



The  
University  
Of  
Sheffield.

# **Embodied Energy and Carbon: A Case Study of a Brettstapel Passivhaus in the UK**

Submitted by

**Dilek Arslan**

A thesis submitted in partial fulfilment of the requirements for the degree of  
Master of Science in Sustainable Architecture Studies

The University of Sheffield  
Faculty of Social Sciences  
School of Architecture

Word Count: 10.998

August 2019

## **Abstract**

Energy demand in building construction materials and carbon emissions in relation to this are growing rapidly and accounts for 36% of the energy and 39% of the carbon emissions from all other sectors. Therefore, lowering the embodied energy and carbon emissions of the materials and operational energy of the buildings are important to mitigate the climate change. In this case study, a Brettstapel Passivhaus home in the UK is analysed to demonstrate the effectiveness and significance of the low impact materials on operational energy and carbon emissions on this type of low energy buildings, which is not yet covered in literature. The objectives of the study are to: (1) analyse the state of the art; (2) define boundaries and challenges which affect the embodied energy/carbon calculations and measurements; (3) establish the embodied carbon emissions and energy data for Brettstapel construction for the UK; (4) comparing the embodied carbon emissions and operational energy/carbon in Passivhauses; and (5) make recommendations for sustaining low impact material choices to decrease the carbon emission in Passivhauses.

Mixed methods approach was used, including a home demonstration tour, interviews, and photo survey are used in this study. A novel software modelling tool (Revit plug-in, H\B:ERT) was used for the material carbon calculations with an Input-Output analysis method. The materials carbon intensities are based on the latest ICE V3.0 database and Environmental Product Declarations (EPD) were used wherever a material data was missing. Overall, the results from the calculations show that using the timber material has significant effect on decreasing the total carbon emission of the building. The embodied carbon emissions from the materials one third of the operational carbon emissions for the home over a 50 years period, this should always be considered in Passivhaus and other low energy building standards.

## **Disclaimer**

I confirm that the research was conducted according to the University of Sheffield ethic rules. Information sheet and consent forms were provided to the interviewees in this study and attached in appendices. The data which was used in the thesis is stored securely and used anonymously.



## **Acknowledgements**

Firstly, I would like to thank to all my family and friends who are always supporting and cheering me on during the thesis process. I also want to especially thank Professor Fionn Stevenson for sharing her endless knowledge, guidance, and for being supportive all the time. Thank you to Ian and Anne Nimmo for opening their house and their warm welcoming, thank you to Sam Foster for sharing all the information and his knowledge about Plummerswood. Finally I would like to thank Turkish Government and Embassy of the Education that they sponsored me during my master period. It was a great opportunity to be in the UK as a master student. I could not imagine to be here without their support.



**Content**

- 1. Introduction .....1
  - 1.1 Background Information .....1
  - 1.2 Research Gap .....2
  - 1.3 Research Aim and Objectives .....2
  - 1.4 Research Scope and Structure .....3
- 2. Literature Review .....4
  - 2.1 Embodied Energy and Carbon Background .....4
  - 2.2 Embodied Energy and Carbon Analysis Methods .....7
  - 2.3 Passivhaus Standard and Principles .....9
  - 2.4 Timber Material and Brettstapel .....12
  - 2.5 Material Databases .....16
  - 2.6 Software Modelling .....18
- 3. Methods .....21
  - 3.1 Research Design .....21
  - 3.2 Case Study and Mixed Method .....22
    - 3.2.1 Home Demonstration Tour .....24
    - 3.2.2 Interviews .....26
    - 3.2.3 Photo Survey .....26
    - 3.2.4 Documentary Analysis .....26
    - 3.2.5 Embodied carbon emissions Calculation .....27
    - 3.2.6 In Use Energy Calculation .....29
- 4. Case Study: Plummerswood .....31
  - 4.1 Background .....31
  - 4.2 Plummerswood in Light of Passivhaus Standard .....33
- 5. Energy Analysis Results .....34

5.1 Embodied Carbon Results .....	34
5.2 In Use Energy Results .....	34
6. Discussion .....	36
7. Conclusion .....	38
7.1 Limitations .....	38
7.1.1 H\B:ERT Plug-In Limitations.....	38
7.1.2 Database Limitations .....	39
7.2 Recommendations .....	40
8. References .....	41
9. Appendices .....	52
Appendix A: Ethics Approval .....	52
Appendix B: Interview Transcripts.....	53
Occupants.....	53
Appendix C: Photo Survey.....	58
Appendix D: Technical Drawings .....	60
Appendix E: H\BERT and Bill of Quantities Calculations (Excel Spread Sheets).....	70
Appendix F: In-Use Calculations (Excel Spread Sheets) .....	76
Appendix G: Solar Thermal Performance Sheet .....	78

## Table List

All tables are author's own unless otherwise stated.

Table 1: Cradle to Cradle, Cradle to Grave, Cradle to Cradle Stages for Materials (Silvestre, de Brito and Pinheiro, 2014).....	5
Table 2: Embodied Energy Modelling (Dixit et al., 2010).....	6
Table 3: Summary of EE/EC Calculation Methods. ....	9
Table 4: Projection for the 2050; Level 4 Represents the Potential Reduction with the Passivhaus (DBEIS, 2010).....	10
Table 5: Material rankings from the study (Kuzman et al., 2013). ....	11
Table 6: Wood Consumption in the UK, 1999-2017 (Forestry Commission, 2018). ....	13
Table 7: Summary for Database Comparison. ....	18
Table 8: Summary of Software Comparison. ....	20
Table 9: Research Process Flow Chart. ....	21
Table 10: Case Study Flow Chart.....	23
Table 11: Embodied carbon emissions Calculation Process.....	30

## Figure List

All figures are author's own unless otherwise stated.

Figure 1: Brettstapel (Maderaestructural.wordpress.com, 2018).....	14
Figure 2: Brettstapel Production Process (based on Sohm Product Brochure). ....	15
Figure 3: Case Study House.....	24
Figure 4: Ground Floor Living Room. ....	25
Figure 5: Ground Floor Guest Room.....	25
Figure 6: First Floor Bridge ....	25
Figure 7: 3D Views from Revit-H\B:ERT.....	28
Figure 8: Plummerswood House Location. ....	31

Figure 9: Plummerswood House, (Foster, 2012). .....32

Figure 10:Plummerswood Floor Plans (TFA is highlighted). .....32



# 1. Introduction

## 1.1 Background Information

Energy is a fundamental need for human daily life. In architecture, technology and human relations inform construction styles, material choices, indoor thermal comfort and air quality. However, since the oil crisis in 1975, there is a major concern about decreasing the energy demand in all sectors, especially in construction, which is responsible for 36% of global final energy consumption (UN Environment and International Energy Agency (UNEIEA), 2017). In parallel to energy demand, the building sector is also one of the main drivers of carbon production; it accounts 39% of the total anthropogenic greenhouse gas emissions (GHG), globally, among economic sectors (UNEIEA, 2017).

Today, decreasing the carbon and energy levels for this sector is important to avoid a catastrophic global temperature increase +2 °C and allow the next generation to inherit a liveable earth (IPCC, 2018). To prevent this temperature increase, 192 parties (including the UK) signed the Paris Agreement to decrease the carbon emissions by 50% by 2030 and to zero by 2050, in relation to energy demand (UNFCCC, 2019).

According to the United Nations report (2016), the UK accounts for 1.55% of the global GHG (for the year 2013). To tackle carbon and energy issues in construction and in use phases, there are various mitigation policies, legislations and benchmarks in the UK, such as Climate Change Act 2008 and 2009, Government Construction Strategy (2011) and, in the EU, the Environmental Product Declarations (EPD) (Pelsmakers, 2016). There are also voluntary energy benchmarks like Passivhaus Standard which requires a maximum of 120 kWh/m<sup>2</sup>/pa primary energy use and can help to keep energy demand in a consistent level (Passivhaus Trust, 2019).

By 2022, it is planned to be build 1.5 million new houses in the UK and the contribution of housing is 70% within the overall construction sector in terms of GHG emission (Committee on Climate Change (CCC), 2019). This urges people to take measurements to tackle these excessive emissions. As materials are the key aspects of constructing a house, lowering material energy consumption can play an important role to decrease the drastic carbon impact to the industry as it can be up to the 20-50% of the building life cycle energy (Anderson, 2017).

One of the low impact materials that can be used to lower GHG emission is timber, as it requires less energy during its production compared to steel, concrete and brick (Buchanan and Levine,

1999). According to Lippke et al. (2004) environmental impact of timber structured house is 31% less than the same size concrete house and 26% less than the same size steel house. The high recyclability and re-usability content of the timber also make it more preferable for the sustainable constructions (Swedish Wood, 2019). As tree sequestrates the carbon throughout its life time, locking up this stored gasses by harvesting it at a certain age ( over 50 years) and using as construction material makes it a part of the climate change strategy ( see *Timber Material and Brettstapel section, pp.12*).

## **1.2 Research Gap**

In the current literature, there is still some uncertainty in defining the boundaries for *Embodied Energy (EE)* and *Embodied Carbon Emissions (ECE)* and even less information about the energy usage in the material life cycle for many products. In particular, there has been no study carried out yet on the ECE for a Passivhaus home, made of Brettstapel in the UK which represents a key research gap in relation to this product and the Passivhaus Standard. For the carbon emissions there is an uncertainty for the calculations because of the fuel mixes in material processes (Hammond et al., 2011). Additionally, there is a lack of sufficient studies about how low energy buildings perform in terms of ECE for the Passivhaus Standard. Also there is a need for evaluating the material selection in Passivhaus buildings more in depth from the perspective of operational energy and ECE as a joint consideration, as this currently is not tackled in the Passivhaus Standard.

## **1.3 Research Aim and Objectives**

The aim of this study is to (1) examine a case study Passivhaus home that is award winning and uniquely constructed using the timber Brettstapel technique, and (2) show the environmental impact of this material choice in terms of ECE from energy in use.

Additionally, providing data and showing the relation between ECE and low energy building design can help designers to choose the right materials to decrease energy demand and greenhouse gas emissions in housing sector. Furthermore showing the boundaries of what is effecting the EC and *Embodied Carbon (EC)* for the materials can prompt people to realise and solve issues associated with this. Introducing new ways of constructing homes for the UK and showing a lower energy demand can help to change the attitudes in construction choices and help to achieve global energy targets.

The objectives of this study are to: (1) analyse the state of the art; (2) define the boundaries and challenges which effect the EE/EC calculations and measurements; (3) establish the ECE and energy data for Brettstapel construction for the UK; (4) compare the ECE and operational energy/carbon in a Passivhaus home; (5) make recommendations for sustaining low impact material choices and decreasing the carbon emission in Passivhaus housing.

#### **1.4 Research Scope and Structure**

The scope of the EE and EC calculations are based on *Cradle to Gate* (see page 4) because of the limited data availability for the carbon factors. A *Cradle to Cradle* (see page 4) approach was never considered, since the assumptions for the materials in relation to life cycle assessment, such as new technologies in future for the production affects the overall all data reliability (Gervasio and Dimova, 2018). Passivhaus is chosen as the low energy benchmark as it is a part of energy strategies in various cities in the UK and the geographical scope of this study is restricted to Scotland as the matter of having the first Brettstapel house in the UK.

## 2. Literature Review

### 2.1 Embodied Energy and Carbon Background

Every material used in building construction uses energy from extraction to using it in the building and demolishing it. *Embodied Energy (EE)* as a term was first used in IFIAS's workshop report (International Federation of Institutes for Advanced Studies, 1978) to define the thermodynamic potential of the products, emphasising the lineal usage of fuel and electrical energy in material production. However, this term has changed over a thirteen year period with the definition represented by Treloar (1997). He defined EE as "*the energy consumed in all activities necessary to support a process*". That led to thinking about the direct and in direct energy usage throughout the building operation.

In general, EE is descriptive of a building material's energy usage during its extraction from the source and transfer to the construction site. According to Milne (2013) EE calculation does not include the materials usage after its implementation in construction or material recycle after building life ended. This understanding called *Cradle to Gate* in terms of building process. However Yohanis and Norton (2002) argued that this understanding should have a much more universal approach, known as *Cradle to Grave* which includes initial, recurring and demolition energy. The Royal Institution of Chartered Surveyors (RICS) (2017) also defines the *Cradle to Grave* steps based on EN 15978 as product, construction, use and end of life. In this definition, materials cannot be used any longer after they are demolished. Another way of assessing material energy is *Cradle to Cradle*. It includes reuse, recovery and recycling stages to *Cradle to Grave* approach (Silvestre et al., 2014; Table 1). In this stage materials are reused or recycled after they are demolished from a building and can be used as a secondary raw material to the new material production (Silvestre et al., 2014). Primary energy saving can be possible by reusing the demolished materials, since material is already produced.

LCA boundaries	Life cycle stages / LCA information modules	Life cycle stage designation and description		
Cradle to cradle	Cradle to gate	A1	Raw material extraction and processing, processing of secondary material input	
		A2	Transport to the manufacturer	
		A3	Manufacturing	
		A4	Transport to the building site	
		A5	Installation into the building	
	Cradle to grave	Use stage - information modules related to the building fabric (B1-B5)	B1	Use or application of the installed product
			B2	Maintenance
			B3	Repair
			B4	Replacement
			B5	Refurbishment
	Gate to grave	Use stage - information modules related to the operation of the building (B6-B7)	B6	Operational energy use
			B7	Operational water use
	Gate to grave	End-of-life stage (C1-C4)	C1	De-construction, demolition
			C2	Transport to waste processing
C3			Waste processing for reuse, recovery and/or recycling (3R)	
C4			Disposal	
	Benefits and loads beyond the system boundary (D)	D	Reuse, recovery and/or recycling (3R) potentials	

*Table 1: Cradle to Cradle, Cradle to Grave, Cradle to Cradle Stages for Materials (Silvestre, de Brito and Pinheiro, 2014).*

Sartori and Hestnes (2007), defines EE as the total energy of initial and recurring energy, which includes all, construction phase, maintenance and repairs throughout the material's life; moreover, this initial energy share can be up to half of the life cycle energy of the building. This substantial percentage leads to a consideration of the relation between material and building life spans. Therefore using a high EE material which has 100 years life span for a house with 60-70 year life span is not a wise and practical choice. The lower the material initial energy compared with the building lifecycle energy the more energy efficient that material is.

Defining the boundaries of the EE of the materials is not certain, however. For example, differently from Sartori and Hestnes, Dixit et al. (2010) includes the demolition and waste disposal of the material as a part of the consumption and they clarify the cradle to grave path in Table 2. Also Chau et al. (2015), just evaluates the extraction, production, transportation to the site and constructional energy as initial EE for the materials; they also assess the demolition energy as a whole building energy and never consider the waste disposal of the products themselves.

Another boundary issue for EE calculations is that energy sources in primary energy stage calculations are mostly based on raising or lowering heating rates in chemical sources (Rasmussen et al., 2018). This shows that factors, such as renewable energy sources in cumulative energy phase, are often not completely included.

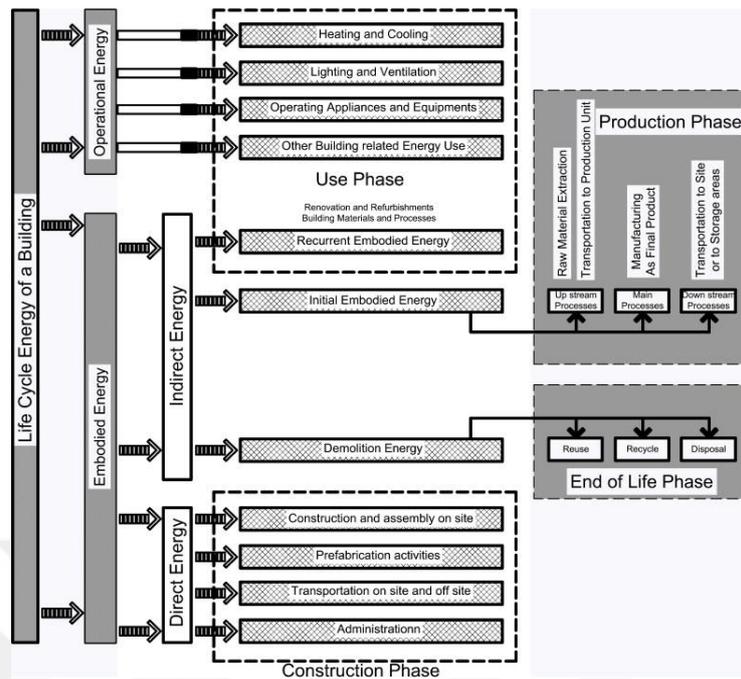


Table 2: Embodied Energy Modelling (Dixit et al., 2010).

EE matters because giving importance to lower EE materials can help to reduce the overall environmental impact during material production. For example, instead of using fossil fuel based power generators, a demanded reduction in EE factor can urge the manufacturers to choose or use renewable energy sources or use less energy during the production process.

As a consequence of the usage of the energy for the material production, construction and operational phases, the ECE of the materials and the buildings are important to evaluate the low energy building strategies for various countries targets for 2050 (Monahan and Powell, 2011; The Institution of Structural Engineers, 2011). Therefore, the fraction of the ECE is becoming more significant. Hammond and Jones (2009) states that the carbon footprints in relation to energy emissions are the main concern in terms of climate change; this gives importance to the concept of ECE. However, although operational carbon emissions has standardisations such as regulations and legislations (*as it stated before*), there is no standard for the ECE of the buildings (UK Green Building Council, 2015) and even though ECE can almost equal to building lifespan carbon emissions in use in some cases, it is not included in building design process either (Monahan and Powell, 2011).

According to WRAP (<http://www.wrap.org.uk/>), ECE in relation with the construction materials can be as much as 50% of the total emission of a building throughout its life time, and

it can only be saved with less material or alternative material usage such as low impact materials (timber) or highly recyclable or re-usable materials (recycled concrete aggregate or reclaimed bricks). In contrast to WRAP, Pomponi and Moncaster, (2016) list a comprehensive literature review to show the importance of using low impact materials as a mitigation strategy. In addition, Bin and Parker (2012), states that as the developments in the technologies in the producing and transporting the materials change carbon emissions over time to time, so assessing the ECE of them is important to provide updated data for the further studies. Differently, Fesanghary et al. (2012) and Häkkinen et al. (2015) highlight that, selecting materials during the design process is critical decision to lower ECE in buildings.

The main issue for the EE of the building and the material is availability of reliable databases for the energy factors for the calculations (Dixit et al., 2010). Also because of the complexity of assessing a building ECE, there is lack of quantitative information available in literature (Scheuer, 2003). Therefore, it is believed that calculating the ECE for the selected case study will provide more in depth discussion for the objectives of this study. Also, instead of using different parameters like kWh for the operational energy and kgCO<sub>2</sub> for the carbon emissions, comparing the overall data in same units (kgCO<sub>2</sub>) can give much better understanding for the discussion. All the estimations for the calculations are made cradle to gate system boundary since there is incompleteness in the cradle to cradle or cradle to grave approaches as they require assumptions for the longevity, maintenance and occupant's life styles which decreases the reliability of them. Since there is no detailed information about what effects the energy consumption in these steps (Dixit, 2019) so these aspects were omitted from this study.

## **2.2 Embodied Energy and Carbon Analysis Methods**

There are five different ways to measure the EE and EC of materials. These are;

- 1- Statistical Analysis,
- 2- Stochastic Analysis
- 3- Process Analysis
- 4- Input-Output Analysis
- 5- Hybrid Analysis

First method is *Statistical Analysis* which uses published statistics and stabilises them with the fit test (Kolmogorov–Smirnov test) to decrease probabilistic disseminations in defined critical

constraints (Wang and Shen, 2013). However, the drawback of this method is lack of trustworthiness and it is expensive whenever applied on all building materials (Baird et al., 1997; Wang and Shen, 2013). The lack of detailed information also leads to assumptions about the data which decreases the reliability of the results.

According to Pullen (2007) the *Stochastic Method* effectively covers the uncertainties in the calculations related with the production process. It is based on Monte Carlo simulation which uses the input data chosen from particular contingent range to generate random variables for the analysis (like in casino machine) (Raynolds, Checkel, Fraser, 1999; Acquaye et al., 2011); however, it is mostly based on input-output and process data. Hence, Eufrasio-Espinosa (2015), highlighted the need for an expanded approach.

Another method for measurement is *Process Analysis* which defines the materials energy/carbon during the particular production stages such as extraction, manufacturing and transportation (Onat et al., 2014 and Menzies et al., 2007). The EE/EC of a material is calculated by multiplying the energy intensity or carbon emission by the quantity of the product used in tonnes and appropriate waste factor (Acquaye, 2010). However, Zhai and Williams (2010) and Fenner et al. (2018) acknowledges that assumptions and excluded steps (manufacturing machinery, industrial gasses for processing or management and maintenance) in the analysis might cause flaws in calculations and affect the data reliability.

Another way of determining the EE and EC is *Input-Output Analysis* which is widely used. It takes the energy prices and carbon/energy intensities with the economic transactions from different economic sectors, and it calculates the intensities in mass of carbon/energy per unit of monetary rate (Acquaye et al., 2011). The scope of this method depends on regional context which can be either single or multiple. The negative side of it, is the variation of the input-output tables and transactions. This could lead to inconsistency in results, as the system uses the same energy intensity for all materials within a sector, and change in prices can cause deviations in the data (Stephen et al. 2013). Moreover, Crawford and Treloar (2003) also mention the limitations of this method, such as the age and conjecture of data, converting the economic information to energy information, using national averages and sector disposition. According to International Energy Agency (2016), both process analysis and input-output methods are helpful to decrease the calculation work. For the process method, designing phase is not included and for the input-output method, data availability defines the system boundaries.

Yet last analysis method is *Hybrid Analysis* which starts with ready input-output data from the final product phase and then uses process analysis when there is difficulty finding reliable and coherent data in complex upstream stages (Dixit, 2013). This method helps to overcome the limitations of both these methods for example; while input-output is providing the broad data, process analysis can provide the small entities for the calculations (Pandey, Agrawal and Pandey, 2010; Moncaster and Song, 2012) and extract more relevant and reliable data when compared with other methods. However, subjectivity and time limitation can also be the drawbacks of this method (Menzies et al., 2007).

As can be seen from the *Table 3* all the methods have benefits and limitations and *Hybrid Analysis* superior to the other methods. However, in this study the calculations are based on *Input-Output Analysis*, due to limitations such as the time constrains and the data availability since there is no open sources for the hybrid method yet.

	DATA	BENEFITS	LIMITATIONS
STATISTICAL ANALYSIS	Physical	Based on national database	Lack of detailed information leads to assumptions
STOCHASTIC ANALYSIS	Physical and Financial	Covers uncertainties in production level	Expanded approach needed
PROCESS ANALYSIS	Physical	Helpful to find out energy in production phase	Incompleteness
INPUT-OUTPUT ANALYSIS	Financial	Mostly used method, consider individual products	Age of the database and changes in transaction
HYBRID ANALYSIS	Physical and Financial	Overcomes both two methods limitations	Assumptions effect the data reliability and time constrains

*Table 3: Summary of EE/EC Calculation Methods.*

### 2.3 Passivhaus Standard and Principles

Operational energy accounts for 80-90% energy demand of a building in the world, so that achieving lower numbers in this stage is highly important to lower the energy use in buildings (Zeng and Chini, 2017). Using benchmarking systems are helpful in achieving these lower energy and carbon targets. They are useful to compare the building energy performance with the published norms or similar buildings to gauge the opportunities to improve and account the energy savings (Energy.gov, 2019).

There are different types of energy benchmarking such as BREEAM (Turner, 2019), LEED (Lee and Koski, 2012), Net Zero Buildings (Pelsmakers, 2015), and especially Passivhaus (Passivhaus Trust, 2019). DBEIS 2050 Pathway Analysis report (2010) illustrates that Passivhaus could play a key role in the UK climate mitigation policy in terms of decreasing energy demand in relation to heating and cooling demand (Table 4). Therefore, *Passivhaus Standard* will be explained next.

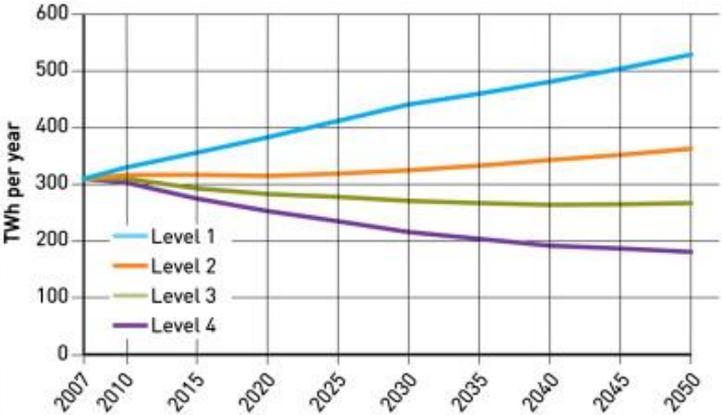


Table 4: Projection for the 2050; Level 4 Represents the Potential Reduction with the *Passivhaus* (DBEIS, 2010).

Passivhaus is a concept which represents affordable, comfortable and energy efficient building design (Feist et al. 2005, Badescu and Sicre, 2003). This concept was always there with vernacular designs; however, it gained much wider visibility with Dr. Wolfgang Feist’ design of his Darmstadt-Kranichstein House in 1990. A passivhaus building, designed according to the passivhaus standard, should consume no more than 15 kWh/m<sup>2</sup>/yr for heating or cooling, and no more than 120 kWh/m<sup>2</sup>/yr for the primary energy (Passivhaustrust.org.uk, 2019). It should have high level of air tightness (0,6 ach @50 Pa), insulation and provide thermal comfort by reducing the air movement (the temperature should vary less than 0.8 °C in the room) (Passpedia.org, 2019a; Tabatabaei Sameni et al., 2015). At the same time, it should be energy and cost efficient. In the design process, to estimate the efficiency of the house, the Passivhaus Planning Package ([https://passipedia.org/planning/calculating\\_energy\\_efficiency/phpp\\_-\\_the\\_passive\\_house\\_planning\\_package](https://passipedia.org/planning/calculating_energy_efficiency/phpp_-_the_passive_house_planning_package)) is used, and also real-time measurements are made to provide validity during the construction and at the end of construction. Since the programme and real construction performance of the building match each other, this makes Passivhaus and PHPP are reliable programme and benchmarking system (Burrell, 2014). It also sets robust targets and high standards to lower energy in-use such as air tightness level in Passivhaus

buildings (*see above*) is ten times lower than the building the Part L building regulations (5 ac @50 Pa).

Stephan et al. (2013), however, criticise the passivhaus concept as being about operational energy consumption rather than taking into account the material EE. However, this is not required by the Passivhaus standard, and there is no relevant data about EE of ecological materials (Passpedia.org, 2019b; Kuzman et al., 2013). That means a Passivhaus building can have higher EE and EC than a traditional English house in terms of material choices in order to reach high level of air tightness and low level of energy consumption in use. Similarly, Andersen (2017) claims that low energy buildings like passivhauses focus more on operational energy, and uses more insulation materials to provide high efficiency; therefore, the EE related to materials are high, and can account 20-50% of the total life cycle of the building.

However, 70% of carbon emission reduction is also possible in operational phase with the correct design (such as orientation and shading) and modelling (McLeod et al., 2012). Hence, EE and EC should be a part of the Passivhaus energy benchmarking system to provide broader efficiency in terms of overall energy saving. Otherwise, this benchmark will not be useful in decreasing the demand in construction phase, including EE and ECE.

Kuzman et al. (2013) consider the materials in Passivhaus homes which includes dwellers and experts' ranking about the material choices and shows that timber material is much more beneficial in Passivhaus design in sights of aesthetics, end-of-life disposal, emissions, health aspect, psychological aspect, functionality, compared to other typical materials (Table 5). This study shows the key criteria for choosing the materials for the owners of the houses and majority of the people chose the solid wood because of the health aspect of it.

**PASSIVE HOUSE**

	aesthetics	end-of-life disposal	emissions	health aspect	psychological aspect	functionality
	0.069	0.077	0.074	0.172	0.118	0.097
brick	0.126	0.250	0.167	0.116	0.137	0.163
solid wood	0.483	0.292	0.330	0.531	0.442	0.286
wood frame	0.322	0.292	0.250	0.273	0.336	0.286
aerated concrete	0.069	0.167	0.250	0.080	0.084	0.265

Table 5: Material rankings from the study (Kuzman et al., 2013).

As can be seen from the table above, carbon emission is the last concern in Passivhaus material preferences for home owners. Airtightness and breathability are also important as part of energy saving criteria of the house. According to Pan (2010), timber structures have lower air permeability than other structural systems like concrete and traditional masonry; however, they have higher permeability than the precast concrete panels. In contrast, if a building with timber structure is combined with good performance insulation materials, it can perform as well as concrete and masonry structures in passivhaus homes (Vinha et al., 2015). Therefore, using timber material in passivhaus design can have significant effect on saving energy and capturing carbon.

Building on the information above concerning EE, ECE and Passivhaus, this study aims to represent that Passivhaus homes can be built and perform well in terms of low ECE with low impact materials as well as energy in use.

#### **2.4 Timber Material and Brettstapel**

Timber is one of the most ancient materials in the history of building construction. Ritter (1992) describes the timber, '*As a building material, wood is abundant, versatile, and easily obtainable.*' Also Tucker and Ambrose (1997) defines the timber as recyclable, reusable and low impact material in terms of energy and similarly, Leskovar and Premrov (2011), specifies timber as the best choice for the energy efficient construction regarding on its thermal conductivity properties. There are two types of timber; soft wood and hard wood. These terms define the trees species depending on leaves and seeds. Soft wood comes from conifer and hard wood comes from deciduous trees. In building sector, both of them has various types of usages based on needs, such as structural or fabric, even as furniture. European whitewood and redwood species are commonly used as softwood in the UK. Although there is an increasing trend on home-grown softwood, still 80% of them are imported from other countries (Forestry Commission, 2018) (Table 6).

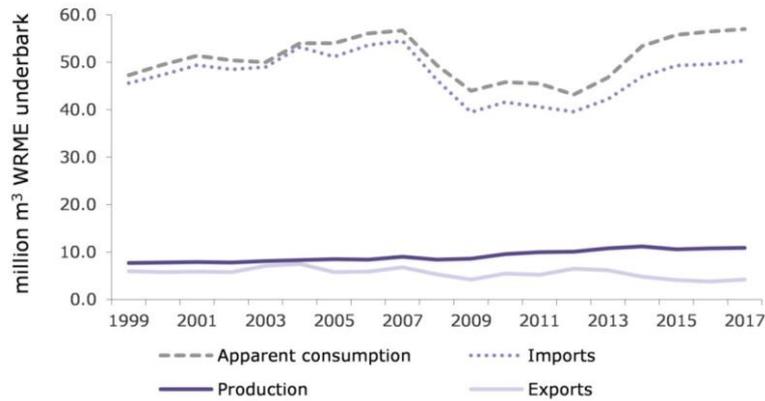


Table 6: Wood Consumption in the UK, 1999-2017 (Forestry Commission, 2018).

Timber is a natural material, unlike concrete or steel and it has non-uniform nature, sometimes it can be hard to estimate its performance. However, it has better performance features than concrete and brick in terms of thermal insulation and thermal expansion (Steiger, 2007). Also carbon storage capacity of the timber outperforms the other materials and the reason to be a climate change mitigation strategy, as 1 m<sup>3</sup> of wood contains approximately 1 tonnes CO<sub>2</sub> (Buildingconstructiondesign.co.uk, 2015). Carbon sequestration is basically locking the carbon which is emitted by the tree throughout its life by harvesting it. Otherwise the stored carbon is starting to decrease when the tree is aged over 50 years (An et al, 2019). However, the carbon emission related to the timber material production decreases the stored carbon in wood up to 18% due to fuel based process and further reduces to 1% over a hundred year building life (Ingerson, 2009).

Moreover, there is a common concern about timber structures in relation to its fire performance. The flammability of the timber makes it less preferable as building construction material, and has some restrictions in some countries (Östman, et al., 2017). Yet, timber has better fire performance than concrete and steel, when it catches fire, it makes outer shell (charring process) to protect its inner parts which helps the structure stand still during the fire (Naser, 2019 and American Wood Council, 2016). Although timber has good fire performance, according to the building regulation requirements such as Eurocodes, there is still need for fire protection for timber (Structural Timber Association, 2014). This can be provided with impregnation of timber, intumescent coatings or installation of fire protector claddings (Kolaitis, et al., 2014).

Another concern about the timber materials is that it may cause deforestation and degradation in woodland areas (Union of Concerned Scientist, n.d.). It is believed that growing interest in wood products and poor forest management causes the degradation in woodland areas (Dudley,

Jeanrenaud and Sullivan, 2014). However, GreenSpec (2019) and Wood for Good (2019) advocate using a certification and verification systems, such as Programme for Endorsement of Forest Certification and Forest Stewardship Council. These can give opportunity to control usage of wood such as choosing the correct type of tree for the construction and other sectors or planting five young trees when one grown tree is cut off.

As a construction material timber has different types of usage in building design such as structural beam and column, flooring or cladding. For the structural purpose, there is a different construction technique and type which also serves as flooring or finishing material at the same time, named *Brettstapel*, which is of particular interest, given its ecological credentials.

Brettstapel is a mass timber construction technique without nails or adhesives. The Brettstapel concept was introduced by a German engineer Julius Natterer in the 1970s. In the early design of Brettstapel producing 600mm solid structural timber from sawn timber, nails were used to join the timber together. After the introduction of dowelled wood by German company Dübelholz in 1999, nails were then replaced with wooden dowels (Figure 1). With 600mm wide and 80-300 mm thick panels, Brettstapel panels can span 8m. The moisture balance of the elements in this design is a key factor to connect them. The moisture percentage for posts and dowels are different from each other, 15% and 8%, respectively. The dowels expand in the panel holes and connect the timberwork more strongly. However, changes in temperature and moisture levels can cause some problems in connections; hence, to support the structure, sometimes nails were used, which made the construction not completely timber.



*Figure1: Brettstapel (Maderaestructural.wordpress.com, 2018).*

In 2001, an Australian company, found a new way of connection to tackle these issues. They introduced V and W connections to reduce rigidity and eliminate the usage of nails in

construction (Figure 1). Today, Germany, Switzerland and Austria has more than 20 company for Brettstapel, and most recently Norway started to produce the construction element for it (Henderson, Foster and Bridgestock, 2012).

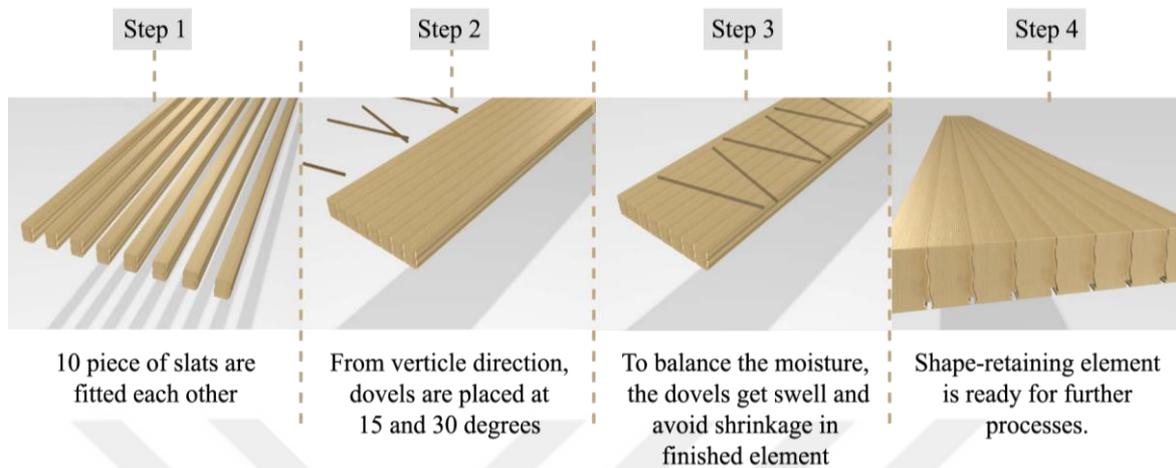


Figure 2: Brettstapel Production Process (based on Sohm Product Brochure).

**Benefits of the Brettstapel System** (Forestryscotland.com, n.d. and Henderson et al., 2012).;

- It gives opportunity to use home grown timber, and low grade timber materials makes the construction cost lower than other systems.
- It performs better than an average timber frame construction in terms of carbon footprint; a cubic meter of a solid timber block sequestrates 930 kgCO<sub>2</sub>.
- Not using any glue or adhesives provides healthy indoor environment for the occupants.
- Brettstapel has significant thermal mass capacity as it is made of solid timber, it provides warmer winters and cooler summers for the indoor environment.
- As timber has low thermal conductivity, the Brettstapel has good level of insulation.
- Since the timber is hygroscopic material, Brettstapel building elements are able to evacuate the moisture through the walls and provides good level of indoor air quality.
- The Brettstapel elements design offers high level of air tightness which means there is less air leakage in buildings.
- Prefabricated building elements decrease the need of labour and construction period

- Owing to the thickness of the elements, the fire performance of a Brettstapel panel has remarkably high resistance. However, to meet building legislations there can be need some protection for surface spread of flame.

The Committee on Climate Change report (2019) promotes use of the timber material in relation its carbon sequestration ability (*see page 12*) to manage the goal of decreasing energy consumption and greenhouse gas inventiveness in buildings by 2050. Also Monahan and Powel's study (2011) outlines a timber framed house with modern construction techniques has 34% ECE than a traditional masonry house. Regarding these factors as the main point of the research, the EE and ECE of the timber material is going to be investigated within the scope of Passivhaus in UK. Within this context, UK's first Brettstapel house will be examined as a cased study, which is Plummerswood house designed by Gaia Architects.

## **2.5 Material Databases**

A database is defined by Britannica (2019) as '*...any collection of data, or information, that is specially organized for rapid search and retrieval by a computer.*' Readily available databases are used for the EE and EC calculation. For the study, a full individual calculation of each construction materials' EE and ECE were never considered due to the time constrains. Instead existing databases were used.

There are different databases available for the carbon calculations (Table 7). WRAP is one of them and is accredited with UK Green Building Council. It includes buildings carbon data, however it does not provide material carbon information and the building carbon calculation data is mainly based on ICE (<http://ecdb.wrap.org.uk/>).

Another database is Athena Lifecycle Inventory which has been establishing by Athena Institute Researchers, since 2002 (<http://www.athenasmi.org/>). It is based on ISO standard procedures and is combined with a software, yet the programme only focuses on North American carbon data, so it is not applicable for the UK. However, in this study, ICE V3.0, Environmental Product Declaration (EPD) reports and UK Government Conversation Factors by Department for Environment Food and Rural Affairs (DEFRA) are used and will be explained next.

The Inventory of Carbon and Energy (ICE) was developed by the University of Bath Sustainable Energy Research Team and first published in 2005 and then updated in 2011 to V2.0 and finally in June 2019 to V3.0 (<http://www.circularecology.com/>). It represents various types of construction material data for EE (up until V2.0 in 2011) and ECE (including V3.0)

with in the cradle to gate boundary condition. Product data are collected from different countries therefore it provides more universal carbon and energy data for the materials; with last update, the EE of the materials are no longer available as it is not seen as being so important in current studies in relation to climate change concerns. This is pity because EE is more robust for assessing the materials' energy and includes renewable energy sources while EC is not and EC can be affected by carbon sequestration content of the materials (timber and straw) while EE is not. Also, the material variety is more limited, but it presents much more detailed information for the materials such as EPD reports and statistic information about the materials (Jones & Hammond, 2019).

A second database is the EU Environmental Product Declaration (EPD) an eco-labelling system which helps to identify a product impact to the environment in line to Product Category Rules and ISO 14025 standard. It provides quantitative data for manufacturers, distributors and consumers in the EU to assess the impact of the products with life cycle impact methodology, such as primary energy and (PE is for EE), water consumption, waste disposal energy and global warming potential (GWP is for EC). Validity of the reports can vary from one to five years (Ibáñez-Forés, et al., 2016 and Envirodec.com, 2019). These documents can be obtained from International EPD System, BRE and individual manufacturer reports.

The last database is the UK Government Conversation Factors by Department for Environment Food and Rural Affairs. It provides carbon and energy factors for the activities which are defined in spreadsheet, like business travel, heat and steam or overseas electricity. This document is updated every year according to the changes in emission factors (DEFRA and DBEIS, 2019). It is useful to convert the energy figures (in electricity or gas) to carbon figures or vice versa.

Database	Strengths	Weaknesses	System Boundary
WRAP	Provides building lifecycle carbon data from different countries	No material carbon data and relies on users data which effects reliability	Cradle to Grave
ATHENA	Provides robust data and analysis for the materials and integrated with software	It just contains Northern America data	Cradle to Cradle
ICE	Widely used open source and applicable for the other countries	Embodied energy and some materials data are no longer available with the new update	Gradle to Gate
EPD	Presents EE and EC data for the specific products at the sam time	For every material the data can vary company to company	Cradle to Grave
DEFRA	Provides rigorous and diverse data for the conversation factors	Overseas electricity data is no longer available	Country Context

*Table 7: Summary for Database Comparison.*

## 2.6 Software Modelling

Software modelling programmes are a highly effective and useful way of presenting predicted building performance and analysis, especially BIM based programmes. BIM is a 3D visualisation tool which provides documentation (e.g. material take offs), energy analysis, collaborative work with team and gives opportunity to change design fast and effectively in its early stages, to achieve sustainable targets (Jalaei and Jrade, 2015; Autodesk.com, 2019; Wu and Issa, 2015). Similarly, Basbagill et al. (2013) address the importance of the BIM tools in early design decisions to lower the environmental impact of the buildings. In literature, BIM is a common way of assessing the life cycle of building. There is a rising trend towards to green BIM understanding which means it accomplishes the sustainability credentials in the building design process; however cradle to grave and cradle to cradle approaches are not currently covered in software programmes and modelling needs correct updates during the design process to eliminate inaccuracies (Soust-Verdaguer, Llatas and García-Martínez, 2017, Lu et al., 2017, Liu, Eybpoosh and Akinci, 2012). Currently, there are a number of modelling programmes and plug-ins that have different advantages and limitations which will be discussed in more detail.

Revit is a BIM based programme which also provides building analysis such as solar radiation, illuminance and building energy performance analysis which work with web based programme named Insight. However, it does not provide in-use or EC emission figures. It requires add-ins (plug-in) or web based assistance such as Sefaira, Green Building Studio (GBS), Tally and H\B:ERT (The comparison of the tools is provided in Table 8).

Sefaira is a plug-in and web based programme, and can collaborate with Revit or SketchUp (<https://sefaira.com/>). It provides energy in-use, cost, in-use carbon emissions and renewable energy application data and allows analysis such as illuminance or thermal comfort. The limitation of this software is that it is based on American standards (e.g. ASHRAE) and the units (e.g. US Dollars for cost or Btu for the energy).

GBS is a web based programme and it allows to use existing Insight folders from cloud or import Revit files as gbXML and it is also useful to assess the LEED credentials (<https://gbs.autodesk.com/GBS/>). The limits of this programme is that carbon assessment is just for building operational performance, and not EE or ECE - no material is considered and renewable energy sources are not updated which effects the operational energy performance scenarios.

Tally is a Revit plug-in for whole Life Cycle Assessment of a building (<https://choosetally.com/>). It uses KT Innovation and thinkstep databases. This plug-in provides embodied environmental impacts for materials but does not cover the constructional phase impact (Nizam et al., 2018). Also, the materials must be assigned in every analysis which is not practical and geographical context is limited with the USA (Basbagill et. al., 2013).

Hawkins\Brown: Emission Reduction Tool (H\B:ERT) was launched in 2018 by Hawkins\Brown studio in corporation with University College London (UCL) as the research partner (<https://www.hawkinsbrown.com/services/H\B:ERT>, 2019). It is a user friendly tool that easily enables to add new formulas for the calculations, and gives people from different professions (such as architects and engineers) opportunity to work in same virtual environment. It is useful in calculating the ECE of the UK materials with their volumes and when compered calculating by hand, it makes the complex calculations very easy. It enables the designers contingency to see the energy consumption of the materials while designing the building. The plug-in uses input-output analysis method in its operational system. In this programme, the input-output method based on University of Bath's ICE V2.0 database for the ECE factors and

CIBSE for the material densities. Plug-in works with materials volumes and adds carbon emission factors, then divides into lifecycle stages such as, production and transportation.

Modelling Tool	Building Carbon Emission	Materials Carbon Emission	Free of Charge	Database
Sefaira	✓	✗	✗	EnergyPlus, Radiance
GBS	✓	✗	✓	USEPA, CARMA
Tally	✓	✓	✗	KTI, thinkstep
HBERT	✓	✓	✓	ICE V2.0

USEPA: U.S. Environmental Protection Agency  
 KTI: Kieran Timberlake Innovation  
 ICE: Inventory of Carbon and Energy

*Table 8: Summary of Software Comparison.*

Among the softwares which are compared above, H\B:ERT is the one which accomplished this study’s aim in terms of assessing the materials carbon and free of charge therefore it will be used in this study.

### 3. Methods

#### 3.1 Research Design

The research design aims to define the research question clearly, by using the collected data (Kirshenblatt-Gimblett, 2006). Regarding on the research process for this study is designed as it follows (Table 9): (1) searching literature about a specific topic (2) identifying the research gap and defining the aim and objectives for it; (3) asking the research question based on the problem; (4) deciding the methods which will be helpful to answer the research question and applying them; (5) analysing the data, gathered by using different methods; (6) interpretation of the analysis data; (7) comparing expected conclusions and analysis results, making recommendations for future studies.

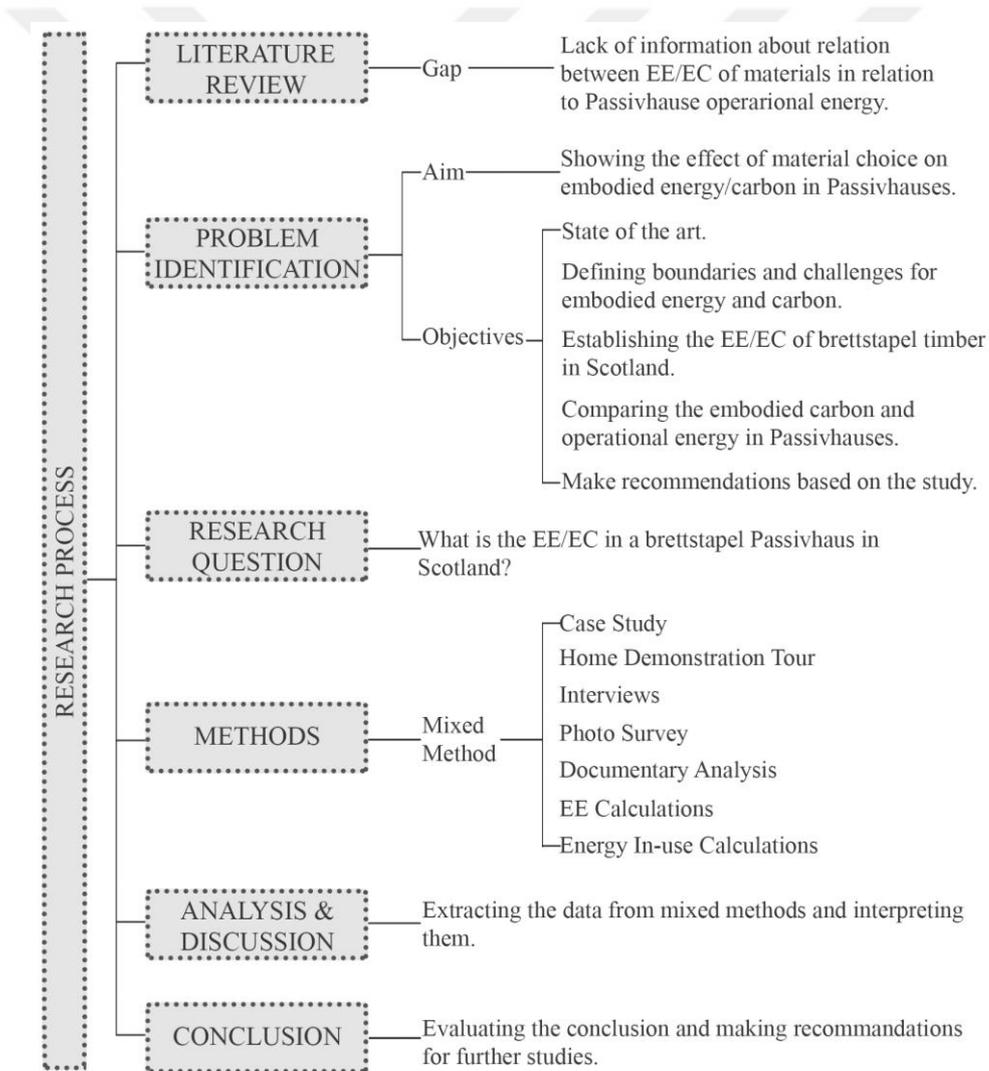


Table 9: Research Process Flow Chart.

In this section, methods which are used to investigate the ECE of timber material, an operational energy in a Passivhaus will be described as a part of the research process. A case study was used as the research method which included mixed methods such as home demonstration, interview, photo survey, documentary analysis, EE calculation and energy in-use calculation and will be explained next.

### **3.2 Case Study and Mixed Method**

Case studies can be both qualitative and quantitative. Qualitative methods are based on observations, assumptions and verbal data and quantitative methods are based on numeric and experimental information about the study. The data collection and the case study type depend on what the researcher is looking for. A study can contain one or multiple cases; however, the weakness of single case study is that it is hard to generalise (Zainal, 2007). Campbell (1975) is also against the idea that one qualitative case study can provide convenient data for the research and Abercrombie, Hill and Turner (1984) state that, one case study does not include reliable data and it just can be a starter for the further studies. However, Flyvbjerg (2006), claims that *'...one can be generalise on the basis of a case study...'* regarding the case's strategically selection for its practice. Also Yin (2003) notes that, one qualified case study can have satisfactory findings for its research area. In a case study, the quality and content of the data collection is important. It must cover the research question, propositions, and units of analysis, linking the data and interpreting them. These five elements help to define the study boundaries and provide validity.

Case study method is of importance in the architectural research field, since it gives an opportunity to compare phenomena and real-life situations (Souza, 2015 and Flyvbjerg, 2006) and helps to examine the example at micro level rather than macro level, which means gathering more detailed data for research question (Zainal, 2007). A common concern about this approach is that it may contain bias because of the researcher's subjective background. Flyvbjerg (2006) is critical of the tendency to over-emphasise the bias in the case study, saying that, every research method has rare subjectivity in it and this knowledge can help to reduce the weak side of the case study.

In this study, one case study was conducted with a passive house example which is the UK's first Brettstapel house, and was designed by Gaia Architects. In Green (2007) classification for the mixed method, *'development'* is chosen which means using one method to develop or inform the other one to provide more extent inquiry for the research question, for example; the

home demonstration tour, interviews and other methods were used to construct 3D model and 3D model helped to collect material data for the calculations. As there is a difficulty to reach the carbon footprint data for all materials from one source, to avoid incompleteness in the study, different databases were combined.

It can be seen from the case study flow chart (Table 10) below, the scope of the design is one Passivhaus case study. Since this study’s aim is to establish data for timber passivhaus in terms of ECE in cradle to gate boundary and analysing with multiple tools to gather data and then linking the collected data with boundary conditions. It can be estimated that, as a conclusion, that data might give information about what is the ECE of Brettstapel passivhaus and its energy in use.

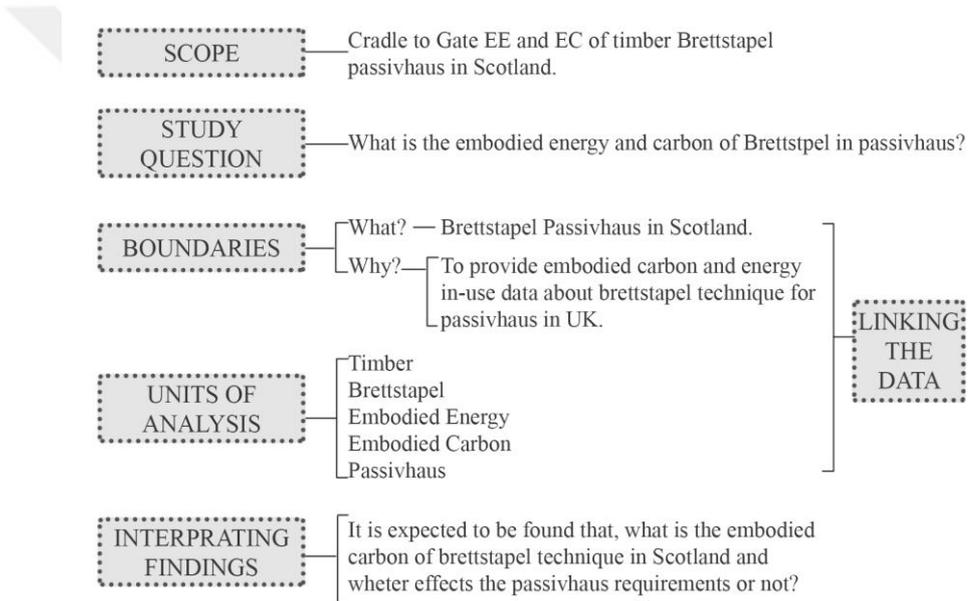


Table 10: Case Study Flow Chart.

A mixed method approach was used to investigate the case study building in terms of understanding the context, energy and carbon calculations. Mixed method is a combination of quantitative and qualitative techniques (Plano Clark and Ivankova, 2017 and Hesse-Biber and Johnson, 2015). Schoonenboom and Johnson (2017), claims that it is a useful and high validity approach which broadens and reinforces the conclusion in a study. There is a concern that mixed methods can also have bias, yet Teddlie and Tashakkori (2012) suggest that mixed method can be accomplished professionally under correct supervision, without any pluralism. According to Creswell and Plano Clark (2017), mixed method outlines theory and philosophy, and can be used where the one data source is insufficient. As it mentioned earlier data availability for the

calculations is a limitation therefore, using the multiple methods and gathering robust data from different approaches might help to compensate the weakness of the study.

Methods that were used as a part of mixed method design are;

### **3.2.1 Home Demonstration Tour**

The home demonstration tour involves a walking tour of the inside and outside of a house and enables the researcher to gain sense about the place and explore the connection between users and space (Kinney, 2017 and Belshaw, 2017). This means that it is helpful to understand the current situation of the house, see how it was built and see if there are any issues. It is based on the researcher's observations and interpretations from what the researcher has seen and discussed during the tour. In Plummerswood, the occupants guided the house tour and explain the material usage and operational aspects of it (Figure 3, 4, 5 and 6).



*Figure 3: Case Study House*



*Figure 4: Ground Floor Living Room.*



*Figure 5: Ground Floor Guest Room*



*Figure 6: First Floor Bridge*

### **3.2.2 Interviews**

Interviews gather experiences and views on the focused topic (Hammarberg, Kirkman and de Lacey, 2016) and are mostly based on what interviewer heard and observed. For this study, Plummerswood occupants and the architect were asked to take part in an interview. An information sheet informing the participants (1) about the study and (2) the consequences of taking part in it which (3) also stated that they were free to withdraw anytime, was provided prior to the interview. The interviews were arranged only after participants read the information sheet and gave written consent, as stated in the ethical approval (Appendix A). The interview consisted of short questions about timber material (Brettstapel), whether they have any difficulties for maintenance, building it or providing it during both in construction and in use. The interview was recorded using researcher's phone and later transcribe (Appendix B).

### **3.2.3 Photo Survey**

A photo survey provides visual data for the study and its readers. It also captures and reflects the life in spaces (Moore et al. 2008). It gives idea about how the house is and how the materials look like. It can also be used as proof to address identified issues in the house or with the material. A professional camera was used to take pictures and mapped with the house plans (Appendix C). Later, during modelling process, they were used as an aid to understanding the house parts, especially, when there was a difficulty to understand technical drawings, it enabled to see what was there in real.

### **3.2.4 Documentary Analysis**

Documentary analysis can be both based on electronic and printed documents and interpreting them. It is used to gain knowledge about the house and material detailing from drawings and build background information from the written or visual documents (Bowen, 2009). Documents can be used as a proof of something and rather than being a stable record it includes interpreting to address deeper meanings and structure in a data (Denscombe, 2017). The documents used in the study were provided by the occupants, the architect and the Brettstapel company (Sohm), and it includes articles, reports, analysis, technical drawings and photos (Appendix D). Additionally, EPD reports, ICE database and UK Conversation Factors spreadsheet were used as electronic documents for the calculations.

### 3.2.5 Embodied carbon emissions Calculation

Database transfer and software integration (using Revit, ICE and Excel) is a very common way of assessing the carbon emissions (Peng, 2016, Shafiq et al., 2015, Iddon and Firth, 2013). With this approach taking of heterogenous data and putting them in a uniform configuration for the counting will help to decrease the interoperability of the modelling programme and material assessment (Shadram et al., 2016), therefore it is feasible to use in this study. All external and inter walls, floors, roof, windows, doors are included and due to lack of information servicing elements (plumbing, electrics, mechanics, heating and sewage) are excluded in calculations.

The following steps were taken to do the EC calculations for the case study (Table 11);

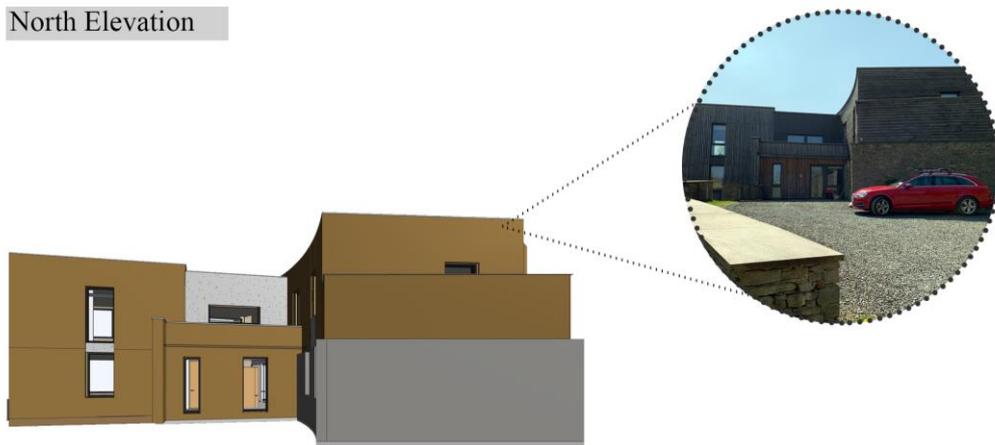
- *Collecting technical drawings and bill of quantities from the architect,*
- *Importing the PDF plan drawings to the Autocad and adjusting the scale of them according to given measurements in drawing.*
- *Importing the scaled plans (.dwg files) to H\B:ERT Revit file in metric units,*
- *To start drawing first looking which materials are used for that particular building element from detail drawings; for example for the ground floor walls, the layers of the external wall are 300 mm field stone, 80 mm ventilated cavity, 16 mm sheating board, 340 mm wood fibre insulation, 19 mm timber sheating board and 80 mm diagonal dübelholz (solid timber) (see Appendix D).*
- *Then using the defined walls in H\B:ERT if they were suitable and if not assigning new materials. Every material was defined differently and given a different name to gather the clear material properties data from material take-off.*
- *After selecting the wall with appropriate material, editing the wall thickness according to the details such as 300 mm for field stone. All the building elements' layers were modelled individually to avoid double accounting, rather than assigning them as components.*
- *These steps were repeated for all the floor floors, interior walls and roof, until finishing the all building (Figure 7).*
- *After finishing the building model, material take-off step were followed to extract material's densities, volumes, mass and areas as Excel spread sheet.*
- *Inserting the carbon intensities data from ICE V3.0 database and EPDs to Excel spread sheet for each material and multiplying them with the declared units (kg, m<sup>2</sup> or m<sup>3</sup>) for*

that material. Then summed all materials EC figures. Applying this step to Bill of Quantities (See Appendix E).

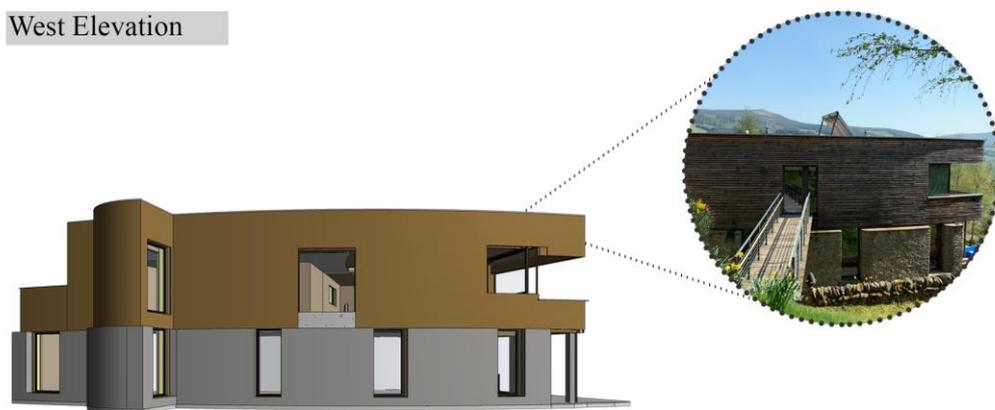
South Elevation



North Elevation



West Elevation



-  Timber Cladding
-  Stone Cladding
-  Fibre Cement Cladding

Figure 7: 3D Views from Revit-H\B:ERT.

### 3.2.6 In Use Energy Calculation

Operational energy for homes can vary hugely and some assumptions had to be made such as life span of the materials and house or users' lifestyle or maintenance, depending on energy database, software and method. Since, Plummerswood house is already constructed and people living there, calculating the operational energy of it regarding on its energy consumption figures (such as electricity and gas bills) was possible without any assumptions on the basis of number of occupants and number of electronic devices that they use or their hot water consumption. Therefore projecting these calculations to its 50 or 100 years life span provides means to compare these with the EE and EC estimations.

In this research operational energy calculations were included within the boundary of treated floor area (TFA) as Passivhaus considers heated floor area for the energy performance of the buildings (Cemesova, 2015) (*See page 32*).

The following steps were taken for the energy in-use calculations for the case study;

- *Collecting the annual energy bills and energy readings from occupants,*
- *Collecting the energy use data from other energy sources that have been used for the energy such as wood for fireplace (simply asked to occupants) and PV panels (Appendix G),*
- *Entering the collected data to Excel spread sheets, summarising the total energy consumption and dividing into TFA,*
- *Inserting the UK conversion factors for the electricity and wood and converting the energy units to carbon.*
- *Comparing the data if it matches with the predicted performance for the passivhaus or not (see Appendix F).*

Table 11 below summarises the overall steps which are followed during the calculation processes.

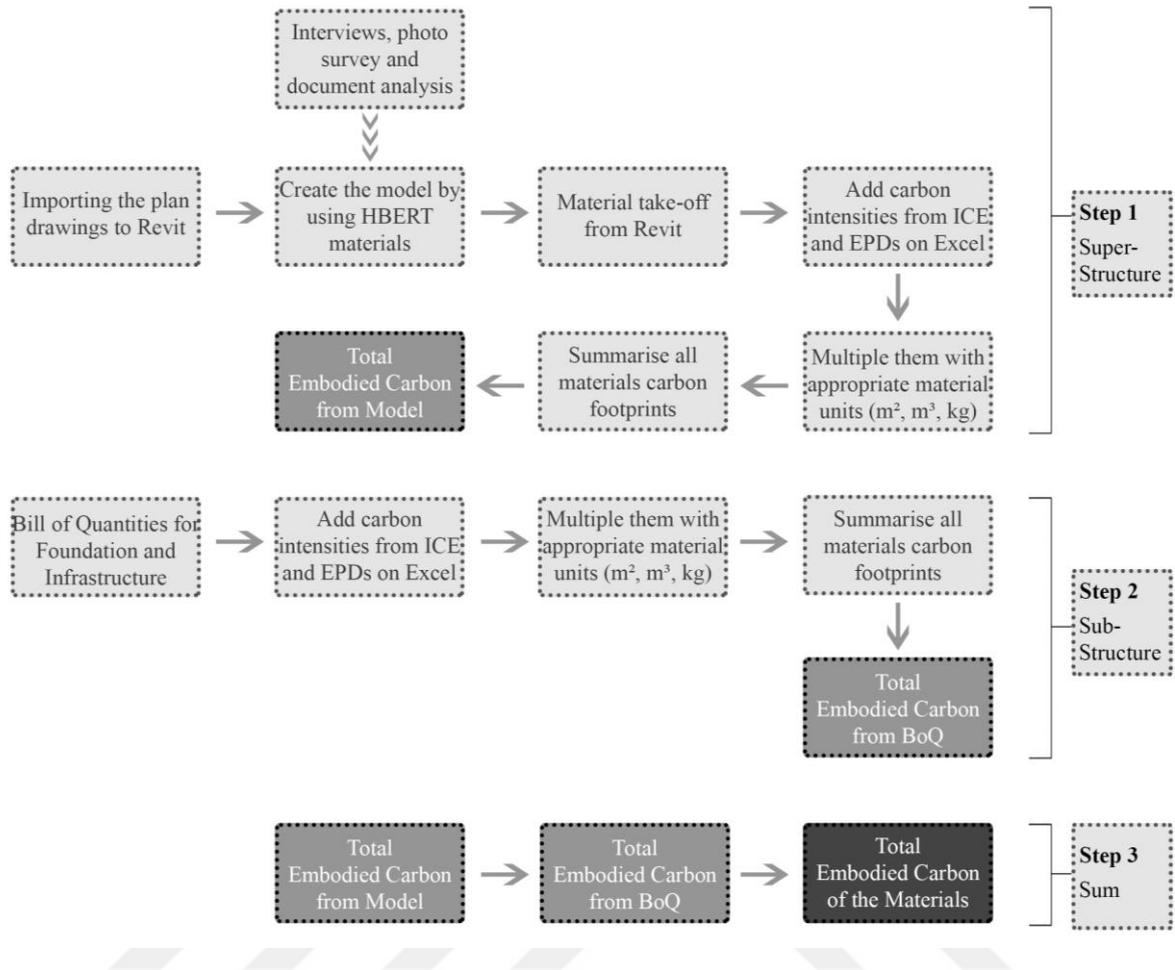


Table 11: Embodied carbon emissions Calculation Process.

## 4. Case Study: Plummerswood

### 4.1 Background

Plummerswood is located in Peebles near Edinburgh on Forestry Commission lands. It oversees the River Tweed and is surrounded with woodlands (Figure 8).

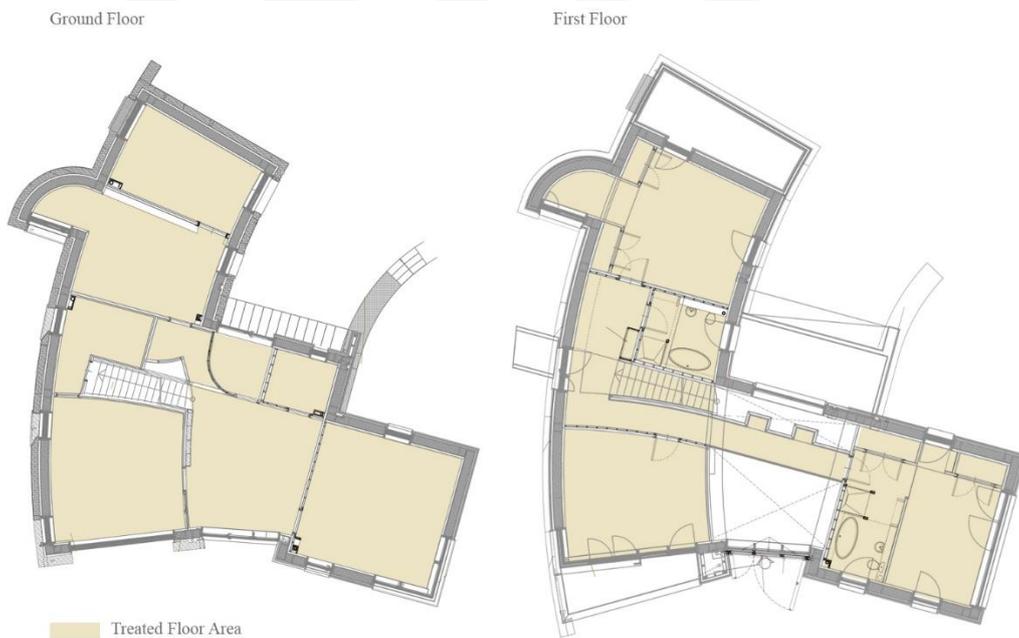


*Figure 8: Plummerswood House Location.*

Plummerswood is a 300 m<sup>2</sup>, 3 bedroom house designed by Gaia Architects, completed in 2011 (Figures 9 and 10), winning the Scottish Homes Award for Architectural Excellence in 2012 and short listed in the Passivhaus Awards in 2013. The owners envisioned an ecological house and the house was planned accordingly (Appendix B). The Brettstapel elements are made of Norway spruce studs, and are designed, constructed and delivered by the Austrian factory, Sohm (Lane, 2011). The prefabricated outer shell of the house was completed within two weeks. A reinforced concrete foundation was built by local company and home grown larch is used on façades. The house is expected to stand 100 years.



*Figure 9: Plummerswood House, (Foster, 2012).*



*Figure 10: Plummerswood Floor Plans (TFA is highlighted).*

The house meets its heating demand with a woodstove which consumes roughly 10 kg daily (Halliday, 2015) in the living room and a tower rail in the bathrooms and uses Mechanical Ventilation with Heat Recovery (MVHR), (set 28 m<sup>3</sup>/hr flow rate; Halliday, 2015) for the ventilation. There is no gas connection, the occupants use just electricity for cooking, lighting and other electrical devices such as TV and computers. Additionally, there are solar thermal (generates 2444 kWh/pa for the domestic hot water, *see Appendix G*) and bio disc (draws 2

kWh daily; Halliday, 2015) connected with the house monitoring system to lower the energy demand of the house.

The house cost £1.25m overall, according to the architect, it cost 25% more than a conventional house due to the currency exchange rates and site location as there is no Brettstapel factory in the UK, yet (Lane, 2011).

#### **4.2 Plummerswood in Light of Passivhaus Standard**

Wanting an ecological house and to promote the usage of timber, the owners used Brettstapel timber construction. As a part of the company contract, Sohm guaranteed to meet the Passivhaus Standard. The air tightness test results in 2016 were less than  $0.6 \text{ m}^3/\text{hr}/\text{m}^2 @ 50\text{Pa}$  and the u-value of the elements is  $0.14\text{W}/\text{m}^2\text{K}$  which both meet Passivhaus requirements (Halliday, 2015). MVHR helps to achieve the standard and enhances the indoor environment in the house. Additionally, the Brettstapel has a carbon preservation capacity and maintains suitable humidity to provide a healthy indoor environment (Pericchi and Cappiello, 2013). The south-east orientation of the house and external blinds help to keep solar heat gain out and to reach the Passivhaus Standard. The energy performance will be explained more in the *Energy Analysis and Discussion* section.

## 5. Energy Analysis Results

### 5.1 Embodied Carbon Results

The total ECE for the super structure materials, modelled with H\B:ERT is 3941.34 kgCO<sub>2e</sub> (Appendix E). The contribution of glass and steel materials is significant, 18335.29 and 26550.24 kgCO<sub>2e</sub>, respectively; however, wood fibre (insulation material) sets negative figure which is (-38298.92 kgCO<sub>2e</sub> for the hardboard and -6568.20 kgCO<sub>2e</sub> for the soft) and decreases the total carbon emission, noticeably. Although, stone had the higher EC among the materials which is 58.1 kgCO<sub>2e</sub>, total carbon emission is not significantly high (1933.60 kgCO<sub>2e</sub>), in relation to amount of the stone which is 33.3 m<sup>3</sup> (declared unit from EPD report), relatively low.

The total ECE for the substructure materials based on Bill of Quantity data is 38477.03 kgCO<sub>2e</sub>, almost ten times higher than the H\B:ERT materials. The usage of concrete and steel material carbon intensities make this figure understandably higher than super structure results. For example, carbon emission of concrete Gen 3, used for the foundation, was 8118 kgCO<sub>2e</sub>. Although, epoxy has the highest carbon intensity which is 3160 kgCO<sub>2e</sub>, the total EC of it is low 16.50 kgCO<sub>2e</sub> since the quantity was small (Appendix E). Also, the carbon emission for the prefabricated concrete elements such as manholes and sanitary products like toilets and sinks are other contributors of this huge total EC, their carbon intensities were 271 and 854 kgCO<sub>2e</sub>, in order.

Overall, when total ECE reflected to TFA, the result was 141,11 kgCO<sub>2e</sub>/m<sup>2</sup>.

### 5.2 In Use Energy Results

Annual electricity consumption for the Plummerswood was 8796 kWh for 2018 which was used for equipment, cooking and lightings, fans and pumps. A solar thermal was used for hot water, which generates 2444 kWh and was a decreasing factor for the total energy need. For the space heating, the occupants were using woodstove 175 days in a year and the wood consumption per day was 10kg (Halliday, 2015). The energy consumed from wood burning was 5880.92 kWh. Overall, house annual primary energy consumption per square meter was 40.70 kWh which is significantly lower than the Passivhaus standard (120 kWh/m<sup>2</sup>). However, the space heating demand was 19 kWh/m<sup>2</sup> which is not complying with the standard, but also this is depending on the wood consumption of the occupants which can be much lower or higher (*see page 37*). After, applying the UK conversion factors for each the energy sources and dividing them to

TFA, the carbon emissions figures were 7.48 kgCO<sub>2e</sub>/m<sup>2</sup> for the electricity, 2 kgCO<sub>2e</sub>/m<sup>2</sup> for the solar thermal and 0.31 kgCO<sub>2e</sub>/m<sup>2</sup> for woodstove. Total carbon emission from the energy in-use was 9.86 kgCO<sub>2e</sub>/m<sup>2</sup> (Appendix F).



## 6. Discussion

The results show that using timber as a structural form of insulation in Brettstapel can achieve significantly lower overall operational energy consumptions and carbon emissions than Passivhaus standard requires. This is critically important for achieving 2050 carbon and energy targets for the UK and other countries (*see page 9*).

The total ECE of Plummerswood is relatively low when compared with Din and Brotas (2016). In their study, they defined 5 different models for the assessing a Passivhaus home in Sweden. Model 1 was using the ICE data base for the building carbon emission and Model 4 was using the EPD reports. The ECE for these scenarios were 61230 kgCO<sub>2e</sub> and 65926 kgCO<sub>2e</sub>, respectively and Plummerswood's is 51210.49 kgCO<sub>2e</sub>. On the other hand, McHendry's (2013) results draws reasonably lower figures than Plummerswood which is 42440 kgCO<sub>2e</sub>, however the building fixtures, surface finishes and ground works were not included in their study which can be the reason of low numbers. However, it would be more useful to compare results in relation to m<sup>2</sup>, as the area of the house also affects the ECE such as bigger house most likely to have higher ECE, due to the material usage.

Furthermore, although insulation materials play an important role to provide fabric efficiency and air tightness in Passivhaus, in general they have higher ECE (EPS= 14,38 kgCO<sub>2e</sub>, Phenolic Foam= 17,6 kgCO<sub>2e</sub>; Densley Tingsley et al., 2015) therefore their contribution to the total carbon emission is huge; however, this situation is reverse in Plummerswood. A 340 mm wood fibre insulation was used in addition to the insulation provided by the Brettstapel fabric of the home to give U-value of 0.14 W/(m<sup>2</sup>K) (Halliday, 2014). Due to its carbon sequestration factor, EPD report for the wood fibre insulation showed that its carbon factor is negative, -1,64E+02 kgCO<sub>2e</sub>, meaning that wood fibre substantially lowers the ECE of the house. However, Ingerson (2009) criticise the carbon sequestration of timber products in relation to repair and renovation needs as stored carbon can be released from discarded timber materials because of these interventions in life time of a house. Therefore, these negative figures for the Plummerswood cannot be guaranteed.

Normally, required insulation thickness is between 250-400 mm to meet Passivhaus standard (120 kWh/m<sup>2</sup>/pa; Passpedia.org, 2015), and in Plummerswood, insulation thickness is 340 mm and achieves three times lower numbers than Passivhaus primary energy standard (Appendix F). Since, the house was achieving the primary energy target, the insulation thickness could

have been less; hence, Brettstapel is suitable construction technique in terms of using less materials which is important to avoid source depletion.

The usage of vast amount of concrete and steel materials for the foundation affects the ECE of the Plummerswood house significantly; total share from substructure was approximately 90% in total ECE. Material substitution can be the decreasing factor for this. For example, instead of using virgin concrete for GEN 3 and C35, preferring concrete with 70% blast furnace slag replacement content can decrease the carbon emissions the total emission by 8%. Also, due to the data constrains, using generic material carbon emissions for the fixing elements like bolts and resins or steel plates may affected the results negatively, as generic values are usually gives higher carbon emission values (see ICE database).

Plummerswood uses electricity but no gas. The UK electricity (0,2556 kgCO<sub>2e</sub>) has higher carbon emission factor than gas (0,2043 kgCO<sub>2e</sub>), for this reason, relying on just electricity can also be a factor that increases the operational energy of the house. On the other hand, the renewable energy generation in Scotland is 51.7% (29.3% for the UK; Gov.scot, 2019a) and carbon intensity is 0.054 kgCO<sub>2e</sub> (Gov.scot, 2019b). Therefore, carbon emission from the electricity for the Plummerswood would have been much lower if it was considered in Scotland context and not in the broader UK context due to the carbon conversation factors; however, there was no available specific data for the Scotland conversation factors.

The operational energy from space heating can change for the Plummerswood depending on woodstove usage, although there is no need for space heating. The contribution of the wood burning for the space heating is 19.56 kWh/m<sup>2</sup> which is higher than Passivhaus standard (15 kWh/m<sup>2</sup>). However, Passivhaus considers heating load (10 W/m<sup>2</sup>) rather than energy threshold (15kWh/m<sup>2</sup>) for the space heating; hence, the requirements for this is alterable which means a Passivhaus home can have higher space heating values than 15 kWh/m<sup>2</sup> as long as providing the heating load (10 W/m<sup>2</sup>) (Passpedia.org, 2019c). As Plummerswood heat load is 4.66 W/m<sup>2</sup>, the house meet with the Passivhaus standard.

Overall, the results pointed that ECE of the materials can be three times lower than 50 years life span of a building and in Kovacic, Reisinger and Honic (2018) study this figure draws similar results for materials and operational carbon for the Passivhaus block in Austria. They also include the carbon sequestration ability of the wood product in which makes these numbers more relevant.

## **7. Conclusion**

Today, carbon emission is a major concern due to the energy consumption. Housing sector plays an important role to tackle this in terms of climate change mitigation strategies. Because of this, this study provides state of art EE/EC in a Brettstapel home in the UK and fills the gap in relation to Passivhaus and this construction material. Also, due to the data availability, carbon emission were calculated. Moreover, cradle to gate scope was applied for the ECE calculations to avoid assumptions related with the occupant life style, products and building life span. However, during the calculations, some assumptions had to be made for the material carbon footprint in relation to data availability.

Calculating the overall greenhouse gas emission for a Brettstapel Passivhaus (both in-use and embodied) gives a holistic result, demonstrating its exceptional performance. Contribution to total ECE from the Brettstapel structure which includes all upper structure is about 10% which is significantly low compared to other studies (Din and Brotas, 2016; McHendry, 2013); however, the groundwork material still pose problem therefore material replacement scenarios should be considered, especially concrete and steel.

This study also showed that H\B:ERT plug in presents limited modelling environment for its users which made the calculation process longer than expected. Further improvements are needed for this plug in, in terms of material variety and database.

Last but not least, the occupant life style and carbon intensity from the grid were other factors which affected the energy in-use. If number of the occupants or electrical devices were higher than operational energy would be higher. Or, if the renewable energy contribution for the UK electricity were higher, then in-use carbon emission would be relatively lower than existing situation. Further, contribution of the electricity sources to the buildings operational carbon emission can be investigated in more broader context.

### **7.1 Limitations**

#### **7.1.1 H\B:ERT Plug-In Limitations**

Although using computational programmes to calculate the energy and carbon is helpful in terms of saving time, it can also bring some issues in providing accurate data. During the modelling process, H\B:ERT plug-in suffered from some shortcomings. The materials in its database are more generic than being specific; for example, it has concrete, timber and stone but does not have any natural stone, hardwood or aerated concrete blocks. Also, there is no

product definitions for plumbing fixtures, or infrastructure elements such as plumbing, electrical services or waste sanitation products. In order to overcome these difficulties the user has to duplicate an existing H\B:ERT materials, assign a new material name and change the properties such as density and thermal conductivity. Addition to this, the plug-in uses an old version of ICE, which is hindering the efficiency and usefulness of the programme. To use updated greenhouse gas intensities, the products data had to be extracted from model and calculated on Excel spreadsheet which made the accounting process longer and more complex than expected. Therefore, updating the database and expanding the material variation may be useful to compensate this programme's current drawbacks.

### **7.1.2 Database Limitations**

At the beginning of the research, the aim was to calculate the EE of the brettstapel passivhaus, and ICE V2.0 database for the materials energy intensities. However, after new database released in June 2019, to provide more updated and realistic data, it was decided to use ICE V3.0 database. The first limitation about the new database is that there is no EE data available in relation to increasing trend for the carbon emission because of the climate change emergency. Therefore, ECE data had to be used in this study, due to this change, with no other readily available open source database to use.

Another limitation about the ICE V3.0 database was the material variety. Although, materials are more detailed than previous version, a large number of material profiles are missing in categories such as plastic, insulation, metals, paint and adhesives. This situation lead the author to use EPDs for the missing products.

EPDs were helpful to compensate the loss data for material carbon intensities, yet they vary from company to company as they have different source and country context and transportation factor for their product. Also, for some building elements such as bolts, pipes, adhesives (epoxy), precast manholes and metal products, there were no available EPD report, so that, manual calculations are made by using the generic material carbon value for that elements which can affect the accuracy of the calculations as it is based on the author's own justification.

## 7.2 Recommendations

Further recommendations related with this study are;

- Current datasets calculations for the buildings just provides overall estimations for the carbon emissions. Research is needed to provide much more complete data every single product.
- EPDs should be provided for every material from every manufacturer as it can vary from manufacturer to manufacturer for the very same product. Then it can be easy to calculate the carbon emissions for the buildings.
- Although Brettstapel is imported from Austria, it has lower impact among the construction materials, therefore producing Brettstapel building elements in the UK with home grown timber is important to achieve carbon targets.
- The main contribution for the ECE was from substructure materials therefore substitution for this materials and how effects the total carbon emission could be the next step.
- Different scenarios can be presented to show how wood fibre thickness is effects the wall and floor performances in terms of U-value, airtightness and thermal conductivity as current thickness performs well than expected for Passivhaus standard.
- The Passivhaus should consider EE/EC emissions as part of its requirements alongside its focus on energy/carbon emissions in use.

## 8. References

- Abercrombie, N., Hill, S. and Turner, B.S. (1984). *Dictionary of Sociology*. [online] Available at: <http://text-translator.com/wp-content/filesfa/Dic-of-Sociology.pdf> [Accessed: 25 Jan. 2019].
- Acquaye, A., Duffy, A. and Basu, B. (2011). Embodied emissions abatement—A policy assessment using stochastic analysis. *Energy Policy*, 39(1), pp.429-441.
- An, H., Seok, H., Lee, S. and Choi, J. (2019). Forest management practice for enhancing carbon sequestration in national forests of Korea. *Forest Science and Technology*, 15(2), pp.80-91.
- Andresen, I. (2017). Towards Zero Energy and Zero Emission Buildings—Definitions, Concepts, and Strategies. *Current Sustainable/Renewable Energy Reports*, 4(2), pp.63-71.
- Autodesk.com. (2019). *BIM Software For Architectural Design*. Autodesk. [online] Available at: <https://www.autodesk.com/solutions/bim/architecture> [Accessed 23 Jul. 2019].
- Azari, R. and Abbasabadi, N. (2018). Embodied energy of buildings: A review of data, methods, challenges, and research trends. *Energy and Buildings*, 168, pp. 225-235.
- Baird, G., Alcorn, A. and Haslam, P. (1997). The Energy Embodied in Building Materials - Updated New Zealand Coefficients and Their Significance. *IPENZ Transactions*, 4(1), pp.46-54.
- Badescu, V. and Sicre, B. (2003). Renewable energy for passive house heating. *Energy and Buildings*, 35(11), pp.1077-1084.
- Basbagill, J., Flager, F., Lepech, M. and Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, 60, pp.81-92.
- Belshaw, K. (2017). *Sense of Place and Walking Tours: A Case Study of the Tour Guys Downtown Toronto Tour*. Master Thesis. University of Waterloo. Waterloo.
- Bin, G. and Parker, P. (2012). Measuring Buildings for Sustainability: Comparing the Initial and Retrofit Ecological Footprint of a Century Home – The REEP House. *Applied Energy*, [online] 93, pp.24-32. Available at: <https://www.sciencedirect.com/science/article/pii/S0306261911003655> [Accessed 19 Jul. 2019].
- Bowen, G. (2009). Document Analysis as a Qualitative Research Method. *Qualitative Research Journal*, 9(2), pp.27-40.
- Britannica. (2019). *Database: Definition, Types, & Facts*. [online] Available at: <https://www.britannica.com/technology/database> [Accessed 29 Aug. 2019].
- Buchanan, A. and Levine, S. (1999). Wood-based building materials and atmospheric carbon emissions. *Environmental Science & Policy*, 2(6), pp.427-437.
- Buildingconstructiondesign.co.uk. (2015). *Carbon sequestration – locking up carbon and unlocking the full potential of timber | netMAGmedia Ltd*. [online] Available at:

- <https://www.buildingconstructiondesign.co.uk/news/carbon-sequestration-locking-up-carbon-and-unlocking-the-full-potential-of-timber/> [Accessed 21 Aug. 2019].
- Burrell, E. (2015). What is the Passive House Planning Package (PHPP)?. [Blog] *PASSIVHAUS IN PLAIN ENGLISH & MORE*. Available at: <https://elrondburrell.com/blog/passive-house-planning-package-phpp/> [Accessed 29 Aug. 2019].
- Campbell, D.T. (1975). Degrees of Freedom and the Case study, *Comparative Political Studies*, 8(2), p.182.
- Cemesova, A., Hopfe, C. and Mcleod, R. (2015). PassivBIM: Enhancing interoperability between BIM and low energy design software. *Automation in Construction*, 57, pp.17-32.
- Chau, C., Leung, T. and Ng, W. (2015). A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Applied Energy*, 143, pp.395-413.
- Circular Ecology. (2019). *Glossary of Terms*. [online] Available at: <http://www.circularecology.com/glossary-of-terms-and-definitions.html#.XV2eO-hKhPY> [Accessed 21 Aug. 2019].
- Crawford, R.H. and Treloar, G.J. (2003). *Validation of the use of Australian Input-Output data for building embodied energy simulation*. Eighth International IBPSA Conference.
- Committee on Climate Change (2018). *Reducing UK emissions: 2018 Progress Report to Parliament*. [online] Committee on Climate Change, pp.90-91. Available at: <https://www.theccc.org.uk/wp-content/uploads/2018/06/CCC-2018-Progress-Report-to-Parliament.pdf> [Accessed 4 Aug. 2019].
- Committee on Climate Change (2019). *UK housing: Fit for the future?*. [online] Committee on Climate Change. Available at: <https://www.theccc.org.uk/publication/uk-housing-fit-for-the-future/> [Accessed 22 Jul. 2019].
- Creswell, J. and Plano Clark, V. (2017). *Designing and conducting mixed methods research*. 3rd ed. Los Angeles: SAGE.
- Crowther, P. (1999). *Design for Disassembly to recover Embodied Energy*. In: The 16<sup>th</sup> International Conference on Passive and Low Energy Architecture. Australia: PLEA 1999, pp.1-6.
- DEFRA and DBEIS, 2019. *UK Government GHG Conversion Factors for Company Report*, UK: Department for Business, Energy and Industrial Strategy.
- Denscombe, M. (2017). *The Good Research Guide For small-scale social research projects*. 6th ed. London: Open University Press, pp.244-245.
- Densley Tingley, D., Hathway, A. and Davison, B. (2015). An environmental impact comparison of external wall insulation types. *Building and Environment*, 85, pp.182-189.
- Department for Business, Energy & Industrial Strategy (2010). *2050 Pathways Analysis*. [online] HM Government, pp.101-102. Available at: [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/68816/216-2050-pathways-analysis-report.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/68816/216-2050-pathways-analysis-report.pdf) [Accessed 9 Aug. 2019].

- DesignBuilder (2018). *Optimizing an Eco-Friendly House Design using DesignBuilder*. [online] Tarragona. Available at: <https://designbuilder.co.uk/casestudies/CasaNS-CaseStudy.pdf> [Accessed 30 Jul. 2019].
- Din, A. and Brotas, L. (2016). Exploration of Life Cycle Data Calculation: Lessons From a Passivhaus Case Study. *Energy and Buildings*, 118, pp.82-92.
- Dixit, M. (2019). Life Cycle Recurrent Embodied Energy Calculation of Buildings: A Review. *Journal of Cleaner Production*, 209, pp.731-754.
- Dixit, M.K. (2018). Life cycle recurrent embodied energy calculation of buildings: A review. *Journal of Cleaner Production*, 209, pp.731-754.
- Dixit, M. (2013). *Embodied Energy Calculation: Method and Guidelines for a Building and Its Constituent Materials*. PhD. Texas A&M University.
- Dixit, M., Fernández-Solís, J., Lavy, S. and Culp, C. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, 42(8), pp.1238-1247.
- Dudley, N., Jeanrenaud, J. and Sullivan, F. (2014). *Bad Harvest?*. 1st ed. [ebook] Routledge. Available at: <https://www.taylorfrancis.com/books/9781315070445> [Accessed 22 Jul. 2019].
- Energy.gov. (2019). *Building Energy Use Benchmarking*. [online] Available at: <https://www.energy.gov/eere/slsc/building-energy-use-benchmarking> [Accessed 23 Aug. 2019].
- Envirodec.com, 2019. *What is an EPD?*. [Online] Available at: <https://www.envirodec.com/What-is-an-EPD/> [Accessed 23 July 2019].
- Eufrasio-Espinosa, R. (2015). *Visio-Spatial life cycle energy model of buildings materials within a bioregional context*. PhD. The University of Sheffield.
- Feist, W., Schnieders, J., Dorer, V. and Haas, A. (2005). Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. *Energy and Buildings*, 37(11), pp.1186-1203.
- Fenner, A., Kibert, C., Woo, J., Morque, S., Razkenari, M., Hakim, H. and Lu, X. (2018). The carbon footprint of buildings: A review of methodologies and applications. *Renewable and Sustainable Energy Reviews*, 94, pp.1142-1152.
- Fesanghary, M., Asadi, S. and Geem, Z. (2012). Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm. *Building and Environment*, 49, pp.245-250.
- Flyvbjerg, B. (2006). Five Misunderstandings about Case-Study Research, *Qualitative Inquiry*, 12(2), pp. 219–245. doi: 10.1177/1077800405284363.
- Forestry Commission (2018). *Forestry Statistics 2018*. [online] Forestry Commission, pp.81-84. Available at: <https://www.forestresearch.gov.uk/tools-and-resources/statistics/forestry-statistics/forestry-statistics-2018/> [Accessed 5 Aug. 2019].

- Forestryscotland.com. (n.d.). *Sustainable Timber Construction Materials from Scotland's Forest and Timber Sector - Brettstapel*. [online] Available at: <http://www.forestryscotland.com/products-and-markets/sustainable-construction-materials/engineered-timber-products/Brettstapel> [Accessed 22 Jul. 2019].
- Foster, S. (2012). *Photograph taken at Edinburgh by Sam Foster*. [Photograph]. At: Edinburgh: Peebles.
- Gaia Group.org (2019). *UK's first Brettstapel Zero Heating Active House* [online] Available at: [http://www.gaiagroup.org/projects/project/65#\\_10](http://www.gaiagroup.org/projects/project/65#_10) [Accessed 13 Feb.2019].
- Gervasio, H. and Dimova, S. (2018). Model for Life Cycle Assessment of Buildings. [online] *JRC Science Hub*. Available at: [http://publications.jrc.ec.europa.eu/repository/bitstream/JRC110082/report\\_d1\\_online\\_final.pdf](http://publications.jrc.ec.europa.eu/repository/bitstream/JRC110082/report_d1_online_final.pdf) [Accessed 18 Jul. 2019].
- Goucher, J. (2018). *IES Virtual Environment*. [online] BEST Directory. Available at: <https://www.buildingenergysoftwaretools.com/software/ies-virtual-environment> [Accessed 30 Jul. 2019].
- Gov.scot. (2019a). *Annual energy statement 2019 - gov.scot*. [online] Available at: <https://www.gov.scot/publications/annual-energy-statement-2019/pages/3/> [Accessed 24 Aug. 2019].
- Gov.scot. (2019b). *Scotland's electricity and gas networks: vision to 2030 - gov.scot*. [online] Available at: <https://www.gov.scot/publications/vision-scotlands-electricity-gas-networks-2030/> [Accessed 25 Aug. 2019].
- Greene, J. (2007). *Mixed Methods in Social Inquiry*. San Francisco: Jossey-Bass.
- Greenspec. (2019). *Programme for Endorsement of Forest Certification (PEFC)*. [online] Available at: <http://www.greenspec.co.uk/building-design/pefc-certified-timber/> [Accessed 25 Feb. 2019].
- Halliday, S. (2015). *Building Performance Evaluation: Domestic Buildings-Post Construction and Early Occupation: Plummerswood-Final Report*. Gaia Research, pp.1-57.
- Hallquist, A. (1978). Energy Consumption: Manufacture of Building Materials and Building Construction. *Habitat Intl*, 3(5-6), pp. 551-557.
- Hammarberg, K., Kirkman, M. and de Lacey, S. (2016). Qualitative research methods: when to use them and how to judge them. *Human Reproduction*, [online] 31(3), pp.498-501. Available at: <https://academic.oup.com/humrep/article/31/3/498/2384737> [Accessed 3 Jun. 2019].
- Hammond, G., Jones, C., Lowrie, F. and Tse, P. (2011). *Embodied carbon emissions*. Bracknell: BSRIA.
- Hammond, G. and Jones, C. (2009). Embodied carbon emissions: The Concealed Impact of Residential Construction. *Global Warming*, pp.367-384.
- Henderson, J., Foster, S. and Bridgestock, M. (2012). *What is Brettstapel?* [online] Brettstapel Construction. Available at: [http://www.Brettstapel.org/Brettstapel/What\\_is\\_it.html](http://www.Brettstapel.org/Brettstapel/What_is_it.html) [Accessed 12 Feb. 2019].

- Hesse-Biber, S. and Johnson, B. (2015). *The Oxford handbook of multimethod and mixed methods research inquiry*. New York: Oxford University Press.
- Häkkinen, T., Kuittinen, M., Ruuska, A. and Jung, N. (2019). *Reducing embodied carbon emissions during the design process of buildings*.
- Ibáñez-Forés, V., Pacheco-Blanco, B., Capuz-Rizo, S. & Bovea, M., 2016. Environmental Product Declarations: exploring their evolution and the factors affecting their demand in Europe. *Cleaner Production*, Volume 116, pp. 157-169.
- Iddon, C. and Firth, S. (2013). Embodied and operational energy for new-build housing: A case study of construction methods in the UK. *Energy and Buildings*, 67, pp.479-488.
- Ingerson, A. (2009). *Wood Products and Carbon Storage: Can Increased Production Help Solve the Climate Crisis?*. [online] Washington, D.C.: The Wilderness Society, pp.1-6. Available at: <https://www.sierraforestlegacy.org/Resources/Conservation/FireForestEcology/ThreatsForestHealth/Climate/CI-Ingerson-TWS2009.pdf> [Accessed 21 Aug. 2019].
- International Energy Agency (2016). *Evaluation of Embodied Energy and CO<sub>2</sub>eq for Building Construction (Annex 57)*. Birmingham: Institute for Building Environment and Energy Conservation, pp.39-50.
- International Federation of Institutes for Advanced Studies (1978). IFIAS Workshop Report, energy analysis and economics. *Resources and Energy*, 1(2), pp.151-204.
- IPCC (Intergovernmental Panel on Climate Change) (2018). *Global Warming of 1.5 °C*. Switzerland: IPCC.
- Jalaei, F. and Jade, A. (2015). Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. *Sustainable Cities and Society*, 18, pp.95-107.
- Jones, C. & Hammond, G., 2019. *Inventory of Carbon and Energy*. London: Circular Ecology and University of Bath.
- Kinney, P. (2019). Walking Interviews. *Social Research Update*, [online] 67. Available at: <http://sru.soc.surrey.ac.uk/SRU67.pdf> [Accessed 3 Jun. 2019].
- Kirshenblatt-Gimblett, B. (2006). *What is Research Design? Part 1: The Context of Design*. [online] New York: University of New York, pp.1-6. Available at: <http://www.nyu.edu/classes/bkg/methods/005847ch1.pdf> [Accessed 6 Jun. 2019].
- Kolaitis, D. I., Asimakopoulou, E. K. & Founti, M. A., 2014. Fire protection of light and massive timber elements using gypsum plasterboards and wood based panels: A large-scale compartment fire test. *Construction and Building Materials*, Cilt 73, pp. 163-170.
- Kovacic, I., Reisinger, J. and Honic, M. (2018). Life Cycle Assessment of embodied and operational energy for a passive housing block in Austria. *Renewable and Sustainable Energy Reviews*, 82, pp.1774-1786.
- Kuzman, M., Grošelj, P., Ayırlmış, N. and Zbašnik-Senegačnik, M. (2013). Comparison of Passivhaus Construction Types Using Analytic Hierarchy Process. *Energy and Buildings*,

[online] 64, pp.258-263. Available at: <https://www.sciencedirect.com/science/article/pii/S037877881300296X?via%3Dihub> [Accessed 19 Feb. 2019].

Lane, T. (2011). The Natural Choice. *Building Magazine*, p.51.

Lee, T. and Koski, C. (2012). Building Green: Local Political Leadership Addressing Climate Change. *Review of Policy Research*, 29(5), pp.605-624.

Leskovar, V. and Premrov, M. (2011). An approach in architectural design of energy-efficient timber buildings with a focus on the optimal glazing size in the south-oriented façade. *Energy and Buildings*, 43(12), pp.3410-3418.

Lippke, B., Wilson, J., Garcia-Perez, J., Bowyer, J. and Meil, J. (2004). CORRIM: Life-Cycle Environmental Performance of Renewable Building Materials. *Forest Products Journal*, 54(6), pp.8-19.

Liu, X., Eybpoosh, M. and Akinci, B. (2012). *Developing As-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera*. Construction Research Congress 2012.

Lu, Y., Wu, Z., Chang, R. and Li, Y. (2017). Building Information Modeling (BIM) for green buildings: A critical review and future directions. *Automation in Construction*, 83, pp.134-148.

Maderaestructural.wordpress.com (2018). *Brettstapel*. [image] Available at: <https://maderaestructural.wordpress.com/tag/brettstapel/> [Accessed 23 Aug. 2019].

McHendry, S. (2013). *The Embodied Energy and Carbon of Passive House*. Master. University of Strathclyde.

McLeod, R., Hopfe, C. and Rezgui, Y. (2012). An investigation into recent proposals for a revised definition of zero carbon homes in the UK. *Energy Policy*, 46, pp.25-35.

Menzies, G.F., Turan, S., Banfill, P.F.G. (2007). Life-cycle Assessment and Embodied Energy: A Review. *Institution of Civil Engineers*, CM4, pp.135-143.

Milne, G.(2013). *Materials Embodied Energy* [online] Your Home. Available at: <http://www.yourhome.gov.au/materials/embodied-energy> [Accessed 18 Dec.2018].

Monahan, J. and Powell, J. (2011). An embodied carbon emissions and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings*, 43(1), pp.179-188.

Moncaster, A. and Song, J. (2012). A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings. *International Journal of Sustainable Building Technology and Urban Development*, 3(1), pp.26-36.

Moncaster, A. and Symons, K. (2013). A method and tool for ‘cradle to grave’ embodied carbon emissions and energy impacts of UK buildings in compliance with the new TC350 standards. *Energy and Buildings*, 66, pp.514-523.

Moore, G., Croxford, B., Adams, M., Refaee, M., Cox, T. and Sharples, S. (2008). The photo-survey research method: capturing life in the city. *Visual Studies*, [online] 23(1), pp.50-62.

Available at: <https://www.tandfonline.com/doi/pdf/10.1080/14725860801908536> [Accessed 3 Jun. 2019].

Mostafavi, N., Farzinmoghadam, M. and Hoque, S. (2013). Envelope retrofit analysis using eQUEST, IESVE Revit Plug-in and Green Building Studio: a university dormitory case study. *International Journal of Sustainable Energy*, 34(9), pp.594-613.

Naser, M. (2019). Fire resistance evaluation through artificial intelligence - A case for timber structures. *Fire Safety Journal*, 105, pp.1-18.

Nizam, R., Zhang, C. and Tian, L. (2018). A BIM based tool for assessing embodied energy for buildings. *Energy and Buildings*, 170, pp.1-14.

Onat, N., Kucukvar, M. and Tatari, O. (2014). Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input–output hybrid life cycle assessment approach. *Building and Environment*, 72, pp.53-62.

Östman, B., Brandon, D. & Frantzich, H., 2017. Fire safety engineering in timber buildings. *Fire Safety Journal*, Issue 91, pp. 11-20.

Pan, W. (2010). Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK. *Building and Environment*, 45(11), pp.2387-2399.

Pandey, D., Agrawal, M. and Pandey, J. (2010). Carbon footprint: current methods of estimation. *Environmental Monitoring and Assessment*, 178(1-4), pp.135-160.

Passipedia.org. (2015). *Passive House suitable wall systems*. [online] Available at: [https://passipedia.org/planning/thermal\\_protection/external\\_walls/passive\\_house\\_suitable\\_wall\\_systems](https://passipedia.org/planning/thermal_protection/external_walls/passive_house_suitable_wall_systems) [Accessed 24 Aug. 2019].

Passipedia.org. (2019a). *Thermal comfort parameters*. [online] Available at: [https://passipedia.org/basics/building\\_physics\\_-\\_basics/thermal\\_comfort/thermal\\_comfort\\_parameters](https://passipedia.org/basics/building_physics_-_basics/thermal_comfort/thermal_comfort_parameters) [Accessed 23 Aug. 2019].

Passipedia.org. (2019b). *What is a Passivhaus?*. [online] Available at: [https://passipedia.org/basics/what\\_is\\_a\\_passive\\_house](https://passipedia.org/basics/what_is_a_passive_house) [Accessed 19 Feb. 2019].

Passipedia.org. (2019c). *Heating load in Passive Houses*. [online] Available at: [https://passipedia.org/basics/building\\_physics\\_-\\_basics/heating\\_load](https://passipedia.org/basics/building_physics_-_basics/heating_load) [Accessed 28 Aug. 2019].

Passivhaus Trust (2019). *Passivhaus: The Route to Zero Carbon*. [online] Passivhaus Trust, p.14. Available at: [http://passivhaustrust.org.uk/UserFiles/File/2019.03.20-Passivhaus%20and%20Zero%20Carbon-Publication%20Version1.2\(1\).pdf](http://passivhaustrust.org.uk/UserFiles/File/2019.03.20-Passivhaus%20and%20Zero%20Carbon-Publication%20Version1.2(1).pdf) [Accessed 22 Jul. 2019].

Passivhaustrust.org.uk. (2019). *Home*. [online] Available at: <http://www.passivhaustrust.org.uk/> [Accessed 29 Aug. 2019].

Pelsmakers, S. (2016). *The Environmental Design Pocketbook*. 2nd, rev. ed. London: RIBA Publishing.

Pericchi, B. and Cappiello, M. (2013). *A Certified Passive Timber House in Scotland: The Brettstapel Construction Principle*. pp.1-5.

- Peng, C. (2016). Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. *Journal of Cleaner Production*, 112, pp.453-465.
- Plano Clark, V. and Ivankova, N. (2017). *Mixed methods research*. Los Angeles: SAGE.
- Pomponi, F. and Moncaster, A. (2016). Embodied carbon emissions mitigation and reduction in the built environment – What does the evidence say?. *Journal of Environmental Management*, 181, pp.687-700.
- Pullen, S. F. (2007). *The Spatial Representation of Embodied Energy of Residential Areas in the Urban Environment*. Doctor of Philosophy Doctoral, The University of Adelaide.
- Rasmussen, F., Malmqvist, T., Moncaster, A., Wiberg, A. and Birgisdóttir, H. (2018). Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings. *Energy and Buildings*, 158, pp.1487-1498.
- Raynolds, M., Checkel, M. and Fraser, R. (1999). Application of Monte Carlo Analysis to Life Cycle Assessment. *SAE Transactions*, [online] 108, pp.1-9. Available at: <http://www.jstor.org/stable/44650581> [Accessed 22 Aug. 2019].
- Ritter, M. (1992). *Timber Bridges*. Washington, D.C.: U.S. Dept. of Agriculture, Forest Service, *Engineering Staff*, p.1.
- Sartori, I and Hestnes, A.G. (2007). Energy Use in the Life Cycle of Conventional and Low-Energy Buildings: A Review Article. *Energy and Buildings*, 39, pp: 249-257.
- Schoonenboom, J. and Johnson, R. (2017). How to Construct a Mixed Methods Research Design. *KZfSS Kölner Zeitschrift für Soziologie und Sozialpsychologie*, 69(S2), pp.107-131.
- Scheuer, C., Keoleian, G. and Reppe, P. (2003). Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *Energy and Buildings*, 35(10), pp.1049-1064.
- Shadram, F., Johansson, T., Lu, W., Schade, J. and Olofsson, T. (2016). An integrated BIM-based framework for minimizing embodied energy during building design. *Energy and Buildings*, 128, pp.592-604.
- Shafiq, N., Nurrudin, M., Gardezi, S. and Kamaruzzaman, A. (2015). Carbon footprint assessment of a typical low rise office building in Malaysia using building information modelling (BIM). *International Journal of Sustainable Building Technology and Urban Development*, 6(3), pp.157-172.
- Silvestre, J.D., de Brito, J., Pinheiro, M.D. (2014). *Cradle to Cradle, Cradle to Grave, Cradle to Cradle Stages for Materials*. [digital image] Available at: <https://www.sciencedirect.com/science/article/pii/S0959652613007087?via%3Dihub> [Accessed 01 May 2019].
- Soust-Verdaguer, B., Llatas, C. and García-Martínez, A. (2017). Critical review of bim-based LCA method to buildings. *Energy and Buildings*, 136, pp.110-120.
- Souza, R. F. C. (2015). *Case Studies as Method for Architectural Research*. [online] Available at:

[https://www.researchgate.net/publication/314147521\\_Case\\_Studies\\_as\\_method\\_for\\_architect\\_ural\\_research](https://www.researchgate.net/publication/314147521_Case_Studies_as_method_for_architect_ural_research) [Accessed 23 Mar. 2019].

Steiger, L. (2007). *Basics Timber Construction*. Basel: Birkhauser Verlag AG, pp.14-15.

Steinmetz-Wood, M., Pluye, P. and Ross, N. (2019). The planning and reporting of mixed methods studies on the built environment and health. *Preventive Medicine*, 126, p.105752.

Stephan, A., Crawford, R.H., Myttenaere, K. (2013). A Comprehensive Assessment of the Life Cycle energy Demand of Passive Houses. *Applied Energy*, 112, pp.23-24.

Structural Timber Association (2014). Fire Safety in Timber Buildings. Structural Timber Engineering Bulletin. [online] *Structural Timber Association*, pp.1-8. Available at: <http://www.structuraltimber.co.uk/assets/InformationCentre/eb7.pdf> [Accessed 22 Jul. 2019].

Swedish Wood. (2019). *Wood is a sustainable construction material - Swedish Wood*. [online] Available at: [https://www.swedishwood.com/about\\_wood/choosing-wood/wood-and-the-environment/wood-is-a-sustainable-construction-material/](https://www.swedishwood.com/about_wood/choosing-wood/wood-and-the-environment/wood-is-a-sustainable-construction-material/) [Accessed 20 Aug. 2019].

Tabatabaei Sameni, S., Gaterell, M., Montazami, A. and Ahmed, A. (2015). Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, 92, pp.222-235.

Teddle, C. and Tashakkori, A. (2012). Common “Core” Characteristics of Mixed Methods Research. *American Behavioral Scientist*, 56(6), pp.774-788.

The Editors of Encyclopaedia Britannica, 2019. *Database*. N.D: Encyclopædia Britannica, inc..

The Institution of Structural Engineers (2011). *A short Guide for Embodied carbon emissions in Building Structures*. The Institution of Structural Engineers, p.4.

The Royal Institution of Chartered Surveyors (2017). *Whole Life Carbon Assessment for the Built Environment*. 1st ed. London: RICS.

Treloar, G.J. (1997). Extracting Embodied Energy Paths from Input- Output Tables: Towards an Input-Outputbased Hybrid Energy Analysis Method. *Economic Systems Research*. 9(4), pp.375-391.

Tucker, S.N. and Ambrose, M.D. (1997). Embodied Energy of Dwellings. In: *ESD Success Applications Conference* [Online] Sydney: CSIRO, pp.1-7. Available at: <https://publications.csiro.au/rpr/download?pid=procite:54757bf5-6619-4ba8-84154012ca2a477e&dsid=DS1> [Accessed: 18 Jan. 2019].

Turner, S. (2019). *Asset Management and Performance - BREEAM*. [online] BREEAM. Available at: <https://www.breeam.com/news/asset-management-and-performance/> [Accessed 22 Jul. 2019].

UK Green Building Council (2015). *Tackling Embodied carbon emissions in Buildings*. [online] UKGBC. Available at: <https://www.ukgbc.org/sites/default/files/Tackling%20embodied%20carbon%20in%20buildings.pdf> [Accessed 19 Jul. 2019].

UN Environment and International Energy Agency (2017). *Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2017*. [online] United Nations Environment Programme, p.6. Available at: [https://www.worldgbc.org/sites/default/files/UNEP%20188\\_GABC\\_en%20%28web%29.pdf](https://www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf) [Accessed 20 Aug. 2019].

UNFCCC (2019). *Framework Convention on Climate Change*. [online] Available at: <https://unfccc.int/resource/docs/2015/cop21/eng/10.pdf#page=30> [Accessed 18 Jul. 2019].

Union of Concerned Scientists. (n.d.). *What's Driving Deforestation: Wood Products*. [online] Available at: <https://www.ucsusa.org/global-warming/stop-deforestation/drivers-of-deforestation-2016-wood-products> [Accessed 9 Mar. 2019].

United Nations (2016). *Framework Convention on Climate Change*. [online] Paris: United Nations, p.33. Available at: <https://unfccc.int/resource/docs/2015/cop21/eng/10.pdf#page=30> [Accessed 18 Jul. 2019].

Vinha, J., Manelius, E., Korpi, M., Salminen, K., Kurnitski, J., Kiviste, M. and Laukkarinen, A. (2015). Airtightness of residential buildings in Finland. *Building and Environment*, [online] 93, pp.128-140. Available at: <https://www.sciencedirect.com/science/article/pii/S0360132315300251> [Accessed 26 Feb. 2019].

Wang, E. and Shen, Z. (2013). A hybrid Data Quality Indicator and statistical method for improving uncertainty analysis in LCA of complex system – application to the whole-building embodied energy analysis. *Journal of Cleaner Production*, 43, pp.166-173.

Woodforgood.com. (2019). *Sustainable Procurement*. [online] Available at: <https://woodforgood.com/why-choose-wood/sustainable-procurement> [Accessed 13 Mar. 2019].

WRAP (n.d.). *Cutting Embodied carbon emissions in Construction Projects*. [online] Waste and Resources Action Programme. Available at: <http://www.wrap.org.uk/sites/files/wrap/FINAL%20PRO095-009%20Embodied%20Carbon%20Annex.pdf> [Accessed 19 Jul. 2019].

Wu, W. and Issa, R. (2015). BIM Execution Planning in Green Building Projects: LEED as a Use Case. *Journal of Management in Engineering*, 31(1), p.A4014007.

Yin, R. (2003). *Case Study Research: Design and Methods*. 3rd ed. California: Sage Publications, Inc. pp. 1-56.

Yohanis, Y.G., Norton, B. (2002). Life cycle operational and embodied energy of a generic office building in the UK. *Energy*, 27(1), pp.77-92.

Zainal, Z. (2007). *Case Study as a Research Method*. *Jurnal Kemanusiaan*, 9. [online] Available at: [https://www.researchgate.net/publication/41822817\\_Case\\_study\\_as\\_a\\_research\\_method](https://www.researchgate.net/publication/41822817_Case_study_as_a_research_method) [Accessed 23 Mar. 2019].

Zeng, R. and Chini, A. (2017). A review of research on embodied energy of buildings using bibliometric analysis. *Energy and Buildings*, 155, pp.172-184.

Zhai, P. and William, E.D. 2010. Dynamic Hybrid Life Cycle Assessment of Energy and Carbon of Multicrystalline Silicon Photovoltaic Systems. *Environmental Science and Technology*, 44(20), 7950-7955.



## 9. Appendices

### Appendix A: Ethics Approval



Downloaded: 10/08/2019

Approved: 20/03/2019

Dilek Arslan

Registration number: 180125261

School of Architecture

Programme: MSc Sustainable Architecture Studies

Dear Dilek

**PROJECT TITLE:** ARC6990 - Sustainable Design Thesis Project

**APPLICATION:** Reference Number 025032

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 20/03/2019 the above-named project was **approved** on ethics grounds, on the basis that you will adhere to the following documentation that you submitted for ethics review:

- University research ethics application form 025032 (dated 24/02/2019).
- Participant information sheet 1056826 version 1 (24/02/2019).
- Participant consent form 1056827 version1 (24/02/2019).

If during the course of the project you need to [deviate significantly from the above-approved documentation](#) please inform me since written approval will be required.

Yours sincerely

Chengzhi Peng

Ethics Administrator

School of Architecture

## **Appendix B: Interview Transcripts**

### **Occupants**

**Interviewee 1:** That direction that we are looking at is south. This is the side of the house that gets most of the sun and it is got most of the glass, but at the same time, so we do not get over heating at summer. The balcony in here is designed to stop too much sun coming in. Those things there, called Brise Soleil and designed to do the same thing.

**Interviewer:** Do you feel it is effective?

**Interviewee 1:** Yes, we don't have over heating in the summer. And here in the launch, some of the upstairs bedroom, we have got external blinds... that come down. They are in outside because if they were in inside by the time they stop the sun, the heat is got in.

**Interviewer:** So whenever sun comes up, you close these blinds?

**Interviewee 1:** Well, just in the summer, we do not want to overheat.

**Interviewer:** How long do you live here?

**Interviewee 1:** How long? Since 2011, so eight years...

**Interviewer:** So you happy?

**Interviewee 1:** Yes.

**Interviewer:** It is nice.

**Interviewee 1:** And then we also... Up there, you can see those windows open. Just, again in the summer, to give some bit of ventilation.

**Interviewer:** How can you close and open that windows?

**Interviewee 1:** It is electric.

**Interviewer:** Oh! It is automatic!

**Interviewee 1:** So you just press the button and the same on this side...just see them up there... So they designed to open as well.

**Interviewer:** Do you have any difficulties with timber materials, like to try find out, try to maintenance it?

**Interviewee 1:** Not yet. Not really. Well, we had a mega disaster in 2015. When one of our water tanks, we realise, was leaking. We were out the house for seven months.

**Interviewer:** Oh! But it was not related with the material, right?

**Interviewee 1:** No, the insurance company is still fighting about it so. The repairs cost them several hundred thousand pounds

**Interviewer:** Why did you choose that wood material for your house?

**Interviewee 1:** Because the architect was so enthusiastic about it.

**Interviewer:** But you did not know anything about what is for.

**Interviewee 1:** No, no.

**Interviewer:** But now, you happy to choose it?

**Interviewee 1:** Oh! Yes, yes... The architect, originally, wanted to house to be all wood. But Anne did not like the thought of big wooden house so we got all these stone which is not structural. It is just for effect.

**Interviewer:** What was your aim to construct this house, in the first place like to have more ecological house or just normal house for your retirement?

**Interviewee 1:** We did not start off with an ecological house in mind but said, the architect was so enthusiastic about this. Probably, fifteen years ago, it was not quite such a buzz about eco stuff, there was no. But he sold this idea and... well, we were keen to something new, see what happened...

**Interviewer:** For example, this construction style, like dowel style (Brettstapel), is little bit strange and your house like a first house that is constructed in this style. How does it feel like for you? Always you have some analysis in your house and for example I come here to look at your house. How does it feel for you?

**Interviewee 1:** Yeah. Quite happy... people to find out more about it.

**Interviewer:** So, how the architect convince you to build like this?

**Interviewee 1:** Well, Anne said, she wanted and the architect was very good at translating... once into something that worked. For example, this wall is curved and people do not normally have curved walls in houses but Anne felt, she like that. And if you come here, that is the aerial view of the house there... and so, there is the front door and we are on that side of it. And you can see how that is curved.

**Interviewer:** Yes. Actually, these walls are also not curved when you are walking there but normally it is curved.

**Interviewee 1:** And then we have got these pods in there and we study here. In here and the room above, so you get a bit more lighting.

**Interviewer:** Like reading place?

**Interviewee 1:** Yes. Do you want to see upstairs?

**Interviewer:** Yes, sure.

**Interviewee 1:** This is umm... I just put the light on.

**Interviewer:** Oh! It is night lighting. Are sure that I should not.. I feel like I should take of my shoes?

**Interviewee 1:** No, that is alright.

**Interviewer:** So, for your electric bills, when we compare with your previous house...

**Interviewee 1:** Well, I am not sure, our previous house had gas heating but this is purely electricity and I think it is between 9000 or 10000 kWh per year and that is the total energy cost. Some of that goes on services such as MVHR takes up some electricity and it is running whole time, and then for the sewage disposal, we have got a bio disk which I think, it runs about 0.4 amps and that is sort of kWh so we do use certain amount of energy for the sewage disposal and in terms of water we have got a borehole and it goes down 90 meters so we need to pumped water up.

**Interviewer:** That is your only energy source for this house? There is no PV panels?

**Interviewee 1:** We have got Solar Thermal and ideally that is give us all hot water, we need... These are two pressurised cold water tanks and water is pumped up to from our borehole. Borehole goes 90 m down, I think. This is our MVHR which running the whole time.

**Interviewer:** This is for heating too, in winter?

**Interviewee 1:** Yes, in winter. It is got a 1.5 kW for heat, because the heat exchangers are not a hundred percent efficient and so all the air that is coming in, is a little bit cooler and the air is going out. So MVHR is going to be cooling the house down in winter. So heater on the inlet, just cancel that down and give you a little bit extra if you needed. And this is the hot water tank here, and this is the pipes coming down from the thermal solar panel on the roof. If you feel that, that is the temperature, that is the water coming in. At the moment it is about 50 °C. That goes in to the bottom of the tank. There is coil at the bottom of the tank, so water, at the bottom of the tank, gets heated and rises up. And there is workshop here.

**Interviewer:** For yourself?

**Interviewee 1:** Well for Anne. She quite likes doing DIY and arti-craft staff and so on.

...

**Interviewer:** So it is a kind of fast construction style too?

**Interviewee 1:** Yes they just brought and...

**Interviewer:** Because building elements already ready to construct it.

**Interviewee 1:** So there is the platform that the house is build on.

**Interviewer:** It is concrete?

**Interviewee 1:** Yes...Are any of these photos interest you?

**Interviewer:** Yes, they will be helpful.

...

**Interviewee 2:** We were working in Edinburgh and we probably talked about two years.

**Interviewer:** For designing?

**Interviewee 2:** For the designing and what we wanted. During this time, we also bought a little bit more land from the Forestry Commission, because originally, it was just a third one acre at the bottom but now we have about two acre. So, during that time we also bought more land and then Forestry Commission gave said it was okay to build up here and planning people said it was okay to build up here. So we did not really talk seriously about what we were going to build but we wait for another two years so about 2008. We went over to Austria, didn't we? We had a look at Passivhauses in Austria. It took one weekend and almost, I can remember thinking that what we were looking at, were sort of boxy. They were like boxes and I said it is not quite I have envisaged as a house I want to live in. I know, I like to eco-friendly aspect but I want it more design in it. At that time, Howard employed Sam Foster and Matt who is help Sam with the design. We got on very well with them. They listened very well and we had good conversations. I had ideas and they had ideas, you know, we really bounced off each other for a year or two, probably before we settle down on design. I remember that final design was more or less we sort of gone full circle we started off with something looked a bit of like this. Tried gone all around doing different things and come back to something that was...like this which was good. So, it took a long time, we built in 2010-11, so it was kind of four or five years, in the process, thinking. And I think, because you spent a lot of time, you get the right thing, you know. I am sure if we built it straight away, I would come up with thinking I want to do something different. I never, ever since we have been in, I sort of feel, I would not change anything, I do not think much. The overall design is... yes, it is right. The interesting thing is the site has changed a lot because it was just an open hillside and it was just fell timber and there was nothing here. So, now this is all natural regeneration of birch and pine and stuff so...

**Interviewee 1:** We have not planted any of these trees.

**Interviewee 2:** We have not planted, most of the trees just come up. This is much taking trees out rather than putting trees in. We get these views...

**Interviewee 1:** I am sorry all my photos are on the One Drive

**Interviewee 2:** One Drive so... you have to come from iCloud.

**Interviewer:** That is okay.

**Interviewee 1:** We have very bad land line broad-band here. We get about 3 megabits per second which is very slow.

**Interviewee 2:** Quite slow.

**Interviewee 1:** Recently we got rid of our land line and we have got 4G mobile broad band and download speed we get 100 megabits per second.

**Interviewer:** But you are quite far away from the city so...

**Interviewee 2:** We are, yes. We are 4 miles from the nearest exchange, I think. So it is one of the penalties of living in country.

**Interviewer:** Can you find anything here that you need, or you have to go to the city?

**Interviewee 2:** We go to Edinburgh, kind of... maybe once. I go to Edinburgh maybe once a week because most of my friends are in Edinburgh, but I think, now that we have been here for seven years, we are going to Edinburgh less maybe, probably going less now. But to start with we went probably quite a lot, now I find most of the things we want around here. You cannot sort of change where you live, kind of instantaneously, somehow, you have to slowly become custom to live in here, you build up, you know what you do here, get to know the people here, so it just takes a few years.

**Interviewer:** So before here you were living in city centre?

**Interviewee 2:** In the city, yes, in Edinburgh. To Edinburgh, by bus, you see somehow one hour and quarter is quite good, it is not that bad at all, really?

**Interviewer:** One and half an hour with bus.

**Interviewee 2:** And of course, in Scotland, we have, once you are over 60, then you get free bus pass so it does not cost us anything to get the bus, it is good... Oh the snowy ones, you got them...Most of our pictures are probably from outside of the house, because we did not tend to come in, if they were working. We did not want to get in there, so we did not get a lot of interior shots, I do not think.

**Interviewer:** But, maybe I have to send you a form that for your consent for this photos.

**Interviewee 1:** Yes.

**Interviewer:** Maybe, later. I should ask to my supervisor.

**Interviewee 2:** Yes, this is fine.

**Interviewer:** Because these are your photos and if I use like mine then it is like plagiarism.

**Interviewee 2:** We got more resources These are interiors as Sohm was putting it up. That is Sohm was still there

**Interviewer:** So pressure test is actually air pressure test?

**Interviewee 2:** Yes.

**Interviewer:** Is there any leakages or not.

**Interviewee 2:** And they did another pressure test, once the fit had been done and at the end of the year as well and that was okay. Just to check the Scottish workmen had not messed it up.

**Interviewer:** So after that there is no test?

**Interviewee 2:** Well, we have had a pressure test since...because we actually got one after all the work was done after the leak and they did another pressure test just to see everything was okay and that was done. Was is it 2016?

**Interviewee 1:** Yes.

**Interviewee 2:** 2016.

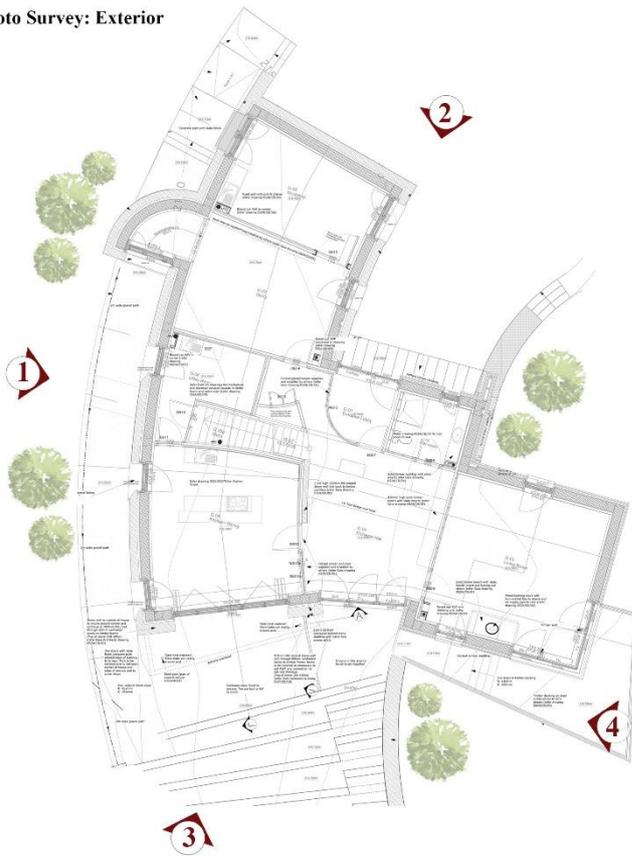
**Interviewer:** After that you got your certificate?

**Interviewee 2:** We got the certificate way back in 2010-11.



# Appendix C: Photo Survey

## Photo Survey: Exterior



## Photo Survey: Ground Floor

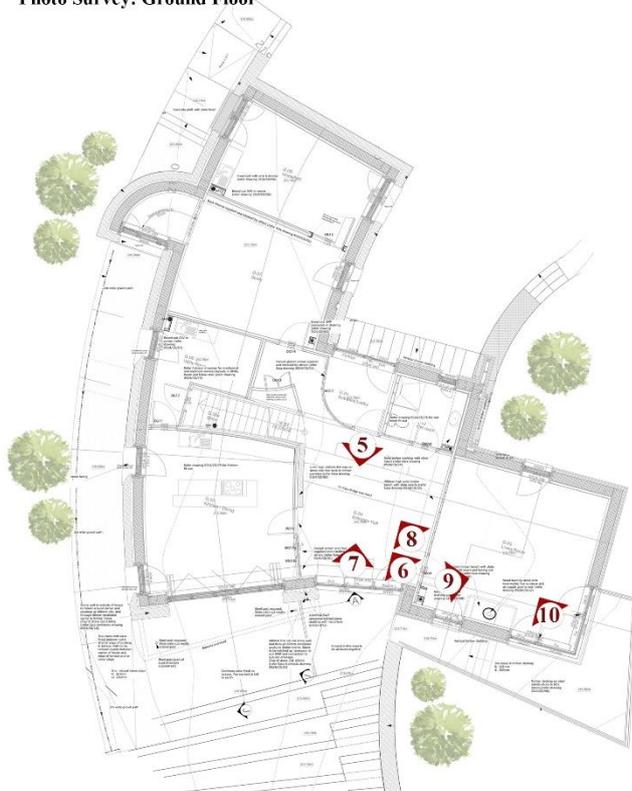


Photo Survey: Ground Floor

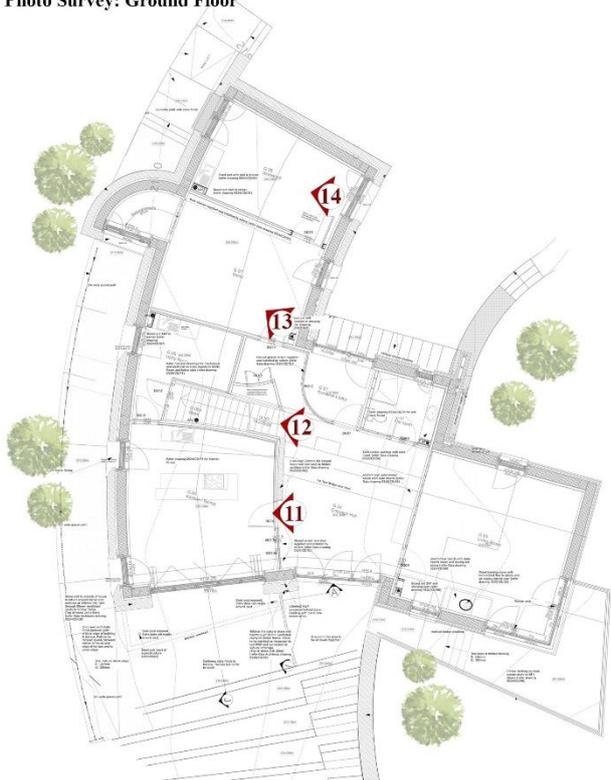
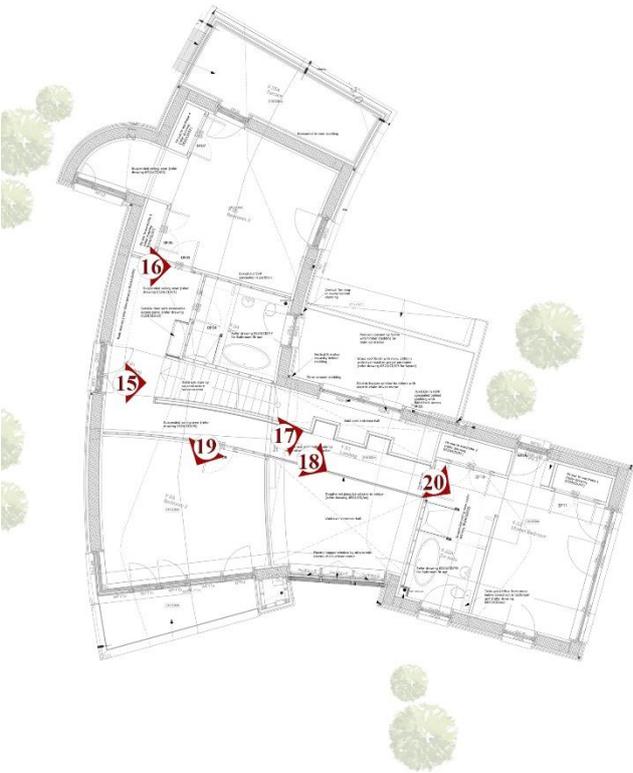
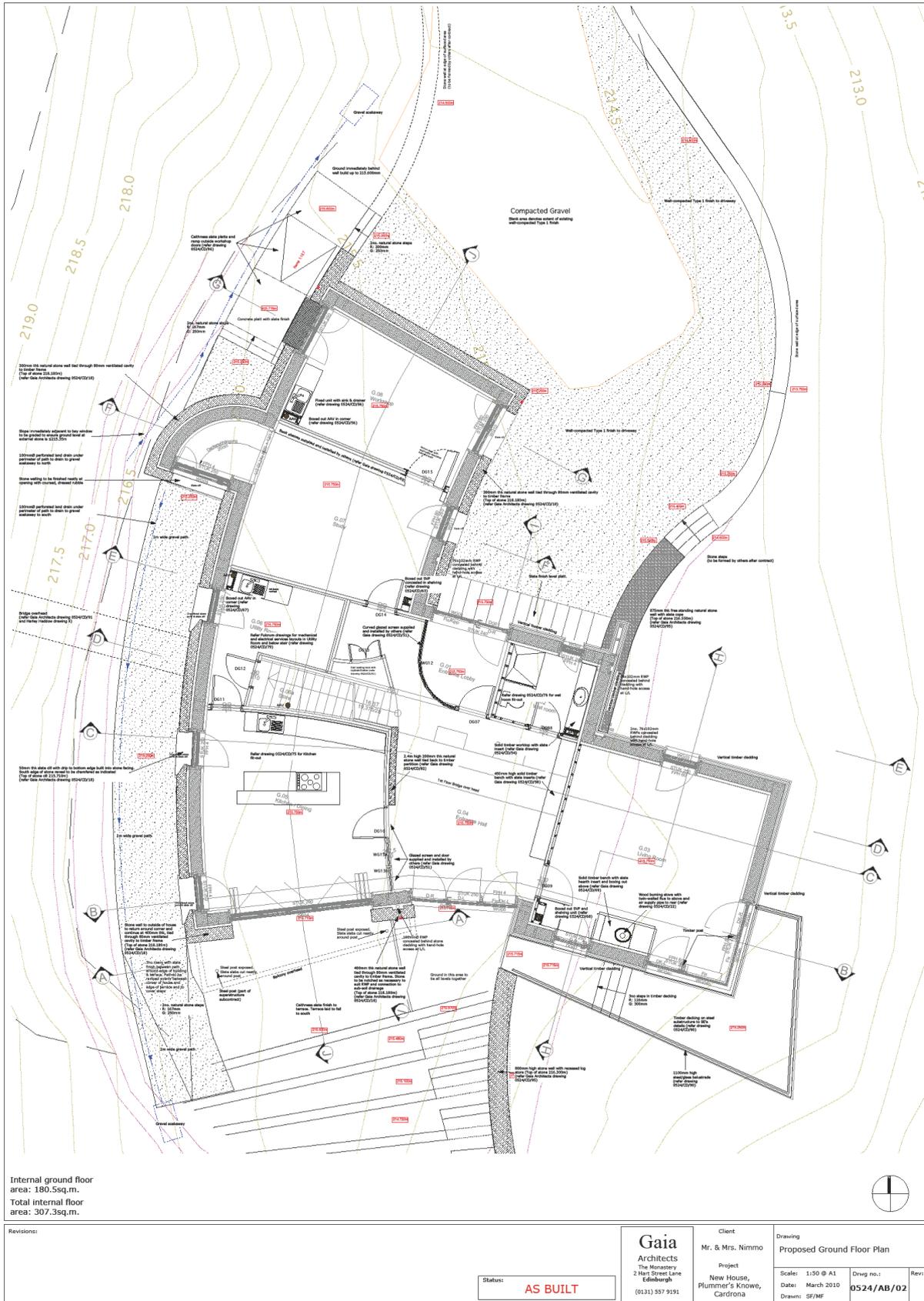
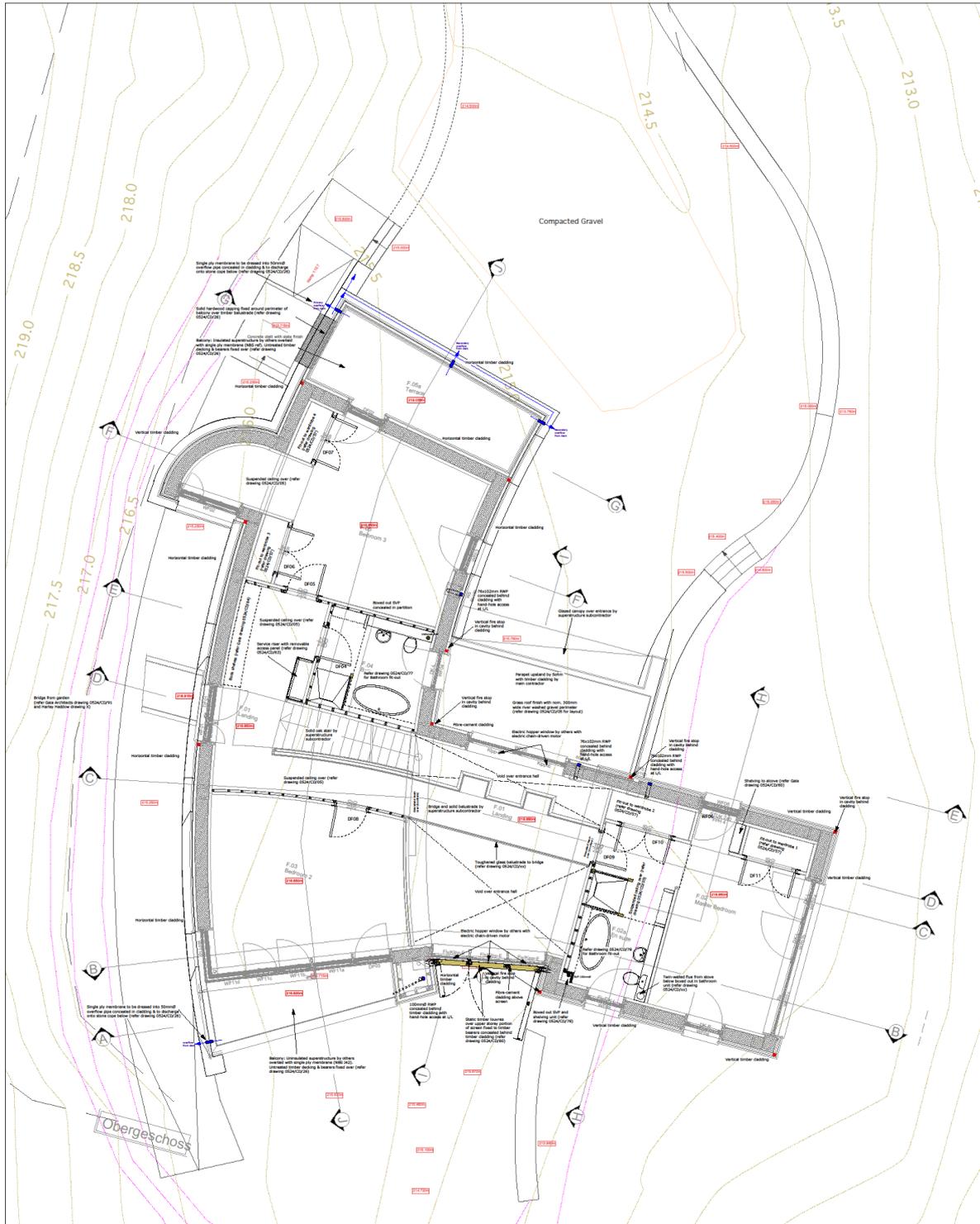


Photo Survey: First Floor



# Appendix D: Technical Drawings



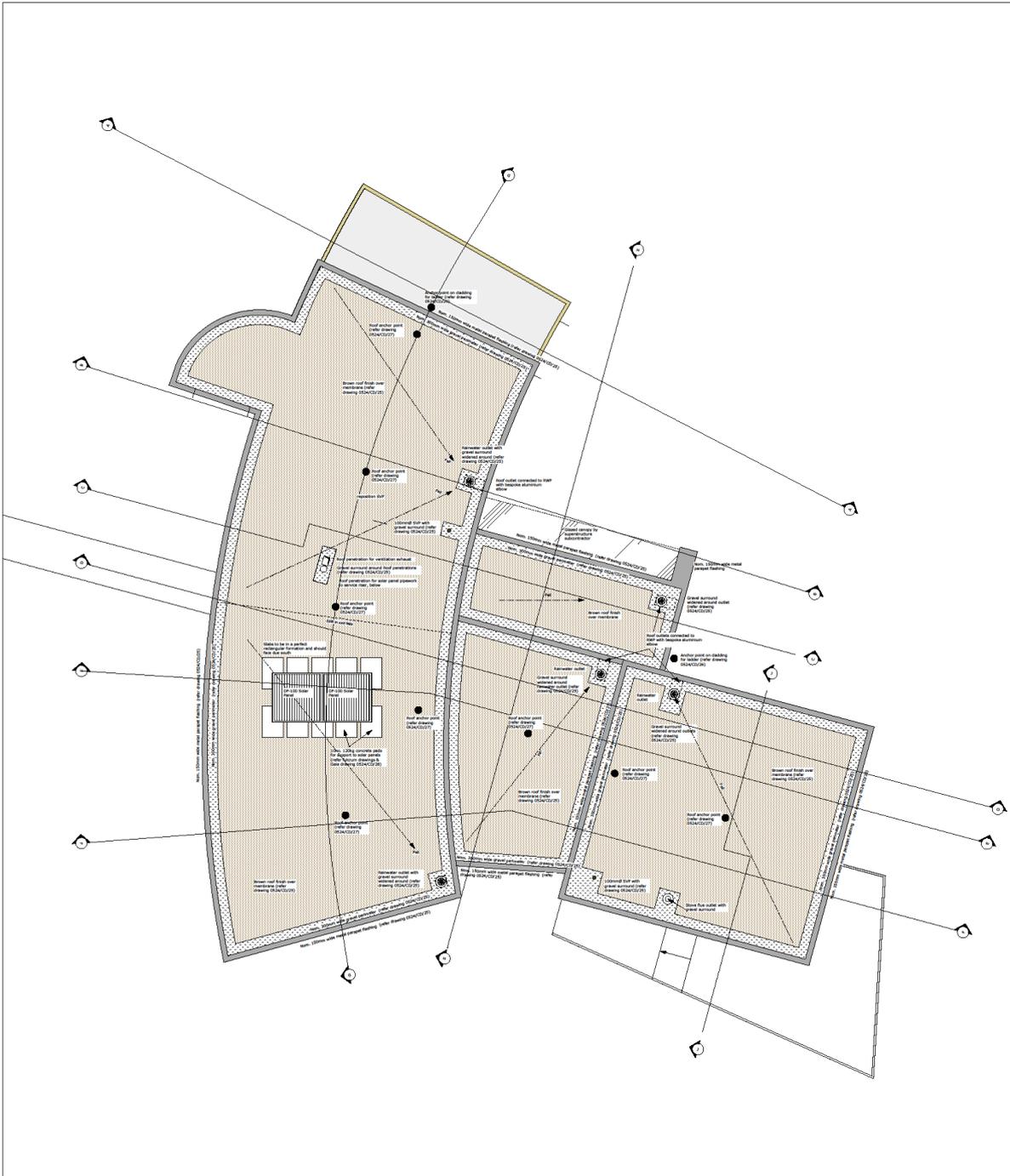


Internal first floor  
 area: 126.8sq.m.  
 Total internal floor  
 area: 307.3sq.m.

Revisions:

Status: **AS BUILT**

<b>Gaia</b> Architects The Monastery 2 West Street Lane Edinburgh (0131) 557 9191	Client Mr. & Mrs. Nimmo	Drawing Proposed First Floor Plan
	Project New House, Plummer's Knowe, Cardrona	Scales: 1:50 @ A1 Date: March 2010 Drawn: SF/MF



Items by main contractor:  
 Single ply membrane  
 Parapet flashings  
 All pop-ups and sealing around these  
 Brown roof finish, water retention mat & gravel edging  
 Roof outlets, downpipes and connection to single ply membrane  
 Solar panel installation incl. support structure  
 Installation of roof anchors on fixing point by Sohm



Revisions:		<b>Gaia</b> Architects The Monastery 3 Haas Street Leith Edinburgh (0131) 557 9191	Client	Drawing	Scale: 1:50 @ A1	Drawg no.: <b>0524/AB/04</b>	Rev:
			Mr. & Mrs. Nimmo	Proposed Roof Plan			
			New House, Plummer's Knowe, Cardrona				















## Appendix E: H\BERT and Bill of Quantities Calculations (Excel Spread Sheets)

Material Name	Volume (m³)	Density (ton/m3)	Weight (ton)	Area	Embodied Carbon kgCO2e/kg	Unit	Databas e	EC
Coir Matting	0,11	0,1	0,01	3,00 m²	2,59E+01	m²	EPD	77,70
Ceramic	0,46	2,13	0,98	44,00 m²	9,79	m²	EPD	430,76
Fibre Cement Cladding	2,35	0,35	0,82	24,00 m²	0,832	tonnes	ICE V3.0	0,68
Window Glasses and Entrance Wall	4,5	2,5	11,25	-	1,63	kg	ICE V3.0	18335,29
Gravel	14,49	1,6	23,18	-	0,00747	tonnes	ICE V3.0	0,17
Fermacell	2,87	0,75	2,15	123,00 m²	1,89	m²	EPD	232,47
Woodfibre Insulation (Soft)	40,05	0,032	1,28	-	-1,64E+02	m³	EPD	-6568,20
Woodfibre Insulation (Hard)	233,53	0,23	53,71	-	-1,64E+02	m³	EPD	-38298,92
Plaster Boards	7,99	0,95	7,59	557,00 m²	1,89	m²	EPD	1052,73
Roof Parapet	1,12	7,8	8,76	-	3,03	1	ICE V3.0	26550,24
Field Stone	33,23	2,2	73,10	-	58,1	m³	EPD	1930,66
Window Frames	2,27	0,51	1,16	-	0,263	m³	ICE V3.0	0,60
Hardwood Battens	33,84	0,7	23,69	-	0,306	m³	ICE V3.0	10,36
Sheating Boards	3,18	0,7	2,22	159,00 m²	0,856	m²	ICE V3.0	136,10
Sarking Boards	22,1	0,65	14,37	125,00 m²	0,455	m³	ICE V3.0	10,06
Wood Battens	0,89	0,6	0,54	11,00 m²	0,681	m²	ICE V3.0	7,49
DD Solid timber and Softwood Battens	126,06	0,51	64,29	-	0,263	m³	ICE V3.0	33,15
<b>Total:</b>								<b>3941,34</b>

Substructure Materials	Unit	Quantity	Embodied Carbon kgCO2/kg	Database	Unit	Material Density	EC
Concrete Grade Gen 3	m <sup>3</sup>	33	246	ICE V3.0	m <sup>3</sup>	-	8118,00
Formwork (500mm)	m	66	0,455	ICE V3.0	m <sup>3</sup>	-	0,18
Concrete Grade RC 35	m <sup>3</sup>	5	301	ICE V3.0	m <sup>3</sup>	-	1505,00
A393 Mesh Reinforcement	m <sup>2</sup>	21	1,99	ICE V3.0	kg	6kg	250,74
900 mm Thermalite Trenchblock	m <sup>2</sup>	16	168	EPD	m <sup>3</sup>	-	2419,20
440 mm Thermalite Trenchblock	m <sup>2</sup>	19	168	EPD	m <sup>3</sup>	-	1404,48
140mm Thick Concrete Blockwork	m <sup>2</sup>	38	9,26E+01	EPD	m <sup>3</sup>	-	492,63
300mm Dry Stane	m <sup>2</sup>	24	58,1	EPD	m <sup>3</sup>	-	1133,66
Lean Mix Concrete	m <sup>3</sup>	1	219	ICE V3.0	m <sup>3</sup>	-	219,00
Zedcor Recycled Polyethylene (300mm wide)	m	69	4,93	EPD	m <sup>2</sup>	-	102,05
100x70mm prestressed lintels	-	10	0,249	ICE V3.0	kg	1760 kg/m <sup>3</sup>	0,02
1200mm Galvanised Straps	-	12	3,03	ICE V3.0	kg	7800 kg/m <sup>3</sup>	3,97
300x300x215 mm Precast Concrete Padstone	-	2	9,26E+01	EPD	m <sup>3</sup>	-	3,70

Concrete Floors	Unit	Quantity	Embodied Carbon kgCO2/kg	Database	Unit	Material Density	EC
Granular Material	m <sup>3</sup>	5	0,00747	ICE V3.0	tonnes	2240 kg/m <sup>3</sup>	83,66
Zedcor PIFA300	m <sup>2</sup>	238	3,42E-02	EPD	m <sup>2</sup>	-	8,14
150 mm Concrete Grade RC 35	m <sup>3</sup>	17	301	ICE V3.0	m <sup>3</sup>	-	5117,00
A193 Mesh Reinforcement	m <sup>2</sup>	316	1,99	ICE V3.0	kg	3kg	1886,52
Formwork (150mm)	m <sup>2</sup>	74	0,455	ICE V3.0	m <sup>3</sup>	-	5,05

Steel Work	Unit	Quantity	Embodied Carbon kgCO2/kg	Database	Unit	Material Density	EC
203x203x46 kg Grade S275 UKC	Tonnes	1,09	1,55	ICE V3.0	kg	-	1689,50
180x190x8 mm Grade S275	-	4	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	21,00
M16 Gr8.8 Bolt Fixings	-	16	2,42	ICE V3.0	kg	7800 kg/m <sup>3</sup>	5,92
114.3x4 Grade S275 (2150mm long)	Tonnes	0,12	2,85	ICE V3.0	kg	-	342,00
193.7x10.00 Grade S275 (2150mm long)	Tonnes	0,49	2,85	ICE V3.0	kg	-	1396,50
200x200x15mm Grade S275 Steel Base Plate	-	9	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	103,62

400x400x15mm Grade S275 Steel Base Plate	-	5	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	230,26
203x203x15 kg Grade S275 Steel Cap	-	5	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	57,56
120x250x12mm Grade S275	-	9	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	62,17
100x150x15mm Grade S275	-	8	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	55,26
150x90x24 Grade S275 UKPFC	Tonnes	0,59	2,46	ICE V3.0	kg	-	1451,40
150x89x16 Grade S275 UKB	Tonnes	0,77	1,27	ICE V3.0	kg	-	977,90
250x150x10mm Grade S275 Steel Plate	-	7	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	50,37
150x90x10mm Grade S275 Steel Plate	-	2	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	5,18
152x89x16 Grade S275 steel Plate	-	12	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	49,18
150x60x12mm Grade S275 Steel Fin Plate	-	28	3,03	ICE V3.0	kg	7800 kg/m <sup>3</sup>	71,47
90x90x7 UKA	Tonnes	0,19	2,46	ICE V3.0	kg	-	467,40
90x90x8 End Plates	-	14	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	17,41
Φ12 Steel Cable (300mm long)	-	4	2,27	ICE V3.0	kg	7800 kg/m <sup>3</sup>	8,01
M16 Gr8.8 Bolt and Fixings (375mm)	-	56	2,42	ICE V3.0	kg	7800 kg/m <sup>3</sup>	83,89
M16 Gr8.8 Bolt and Fixings (50mm)	-	110	2,42	ICE V3.0	kg	7800 kg/m <sup>3</sup>	40,73
M16 Resin Anchor	-	4	4,06	ICE V3.0	kg	7800 kg/m <sup>3</sup>	5,91
Bitumen Paint	m <sup>2</sup>	7	0,222	ICE V3.0	kg	-	0,08

Wing Walls	Unit	Quantity	Embodied Carbon kgCO <sub>2</sub> /kg	Database	Unit	Material Density	EC
Plank and Struts (1m)	m <sup>2</sup>	60	0,263	ICE V3.0	m <sup>3</sup>	-	15,78
Concrete Grade Gen 3	m <sup>3</sup>	15	246	ICE V3.0	m <sup>3</sup>	-	3690,00
Formwork (500mm)	m	4	0,455	ICE V3.0	m <sup>3</sup>	-	0,01
900mm Thermalite Trenchblock	m <sup>2</sup>	4	168	EPD	m <sup>3</sup>	-	604,80
500mm Thermalite Trenchblock	m <sup>2</sup>	4	168	EPD	m <sup>3</sup>	-	336,00
400mm Thermalite Trenchblock	m <sup>2</sup>	18	168	EPD	m <sup>3</sup>	-	1209,60
100mm Dense Concrete Block	m <sup>2</sup>	8	0,093	ICE V3.0	m <sup>3</sup>	-	0,07

500mm Dry Stane Wall	m <sup>2</sup>	3	58,1	EPD	m <sup>3</sup>	-	236,18
600mm Dry Stane Wall	m <sup>2</sup>	3	58,1	EPD	m <sup>3</sup>	-	283,41
900mm Dry Stane Wall	m <sup>2</sup>	3	58,1	EPD	m <sup>3</sup>	-	425,12

Drainage	Unit	Quantity	Embodied Carbon kgCO <sub>2</sub> /kg	Database	Unit	Material Density	EC
100mm Dia ESVC Drain Pipes	m	169	0,46	ICE V2.0	kg	-	722,98
Class P Pipe Bedding	m	137	0,007	ICE V3.0	kg	2240 kg/m <sup>3</sup>	319,87
Class Z concrete surround	m	5	229	ICE V3.0	m <sup>3</sup>	-	145,42

Manholes	Unit	Quantity	Embodied Carbon kgCO <sub>2</sub> /kg/kg	Database	Unit	Material Density	EC
Concrete Grade C15	m <sup>3</sup>	1,5	229	ICE V3.0	m <sup>3</sup>	-	343,50
Concrete Grade C20/40	m <sup>3</sup>	3,5	267	ICE V3.0	m <sup>3</sup>	-	934,50
Precast Concrete Manhole Rings to BS5911 (1050mm)	m	4	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,03
Precast Concrete Manhole Rings to BS5911 (1200mm)	m	6	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,07
Precast Concrete Manhole Rings to BS5911 (900mm)	m	1	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,01
Precast Concrete Intake Slab (1050mm)	-	3	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,05
Precast Concrete Intake Slab (1200mm)	-	3	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,06
Precast Concrete Intake Slab (900mm)	-	1	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,01
50mm Epoxy (900mm)	-	2	3160	EPD	tonnes	2,25 kg/m <sup>3</sup>	0,43
50mm Epoxy (1050mm)	-	4	3160	EPD	tonnes	2,25 kg/m <sup>3</sup>	1,14
50mm Epoxy (1200)	-	3	3160	EPD	tonnes	2,25 kg/m <sup>3</sup>	12,80
One Brick Engineering	m <sup>2</sup>	6	35,2	ICE V3.0	m <sup>2</sup>	-	211,20
Cast Iron (heavy duty) 675x675mm	-	2	2,03	ICE V2.0	kg	7870 kg/m <sup>3</sup>	0,00
Cast Iron (medium duty) 600x600mm	-	7	2,03	ICE V2.0	kg	7870 kg/m <sup>3</sup>	0,01
Form 100mm Channel Branch	-	9	3,155	EPD	kg	-	64,17

Treatment Plant	Unit	Quantity	Embodied Carbon kgCO <sub>2</sub> /kg/kg	Database	Unit	Material Density	EC
Concrete Grade C30	m <sup>3</sup>	8	301	ICE V3.0	m <sup>3</sup>	-	2408,00

Klargester BA6 Biodisc Unit	kg	310	2,46	ICE V3.0	kg	-	762,60
63mm Dia Black Duct	m	30	3,155	EPD	kg	1380 kg/m <sup>3</sup>	13,06
Class P Pipe Bedding	m	30	0,007	ICE V3.0	kg	2240 kg/m <sup>3</sup>	0,03

Soakaway	Unit	Quantity	Embodied Carbon kgCO <sub>2</sub> /kg/kg	Database	Unit	Material Density	EC
650mm of 20-50mm Gravel	-	2	0,00747	ICE V3.0	tonnes	1.6 t/m <sup>3</sup>	0,02
110mm Large Slotted Pipe (9,5m)	-	2	3,155	EPD	kg	1380 kg/m <sup>3</sup>	744,52

Rainwater Drainage	Unit	Quantity	Embodied Carbon kgCO <sub>2</sub> /kg/kg	Database	Unit	Material Density	EC
100mm Dia ESVC Drain Pipes	m	119	0,46	ICE V2.0	kg	-	509,08
Class P Pipe Bedding	m	165	0,007	ICE V3.0	kg	2240 kg/m <sup>3</sup>	349,27
Class Z Concrete Surround	m	5	229	ICE V3.0	m <sup>3</sup>	-	146,56

Manholes	Unit	Quantity	Embodied Carbon kgCO <sub>2</sub> /kg/kg	Database	Unit	Material Density	EC
Concrete Grade C15	m <sup>3</sup>	1	229	ICE V3.0	m <sup>3</sup>	-	229,00
Concrete Grade C20/40	m <sup>3</sup>	2,5	267	ICE V3.0	m <sup>3</sup>	-	667,50
Precast Concrete Manhole Rings to B5911 (1200mm)	m	8	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,10
Precast Concrete Manhole Rings to B5911 (1050mm)	m	1	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,01
Precast Concrete Manhole Rings to B5911 (900mm)	m	1	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,01
Precast Concrete Intake Slab (1200mm)	-	4	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,09
Precast Concrete Intake Slab (900mm)	-	1	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,01
Precast Concrete Intake Slab (1050mm)	-	1	271	EPD	tonnes	0,35 kg/m <sup>3</sup>	0,02
50mm Epoxy(1200mm)		4	3160	EPD	tonnes	2,25 kg/m <sup>3</sup>	1,61
50mm Epoxy(1050mm)		1	3160	EPD	tonnes	2,25 kg/m <sup>3</sup>	0,31
50mm Epoxy(900mm)	-	1	3160	EPD	tonnes	2,25 kg/m <sup>3</sup>	0,22
One Brick Engineering	m <sup>2</sup>	4	35,2	ICE V3.0	m <sup>2</sup>	-	140,80
Cast Iron (heavy duty) 675x675mm	-	2	2,03	ICE V2.0	kg	7870 kg/m <sup>3</sup>	0,00

Cast Iron (medium duty) 600x600mm	-	4	2,03	ICE V2.0	kg	7870 kg/m <sup>3</sup>	0,01
Form 100mm Channel Branch	-	6	3,155	EPD	kg	-	49,22

High Level Bridge to First Floor	Unit	Quantity	Embodied Carbon kgCO <sub>2</sub> /kg/kg	Database	Unit	Material Density	EC
Plank and Struts (1m)	m <sup>2</sup>	4	0,263	ICE V3.0	m <sup>3</sup>	-	1,05
Concrete Grade RC35	m <sup>3</sup>	0,5	301	ICE V3.0	m <sup>3</sup>	-	150,50
Steel Mesh A252	m <sup>2</sup>	1	1,99	ICE V3.0	kg	4 kg	7,96
Steel Grade S275 UKC	Kg	668	1,27	ICE V3.0	kg	-	848,36
150x150x8mm Steel End Plate	-	10	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	34,54
100x100x8mm Steel End Plate	-	8	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	12,28
M16 Resin anchor (150mm)	-	4	4,06	ICE V3.0	kg	-	4,68
M12 Resin anchor (150mm)	-	4	4,06	ICE V3.0	kg	-	3,15
M16 Bolt	-	8	2,42	ICE V3.0	kg	-	2,96
M12 Bolt	-	20	2,42	ICE V3.0	kg	-	4,07
150x80x10mm Steel Base Plate	-	12	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	27,63
M16 Bolt	-	24	2,42	ICE V3.0	kg	-	8,89
60x12mm Steel Flat Bar Baluster (970mm)	-	24	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	321,62
60x12x80mm Steel Flat Bar Packer	-	12	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	13,26
50x12mm Steel Flat Bar Top Rail	m	14	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	161,18
50x12x70mm Steel Flat Bar Tongue	-	12	2,46	ICE V3.0	kg	7800 kg/m <sup>3</sup>	9,67
Total:							47136,78

Sanitary	Unit	Quantity	Embodied Carbon kgCO <sub>2</sub> /kg/kg	Database	Unit	Material Density	EC
Toilet	-	3	854	EPD	tonnes	-	39,71
Sink	-	3	854	EPD	tonnes	-	39,71
Shower Tray	-	3	854	EPD	tonnes	-	39,71
Bathtub	-	1	854	EPD	tonnes	-	13,24
Total							47269,15

## Appendix F: In-Use Calculations (Excel Spread Sheets)

Electricity (2018-2019)	Month	kWh	Annual Energy (kWh)	Treated Floor Area (m <sup>2</sup> )	Annual Energy per sqm
	January	60741	8796	300,6	29,26
	February	61907			
	March	63277			
	April	64006			
	May	64384			
	June	64749			
	July	65104			
	August	65567			
	September	66038			
	October	66650			
	November	67730			
	December	69537			
	Annual	8796			

Annual Energy (kWh/m <sup>2</sup> )	Electricity Conversion Factor	Annual Carbon Emission per sqm
29,26	0,2556	7,48

Wood Stove (2018-2019)	Days	Daily Usage (tonne)	Carbon Emission (kgCO <sub>2</sub> )	Carbon Intensity (kgCO <sub>2</sub> /kWh)	Annual Energy (kWh)	Treated Floor Area (m <sup>2</sup> )	Annual Energy (kWh/m <sup>2</sup> )
	175	0,01	63,85	0,019	5880,92	300,6	19,56
	Annual Energy (kWh/m <sup>2</sup> )	Conversion Factor	Annual Carbon Emission per sqm				
19,56	0,0156	0,31					

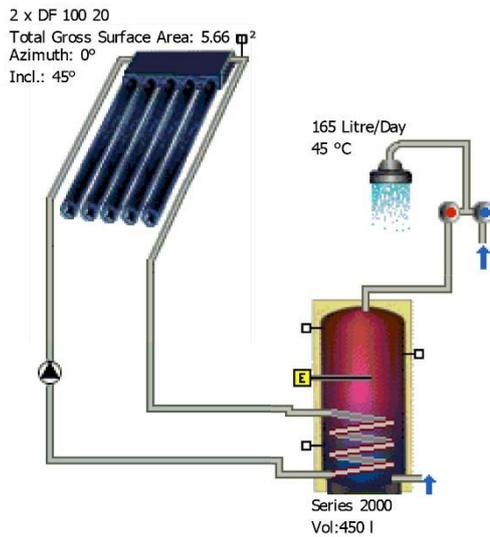
Solar Thermal (2018-2019)	Annual Energy Generation (kWh)	Treated Floor Area (m <sup>2</sup> )	Annual Energy (kWh/m <sup>2</sup> )
	2444	300,6	8,13
	Annual Energy (kWh/m <sup>2</sup> )	Conversion Factor	Annual Carbon Emission per sqm
8,13	0,2556	2,08	

Building Carbon Footprint from Operational Energy Demand							
Comparison between standard and case study	Case	Regulated carbon Emissions KgCO <sub>2</sub> /m <sup>2</sup> per year			Unregulated carbon Emissions KgCO <sub>2</sub> /m <sup>2</sup> per year		Total Emissions KgCO <sub>2</sub> /m <sup>2</sup> per year
		Space Heating	Hot Water	Lighting, fans, pumps.	Equipment	Cooking, catering	
	<b>Passivhaus Standard</b>	3-8	11	5	13	3-8	35-45
<b>Plummerswood</b>	0,31	2	7,48			9,87	

Building Energy Usage from Operational Energy Demand							
Comparison between standard and case study	Case	Regulated carbon Emissions KWh/m <sup>2</sup> per year			Unregulated carbon Emissions KWh/m <sup>2</sup> per year		Total Emissions KWh/m <sup>2</sup> per year
		Space Heating	Hot Water	Lighting, fans, pumps.	Equipment	Cooking, catering	
	<b>Passivhaus Standard</b>	15	55	10	25	15	120
<b>Plummerswood</b>	19,56	8,13	29,26			40,69	

## Appendix G: Solar Thermal Performance Sheet

**Baxi Commercial Heating (Andrews)**  
**Wood Lane, Erdington, Birmingham B24 9QP**  
 Plummer's Knowe  
 Variant1



### Results of Annual Simulation

Installed Collector Power:	3.96 kW	
Installed Gross Solar Surface Area:	5.66 m <sup>2</sup>	
Collector Surface Area Irradiation (Active Surface):	4.33 MWh	1,006.03 kWh/m <sup>2</sup>
Energy Produced by Collectors:	2,341.48 kWh	543.77 kWh/m <sup>2</sup>
Energy Produced by Collector Loop:	2,114.10 kWh	490.97 kWh/m <sup>2</sup>
DHW Heating Energy Supply:	2444.51 kWh	
Solar Contribution to DHW:	2114.1 kWh	
Energy from Auxiliary Heating:	1264.7 kWh	
<b>Natural Gas (H) Savings:</b>		<b>260.1 m<sup>3</sup></b>
<b>CO2 Emissions Avoided:</b>		<b>550.05 kg</b>
<b>DHW Solar Fraction:</b>		<b>62.6 %</b>
<b>Fractional Energy Saving (EN 12976):</b>		<b>56.6 %</b>
<b>System Efficiency:</b>		<b>48.8 %</b>