aug | 32.04 | 360 | 17:30, 27/Jul | 35.83 | 1075 |
| | Kitchen | 19:30, 27/Jul | 24.86 | 0 | 18:30, 27/Jul | 31.49 | 461 |
| | Bedroom 1 | 18:30, 27/Jul | 23.65 | 0 | 18:30, 27/Jul | 29.07 | 133 |
| | Hall 2 | 20:30, 27/Jul | 26.6 | 19 | 20:30, 27/Jul | 33.09 | 534 |
| 2nd Storey | Bedroom 2 | 16:30, 27/Jul | 31 | 130 | 17:30, 27/Jul | 38.19 | 889 |
| | Bedroom 3 | 15:30, 27/Jul | 30.17 | 101 | 17:30, 27/Jul | 38.37 | 891 |
| | Bathroom | 19:30, 27/Jul | 24.82 | 0 | 18:30, 27/Jul | 34.47 | 534 |
| | Store/ Cloakroom | 19:30, 27/Jul | 24.69 | 0 | 18:30, 27/Jul | 34.45 | 560 |
| | Hall 1 | 16:30, 27/Jul | 28.69 | 33 | 17:30, 27/Jul | 39.74 | 964 |
| | Living room | 14:30, 04/Aug | 35.77 | 647 | 16:30, 27/Jul | 41.57 | 1589 |
| | Kitchen | 19:30, 27/Jul | 26.74 | 23 | 18:30, 27/Jul | 36.43 | 1033 |
| | Bedroom 1 | 17:30, 27/Jul | 25.82 | 4 | 18:30, 27/Jul | 33.83 | 573 |
| | Hall 2 | 18:30, 27/Jul | 27.45 | 23 | 18:30, 27/Jul | 37.27 | 821 |
| | Greenhouse | - | - | - | 15:30, 27/Jul | 38.38 | 486 |

| | 3-storey dwelling | No Greenhouse | | | With Greenhouse | | |
|---|---|---|---|---|---|---|---|
| | **Room** | **Peak Air Temperature** | | **Hours** | **Peak Air Temperature** | | **Hours** |
| | | **Time** | **(°C)** | **T>25°C** | **Time** | **(°C)** | **T>25°C** |
| **1st Storey** | Bedroom 2 | 16:30, 27/Jul | 28.32 | 38 | 17:30, 27/Jul | 33.23 | 451 |
| | Bedroom 3 | 16:30, 27/Jul | 27.35 | 20 | 17:30, 27/Jul | 32.73 | 419 |
| | Bathroom | 19:30, 27/Jul | 23.2 | 0 | 18:30, 27/Jul | 29.9 | 159 |
| | Store/ Cloakroom | 19:30, 11/Aug | 23.21 | 0 | 18:30, 27/Jul | 29.86 | 164 |
| | Hall 1 | 17:30, 27/Jul | 26.24 | 18 | 17:30, 27/Jul | 34.51 | 532 |
| | Living room | 15:30, 04/Aug | 32.02 | 356 | 16:30, 27/Jul | 35.22 | 1018 |
| | Kitchen | 19:30, 27/Jul | 24.8 | 0 | 18:30, 27/Jul | 31.01 | 404 |
| | Bedroom 1 | 18:30, 27/Jul | 23.57 | 0 | 18:30, 27/Jul | 28.62 | 108 |
| | Hall 2 | 19:30, 27/Jul | 25.17 | 3 | 21:30, 27/Jul | 31.95 | 476 |
| **2nd Storey** | Bedroom 2 | 16:30, 27/Jul | 31 | 136 | 16:30, 27/Jul | 36.38 | 729 |
| | Bedroom 3 | 15:30, 27/Jul | 30.12 | 113 | 16:30, 27/Jul | 36.26 | 721 |
| | Bathroom | 19:30, 27/Jul | 24.61 | 0 | 18:30, 27/Jul | 32.22 | 366 |
| | Store/ Cloakroom | 19:30, 27/Jul | 24.5 | 0 | 18:30, 27/Jul | 32.23 | 383 |
| | Hall 1 | 16:30, 27/Jul | 28.63 | 34 | 17:30, 27/Jul | 37.79 | 829 |
| | Living room | 14:30, 04/Aug | 36.24 | 748 | 16:30, 27/Jul | 39.62 | 1497 |
| | Kitchen | 19:30, 27/Jul | 26.7 | 25 | 18:30, 27/Jul | 34.12 | 829 |
| | Bedroom 1 | 18:30, 27/Jul | 25.52 | 3 | 17:30, 27/Jul | 31.46 | 366 |
| | Hall 2 | 19:30, 27/Jul | 27.99 | 35 | 20:30, 27/Jul | 34.44 | 804 |
| **3rd Storey** | Bedroom 2 | 16:30, 27/Jul | 31.12 | 134 | 17:30, 27/Jul | 37.75 | 850 |
| | Bedroom 3 | 15:30, 27/Jul | 30.3 | 119 | 17:30, 27/Jul | 37.93 | 863 |
| | Bathroom | 19:30, 27/Jul | 25.02 | 1 | 18:30, 27/Jul | 34.13 | 501 |
| | Store/ Cloakroom | 19:30, 27/Jul | 24.9 | 0 | 18:30, 27/Jul | 34.12 | 518 |
| | Hall 1 | 16:30, 27/Jul | 28.81 | 35 | 17:30, 27/Jul | 39.26 | 933 |
| | Living room | 14:30, 04/Aug | 36 | 680 | 16:30, 27/Jul | 41.14 | 1572 |
| | Kitchen | 19:30, 27/Jul | 26.91 | 25 | 18:30, 27/Jul | 36.08 | 1002 |
| | Bedroom 1 | 17:30, 27/Jul | 25.97 | 5 | 18:30, 27/Jul | 33.54 | 544 |
| | Hall 2 | 19:30, 27/Jul | 29.04 | 80 | 18:30, 27/Jul | 36.89 | 795 |
| | Greenhouse | - | - | - | 15:30, 27/Jul | 37.75 | 440 |