Department of Mechanical and Aerospace Engineering

The Embodied Energy and Carbon of Passive House

Author: Stuart McHendry

Supervisor: Dr Paul Tuohy

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Abstract

The main objective of this body of work was to establish a method of calculating the embodied energy and embodied carbon associated with the building of a passive house. In addition, a practical modelling 'tool' was designed and developed that would allow for the application of informing decision-makers at the earliest possible stage of the design process.

This software 'tool' was developed to support the PHPP (Passive House Planning Package) and to provide a method for integrating construction embodied energies and the consequent carbon emissions along with the existing developmental operational energy and carbon emission analysis to provide a 'more complete' understanding of the energetic activity of this system of built environment.

Different criteria for defining the 'embodied energy' and 'carbon counting' have been considered, along with different systems of calculation, and a methodology has been chosen that was considered most applicable to this study.

Alternative systems of base data have been assessed for the benefit of providing both scope and possibly illumination. And the results of this have been included for comparative purposes.

The project was carried out with an industrial partner, an architect for the mutual benefit of information exchange, design development and case study analysis.

The main findings for the case study passive house, based on the initial limited evaluation criteria, suggest that that Embodied Energy (EE) accounted for between 17% and 25% of the estimated lifetime energy demands (Operational Energy (OE) and EE), (Using Inventory of Carbon and Energy (ICE) EE source data). However, with different build-up materials this value could rise up to 40% or drop to less than 10% of the total estimated lifetime energy demands. These are however fairly conservative estimates, and the scope of this study did not include several additional sources of EE. So these figures can be taken as lower estimates. Therefore these results can be expected to rise with more detailed modelling and analysis.

Through the design and development of the analysis tool, the typical lifetime energy demands of a passive house may be more accurately calculated and modelled. Therefore better, or at least more informed decisions may be made during the building design.

It has been noted that this complex area of analysis and this system, like any good model are just that – a model, and should therefore be considered as a map that must firstly be understood well, and then used as a guidance tool only. The chosen boundaries along with the analytical methods that are applied will correspondingly impact the results obtained - that is the nature of this area and Life Cycle Analysis (LCA) in general. Therefore these ideas have developed towards a practical, systemic method for understanding that may have useful applications.

Finally, recommendations are made for future work.

Acknowledgements

I'd like to thank Dr Paul Tuohy for his help and support during this project, the teaching staff from the Department of Mechanical Engineering, especially Dr Paul Strachan, my family for all their continued help, and all the friends who have made the past year fun! I'd like to make special mention to the one and only Jacqueline, for making this possible - you are a star!

Extra-specially, I want to also mention Natalie Chrystal for inspiring me during very busy times with her spirit and lightness of heart.

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Glossary of Abbreviations

AP – Acidification Potential

BRE – Building Regulations Establishment

BRE Green Guide – Part of BREEAM, this is a reference guide for developers, architects and building designers that evaluates the environmental credentials of building components and materials. Using credit allocation based on 12 environmental indicators throughout the LCA, to achieve an A+ to E ranking system. This is constantly updated with the latest revision June 2013

BREEAM – Building Research Establishment Environmental Assessment Method. For assessing, rating and certifying the sustainability of buildings

BSI - British Standards Institution

BSRIA – Building Services Research and Information Association

Carbon Trust – Established in 2001 as a not-for-profit international organization working with businesses, governments and the public sector in the transition to a low carbon economy. Mission goal is to de-carbonize the economy.

CSH – Code for Sustainable Homes

DECC – Department of Energy and Climate Change

DEFRA – Department for Environment, Food and Rural Affairs. UK Government

DHW – Domestic Hot Water

EBM – Ecology of Building Materials

ECO2 – Embodied Carbon

ECO2e – Embodied Carbon equivalent

Eco-soft 5.0 – Commercial software tool, created by the IBO for the purposes of the ecological assessment of buildings and their components

EE – Embodied Energy

EI – Environmental Impact

ENVEST – A software tool that informs the design process to deliver buildings with low environmental impact and whole-life cost. Developed by BRE

FCCC – Framework Convention on Climate Change

GHG – Green House Gas

GWP – Global Warming Potential

IBO – The Austrian Institute for Healthy and Ecological Building was founded in 1980. An independent, scientific, non-profit society with the aim of providing information on the impact of buildings on human health, well-being and that of the wider environment.

IBO: Details for Passive House, 2009 – Catalogue of ecological building elements and the physics involved. The second edition now conforms to passive house standards with an updated ecological evaluation.

ICE – Inventory of Carbon and Energy. Published by the University of Bath and based on data from hundreds of comparative studies. Recently been adopted by BSRIA as their Standard Material Assessment Procedure.

IPCC – Intergovernmental Panel on Climate Change. The international body for the assessment of climate change. Established by UNEP and WMO in 1988.

LCA – Life Cycle Analysis

LCEA – Life Cycle Energy Analysis

NOAA – The National Oceanic and Atmospheric Administration.

OE – Operational Energy

PAS2050:2011 – Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. Developed by the BSI along with the Carbon Trust and Defra.

PASSIVHAUS – German for passive house, this was the original name used for the design concept.

PH – Passive House

PHPP – Passive House Planning Package

PE – Primary Energy

SEDA – Scottish Ecological Design Association. Formed in 1991 as a means to share knowledge, skills and experience of ecological design. Members include academics, architects, artists, builders, planners, students, ecologists, landscape designers, material suppliers and woodworkers.

SERT – Sustainable Energy Research Team

SHD – Space Heating Demand

SHL – Space Heating Load

SSHD – Specific Space Heating Demand

TFA – Treated Floor Area

UNCED - United Nations Conference on Environment and Development

UNEP – United Nations Environment Programme.

WMO – World Meteorological Organization.

Chapter 1 - Introduction

Objectives

The purpose of this investigative study is to understand and then determine a method of calculation for the embodied energy and embodied CO2 emissions of a passive house. The necessity for an analytical accounting methodology in this area is quite apparent, and on many levels. With the Earth's biosphere accumulating greenhouse gases (GHG) and with a continuing global reliance on fossil fuels, (Keeling, 1960), (IPCC, 2007), (IEA, 2012) alternative options, in order to be effective need to be well-founded. The relationship between GHG's and the built environment, from a life cycle analysis (LCA) perspective is not well known – therefore a second reason for this work is to gain better understanding. And finally, the value of embodied energy and carbon emission data at the building design stage is even less understood, therefore the possibility and applicability of a practical 'calculator' for passive house in this area, could help to create more informed decision-making and help develop design principles that can lead to low emission, sustainable housing for the future.

In the UK over the past 30 years or so, the construction industry has progressed in the design and development of more energy efficient homes. Public awareness of the necessity for energy conservation, in terms of both environmental and supply/resources has likewise grown considerably too. Add into this mix the major economic factors of the global recession and rising energy costs and it is unsurprising that assessment of energy and carbon emissions associated with the construction industry has been increasing. However, this focus has been overwhelmingly concerned with the energy required for the operation of a building (OE) during its lifetime (Dixie et al, 2012), (Menzies, 2011). Estimates for the energy that is directly dependent on the materials used, varies across a wide range. These have varied from less than 10% up to 25% of the total energy used over the whole building life cycle (Moncaster, 2012), (Berge, 2009) (Kram, 2001). However, with the development of low energy buildings over the past twenty years happening simultaneously with an increase in construction energy required to build these homes, estimates have put the Embodied Energy (EE) at up to 50% of total lifetime energy used (Thormark, 2007). Additionally with the EU 'near zero carbon home' building standard just a few years' away (EU, 2006), the understanding of EE and embodied emission analysis starts to become quite relevant. And consequently the issue of building material choices, and their embodied energy impact can be considered important alongside the operational energy used.

The tools, software and hardware technologies, and the programs that currently exist to measure, monitor and evaluate the Operational Energy (OE) and CO2 emissions of construction, are both widespread and reasonably common-place now. Yet methods to understand, calculate and reduce the embodied energy and CO2 emissions in a practical sense are still relatively un-developed.

For example (and this is the area this project shall focus on) Passive House's (PH) are widely recognised as the leading standard in energy efficient design. Yet the formal passive house design methodology and corresponding design software package PHPP does not include embodied energy or embodied CO2 emissions in the energy analysis (PHPP 7, 2012).

Therefore the main objective of this project is to address this issue.

Additionally this study will also consider the Life-Cycle-Analysis (LCA) methodology, or the systemic inter-related life cycle approach. By applying this approach, it is hoped more understanding of key concepts will be gained. Brief explanations of relevant key concepts will be provided, along with some background and the methodologies used throughout. Attempts to 'bring-in' wider scoping issues will also be discussed to provide perspective.

The main objectives of this study are to answer the following questions:

- What is the embodied energy of a typical passive house?
- Where is the majority of this energy being expended?
- What are the most energy intensive parts of a passive house?
- What are the most and least energy intensive materials to use?
- Can a robust embodied energy and carbon calculator tool be successfully developed? And can it be embedded into or integrated alongside the PHPP?

- How much difference does variation of the construction materials of a passive house make to the total embodied energy and carbon dioxide emissions?
- How much does the typical embodied energy of a passive house contribute to the total lifetime energy use?
- What is the optimal insulation level for a typical passive house, in terms of both embodied and operational energy required?

Methods

- To understand and then determine a method for the evaluation of the embodied energy and the embodied CO2 emissions, for passive house.
- Design, build, develop and test a software tool that will enable easier understanding of the embodied energy and embodied CO2 emissions for passive house through quantification and calculation.
- Using the developed software tool, analyse the embodied energy and embodied CO2 emissions for passive house.

Outcome

It is planned that this study should provide three useful outcomes. Firstly, a practical software tool, that is to be made freely available for educational purposes. Secondly, some insights into the embodied properties of passive houses through case study analysis and understanding of key ideas. Finally, an evaluation of these ideas and insights and development into conclusions that may be of benefit for further study.

To summarise then, the wider purposes for carrying out this study are essentially to guide and support the development of more creative ‘holistic’, sustainable and low-emission housing designs. Concerned with focusing building practices towards these needs, it is hoped that 10-15 years into the future a more complete understanding of life-cycle thinking and embodied principles will have led to the establishment and common practice building of low emission and healthy passive housing that are sustainable for future generations to come.

Chapter 2 – Background and Key Areas

1.1 Overview

In 1956, Charles David Keeling, a postdoc at Caltech, California working under Professor Harrison Brown travelled to Mauna Loa, Hawaii. He had previously been encouraged by Brown to investigate the CO2 equilibria between rocks, water and air, and had built a precision gas manometer to do that. While in California he had discovered daily diurnal atmospheric cycling and more significantly a repeatedly consistent free atmospheric CO2 value, and had learned two lessons:

- "That the Earth system might behave with surprising regularity
- The necessity of making highly accurate measurements to reveal that regularity"

(SCRIPPS, 2013)

He had contacted the National Oceanic and Atmospheric Administration (NOAA) (formerly the US Weather Agency) and along with the Scripps Institution of Oceanography he had agreed to go to Hawaii to conduct continual monitoring to determine just how stable this background might be. Four years later he published a paper on what he had found: The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere (Keeling, 1960).

He had found a regular seasonal atmospheric CO2 cycle, but also a general trend. The work still continues today:

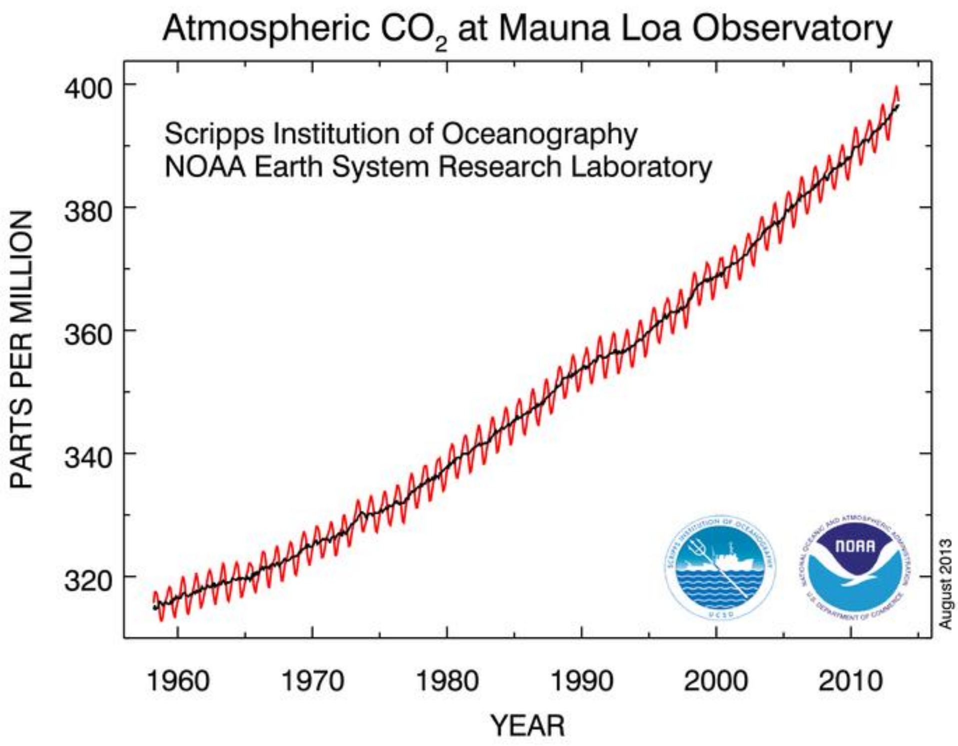


Figure 1: The ‘Keeling Curve’, updated to August 2013, Mauna Loa, Hawaii (NOAA, 2013).

This chart is more commonly known as the ‘Keeling curve’. Interestingly you can see the diurnal cycle, the collective seasonal ‘breathing’ of the predominantly northern hemisphere’s plant kingdom accumulating CO2 in the spring and then releasing it back in the autumn.

The release of this work resulted in a research program being launched in the 1970s to study the consequences. But this work was also influential in developing and understanding accurate monitoring and measuring devices and the concept of natural cyclic systems, both key ideas.

This annual rising of atmospheric CO2 levels has been associated with anthropogenic Greenhouse Gas (GHG) emissions from very early on. And it had been speculated that there were fossil fuel based atmospheric accumulations of GHG’s. But now there was some evidence.

Keeling had calculated that “At the South Pole the observed rate of increase is nearly that to be expected from the (increasing global) combustion of fossil fuel” (Keeling, 1960).

CO_2 has been estimated to stay in the atmosphere for 50-200 years, and is widely recognised as the primary anthropogenic greenhouse gas, with typical estimates at around 84% (EPA, 2013) of total greenhouse emissions from human activities. Although it is natural to find CO_2 in the atmosphere, as part of the carbon cycle. The additional, anthropogenic CO_2 and the rate-of-loss of natural sinks through deforestation and oceanic acidification appear to be major factors in contributing to this background trend.

The main concern with this rising level of atmospheric CO_2 is both its properties as a GHG and the apparent unknown consequences on the natural cycle. This has been linked with the concept of global warming (IPCC, 2007) by creating positive feedback gains such as solar absorption and oceanic acidification and therefore impacting the dynamically balanced, self-regulating global life system or Gaia (Lovelock, 1974), (Harding, 2009).

In 1987 a report was published by the United Nations World Commission on Environment and Development (WCED) titled ‘Our Common Future’ (UN, 1987). It was the culmination of four years of international research involving:

“Senior government representatives, scientists and experts, research institutes, industrialists, representatives of non-governmental organizations, and the general public” (Bruntland, 1987)

The format has been recognised as fairly inclusive with public meetings held around the world. The purpose was to discuss the issues of the environment and development together.

The mandate was to:

- “ Re-examine the critical issues of environment and development and to formulate innovative, concrete, and realistic action proposals to deal with them;
- Strengthen international cooperation on environment and development and to assess and propose new forms of cooperation that can break out of existing patterns and influence policies and events in the direction of needed change.
- Raise the level of understanding and commitment to action on the part of individuals, voluntary organizations, businesses, institutes, and governments” (Bruntland, 1987: 347).

Key concepts of the report included the interconnectedness of issues, and the recognition that environmental limits exist to economic growth.

The report offered recommendations for a sustainable course of development, but did not go on to define exactly how this would be accomplished. Consequently much confusion and interpretation of what sustainable development actually meant ensued.

In the report it is defined as:

> "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Bruntland, 1987)

This work led the way to the Rio Earth summit, Agenda 21, the Rio Declaration and the Sustainable Development Commission. And along with the United Nations Conference on the Human Environment, that took place in Stockholm, Sweden in 1972 are attributed as being pivotal in bringing public and political attention to environmental matters.
In response to these, the European Union has brought forth a programme of directives, recommendations and guidance aimed at sustainable development and mitigation of GHG emissions from fossil fuel use. (EU, 2013).

Energy generation is the main purpose for the combustion of fossil fuels and the chart below shows the latest statistics for electrical energy generation in the UK, values are in TWh/annum.

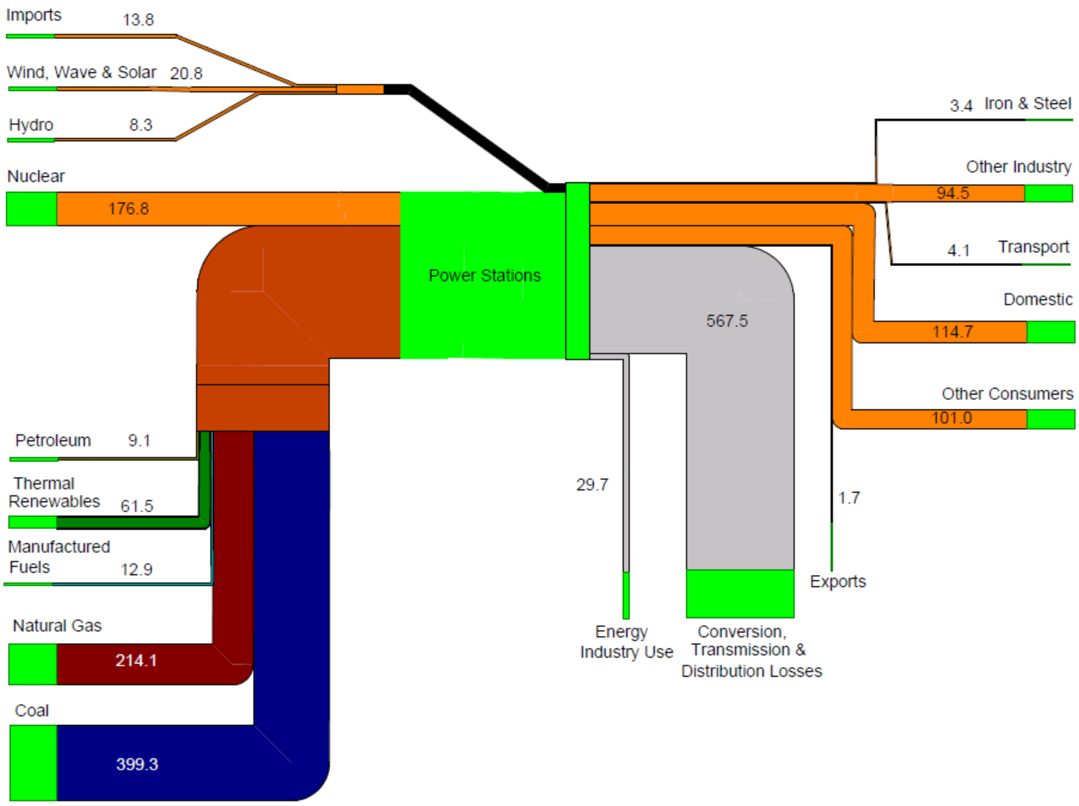


Figure 2: UK Electricity Flow Chart 2012 – TWh (DUKES, 2013)

Three things are clearly noticeable from this data, firstly the huge dependence of electricity production on fossil fuel combustion. Secondly the massive losses of Primary Energy (PE) due to conversion, transmission and distribution, approx. 2/3! And thirdly, that domestic consumption is the prime user or demand for this form of energy.

The chart below takes a different perspective and looks specifically at one type of fossil fuel – natural gas, and looks at the linear ‘flow’ of this energy source. Stats are for the UK, and again values are in TWh/annum.

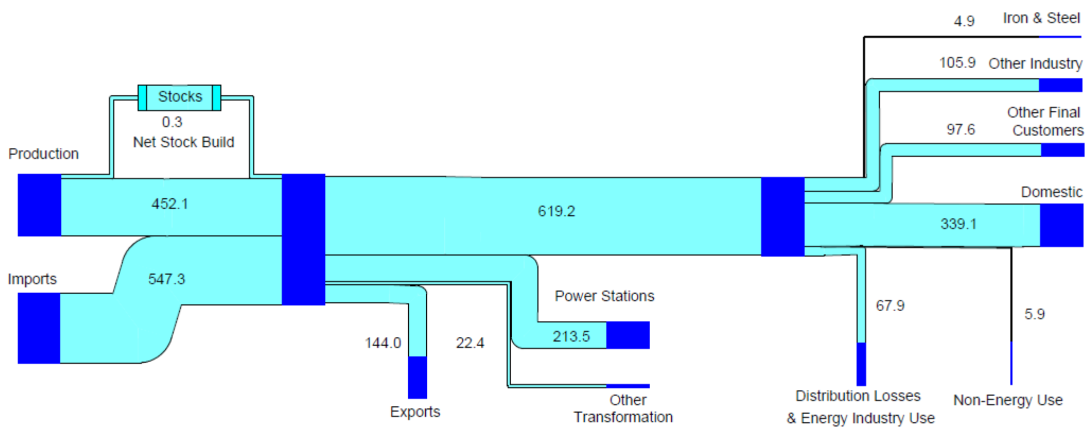


Figure 3: UK Natural Gas Flow Chart 2012 – TWh (DUKES, 2013)

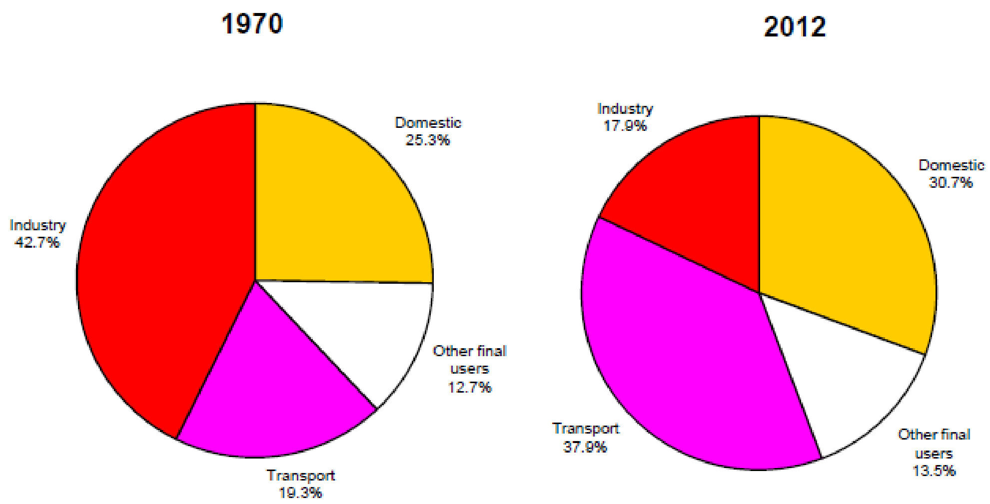


Figure 4: Energy Consumption by final user (DUKES, 2013)

There are several clearly significant observations regarding this data. Firstly, the large amount of supply (of gas) to power stations (As detailed in figure 2). Secondly, and again like electrical energy generation, the dominance of demand by the domestic sector (this is further detailed in figure 4 – illustrating its significance in terms of UK total energy demand). Thirdly, and interestingly the dependence on importation of fossil fuels – approx. 50% of gas, that is required to meet these direct energy and in-direct electrical energy domestic household demands.

This third factor illustrates another consequence of fossil fuel energy generation, namely global resource exhaustion. Considering the relatively short timescales of use and to mention nothing of future generations needs, this 'dependency' on imports, and on fossil fuel energy generation in general has led to ever more extreme measures to sustain – more energy intensive, with greater potential for destruction and pollution. Evidence of this historical 'pattern' in the UK, leading to exhaustion is shown below.

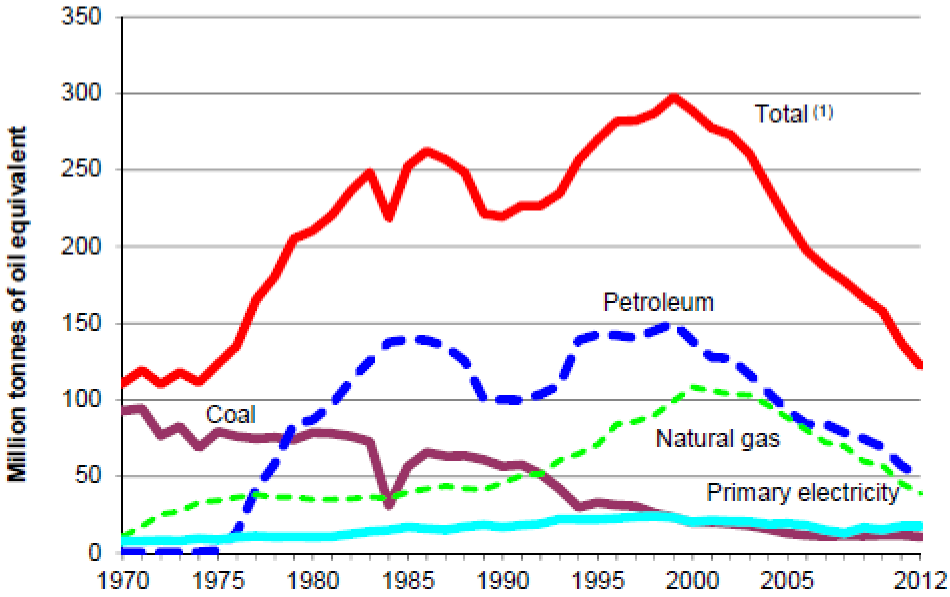


Figure 5: UK Production of Primary fuels 1970-2012 (DUKES, 2013)

Therefore alternatives need to be found. A useful summary of alternatives for meeting this energy demand is charted below, along with their up-to-date UK stats.

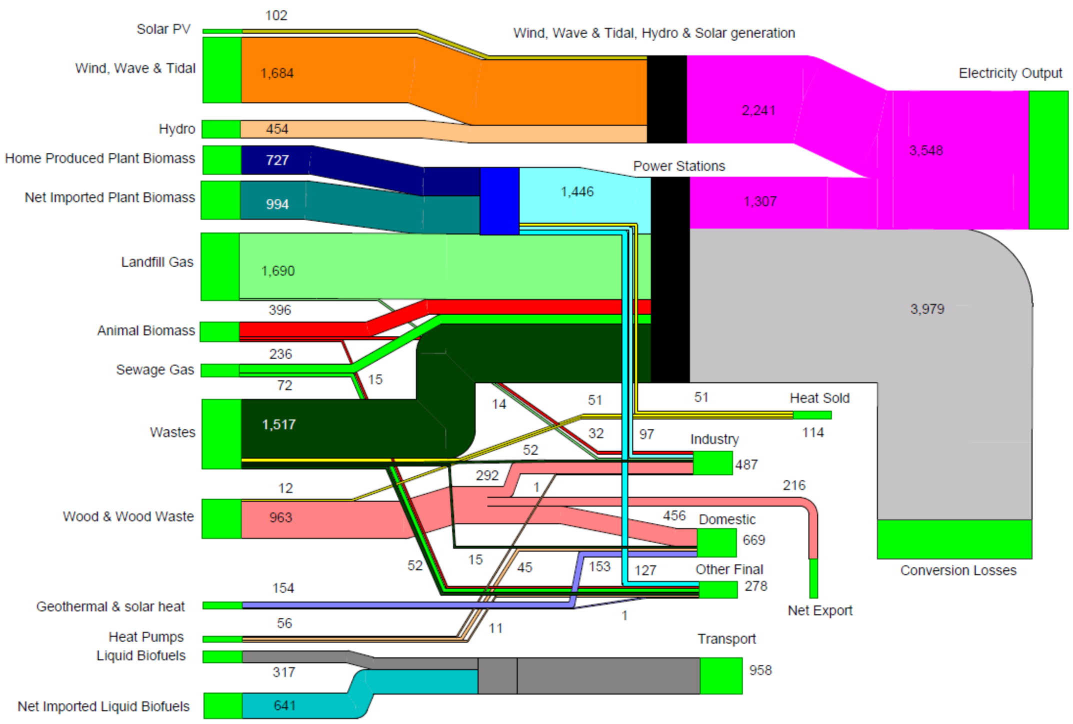


Figure 6: Renewables Flow Chart 2012 – ttooe (DUKES, 2013)

Some points of note about this chart follow. Initially, and on first impressions the power station conversion losses are massive too – however, interestingly, for many of these types of supply losses are not so important, since the primary energy source is renewable or sustainable. Secondly, however the big issue with many of these ‘alternatives’ is their inability to meet the base-load demands due to the intermittent and unpredictable nature of supply. An example of one of the biggest of these base load demands is for space heating. Data for the UK domestic space heating demand is shown below, for the past 40 years, firstly as a percentage of domestic energy consumption in figure 7, and then quantified in pJ in figure 8:

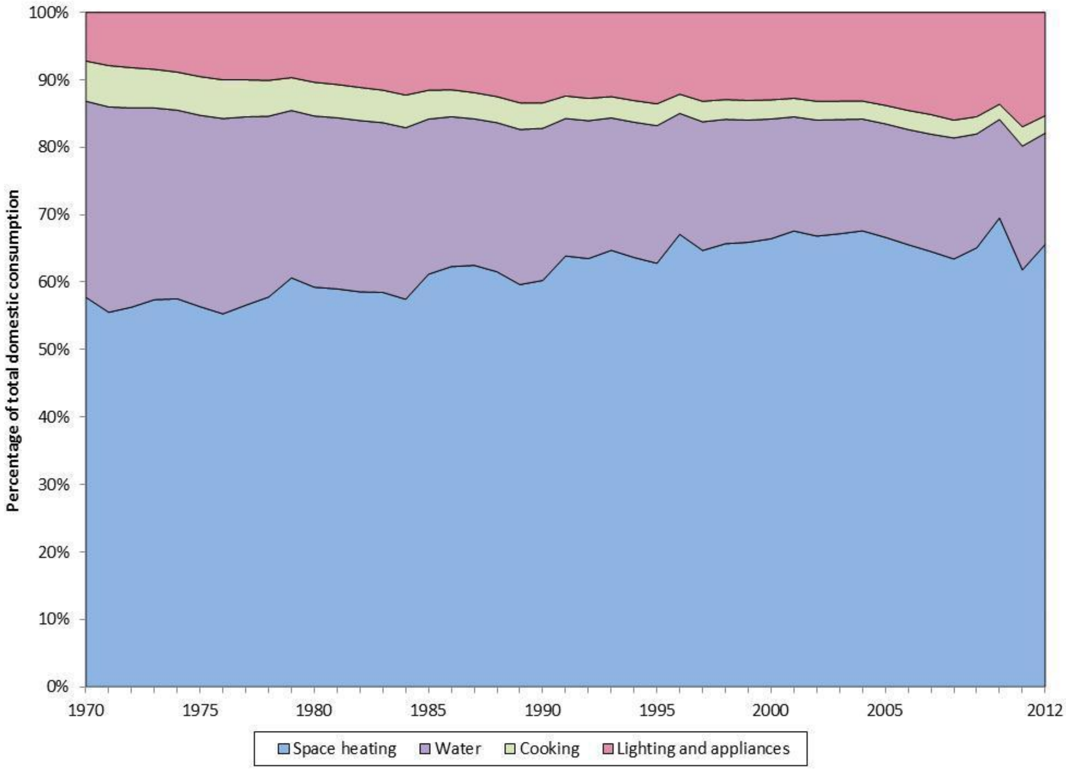


Figure 7: Domestic final energy consumption by end use, UK (1970-2012) (DECC, ECUK Table 3.04)

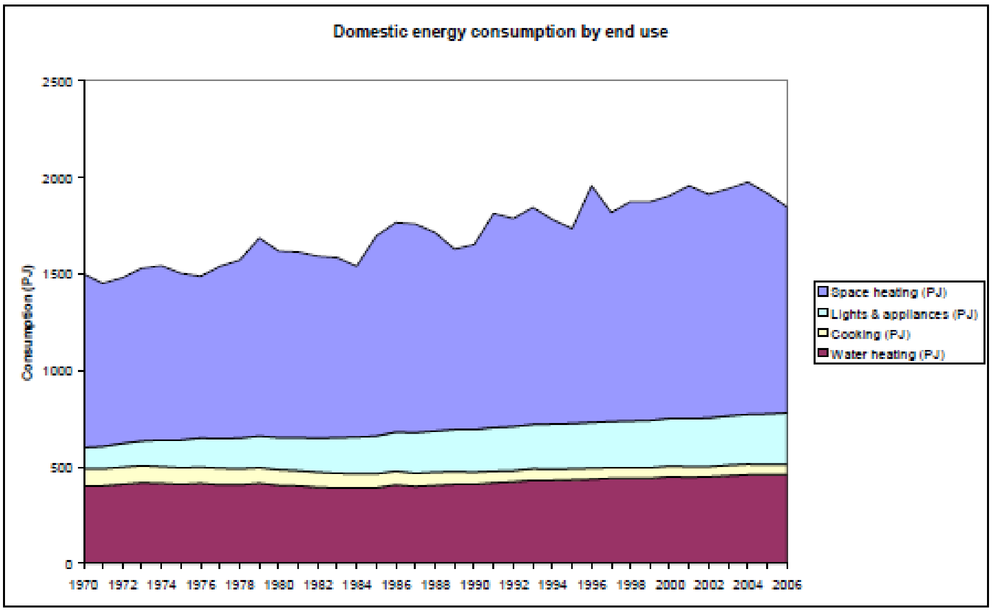


Figure 8: Domestic energy consumption by end use (BRE, 2006)

Iceland has an almost entirely renewable energy supply – approx. 85% (Geothermal and Hydro) (NEA, 2011) and serves as a very interesting example of how to 'manage' these base load issues. Recognising their costly dependence on external fossil fuels, over half a century ago they began to use the islands geological propensity for near surface 'hot rocks' to provide both domestic space heating (90% in 2011 – (NEA, 2011)) and hot water. Expanded this over the next 50 years or so, the off-loading of base-load space and water heating from direct or in-direct fossil fuel supply has allowed other energy demands to be met more easily, and managed more sustainably. Although this approach is highly dependent on rare local geological phenomena, the methodology of moving the base-load away from a fossil-fuel based source is key.

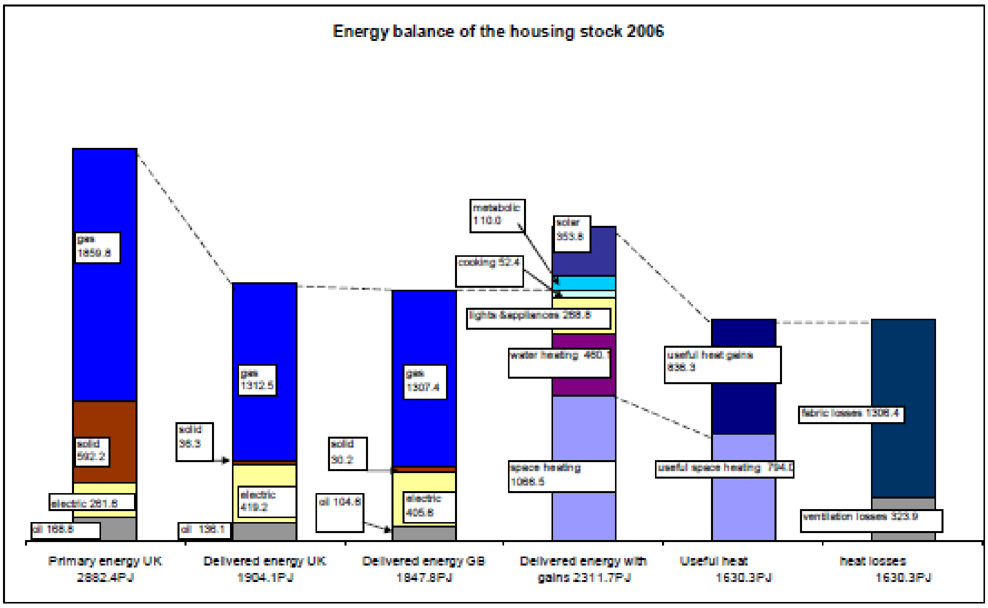


Figure 9: Energy balance of the UK housing stock 2006 (BRE, 2006)

The chart above illustrates the transition of energy from primary fossil fuel to the household – essentially highlighting the energy balance for the UK housing stock, in terms of required energy supply and consequential losses, along with any gains acquired. This further highlights in-efficiencies and high primary fossil-fuel use, and is indicative of the UK and western world's general extremely high dependence on fossil fuels for space heating demands, domestic or otherwise. However, this data only addresses the primary Operational Energy (OE) domestic household demands. What about the energy required for the materials and construction of the house?

According to the United Nations Environment Programme in 1999 construction activities contributed over 35% of total global CO2 emissions – more than any other industry (UNEP, 2007). In the UK 380 million tonnes of resources are consumed by the construction industry annually (BRE, 2008).

According to the IEA:

"The building industry is one of the biggest energy consumers. Between the production, operation and demolition stages of build it accounts for over 40% of the total society energy use. This emphasises the importance of sustainable practices in the industry, and the opportunity for improvement." (IEA 2008).

1.2 Policies and Regulations

At the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992, or the 'Earth Summit' as it is more commonly known, participants from 172 governments including 108 heads of state were in attendance. Here the Framework Convention on Climate Change (FCCC) was agreed. This was followed up by the first Conference of Parties (COP1) held in Berlin in 1995 where specific emission targets were outlined before agreement was reached in Kyoto Japan, in 1997. This agreement, known as the 'Kyoto Protocol' was finally ratified and brought into effect in 2005. Parties to the FCCC and the Kyoto Protocol agreed to the setting of targets for reducing the emissions of six defined Green House Gases (GHG), namely Carbon Dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O), Hydroflourocarbons (HFC's), Perflourocarbons (PFC's), and Sulfur Hexaflouride (SF6). This was over the period up to 2012, and in relation to 1990 levels as the base year.

The objective of this was simple – to bring about the stabilisation of atmospheric GHG's at a level that would avoid anthropogenic interference of the climate system. (UNFCCC – Article 2), (UNFCCC – Status of Ratification of the Kyoto Protocol, 1997).

In line with the Kyoto Protocol second round targets (2013-2020), the European Union created the 20-20-20 strategy that is committed to reducing its GHG emissions and primary energy consumption by 20% and increasing renewable energy generation to 20% by 2020 (EU, 2006). It has also endorsed objectives to reduce the EU Greenhouse Gas (GHG) emissions by 80-95% of 1990 levels by 2050 (EU, 2013).

These measures are being tackled by various initiatives including the 'Europe 2020 Growth Strategy' implemented through binding legislation. The 'European Climate Change Program (ECCP)' – through policies and measures, the 'EU Emissions Trading System' – key tool for reducing industry's GHG. And finally the mainstreaming into other policies (EU, 2013).

In the UK, the Climate Change Act was implemented in 2008, and the Climate Change (Scotland) Act 2009, as responses to the EU and Kyoto legislation, these set out 'legally binding' targets of reducing GHG emissions by at least 34% (42% in Scotland) of 1990 levels by 2020 and 80% by 2050 (CCA, 2008). Proposals to achieve this involve setting national policy and strategies that include energy conservation, efficiency, and the development of low carbon technologies and renewable energy generation.

Policies to address these targets, with respect to the construction industry can be, more or less divided into three broad categories:

Regulatory instruments: The main form these takes is the building energy code – a collection of minimum energy performance requirements, primarily for the purposes of ensuring the consideration at the building project design stage. This is part of the Standard Assessment Procedure (SAP) set forth by the EU and mandatory by all member states.

Informative instruments: These include appliance and building labels, public and media information programs and education. Energy Performance Certificate (EPC) is the European mandatory energy label for buildings.

Incentive schemes: Designed to encourage more energy efficient or conscious behaviour. This area includes all fiscal, financial and 'other' incentives and sometimes dis-incentives, aimed at producing energy reductions or more environmentally friendly activities.

The main regulatory standards in Scotland are to be found in (Building Regulations Scotland, 2009). These are larger based on and governed by the aforementioned EU policies and directives. There is no legislation requiring embodied energy calculation in buildings (Moncaster et al, 2012).

Governments can also incentivise and influence the private sector by means of 'legislative controls and schemes', such as the carbon pricing and trading market, taxation, compliance necessitated environmental assessment procedures such as BREEAM that lead towards industry best practice, covering a range of issues involving and including materials selection, energy efficiency and water, material waste, indoor environment quality, and local community.

Embodied carbon or energy has not as yet, been specifically dealt with or defined by UK or Scottish Government policy. And further there is no general consensus on the area with regards to methods for quantifying and calculation within the industry.

However the UK Governments 'Low Carbon Construction' report by the Innovation and Growth Team, stated in its recommendations that the priorities are to adopt a whole-life carbon appraisal system and therefore to agree (with industry) and introduce a sufficiently rigorous assessment system (for measuring embodied carbon) (Government, 2010).

1.3 Passive House

The Passive House (PH) concept is an internationally recognised performance based energy standard in construction. Possibly the only one. It is certainly one of the most energy efficient construction standards, and the Passive House concept is considered as an essential basis for every future-oriented building concept (PHPP 7, 2012). Interestingly the EU driven construction target of 'nearly zero energy buildings', one that is still yet to be accurately defined, would seem quite hard to achieve without employing passive house technologies.

Based on the original conceptual ideas on seasonal energy balances, by C. U. Brunner in Switzerland, publishing in ‘Energie im Hochbau’ (Energy in Buildings) in 1988, this was further progressed at the Institute for Housing and the Environment in Darmstadt Germany from 1989-1995 by Wolfgang Feist, Witta Ebel, and Tobias Logga where the building technique were adapted for the specific case of super-insulation, that resulted in the redundancy for a conventional heating system.

Defined by one of its developers, Prof. Dr. Wolfgang Feist (Passive House Institute Darmstadt) as follows:

> “The passive house is the result of the further development of the low-energy house. The key components are the excellent heat protection, very good airtightness and passive houses’ highly efficient heat recovery from exhaust air. A conventional heating system is superfluous due to the combined use of internal and solar heat gains. The passive house concept leads to the highest degree of comfort with minimal energy consumption."
>
> (IBO, 2013)

Passive houses are built not as a method, but more as a design concept, to achieve more sustainable housing with improved indoor environments.

Central to the concept is space heating (and cooling) through passive measures. This is achieved through the physics of thermodynamically efficient building. But it goes further than this. It is an all-inclusive conceptual approach that covers the hot water supply, indoor air quality - the corresponding thermal impacts of these, and evaluation and minimisation of the primary (operational) energy demand. Of course that is just the concept, and what happens in practice is the real test. And there is certainly a good test base for that.

The concept can be considered as a ‘holistic’ one – one that considers the whole of the building, and the integration of several key component parts is required to achieve the whole building PH standard. Interestingly this emphasises the idea of the whole as being greater than the sum of the individual parts.

Key to the PH concept and design are the physical characteristics of the local climate. Therefore integral to the PHPP software modelling has been the development of regional climate data that allows for the impacts of these to be properly integrated into the design process.

Here are a few examples of historical passive house use:

Figure 10: China – house with passive cooling features (Passipedia, 2013)

Examples such as this one using passive cooling, shows the traditional nature of passive principles in construction. Below we can see another example, this time using passive construction principles for heating in a more northerly climate (Adamson, 1992).

Figure 11: Icelandic house with passive heating technology (Passipedia, 2013)

Below is a picture of Fridtjof Nansen's polar ship – the Fram (1883). This pioneering and famous Norwegian exploration ship has been widely recognised as the first fully functional passive house – or ship to be exact!

With 15 inch thick, well-insulated and air-tight walls, triple glazing and custom ventilation techniques this was a true design marvel for exploring the poles.

Incidentally, the ship is still in very good condition berthed in a purpose built museum in the centre of Oslo.

Figure 12: The Fram, historical Passive Boat (PB) (Passipedia, 2013)

Figure 13: Conceptual modern terraced PH in Darmstadt, Germany (Passipedia, 2013)

In 1990, in Darmstadt Germany, a group of scientists began the ‘Passive House Preparatory Research Project’ which was an international co-operation including Bo Adamson and Gerd Hauser. The purpose for this was to systematically research energy efficient housing and to prototype and develop new components. Insulated window frames, reduced thermal bridges, and CO2 regulated ventilation systems were three achievements of this project – prototypes of these were built manually by hand. These were then incorporated into the design of a four terraced block of houses (Shown above) these were constructed with a whole range of integrated monitoring systems assessing components and the building’s energy performance (Passipedia, 2013).

The definition for a Passivhaus is:

“A Passive House is a building, in which thermal comfort (ISO 7730) can be provided solely by post-heating or post-cooling of the fresh air flow which is required for good indoor air quality (DIN 1946) - without using recirculated air in addition.”

Passipedia, 2013.

This is a functional definition and one that is valid for all climates. This concept can be said to have been discovered and it is clear that the nature of the PH standard is a conceptual one and not just a generic or randomly set standard.

As a performance based energy standard, the PH needs to meet a set of targets to achieve its status these targets are shown below:

Specific Heating Demand	≤ 15kWh/m².yr
(or) Specific Heating Load	≤ 10W/m²
Specific Cooling Demand	≤ 15kWh/m².yr
Specific Primary Energy Demand	≤ 120kWh/m².yr
Airtightness	≤0.6ach @50pascals (n50)

Table 1: The criteria for meeting the PH standard (BRE, 2013)

To achieve the standard and gain certification the primary energy demand target must be met in all cases. This value must include space heating domestic hot water (DHW), lighting, fans pumps and all projected appliance consumption. The standard also requires that *either* the space heating demand (SHD) or the space heating load (SHL) is met. And in line with thermal comfort levels, the certified PH should not fall below 16 degrees C.

What is worth noting is the *specific primary energy demand* target max value of 120 kWh/m^2.yr. This key value is known to have been achieved for residential buildings, with reasonable effort for all types of climates around the world (PHPP 7, 2012).

Typically what this means is that the following *minimal* requirements need meeting:

- A recommended opaque fabric U-values of $\leq 0.15 W/m^2$.
- U-values for windows and doors (for both the frame and glazing) need to be $\leq 0.8 W/m^2K$ ($0.85 W/m^2.K$ installed).
- Thermal bridging ideally needs to be eliminated or minimised, a psi value of $<0.01 W/m^2K$ is considered thermal bridge free.
- An air pressure test must result in an n50 airtightness level of 0.6ach, averaged over pressurisation and depressurisation.
- Whole house mechanical ventilation with heat recovery (MVHR) that is 75% efficient or better, with a low specific fan power.

Figure 14: PH typical specification requirements (BRE, 2013)

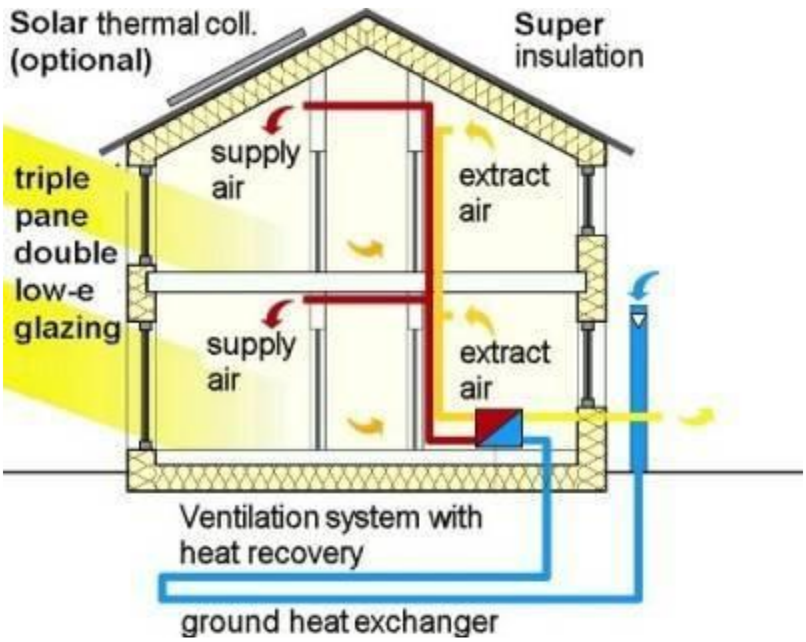


Figure 15: PH process diagram (Passipedia, 2013)

It has been recognised that the PH building standard is possible to achieve with refurbishments, but that it is impractical due to difficulties with works and costs. Therefore the EnerPHit standard has been created as a good practice refurbishment guide for PH specific renovations. This also has validation requirements and to achieve certification requires meeting the slightly less stringent criteria set out (Passive House Institute, 2013). These requirements are shown below:

Criteria	Passivhaus	EnerPHit
Specific Heat Demand	≤ 15 kWh/ m^2.yr	≤ 25 kWh/ m^2.yr
Primary Energy Demand	≤ 120 kWh/ m^2.yr	≤ 120 kWh/ m^2.yr
Airtightness	n50 ≤0.6	n50 ≤1.0

Table 2: EnerPHit PH Standard refurbishment criteria (BRE, 2013)

These criteria, for both new-build and refurbishment are not arbitrary targets neither. The levels have been set to conform to climate protection objectives. This is quite a good idea. Not only does it quantify and define, at a household level what is required, but by integration into both the new-build (and refurbishment) design processes and regulated through the validation and certification scheme it is a useful way to develop both public awareness and adherence. (PHPP 7, 2012).

A point of interest is that although PH as a specific energy performance standard can and does achieve very high levels of energy efficiency this does not necessarily translate to the BREEAM ratings and Code for Sustainable Homes (CSH) UK standards. Specifically because these two are both sustainability assessment ratings and as such cover a wide variety of environmental issues, besides energy efficiency. These are over-arching and can therefore typically be used in addition to the PH standard for assessment purposes. This however highlights current limitations of the PH standard and assessment procedure.

It is a requirement that in order to meet the design standard for 'passive house' a building must also achieve an expected reduced hot water and primary energy usage. This is often achieved through the use of integrated solar thermal, while the lack of space heating/cooling energy demand will naturally vastly reduce the primary energy demand.

It was initially a German energy label, a voluntary label that had a demanding low-level limit on energy use.

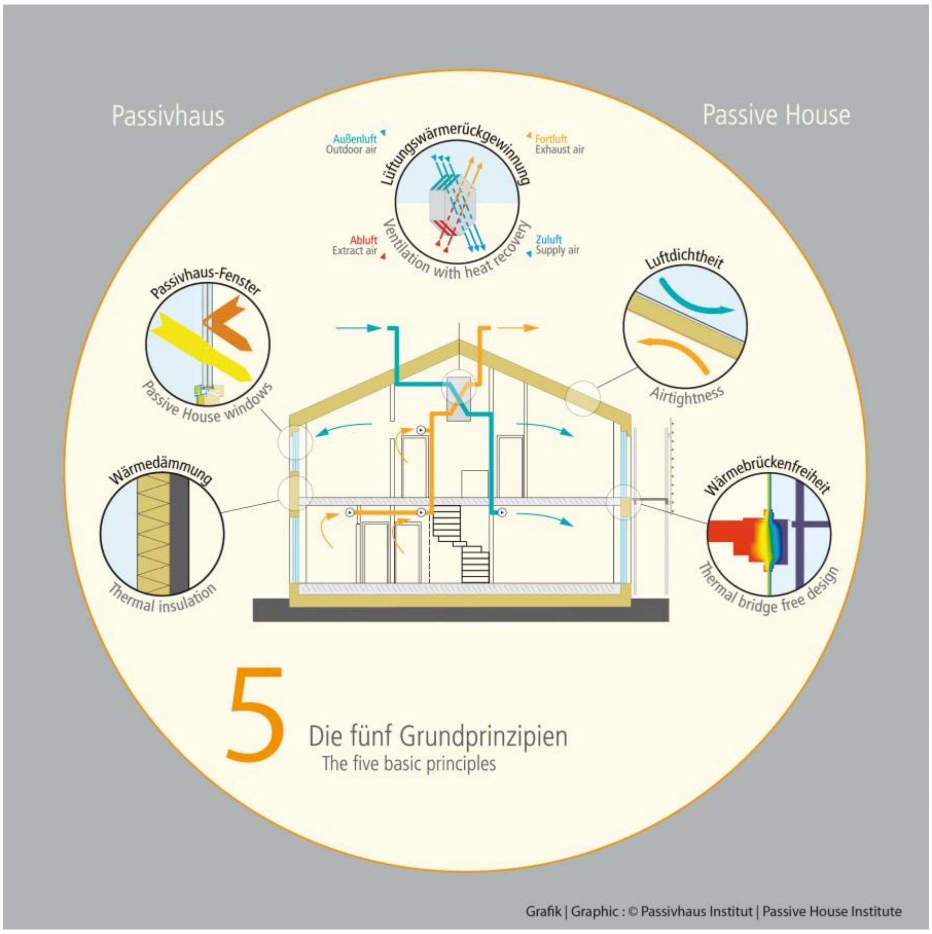


Figure 16: How the passive house system works (Passipedia, 2013)

Examples of Passive House

According to the International Passive House Association (IPHA), there are over 40,000 passive houses in use worldwide (IPHA, 2013). They have been built over Europe, Asia, Australia, North and South America and even Antarctica. The first built in Germany was in Darmstadt in 1991. While the first in the UK was in 2001, and in Scotland in 2003.

This international growth is especially interesting in light of the many different climates found across the planet. The earliest passive house designs had been initially limited to the central European climate, based on the key passive house design principle of understanding the climate and then building appropriately.

Interestingly the PH standard is a quality standard and therefore demands no particular method of construction. It is based on physical principles and consequently each PH building should and can be adaptable to its specific climate.

The chart below shows typical PH performance in comparison with low energy buildings:

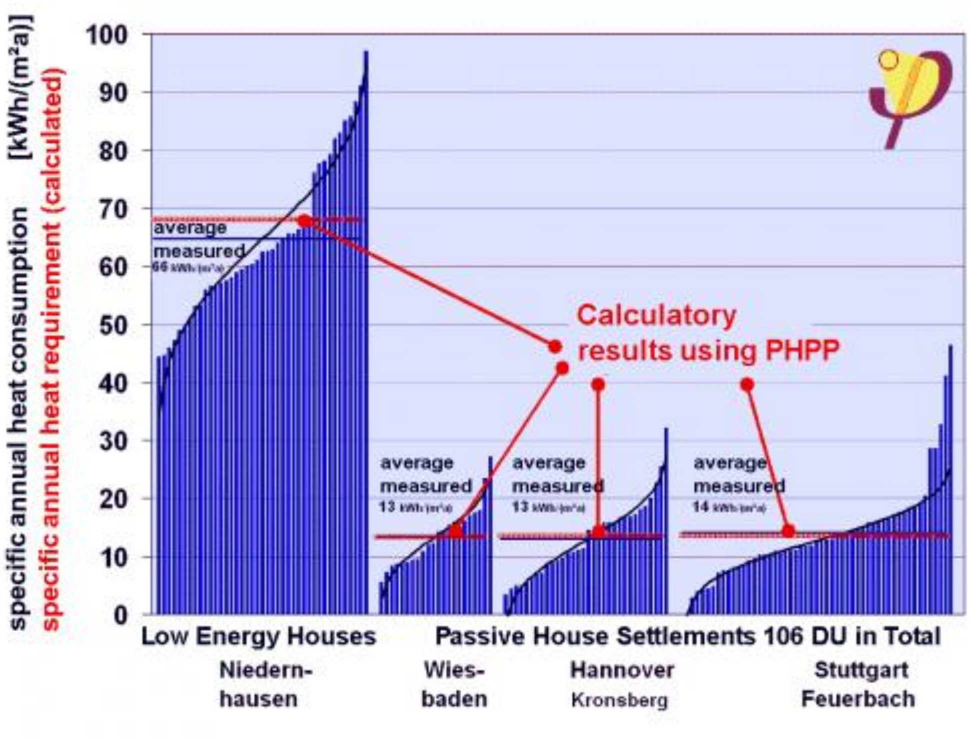


Figure 17: PH energy performance against typical low energy buildings (Passipedia, 2013)

As with any form of energy analysis and assessment, it is important to have a valid set of metrics. When attempting to compare the energy performance of different building constructions a common metric used is the average annual heating requirement (energy) divided by the Treated Floor Area (TFA). This is usually measured in units of kilowatt hours per metre squared per annum - kWh/m^{2}a. Interestingly for PH the method for calculating the floor area is slightly different from standard by only considering the useful floor area. By not including crouch space, or other dead spaces the PH floor area values will be less than normal.

This means that PH energy performance values are on the conservative side.

1.4 The Passive House Planning Package (PHPP)

It has been fairly well understood that a detailed dynamic energy simulation program is required to plan a passive house. But that is in fact not the case. In the last few years and contrary to this natural assumption the experience gained by the Passive-house Institute has shown that stationary energy balancing procedures deliver sufficiently accurate results for PH's. However, if required they can be validated beforehand with a dynamic simulation (Passipedia, 2013) (BRE, 2013).

What this has essentially done is made it possible to simplify the PH design process for standard buildings with a straight-forward software tool. However issues such as impacts of thermal storage capacities or peak summer temperatures are recognised as intrinsically complex systems that require dynamic building simulation tools to estimate.

Integral to attaining the passive house building and design standard, and a big part of the design process itself is carried out with the analytical software tool called the Passive House Planning Package (PHPP). This works as essentially three simultaneous tools - design, energy performance evaluation, and verification, all used in the development of building a house to the specification and achieving certification as PH. (PHPP 7, 2012).

Created by the Passivhaus Institute the PHPP is an Excel based energy calculation tool. It has been developed around the fairly standard core energy calculation methods used throughout Europe. It is specifically a design tool to model the performance of potential PH projects. It has been developed with the intention of being used by anyone who is involved with PH design. For certification to the PH standard, verification must be achieved with the tool, based on the modelling design and checked by the building assessment, as a means of quality control.

Built into the software package are several useful analysis tools for:

- Energy balance calculations
- U-value calculations
- Ventilation design for comfort
- Calculating heating and cooling loads
- Summer comfort calculations
- Localised climate data

The software is a compilation of 35 different Excel spreadsheets, each covering a different aspect of the design process, energy evaluation or verification. There are multiple fields on each spreadsheet and together they all combine to cover all the criteria relevant to the energy balancing and performance characteristics of the planned PH. The diagram below illustrates how they each 'flow' into the overall design process for residential building:

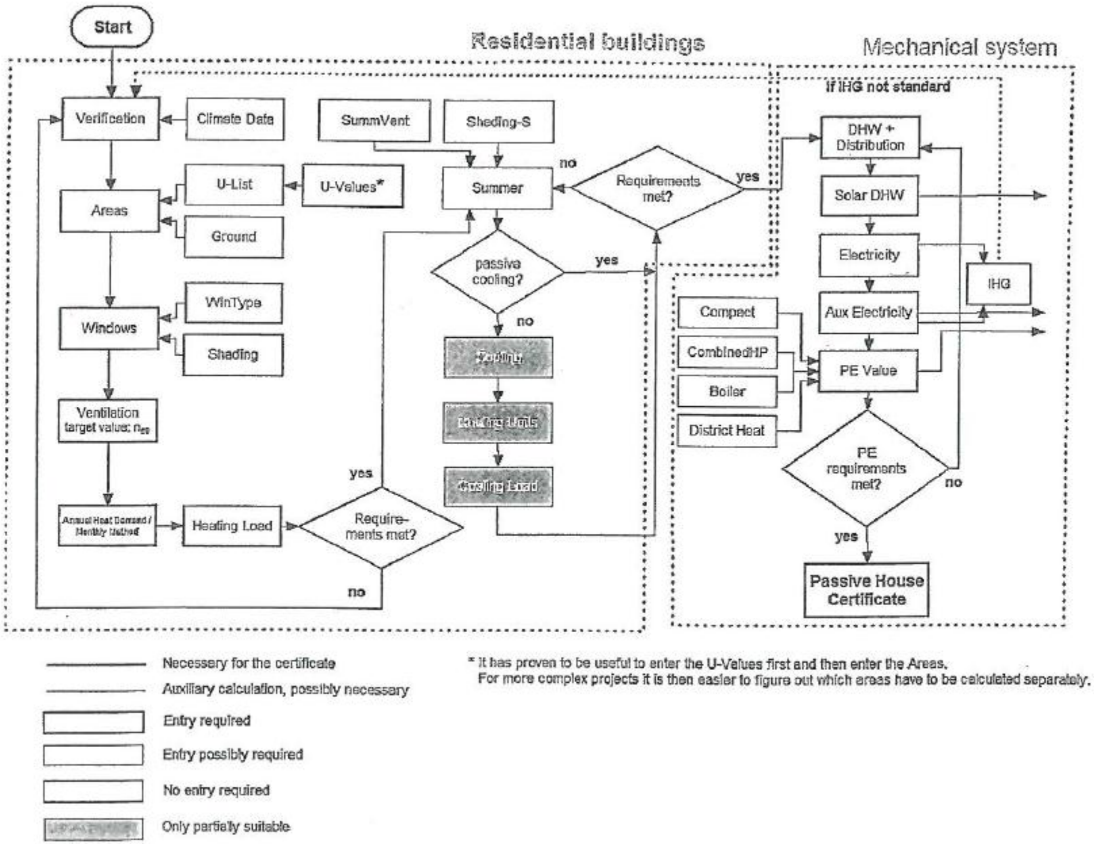


Figure 18: PHPP process flow chart and field inputs (PHPP 7, 2012)

An example of a PHPP input field from the areas spreadsheet is shown below:

Summary						Building Element Overview	Average U-Value [W/(m²K)]
Group No.	Area Group	Temp Zone	Area	Unit	Comments		
1	Treated Floor Area		162.54	m²	*Living area or useful area within the thermal envelope*		
2	North Windows	A	8.04	m²	Results are from the Windows worksheet.	North Windows	0.828
3	East Windows	A	11.24	m²		East Windows	0.876
4	South Windows	A	4.47	m²		South Windows	0.878
5	West Windows	A	36.58	m²		West Windows	0.739
6	Horizontal Windows	A	0.00	m²		Horizontal Windows	
7	Exterior Door	A	0.00	m²	*Please subtract area of door from respective building element*	Exterior Door	
8	Exterior Wall - Ambient	A	221.25	m²	*Window areas are subtracted from the individual areas specified in the "Windows" worksheet.*	Exterior Wall - Ambient	0.116
9	Exterior Wall - Ground	B	0.00	m²	*Temperature Zone "A" is ambient air.*	Exterior Wall - Ground	
10	Roof/Ceiling - Ambient	A	133.00	m²	*Temperature zone "B" is the ground.*	Roof/Ceiling - Ambient	0.115
11	Foor slab/ basement ceiling	B	117.69	m²		Foor slab/ basement ceiling	0.125
12			0.00	m²	*Temperature zones "A", "B","P" and "X" may be used. NOT "I"*		
13			0.00	m²	*Temperature zones "A", "B","P" and "X" may be used. NOT "I"* Factor for X		
14		X	0.00	m²	*Temperature zone "X": Please provide user-defined reduction factor (0 < f, < 1):* 75%		
						Thermal Bridge Overview	Ψ [W/(mK)]
15	Thermal Bridges Ambient	A	0.00	m	*Units in m*	Thermal Bridges Ambient	
16	Perimeter Thermal Bridges	P	0.00	m	*Units in m; temperature zone "P" is perimeter (see Ground worksheet).*	Perimeter Thermal Bridges	
17	Thermal Bridges Floor Slab	B	0.00	m	*Units in m*	Thermal Bridges Floor Slab	
18	Partition Wall to Neighbour	I	0.00	m²	*No heat losses, only considered for the heating load calculation.*	Partition Wall to Neighbour	
Total Thermal Envelope			532.27	m²		Average Therm. Envelope	0.194

Table 3: The PHPP summary field from the Areas spreadsheet (PHPP 7, 2012)

Passive House Planning

CLIMATE DATA

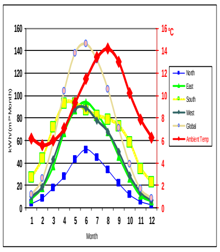
Standard/regional climate: Select here. Regional climate data

Select region here: User Data

Select regional climate here: 15 West Scotland

Building:	New Farmhouse
Use regional data?	Yes
Climate building	15 West Scotland
Chosen method for annual heating demand:	Monthly method
Monthly data:	15 West Scotland
Annual data:	
Use annual climate data set	No
Results:	
Annual Heat Demand	12.6 kWh/(m²a)
Heating load	9.1 W/m²

Transfer to annual method		
H_T	205	d/a
G_t	64	kKh/a
North	71	kWh/(m²a)
East	151	kWh/(m²a)
South	322	kWh/(m²a)
West	169	kWh/(m²a)
Horizontal	232	kWh/(m²a)



	Month	1	2	3	4	5	6	7	8	9	10	11	12	Heating Load		Cooling Load
	Days	31	28	31	30	31	30	31	31	30	31	30	31	Weather 1	Weather 2	Radiation
Parameters for PHPP calculated ground temperatures:	15 West Scotland	Latitude:	56.5	Longitude ° East	-5.4	Altitude m	3	119	Daily Temperature Swing Summer (K)		4.4	Radiation Data:	kWh/(m²*month)	Radiation: W/m²		W/m²
Phase shift months	Ambient Temp	6.2	5.6	6.0	7.1	9.4	11.5	13.4	14.2	13.0	10.2	7.9	6.3	0.8	2.8	16.2
2.00	North	4	9	18	28	43	52	45	34	22	12	6	3	4	4	39
Damping	East	8	18	37	67	87	94	84	68	46	26	11	6	9	5	71
-1.05	South	27	44	72	93	93	87	82	79	73	58	35	23	41	17	99
Depth m	West	10	19	43	70	88	89	78	68	50	29	14	7	11	7	79
3.32	Global	12	26	59	104	138	146	132	106	71	39	17	9	12	9	128
Shift of average temperature K	Dew Point	3.0	2.3	3.4	4.4	6.9	9.2	11.1	11.9	10.4	7.4	5.1	3.2	3d	3d	3d
1.60	Sky Temp	-3.1	-4.2	-3.3	-2.9	-0.2	2.4	5.3	6.3	4.9	1.8	-1.0	-3.2			3.0
	Ground Temp	10.0	9.6	9.6	10.1	11.0	12.0	12.8	13.3	13.2	12.7	11.8	10.9	9.6	9.6	13.9

Figure 19: The top input fields of the PHPP Climate Data spreadsheet. (PHPP 7, 2012).

Key to the original concept of Passivhaus is the idea through the combination of an ongoing developmental process of the design analysis accompanied by a verification procedure to achieve the standard. Or in simpler terms the house is performance tested after completion to receive certification.

The software tool PHPP provides the basis for the testing and this technique of building design and appraisal development has been ongoing since its inception with the goal of delivering an optimised process that produces buildings that achieve the design performance specifications.

The PHPP is a static modelling system, but despite this has had great success in accuracy of results. This can, in part be attributed to the design process carried out in first developing the software. Using an iterative strategy, and based on very careful monitoring of building performance of *each* project, there has been a process of honing and ‘re-defining’ the modelling method to achieve success. This has taken place over a period of time, the software is now 15 years old, which has allowed the progressive development by experience and knowledge of the specific area of passive house building.

Life Cycle Analysis (LCA)

It could be stated simply that a Life Cycle Assessment or Analysis (LCA) is basically a consideration and documentation of the wider environmental impacts of a product or process, appraised throughout its ‘life-time’.

Possibly something as simple as the diagram below can illustrate the concept:

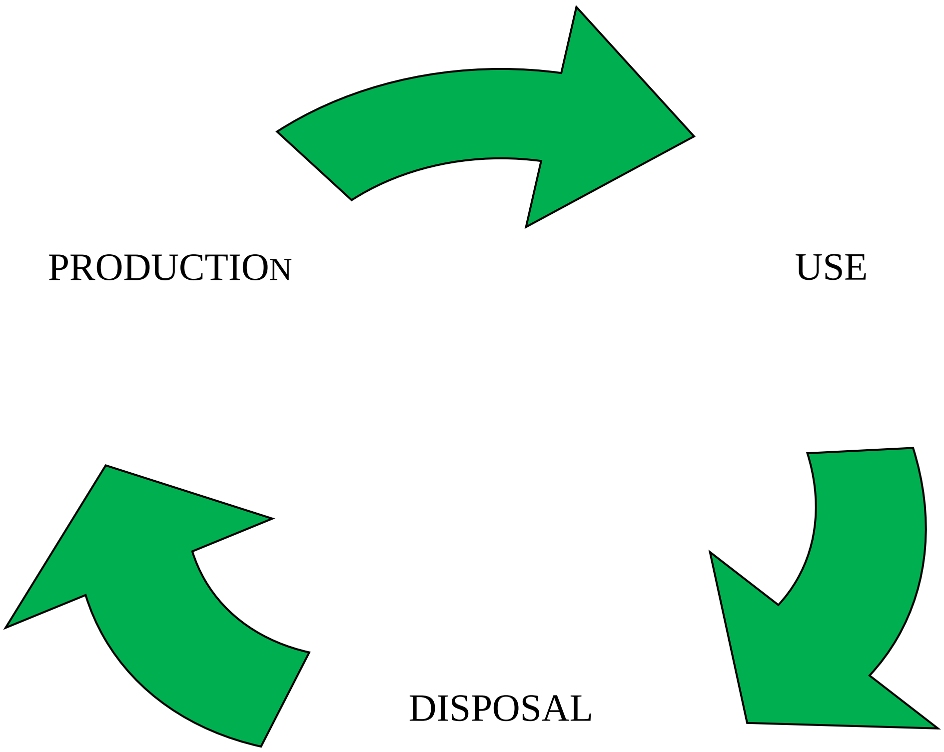


Figure 20: LCA.

Therefore in essence it can be seen as a wide perspective of appraisal, with *life-cycle* implying a holistic or fair assessment as oppose to narrower, short-term and environmentally limited outlooks.

LCA can be considered as a form of environmental accountancy that assesses the complete range of environmental effects or impacts that are attributed to the product, process or service for the purposes of making improvements, informing policy and supporting decision-making. This can be achieved through the following positive benefits:

- Prevents problems associated with the shifting of environmental impacts
- Enables secondary impacts to be identified and mitigated
- Can be used to help reduce environmental pollution and resource use
- Can allow a better understanding of the real costs of manufacturing and design (financially and environmentally), e.g. revealing hidden environmental costs

However simple in theory as LCA is, the application in practice to large, complex or multi-variable processes, products or systems can quickly present challenges.

In 1997 the International Standards Organisation (ISO) established a standard for the procedure of conducting LCA. This was formally laid out and subsequently updated in 2006:

- ISO 14040:2006 – Outlining the LCA principles and framework
- ISO 14044:2006 – Covers guidelines and requirements.

These documents define a standard methodology for LCA process and procedural development. The standards are designed to be broadly used and applicable to a variety of things. The methodological structure has four main stages that as illustrated by the process flow chart follow a natural progression:

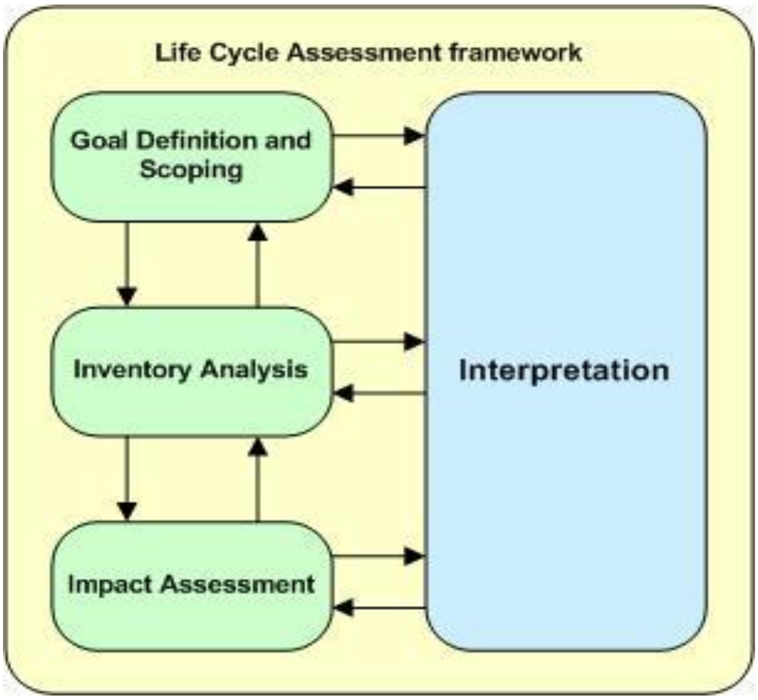


Figure 21: The ISO 14040 LCA phases and flow structure (ISO 14044:2006).

The four phases are:

- Goal Definition and Scoping:
- Inventory Analysis:
- Impact Assessment:
- Interpretation:

As illustrated, the process is quite flexible and re-visiting stages is quite normal, therefore although there is a progressive nature to the structure, the final interpretation stage allows for an on-going, cyclical flow and improvement methodology.

For the application of LCA to products or buildings it is quite common to break down the life-cycle into four periods for consideration:

- Production
- Assembly
- Use
- Disposal

Distinctions like these prove very useful for conducting meaningful analysis by aiding understanding of what are complex issues. This categorisation therefore highlights how the LCA procedure is used not only to assess and quantify environmental impacts, but it also provides a structural framework, to understand and manage this quantification and environmental impact appraisal.

The diagram below illustrates this breakdown:

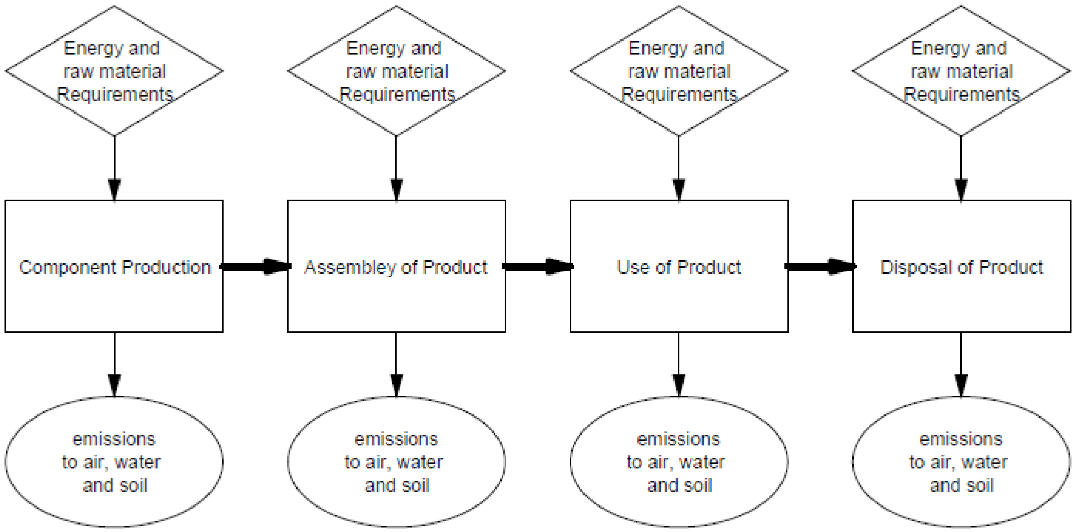


Figure 22: Different stages of LCA assessment for buildings (McManus, 2005)

Essentially if you imagine drawing a line, a boundary around the building, and throughout its life, then this is your line of demarcation for the assessment of everything that crosses it. This can be considered as a typical ‘process flow’ boundary. Boundaries like these are central to the procedure of establishing the buildings inputs and outputs, and the process of LCA in general. Alternative boundary systems for LCA analysis include ‘input/output’ analysis techniques, but these are less useful for the purposes of construction assessment. LCA’s in the field of construction and buildings typically cover the extraction and processing of raw materials, manufacturing, transportation and distribution, the use, re-use, maintenance and then final disposal or recycling. (Consoli et al, 1993) or (Berge, 2009).

With regard to the ISO standard LCA, the process of setting and defining boundaries occurs in phase one – Goal Definition and Scoping. The boundaries can be inter-related to the purpose for the LCA, and therefore definition at the same stage is important. However, boundary definition is also important because this will impact the outcomes of the LCA.

Boundaries that need defining can be categorised as temporal, analytic or methodological (ISO 14044:2006).

Below are typical examples of temporal boundaries used in construction LCA:

Cradle to Gate	From the extraction, through the manufacturing and packaging to when ready for site delivery.
Cradle to Site	As above, but including transportation to site and any on-site processing required to make use of the product.
Cradle to Grave	All the processes a product or component goes through. Assuming no end-of-life residual value.
Cradle to Cradle	Similar to ‘cradle-to-grave’ however considers a residual value left in buildings, e.g. the re-cycling of construction materials for similar products, different products or energetic

	value.

Table 4: Life Cycle variants of common temporal boundaries used within construction LCA (Menzies, 2011).

An appreciation for the methodologies used for LCA gives a good beginning to then go on and explain both embodied energy and embodied carbon. With this understanding it may be possible to bring clarity to these terms.

Embodied Energy (EE)

The embodied energy of a building is essentially the energy used during the manufacturing of materials and components, and during the construction processes, refurbishment and demolition of the building.

The Building Services Research and Information Association describe EE as:

"The total primary energy consumed from direct and indirect processes associated with products or services. This includes material extraction, manufacture, transportation and any fabrication before the product is ready to leave the factory gate"

(BSRIA, 2013).

However there is no standard calculation methodology or procedure (ISO, 2006), (Government, 2011), (Dixie et al, 2012), (Moncaster et al, 2012). Another definition, this time taken from 'The Ecology of Building Materials', (Berg, 2009) states:

"The embodied energy of a product includes the energy used to manufacture it all through the process of mining or harvesting the raw materials, refining, processing, and various stages of transport, to the finished product at the factory gate. Other inputs include, for example, the energy costs of restoring mined areas, marketing and packaging, even though they may be minor. Also included in the embodied energy is the combustion value of the raw materials themselves, often called feedstock. If incinerated after subsequent demolition the energy content recovered from the product will be given as a negative value and subtracted from the total energy consumed. However, as noted above, the valuable energy content that could be recovered by combustion may be lost due to problematic non-flammable or toxic additives."

(Berge, 2009)

These two definitions differ by their temporal boundaries (As highlighted in table 4) and their inclusion of feedstock energy, or not. Much research has highlighted several factors that impact the variability of embodied energy analysis – these are listed below as a matrix along with the lead authors associated with the work. Notice the ISO 14040:2006 LCA standard is listed in the table:

Authors and Year of Study/ Research	*Parameters*									
	(1) System	*(2) Method of EE Analysis*	*(3) Geographic Location*	*(4) Primary and Delivered Energy*	*(5) Age of Data*	*(6) Data Source*	*(7) Completeness of data*	*(8) Manufacturing Technology*	*(9) Feedstock Energy Consideration*	*(10) Temporal Representation*
Buchanan and Honey, 1994			√		√			√		
Pears, 1996		√		√		√		√		
Pullen, 1996		√	√			√	√			
Alcorn and Wood, 1998			√		√	√	√			√
Lippiatt, 1999			√					√		√
Pullen, 2000a				√						
Pullen, 2000 b		√	√		√			√	√	
Treloar et al., 2001a		√	√	√				√		
Miller, 2001	√	√								
Glover et al., 2002	√									
Junnila and Horvath, 2003	√		√			√				√
Ding, 2004	√		√		√	√				
Horvath, 2004	√	√								
Suh et al., 2004	√									
Crawford and Treloar, 2005		√								
ISO 14040, 2006	√		√		√		√	√	√	√
Lenzen, 2006	√		√		√			√		√
Holtzhausen, 2007		√	√					√		
Menzies et al., 2007			√		√	√	√	√		
Nassen et al., 2007		√								
Sartori and Hestnes, 2007			√	√		√			√	
Hammonds and Jones, 2008	√	√	√		√					
Peereboom et al., 2008			√		√	√		√		√

Table 5: Matrix of parameters identified as causing EE variation and the associated study authors (Dixie et al, 2012).

Since embodied energy is normally assessed and understood as part of a life cycle analysis, let's summarise within this context to better understand such variation and to develop a working solution.

The standard LCA assessment methodology (ISO 14044:2006) identifies four development phases for carrying out a life cycle analysis. The first of these phases titled Goal and Scope Definition – is when the goal of the assessment is chosen, the level of detail is defined, the target audience is identified, the intended application is stated, and the use of the results are considered, as is the original reasons for carrying out the analysis (ISO 14044, 2006). Also, and importantly the boundaries are defined in this phase – specific to the goals of the assessment.

Therefore in practice, the evaluation of EE, in accordance with the international formal standard procedure for LCA, set out by ISO (14040 and 14044), and more specifically for Life Cycle Energy Analysis (LCEA) allows flexibility.

Therefore variability in EE values, from different sources can be expected. This is symptomatic of both this area of study and LCA in general. Consequently this was significant in defining how this investigative study would be approached and developed.

Embodied CO2 Equivalent (ECO2e) Emissions

The quantification and calculation of associated GHG emissions is an important output in the application of the LCA and LCEA assessment tools. Essentially this allows the carbon footprints of products, organisations, houses and people to be estimated.

A carbon footprint has been defined as:

> "The total greenhouse gas emissions caused directly and indirectly by a person, organisation, event or product, and is expressed as a carbon dioxide equivalent (CO2e)"
>
> (Carbon Trust, 2013).

A carbon footprint should account for all six Kyoto GHG emissions (WRI, 2001), (Carbon Trust, 2013). It is useful for understanding, communicating and reducing GHG emissions. It is similar in principle but of a more specific focus than the 'Ecological Footprint' - this assessment is much wider and more holistic in nature, and considers the planets capacity to absorb such emissions (Wackernagel et al, 1997), (Global Footprint Network, 2010).

The table below highlights three ‘scopes’ for the carbon footprint assessment for businesses or organisations. These were set-out in the GHG Protocol – a carbon accounting tool for industry and government created in 2001 by the World Resources Institute and the World Business Council for Sustainable Development:

Scope 1	Scope 2	Scope 3
Fuel combustion	Purchased electricity, heat and steam	Transport – business
Company vehicles		Waste disposal
Process emissions		Transport – product
Fugitive emissions		Transport – commuting
		Leased assets, franchises, outsourcing
		Production of purchased materials
		Use of products

Table 6: GHG Protocol – 3 scopes of carbon emissions (Carbon Trust, 2013).

In order to quantify all (Kyoto defined) GHG’s into one single CO2e or carbon footprint value, the gases are assigned a ‘carbon equivalent’ quantity called Global Warming Potential (GWP). This value is relative to the ‘indicator’ or base-line gas – CO2. The table below illustrates up-to-date data:

Substance	Global Warming Potential (GWP) (Over 100 year time horizon)
Carbon Dioxide (CO2)	1
Methane (CH4)	25
Nitrous Oxide (N2O)	298
Hydroflourocarbons (HFC)	77-14800
Perflourocarbons (PFC)	7500-17700
Sulfur Hexaflouride (SF6)	16300

Table 7: Global warming potential for greenhouse gases over 100 year period (IPCC, 2007).

Greenhouse Gases (GHG's) can be characterised by three aspects, their abundance, their energy absorption (heat retention) and their atmospheric longevity. The Global Warming Potential (GWP) is a measure of the total energy that a gas absorbs (by mass) over a particular period of time in comparison with carbon dioxide (CO2). CO2 is given a GWP of one and serves as a baseline for all other gases to be compared.

For example, methane has a GWP greater than 20 times bigger than CO2, over the one hundred year timeline. But CH4 only has an atmospheric lifetime of about 10 years. However for an equal mass, it absorbs a lot more energy than CO2. This illustrates the value of the GWP system in creating a standard system to quantify and compare. However the relativity of these values to the timescales used must be borne in mind. And for this reason the IPCC published with three timescales 25 years, 100 years and 500 years (IPCC, 2007).

Chapter 3 - Datasets

Inventory of Carbon and Energy (ICE)

For the purposes of this study, and in accordance with standard LCA practice it was important to select both appropriate and valuable sources of base data for this investigation.

Therefore with over 400+ datasets, UK specific and concentrating on construction, the first of the three base data sources was selected – the Inventory of Carbon and Energy (ICE) version 2, developed by Hammond and Jones of the Sustainable Energy Research Team (SERT), University of Bath, in 2008 and updated to the latest version in 2011. This database has been chosen because its primary focus is on construction materials, it identifies primary and secondary materials and is aimed at typical and usable market products (Hammond and Jones, 2010). Not only that, but it has been made freely available. Based on embodied energy and carbon information from academic research, industry statistics, government publications, and other LCA databases this inventory has been integrated into several footprint calculators and is recommended and used by the Building Services Research and Investigative Association (BSRIA), and the 'Greenhouse Gas Protocol' (BSRIA, 2013), (WRI, 2001). Including data on embodied energy, CO2 and CO2e emissions using cradle to gate, site and grave boundaries. Data transparency is very good with system boundaries, data types, allocation methods, technologies, original sources (references provided), year, and uncertainty generally estimated (ICE, 2011).

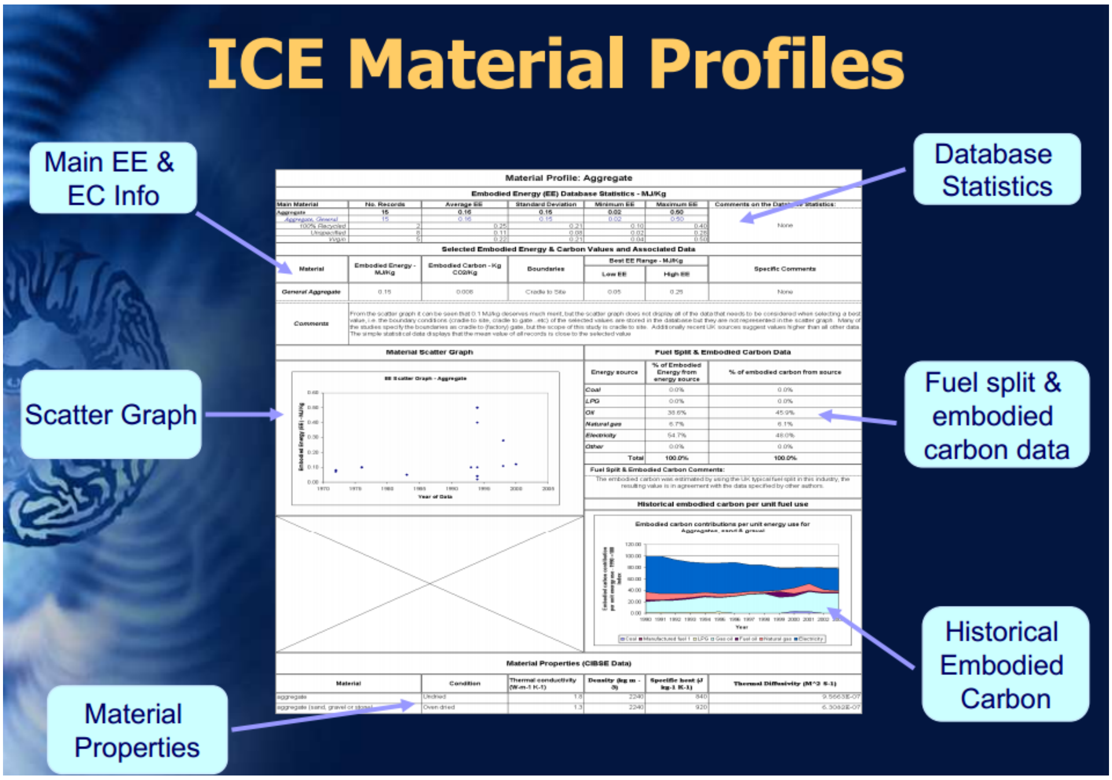


Figure 24: The ICE typical material profile datasheet (Hammond and Jones, 2010).

Material Profile: Steel

Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Steel	180	31.25	16.50	6.00	95.70	None
Steel, General	154	29.36	13.45	6.00	77.00	
50% Recycled	2	32.75	20.86	18.00	47.50	
Market Average	11	25.68	5.92	18.20	36.00	
Other Specification	2	19.40	0.71	18.90	19.90	
Predom. Recycled	33	13.60	4.86	6.00	23.40	
Unspecified	49	31.96	10.61	12.50	77.00	
Virgin	57	37.48	12.07	12.00	63.42	
Steel, Stainless	21	45.68	28.84	8.20	95.70	
Market Average	3	48.36	6.22	40.20	51.48	
Predom. Recycled	2	11.00	0.00	11.00	11.00	
Unspecified	8	43.10	32.21	8.20	95.70	
Virgin	8	57.80	28.76	12.00	81.77	
Steel, Structural	5	30.91	3.74	25.50	35.90	
Unspecified	2	28.67	4.48	25.50	31.83	
Virgin	3	32.40	3.10	30.00	35.90	

Table 8: ICE material profile for steel – notice the number of records (ICE 2.0, 2011).

Annex A: Boundary Conditions

The boundaries within the ICE database are cradle-to-gate. However even within these boundaries there are many possible variations that affect the absolute boundaries of study. One of the main problems of utilising secondary data resources is variable boundaries since this issue can be responsible for large differences in results. The ICE database has its ideal boundaries, which it aspires to conform to in a consistent manner. However, with the problems of secondary data resources there may be some instances where modification to these boundaries was not possible. The ideal boundaries are listed below:

Item	Boundaries treatment
Delivered energy	All delivered energy is converted into primary energy equivalent, see below.
Primary energy	Default method, traced back to the 'cradle'.
Primary electricity	Included, counted as energy content of the electricity (rather than the opportunity cost of energy).
Renewable energy (inc. electricity)	Included.
Calorific Value (CV)/Heating value of fossil fuel energy	Default values are Higher Heating Values (HHV) or Gross Calorific Values (GCV), both are equivalent metrics.
Calorific value of organic fuels	Included when used as a fuel, excluded when used as a feedstock, e.g. timber offcuts burnt as a fuel include the calorific value of the wood, but timber used in a table excludes the calorific value of the wooden product.
Feedstock energy	Fossil fuel derived feedstocks are included in the assessment, but identified separately. For example, petrochemicals used as feedstocks in the manufacture of plastics are included. See above category for organic feedstock treatment.
Carbon sequestration and biogenic carbon storage	Excluded, but ICE users may wish to modify the data themselves to include these effects.
Fuel related carbon dioxide emissions	All fuel related carbon dioxide emissions which are attributable to the product are included.
Process carbon dioxide emissions	Included; for example CO_2 emissions from the calcination of limestone in cement clinker manufacture are counted.
Other greenhouse gas emissions	The newest version of the ICE database (2.0) has been expanded to include data for GHGs. The main summary table shows the data in CO_2 only and for the GHGs in CO_2e.
Transport	Included within specified boundaries, i.e. typically cradle-to-gate.

Table 9: ICE database boundary conditions (ICE 2.0, 2011).

The importance of the source data is such that analysis and software tools can be misleading and results suspect if the source data is not credible.

The Inventory of Carbon and Energy or ICE is an extensively researched database of building materials and their properties, specifically focusing on the embodied properties of energy and carbon. Published by the sustainable energy research team (SERT) of the University of Bath, and was compiled and written by Prof. Geoff Hammond and Craig Jones in 2011 (ICE, 2011). The methodology uses the 'cradle to gate' analysis with publicly available information, which omits the demolition and consequent recycling, combusting or dumping end stage of the full Life Cycle Analysis LCA. Also, no account is taken of the efficiency of the manufacturing, nor of where the materials have been sourced.

The main reasons for this database choice were threefold; the broad range of data available, the depth and detail of analysis involved in the calculations, and the respected nature of the database in the industry (reference, 2013).

Its' limitations as mentioned above include a lack of full LCA methods and the consequential omission of potentially important qualities such as recyclability or waste. Additionally, it could be stated, though perhaps slightly harshly that this, very specific study or measurement process can have a misleading effect on understanding the whole process.

Timber biogenic carbon storage and carbon sequestration are excluded from this analysis method data. However the off-cut waste from processing has been included as biomass fuel to allow the user control over whether to include these as CO2 neutral or not. This is not really a significant issue, but for this study they have been considered neutral.

Details for Passive House – A Catalogue for Ecologically Rated Constructions (IBO)

The second database picked for this study was chosen because it is a directory of materials specifically aimed at passive house construction. Details for Passive House - A Catalogue of Ecologically Rated Constructions, was published by the Osterreichisches Institut fur Bauen und Okologie (IBO) - Austrian Institute for Building and Ecology, 3rd Edition, 2009 (IBO, 2013). Also known as Osterreichisches Institut fur Baubiologie und Bauokologie – The Austrian Institute for Healthy and Ecological Buildings, it was founded in 1980 for the purposes of providing up-to-date information on the impact of buildings on human health and well-being, and on the environment.

The book contains build-up construction descriptions and schematics, structural-physical descriptions, ecological ratings and material data – all for passive house design and construction. For each of the build-ups there is an ecologically optimised alternative provided. This reference book provides information on the embodied energy of materials, CO2e GWP and acidification potential (AP) data. The book provides optimal material choices, based on all of these environmental aspects, for different applications of building.

An important aspect of this system is the consideration of carbon sequestration or emission off-setting. That is the ability or (embodied) attribute of a material having removed carbon from the atmosphere. Inclusion of this aspect in carbon footprint calculations is achieved through using negative values for these materials.

For instance timber while growing naturally takes in CO2 from the atmosphere. This would normally be released back into the atmosphere at the end of the trees life, as it decomposes, as part of the natural cycle. Or similarly if it is cut down and burned. However if the tree is used for construction then the CO2 is said to be sequestrated from the normal carbon cycle and prevented from returning to the atmosphere (for the duration of its use). Therefore the CO2 that would have been released back into the atmosphere is instead locked into the construction. Therefore the avoidance of CO2 emissions from using timber can be reflected by means of a low or negative embodied CO2 value representing the reduction of atmospheric carbon. In this way the system recognises the 'value' of sequestration and the delaying of CO2e emissions till replacement trees may be grown. If the wood comes from a sustainable forest, then this is both a renewable resource base and a sustainable solution to stabilising resource and construction CO2e emissions.

The Ecology of Building Materials (EBM)

The third and final source of base data used for this work is the reference manual – the Ecology of Building Materials, second edition, by B Berge, published in 2009. This is an extensive and in-depth analysis of building materials and their origins, specifically from an ecological perspective. This source of data was selected for that very reason, that it takes a slightly different methodology to understanding building involving a 'holistic' approach that circumvents several issues. Based on the work of academia, governments, specialist institutes and reference publications this book is a very well written account of both historical and up-to-date environmental and sustainable construction practices and, specifically materials. The first edition won silver at the 'Chartered Institute of Buildings' Literary Awards 2001.

Below is a table of climatic materials taken from the book:

Material	Specific thermal conductivity [W/mK]	Specific thermal capacity [kJ/kg K]	Loss factor [%]	Quantity needed for thermal resistance R = 3.75 [kg/m² 50 years]	Global warming potential GWP [kg CO_2-equ./m² 50 years]	Environmental evaluations						
						Effects on resources		Effects of pollution		Env. potential		Env. profile
						Materials	Energy	Production and use	As waste	Recycling	Local production	
Wood fibre matting with polyolefines, 45 kg/m³	0.039	2.1	5	7.2	**3.5**	2	3	2	2			**2**
Porous wood fibre boards, wet process, 130 kg/m³	0.043	2.1	10	23	**18**	1	3	1	2			**2**
Porous wood fibre boards, dry process, 130 kg/m³	0.043	2.1	10	23	**15**	2	3	3	3			**2**
Matting of flax fibre, with polyolefines, 25 kg/m³	0.04	1.6	5	3.9	**5.5**	2	3	2	2			**2**
Matting of hemp fibre, with polyolefines, 25 kg/m³	0.045		5	4.4	**4.0**	2	3	2	2			**2**
Straw bales, 90 kg/m³, lifespan 25 years	0.052		5	37	**−13**	1	1	1	1		√	**1**
Recycled cellulose, loose fill, 45 kg/m³	0.042	1.8	1	7.2	**−4**	2	2	3	3	√		**2**
Matting of fresh cellulose fibre, with polyolefines, 45 kg/m³	0.04	1.9	5	7.1	**3.0**	2	3	2	2			**2**
Matting of wool, with polyesters, 18 kg/m³	0.04	1.3	5	2.8	**2.0**	2	2	2	2			**2**
Matting of recycled textiles, with polyesters, 25 kg/m³	0.038		5	3.7	**5.0**	1	2	2	2			**2**

Table 10: Data table for climatic materials profiling several environmental parameters (Berge, 2009).

The environmental evaluations are based on a customised scale of 1-3, with one the most eco-friendly and three the least. The environmental potential column indicates potentials for recycling or local production. This ‘traffic-light’ system is also applied overall to the material in the last column as a summation in general. For the purposes of this study, this base data reference source contains GWP values, however does not include embodied energy values.

These GWP (or CO2e) values include carbonatation (50 years), carbon storage or sequestration (50 years), and emissions from final product incineration, based on fossil fuels (feedstock). The carbon storage is based on net weight of the material.

Interestingly this data and reference source is very useful for assessing the position of GWP as a relevant overall indicator for environmental impact.

Specific to this methodological approach, Berge investigates the key issues and questions that surround the sustainability of buildings and their materials.

Chapter 4 – Omitted Key Environmental Areas

There are several key environmental areas, inter-related with EE and ECO2e, which although very relevant are not considered in this study. They are simply beyond the scope of this rather focussed piece of work. Therefore to avoid a fragmented approach, before beginning this investigation it is important to identify these areas and briefly discuss them to illustrate the importance of the bigger picture and the necessity of adopting a more holistic assessment and decision-making process.

Resources

The resource base for building is fundamental, without it there can be no building. Therefore a consideration of this area is necessary for building design decision-making, especially in the context of progression towards ecological and sustainable building practices.

"Worldwide 62 billion tons of natural resources – minerals, wood, metals, fossil and bio-mass fuels, and construction material are extracted annually." (OECD, 2012).

This has increased by 65% since 1987 (OECD, 2012). Resources are especially relevant to the construction industry for this is the largest consumer of raw materials in the European Union (O'Brien, 2011). And in the UK it is responsible for the consumption of 90% of non-energy minerals (UK Government, 2009).

Below is a flow chart highlighting the cycle of materials:

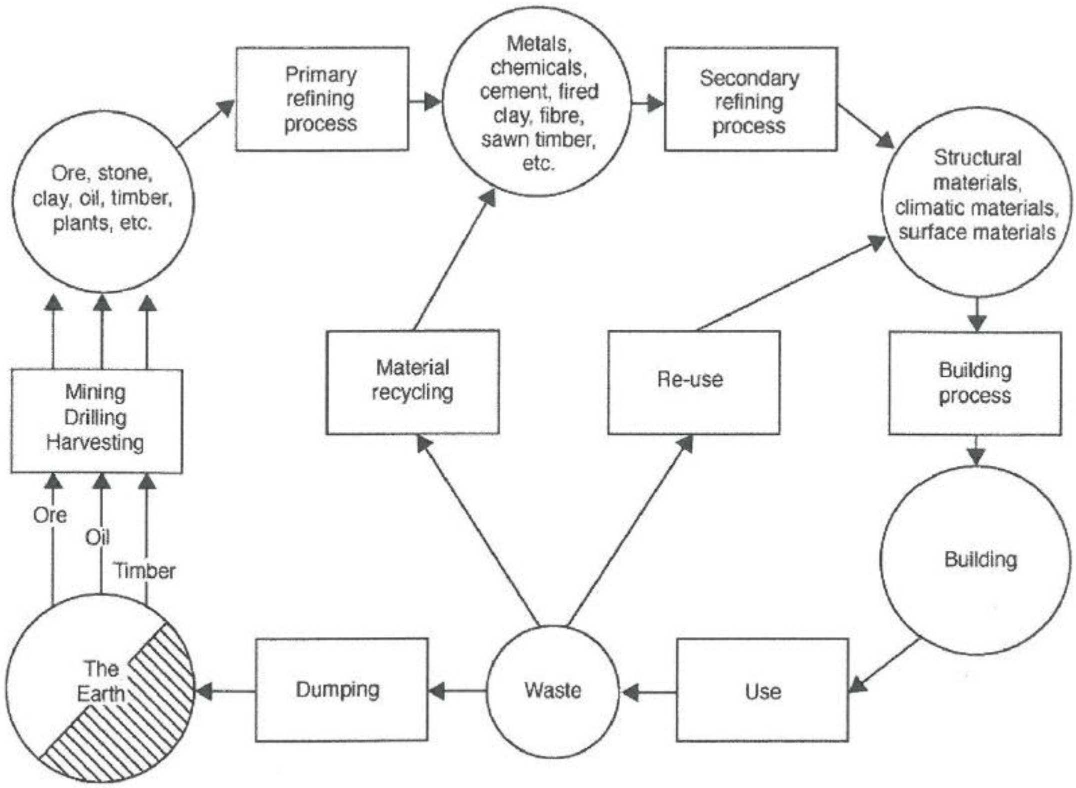


Figure 25: The cycle of materials (Berge, 2009).

Embodied Toxicity

Another highly important issue is that of 'embodied toxicity' of materials used in the construction industry (SEDA, 2005). Using full life cycle analysis, this area needs to include the disposal and any treatment of materials at the end of life stage, alongside the initial processing and manufacturing.

Systems of LCA metrics that can begin to account for and quantify these environmental Impacts (EI) have been developed, typically taking the form of a 12 point scale or such-like - an example classification of this type is provided below – this also includes GHG impact (Anderson et al., 2009):

Climate Change	Water Extraction	Mineral Resource Extraction
Stratospheric Ozone Depletion	Human Toxicity	Eco-toxicity to Fresh Water
Nuclear Waste	Eco-toxicity to Land	Waste Disposal
Fossil Fuel Depletion	Eutrophication	Photochemical Ozone Creation
Acidification		

Table 11: LCA Environmental Impacts (Anderson et al., 2009)

Specifically in relation to the building industry, toxicity or pollution can be referred to in two ways, as energy pollution or material pollution.

Energy pollution – This broadly covers and describes both the amount and source of energy used in manufacturing materials. Additionally, transportation is included in this category, of both raw materials and final goods.

In the UK the predominant energy sources are fossil fuels and nuclear power. While renewables are increasing, but slowly.

As was mentioned earlier fossil fuels, and their combustion create the vast majority of anthropogenic greenhouse gas emissions, for example CO2. However other pollutants emitted include acids such as SO2 and particulates. Waste incineration, depending on its content, can also be a big source of pollution.

As an example the table below details the typical different levels of pollution, per km from common transportation types:

Type of transport	CO2 (g/ton km)	SO2 (g/ton km)	NOx (g/ton km)
By air	1650	0.9	7.7
By road			
• Light truck (14 tonnes), diesel	175	0.04	1.8
• Heavy truck (40 tonnes), diesel	50	0.03	0.55
By rail, diesel	18	0.005	0.36
By sea			
• Small ship (less than 3000 tonnes), diesel	25	0.4	0.7
• Large ship (larger than 8000 tonnes), diesel	15	0.26	0.43

Table 12: Typical freighting pollutants (Berge, 2009)

Material pollution – This covers pollutants to the earth, water and air, sourced from the material itself and during its life-cycle, including processing, in-life use and end-of-life breakdown or decomposition. This is an extremely tricky area to fully understand, in part due to the considerable number of chemicals, materials and new substances in use within the construction industry, but also because of the complexity of the natural environmental systems, and the inter-relationship between the two. To achieve certainty regarding the relationships between these substances and long-term effects on the environment and living beings is difficult. Despite this and a lack of research, much empirical evidence is now beginning to appear with many studies finding strong evidence of impact (Liddell et al, 2008).

In the building industry, during the operational phase of a buildings life, these forms of pollution have been linked with specific detrimental health impacts to the building occupants. This has often been empirically classed as ‘sick building syndrome’.

At the end of a buildings lifecycle comes the de-construction stage, which typically involves either waste or re-cycling of materials. It has been noted that the most dangerous materials are heavy metals and other poisons, second to this are fossil-fuel derived plastics and other non-biodegradable substances. Whether for incineration or landfill, there is the risk of these harmful substances impacting the environment, through either quantity, toxicity or both. Preventative measures can help to reduce this pollution, for example flue gas purifiers or site containment measures.

Waste and Recycling

The third and final additional criteria to be discussed is the issue of waste and recycling. Again, because of the massively high material throughput that happens in the construction industry, it is vitally important to consider the consequences of this and gain an appreciation of the options available when deciding on what building materials to use.

Responsible for around 33% of annual waste in the EU (O’Brien, 2011), construction and demolition waste is a big issue. To investigate this further it is useful to look at the typical end of life stage of buildings. There are normally three options to recycling the building components, these are:

A: Re-use

B: Material recycling

C: Energy recovery

The second option, material recycling is essentially to a lower grade of building material, for example the breaking down of bricks for use as aggregate.

The third stage, energy recovery is typically the combustion of the materials for the release of the embodied ‘feedstock’ energy. This value of ‘feedstock’ energy is quick often taken into consideration for EE calculations. However, as with the previous section, these values can be rendered void if toxic materials are added, or if the material is used in a composite manner in the building.

The best option if possible, is obviously the first, to reuse. By doing this you are not only avoiding waste, or recovering some materials or energy, but are actually eliminating EE from the next building.

The alternative to recycling of course is dumping. This however is not all bad and there is further distinction with some kinds of dumping that are termed ‘global recycling’ where the materials are compostable or in some other way biodegradable and therefore dumping is reintegrating the materials back into a natural cycle. Interestingly ordinary global recycling is based almost completely on closed cycles, which results in very little waste. This method can be, at times more sensible than standard re-cycling or energy recovery, particularly when you transport over long distance.

Chapter 5 – Embodied Energy Software Tool (EEST)

Design

The motivation for designing a software tool is for ease of calculation, to gain better understanding of embodied energy and emissions, and to meet the requirement for awareness of embodied energy and emissions of passive house construction at the PHPP design process stage. So to address this need, the design requirement identified were that the current PHPP software should be enhanced with a software tool that is integrated, either embedded or as a separate, stand-alone configuration, that would enable the quantification and calculation of the project embodied energy and CO2e emissions. This would therefore fit in with the overall goal of allowing the inclusion of this quantification into the PHPP future design procedure and perhaps standard.

Ideally the goal was to follow the same or similar layout and format to the current design software, and to be based on the metrics and specifications outlined and used in the PHPP.

Additionally, the design was to be analytic, flexible and easily upgradeable, both structurally and with base data sources. Also important was the capacity to allow detailed analysis and breakdown of results for the construction project.

In line with the PHPP software, the new 'tool' would be Excel based. Also by integrating into the PHPP design method it should focus only on the massive construction elements - the exterior walls, foundations, floors, roof, internal walls and windows, and their corresponding embodied energy and embodied CO2 emissions. It should not work with additional fittings, fixtures, surface finishes, external groundwork or building services.

Although the current PHPP software calculates the primary operational energy and carbon emissions of the building ventilation and hot water services, the embodied component of these systems is not considered and shall similarly not be looked at here.

One of the key design advantages of the existing PHPP software is its generally accessible algorithms, comprehensible content, flexibility and comparatively uncomplicated nature, this all leads to empowering its users – architects, engineers, building services specialists and energy consultants. The simplicity of the software allows them to see instantaneous results of design changes, therefore supporting easy optimisation of their designs and components on the basis of accurate data. This is, after all what any good tool should be, an extension of your abilities.

Therefore in designing the integrated Embodied Energy Software Tool (EEST), it was decided to maintain this same design approach methodology.

Methodology

The initial stage of designing the tool can be summed up as information gathering and planning. It was very important to consult with the industrial contact – architect, to establish how they used the PHPP, what areas of embodied energy and carbon they were most interested in. And why they needed this tool, what value would it bring them that was not commonly available? They identified an interest for specific information on the area of insulation with a view to possible eco-friendly alternatives. Helpfully, the contact also provided in-depth information that would later be used in the case study.

It was also important to begin establishing and collecting information on what the tool inputs and outputs would be:

The inputs to include the source data, relevant metrics, base construction data and current PHPP field data.

While the outputs would include embodied energy and CO2e emissions data, breakdown of contributions and integration with current PHPP data for LCA.

In designing the tool, it was an intended design methodology to develop an initial prototype early on, and then to begin 'beta' testing this straight away. This way accurate information on how it succeeded or failed could be obtained quickly, and revisions to design could be made.

Additionally this methodology allowed the industrial contact to also trial the tool and feedback their responses.

So it was envisioned to get an early prototype available for industrial trials and to use a continuous developmental process, with numerous designs to achieve a successful outcome.

It is important to recognise the inherent dangers in creating user friendly and potentially simpler tools. The results can become misleading, or erroneously attributed if care is not taken to understand, essentially what is being done, what values are being used and where these come from.

The first concept was a fairly straightforward array across an excel spreadsheet with columns for the various construction areas, and rows for the constituent layers in each.

						Design project	**New Farmhouse**				
Construction breakdown	Embodied						Embodied				
Walls - materials ins	Energy (Mj/kg)	Carbon (kgCO2/kg)	Density (kg/m^3)	n - Energy (Mj/kg)	- Carbon (kgCO2/kg)	**Floor - materials**	Energy (Mj/kg)	Carbon (kgCO2/kg)	Density (kg/m^3)	Calculation - Energy	Calculation - Carbon
gypsum plasterboard	6.8	0.4	800	14934.0	840.7	oak floor finish	7.8	0.47	700	14136.9	851.8
air gap	0.0	0.0	0	0.0	0.0	150mm slab	2	0.215	1850	65318.0	7021.7
osb	9.5	0.5	800	30266.3	1624.8	polyfoam	86.4	2.7	24	61010.5	1906.6
mineral wool insulation	16.6	1.2	24	3966.5	286.7	Sand blinding 25mm	0.1	0.005	2240	659.1	33.0
mineral wool insulation	16.6	1.2	24	22917.4	1656.7	Hardcore 150mm	0.1	0.005	2240	3954.4	197.7
mineral wool insulation	16.6	1.2	24	3966.5	286.7	First floor					
osb	9.5	0.5	800	15973.9	857.5	Timber board 20mm	16	0.86	600	8611.2	462.9
50mm sw batons	7.4	0.5	510	3479.1	211.6	Insulation 200mm (m	16.6	1.2	24	3573.6	258.3
100mm sw batons	7.4	0.5	510	13916.3	846.3	100mm sw batons	7.4	0.45	510	2821.1	171.6
100mm sw batons	7.4	0.5	510	13916.3	846.3	100mm sw batons	7.4	0.45	510	2821.1	171.6
Joists:						Joists					
timber batons volume (m^	0.9					100mm sw batons vo	0.7475				
sw JJ1 end volume (m^3)	3.7					100mm sw batons vo	0.7475				
sw JJ1 end volume (m^3)	3.7		Total	123336.4	7457.3	Distance between ba	0.6		Total	162905.8	11075.1
Overall project total Embodied Energy (Mj)	497885.2	**Overall project total Embodied CO2**	36173.9								

Figure 26: The first software design.

The basic approach concept used was to begin with the building structural layers contained within the PHPP, but to enhance this with additional data to build-up a collection of all the materials used, and then to add to each of these both the quantities (based on calculations from data already contained within the PHPP and additional summations), and quantified embodied properties taken from external inventories to be located in an integrated 'materials database'.

This demo worked well and it would calculate the total construction embodied energy and CO2 emissions based on a volumetric and density quantification method.

From the first demo it was decided to create drop-down menus for the material input fields that would be directly linked to this database, and to subsequently link this to an array of the specific materials properties.

It was felt that this would greatly enhance the software's usability. Other lessons learned included more straight-forward sectioning and possibly a different element breakdown approach.

With these improvements, the second prototype was created:

3	Structural Materials	Thickness (m)	% of Area	Energy (Mj/kg)	Carbon (kgCO2/kg)	Density (kg/m^3)	Layer Embodied Energy (Mj)	Layer Embodied Carbon (kgCO2)	Climatic Materials	Thickness (m)
4	**Foundations**								**Floors**	
5	Aggregate - General	0.2	100.0	0.1	0.0	2240.0	3954.4	197.7	Insulation - Cellulose	0.2
6	Sand - General	0.0	100.0	0.1	0.0	2240.0	659.1	33.0	Insulation - Polystyrene	0.3
7	None			5.0	6.0	7.0	0.0	0.0	None	
8	None			5.0	6.0	7.0	0.0	0.0	None	
9	None			5.0	6.0	7.0	0.0	0.0	None	
10	**Floors**								None	
11	Concrete - General	0.2	100.0	1.0	0.1	0.0	0.0	0.0	None	
12	Timber - Sawn softwood	0.1	10.0	7.4	0.5	510.0	6134.3	373.0	None	
13	None			5.0	6.0	7.0	0.0	0.0	**Walls**	
14	Aluminium - General Aluminium - Virgin Aluminium - Recycled Aluminium - Cast Products - General Aluminium Cast Products - Virgin Aluminium Cast Products - Recycled Aluminium Extruded - General Aluminium Extruded - Virgin			5.0	6.0	7.0	0.0	0.0	Insulation - Cellulose	0.0
15				5.0	6.0	7.0	0.0	0.0	Insulation - Cellulose	0.3
16				5.0	6.0	7.0	0.0	0.0	Insulation - Cellulose	0.0
17				5.0	6.0	7.0	0.0	0.0	None	
18				5.0	6.0	7.0	0.0	0.0	None	
19	**Walls**								None	
20	Timber - Sawn softwood	0.1	25.0	7.4	0.5	510.0	10437.2	634.7	None	
21	Timber - Sawn softwood	0.0	25.0	7.4	0.5	510.0	9393.5	571.2	None	
22	Timber - Sawn softwood	0.0	25.0	7.4	0.5	510.0	9393.5	571.2	None	
23	None			5.0	6.0	7.0	0.0	0.0	None	
24	None			5.0	6.0	7.0	0.0	0.0	**Roof**	
25	None			5.0	6.0	7.0	0.0	0.0	Insulation - Cellulose	0.2
26	None			5.0	6.0	7.0	0.0	0.0	Insulation - Cellulose	0.1
27	None			5.0	6.0	7.0	0.0	0.0	Insulation - Cellulose	0.1
28	None			5.0	6.0	7.0	0.0	0.0	None	

Figure 27: The second software modelling design.

Results

Several other software designs, or concepts were made, along with a number of stylistic upgrades and a decision was made to develop into two separate tools for practical purposes. Each designed for different applications, the first is a fully integrated tool that allows for easy LCA analysis with PHPP data results. While the second would be a stand-alone tool that would analyse and assess the specific areas of embodiment and allow for much more detailed analysis.

Sections of the user interface, for both are shown below:

Passive House Planning

E M B O D I E D   E N E R G Y   O F   B U I L D I N G   E L E M E N T S

*Note for window data use box in column AF

Building: New Farmhouse

Assembly No.: 1 — Building Assembly Description: External Wall

Assembly Area m2 : 221.25

	Area Section 1	[Mj/kg]	[kgCO2/k	[kgCO2e/kg]	λ [W/(mK)]	kg/m3	Area Section 2 (optional)	[Mj/kg]	[kgCO2/k	[kgCO2e/k	λ [W/(mK)]	kg/m3	Area Section 3 (optional)	[Mj/kg]	[kgCO2/kg]	[kgCO2e/kg]	λ [W/(mK)]	kg/m3	Thickness [mm]
1.	gypsum plasterboard	6.75	0.38	0.39	0.210	950													13
2.	air gap				0.306		timber battons	7.400	0.190	0.200	0.130	630							50
3.	OSB	15.00	0.42	0.45	0.130	800													18
4.	mineral wool insulati	23.30	1.20	1.28	0.032	30	sw JJI end	7.400	0.190	0.200	0.130	630	OSB flange	15.00	0.42	0.45	0.130	800	45
5.	mineral wool insulati	23.30	1.20	1.28	0.032	30							OSB flange	15.00	0.42	0.45	0.130	800	260
6.	mineral wool insulati	23.30	1.20	1.28	0.032	30	sw JJI end	7.400	0.190	0.200	0.130	630	OSB flange	15.00	0.42	0.45	0.130	800	45
7.	OSB	15.00	0.42	0.45	0.090	800													10
8.																			

Percentage of Sec. 2 (%): 25 — Percentage of Sec. 3 (%): 10 — Total: 440.0 mm

Embodied Energy: 273902 Mj
Embodied CO2: 9359 kgCO2
Embodied CO2e: 9952 kgCO2e

Figure 28: Integrated PHPP Embodied Energy Software Tool (EEST).

Surface Material	Layer Thickness	Area	Embodied Energy	Embodied CO2	Embodied CO2 Equivalent	Density	Thermal Conductivity (W/mK)	Layer Embodied Energy	Layer Embodied CO2	Layer Embodied CO2e			
Foundations	(m)	(%)	(Mj/kg)	(kgCO2/kg)	(kgCO2e/kg)	(kg/m^3)	(W/mK)	(Mj)	(kgCO2)	(kgCO2e)	**Total Foundation EE**	**3171**	**Mj**
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0	**Total Foundation ECO2**	**#VALUE!**	**kgCO2**
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0	**Total Foundation ECO2e**	**161**	**kgCO2e**
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
Floor - Ground											**Total Ground Floor EE**	**99370**	**Mj**
Sawn Hardwood	0.0220	100.0	3.06	-	-1.14	630.00	0.23	4991.4	#VALUE!	-1859.5	**Total Foundation ECO2**	**#VALUE!**	**kgCO2**
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0	**Total Foundation ECO2e**	**3878**	**kgCO2e**
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
Floor - First											**Total First Floor EE**	**24919**	**Mj**
Sawn Hardwood	0.0220	100.0	3.06	-	-1.14	630.00	0.23	1902.2	#VALUE!	-708.6	**Total First Floor ECO2**	**#VALUE!**	**kgCO2**
Plasterboard	0.0130	100.0	4.44	-	0.21	850.00	0.16	2200.4	#VALUE!	103.6	**Total First Floor ECO2e**	**-1984**	**kgCO2e**
Plywood	0.0090	100.0	15.00	0.42	0.45	700.00	0.15	4238.3	118.7	127.1			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
Walls											**Total External Walls EE**	**313041**	**Mj**
Oriented Strand Bc	0.0100	100.0	15.00	0.42	0.45	800.00	0.17	26549.4	743.4	796.5	**Total External Walls ECO2**	**#VALUE!**	**kgCO2**
Oriented Strand Bc	0.0180	100.0	15.00	0.42	0.45	800.00	0.17	47788.9	1338.1	1433.7	**Total External Walls ECO2e**	**-1288**	**kgCO2e**
Plasterboard	0.0130	100.0	4.44	-	0.21	850.00	0.16	10854.7	#VALUE!	511.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
Internal Walls											**Total Internal Walls EE**	**12582**	**Mj**
Plasterboard	0.0130	100.0	4.44	-	0.21	850.00	0.16	1201.0	#VALUE!	56.5	**Total Internal Walls ECO2**	**#VALUE!**	**kgCO2**
Plasterboard	0.0130	100.0	4.44	-	0.21	850.00	0.16	1201.0	#VALUE!	56.5	**Total Internal Walls ECO2e**	**-314**	**kgCO2e**
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
Roof											**Total Roof EE**	**377001**	**Mj**
Plasterboard	0.0130	100.0	6.75	0.38	0.39	950.00	0.16	11087.2	624.2	640.6	**Total Roof ECO2**	**#VALUE!**	**kgCO2**
Plywood	0.0090	100.0	13.82	-	0.09	630.00	0.15	10421.8	#VALUE!	67.1	**Total Roof ECO2e**	**9602**	**kgCO2e**
Plywood	0.0180	100.0	13.82	-	0.09	630.00	0.15	20843.6	#VALUE!	134.2			
Zinc - General	0.0050	100.0	42.50	-	2.65	7200.00	113.00	203490.0	#VALUE!	12688.2			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
None			0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0			
							Total Surfaces	346770.1	#VALUE!	14046.8			

Figure 29: Stand-alone Embodied Energy Software Tool (EEST).

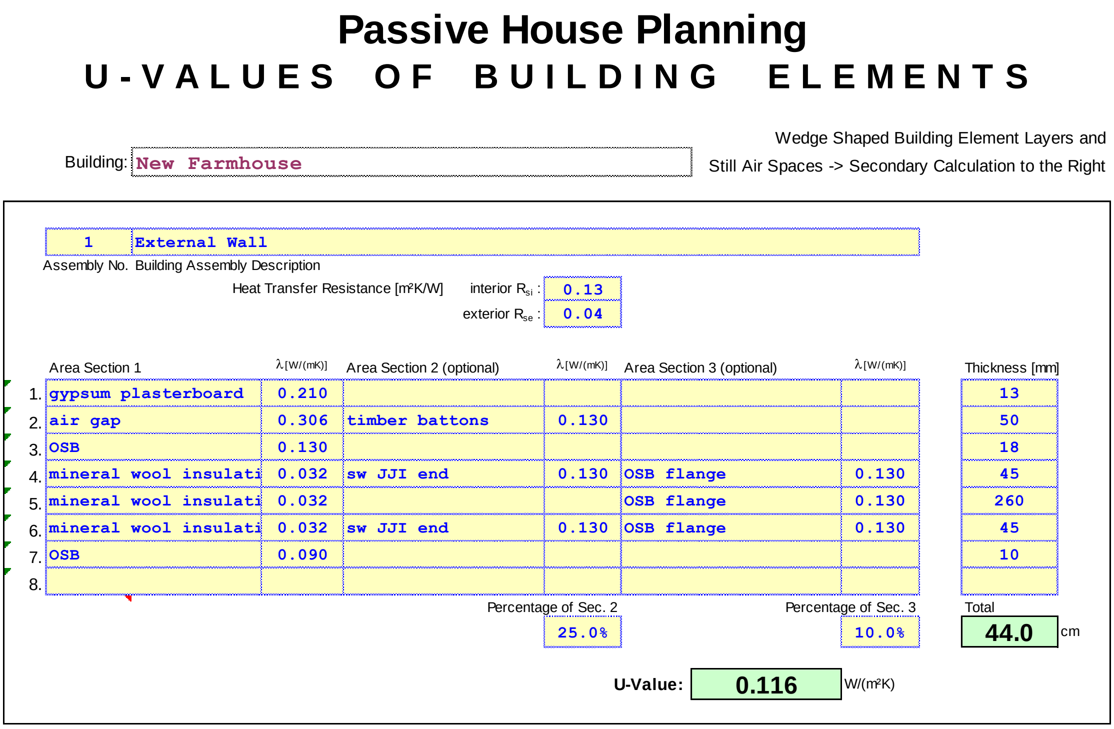
Experience gained from using both these tools determined their individual design evolutions. The first 'integrated' tool has inputs from several PHPP spreadsheets, and similarly outputs embedded in both the PHPP verification worksheet and primary energy calculation sheet. The first of these is shown below:

Specific Demands with Reference to the Treated Floor Area						
Treated Floor Area:	162.5	m^2				
	Applied:	Monthly method		PH Certificate:		Fulfilled?
Specific Space Heating Demand:	13	$kWh/(m^2a)$		15	$kWh/(m^2a)$	Yes
Heating Load:	9	W/m^2		10	W/m^2	
Pressurization Test Result:	0.2	h^{-1}		0.6	h^{-1}	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	101	$kWh/(m^2a)$		120	$kWh/(m^2a)$	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	58	$kWh/(m^2a)$				
Specific Primary Energy Reduction through Solar Electricity:		$kWh/(m^2a)$				
Frequency of Overheating:	0	%	over	25	°C	
Specific Useful Cooling Energy Demand:		$kWh/(m^2a)$		15	$kWh/(m^2a)$	
Cooling Load:	0	W/m^2				
Total Embodied Primary Energy:	1655	kWh/(m2)				
Total Embodied Emissions - CO2 Equivalent:	281	kg/(m2)				
Total Operational Primary Energy (no household applications):	58	kWh/(m2a)				
Total Operational CO2 Equivalent (no household applications):	15	kg/(m2a)				
LCA - Total Primary Energy Use (50 year life, no microgen, no household applications):	4577	kWh/m2				
LCA - Total Emissions CO2 Equivalent (50 year life, no microgen, no household applications):	1045	kg/(m2)				

Figure 30: PHPP verification field with embedded inputs from embodied tool.

Another key area of these software designs were their use of the base database. Early on in the investigation of the PHPP software it was discovered that no materials database existed, although data is provided of typical values for a number of complete build-ups. Instead the user is required to research and input this data independently, leaving the responsibility for the build achieving the strict passive house performance targets largely at the door of the architect, and their competency.

Therefore when designing this software is was immediately apparent that a complete database of source data would be needed. However, this also meant that the existing PHPP design process and structural layer build-up could not be used as a foundation for building up the enhanced spreadsheets. Another quickly apparent issue, concerning the enhancement of the current software fields was space, or more specifically the lack of it. These fields were already quite large, and they were almost full with inputs, outputs and reference cells. For building up an embodied energy profile would require at the very least several input fields, and so consequently this idea was discarded and was to be replaced by a separate, yet closely integrated embodied energy worksheet.



Passive House Planning

U-VALUES OF BUILDING ELEMENTS

Building: New Farmhouse

Wedge Shaped Building Element Layers and Still Air Spaces -> Secondary Calculation to the Right

Assembly No. 1 — Building Assembly Description: External Wall

Heat Transfer Resistance [m²K/W] — interior R_{si}: 0.13 — exterior R_{se}: 0.04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	gypsum plasterboard	0.210					13
2.	air gap	0.306	timber battons	0.130			50
3.	OSB	0.130					18
4.	mineral wool insulati	0.032	sw JJI end	0.130	OSB flange	0.130	45
5.	mineral wool insulati	0.032			OSB flange	0.130	260
6.	mineral wool insulati	0.032	sw JJI end	0.130	OSB flange	0.130	45
7.	OSB	0.090					10
8.							

Percentage of Sec. 2: 25.0% — Percentage of Sec. 3: 10.0% — Total: 44.0 cm

U-Value: 0.116 W/(m²K)

Figure 31: Typical example of PHPP software field.

There was also the rather tricky and problematic area of the materials database. Quickly it was becoming obvious that not all of the databases researched and investigated contained all the data for the materials, and not all the construction materials were found in all of the databases. Therefore, as it turns out the solution came from an externality in the form of the data analysis requirement for a comparative source base data study.

This idea first presented itself as an opportunity to allow a deeper insight into the nature of both embodied properties of materials; specifically in response to the obvious, and well-known variability's of this area. It was imagined that if you could conduct a study that, rather than predominantly focusing on one base data set, but that could look at the case study and analyse with several sets of information, it may just be possibly to triangulate and reference these to each other. Perhaps these different perspectives on the area could, both shed some light on what we are dealing with and simultaneously teach us about the base data sets themselves and their nature.

So that was the concept, and it helped to solve the software issue of single dataset reliability – use multiple.

Therefore this introduced an additional requirement for the software analysis tool to be simple in operation and capable of easily managing multiple sources of data input.

Because of these issues several database worksheets, and corresponding input routines were designed and optimised before finally settling. An example is shown below:

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments	Thermal Capacity	Density
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon	W/mK	kg/m3
None						
Aggregate						
General (Gravel or Crushed Rock)	0.083	0.0048	0.0052	Estimated from measured UK industrial fuel consumption data	1.8	2240
Aluminium	Main data source: International Aluminium Institute (IAI) LCA studies (www.world-aluminium.org)					
Al - General	155	8.24	9.16	Assumed (UK) ratio of 25.6% extrusions, 55.7% Rolled & 18.7% castings. Worldwide average recycled content of 33%.	230	2700
Virgin	218	11.46	12.79		230	2700
Recycled	29.0	1.69	1.81		230	2700
Cast Products	159	8.28	9.22	Worldwide average recycled content of 33%.	230	2700
Virgin	226	11.70	13.10		230	2700
Recycled	25.0	1.35	1.45		230	2700
Extruded	154	8.16	9.08	Worldwide average recycled content of 33%.	230	2700
Virgin	214	11.20	12.50		230	2700
Recycled	34.0	1.98	2.12		230	2700
Rolled	155	8.26	9.18	Worldwide average recycled content of 33%.	230	2700
Virgin	217	11.50	12.80		230	2700
Recycled	28	1.67	1.79		230	2700
Asphalt						
Asphalt, 4% (bitumen) binder content (by mass)	2.86	0.059	0.066	1.68 MJ/kg Feedstock Energy (Included). Modelled from the bitumen binder content. The fuel consumption of asphalt mixing operations was taken from the Mineral Products Association (MPA). It represents typical UK industrial data. Feedstock energy is from the bitumen content.	1.2	2300
Asphalt, 5% binder content	3.39	0.064	0.071	2.10 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.	1.2	2300

Figure 32: Inventory database for ICE data input to PHPP-EEST application (ICE, 2011)

A further spreadsheet design was created called the Embodied List or E-List sheet for short. This encompassed bringing together the key data from the E-Values spreadsheet for specific building elements. The purpose for this is to create a basis for a future database of construction element build-up embodied properties. So the user can quickly see how a building element compares to historical records and possibly industry ‘typical’ examples. This is as far as this spreadsheet was taken as it is one for the future. But the core idea, seems a good one and could prove very useful for practical, quick easy passive house embodied energy/CO2e emissions assessments.

Passive House Planning						
EMBODIED VALUES LIST						
	Compilation of the building elements calculated in the Embodied Energy worksheet and other construction types from databases.					
	Type					
Assembly no.	**Assembly Description**	**Embodied Energy**	**Embodied Carbon**	**Embodied Carbon Equivalent**	**Total Thickness**	
		Mj/kg	kgCO2/kg	kgCO2e/kg	m	
1	External Wall	273902.245	9359.318	9952.102	0.440	7
2		20171.186				30
3						53
4						76
5						99
6						122
7						145
8						168
9						191
10						214
11						237
12						260
13						283
14						306
15						329
16						352

Figure 33: E-List, project build-ups would be stored allowing the user easy reference and comparison for current build-ups. Linked to the E-Values spreadsheet allowing instant updates.

Chapter 6 – Case Study

New Farmhouse

A case study was provided to the project through the co-operation of the industrial contact Kirsty MaGuire Architects. The building was constructed in the last 12 months, so it is a very current case-study. It is a detached, two-storey residential passive house. The construction has been designed and certified to passive house standard. It is of a barrel-roofed, timber joist structural build, and is shown below:

Figure 34: Case Study passive house – New Farmhouse (KMA, 2012).

Assessment Areas

For this study we were interested in analysing the total embodied energy and embodied CO2 equivalent emissions of the construction. Using the software tool developed during the initial stages of the project, a calculation for these values could be made. The developed EEST was integrated into the PHPP software to enable the picking up of key values from the pre-existing fields, and to allow a more fluid, user-friendly experience. This was also important in achieving the significant additional goal of illustrating how a final integrated energy and CO2e LCA could look for passive house design. There were additional fields to be filled-in manually to specify materials used from a drop-down menu. Finally certain dimensions, found on the PHPP spreadsheets, are asked to be entered manually, this allows the user to be comfortable that the software tool is fully compatible with the existing building design specifications.

Initial areas of study included the impact of insulation and structural material changes on the project embodied properties. Also investigated were the relative merits of these insulation types, with a comparative analysis carried out. Then a more focused study was undertaken into the life cycle impact of these insulation levels, bringing in the passive house PHPP software analysis to calculate the operational energy of the project.

The second software tool that was developed also allowed a more detailed analysis to be conducted. This concentrated on the breakdown of the embodied properties. Looking at both what contributed and how much. The build was categorised in several ways to allow maximum data retrieval and benefit understanding.

It was hoped that this stage would potentially cast some light onto the subject and perhaps specific, 'key' areas of understanding could be identified and insights gained.

Options and Evaluations

For the analysis several types of insulating materials, several types of construction materials and a few construction build-ups shall be investigated.

The architect's design standard for the Farmhouse project were used as the baseline and the initial analysis used these 'base case' designs and material plans. The architectural designs and material specification build-ups are shown below:

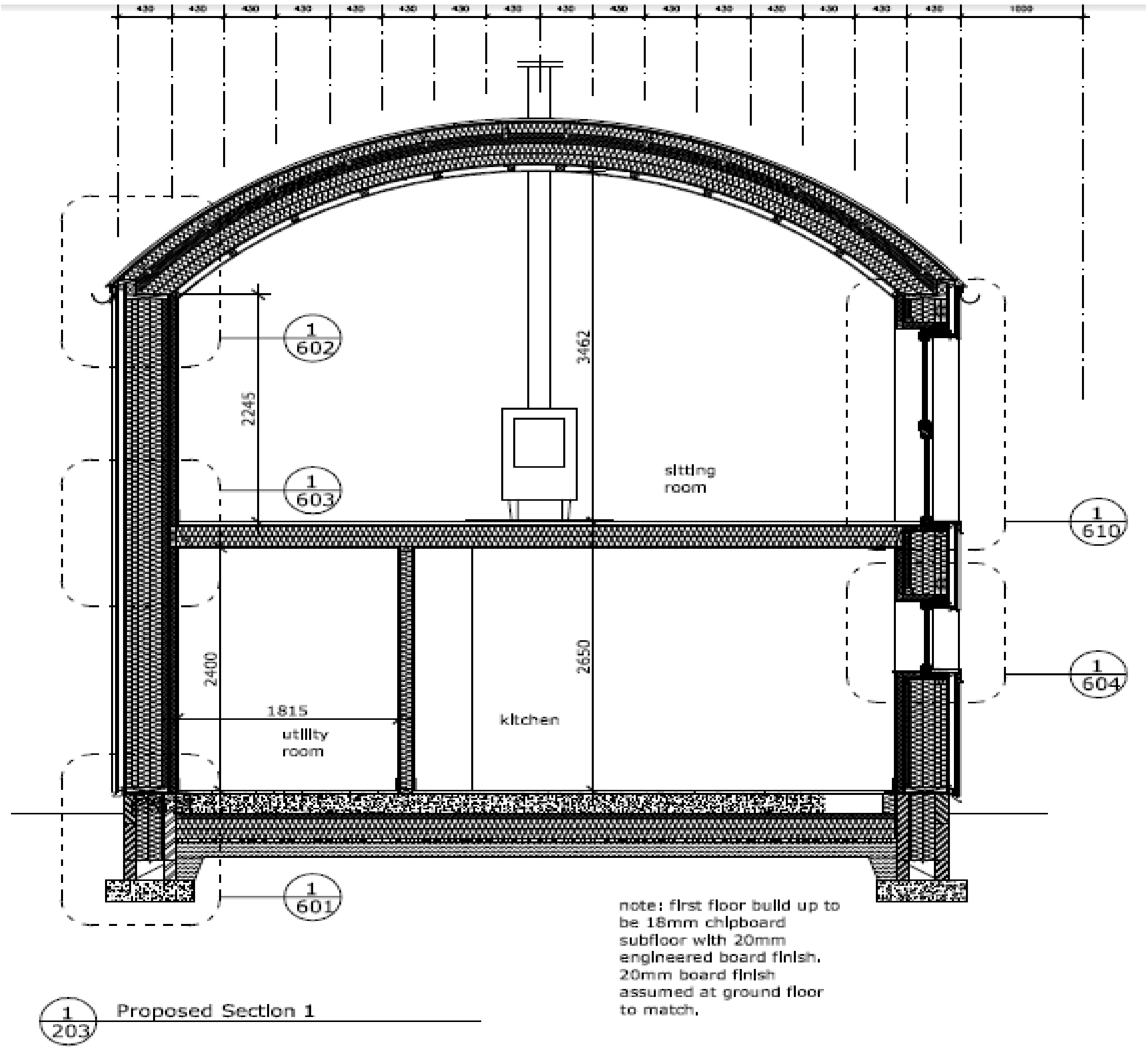


Figure 35: Case study construction section (KMA, 2012)

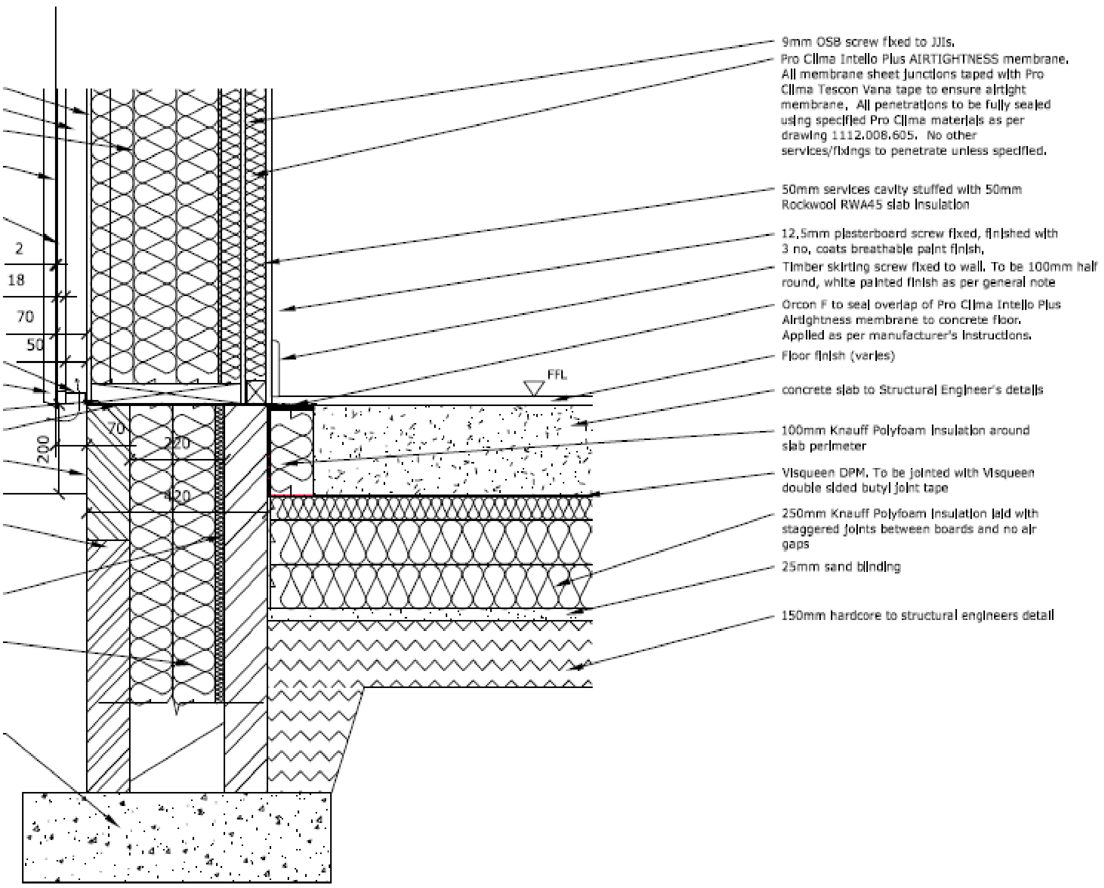


Figure 36: Case study ground floor and foundation sectional schematic detailing (Kirsty MaGuire Architects, 2012)

This diagram highlights the key sections or building components of the main building envelope under consideration in this study:

- External Walls
- Foundations
- Ground Floor
- 1st Floor
- Windows
- Internal Walls
- Roof

Analysis and Results

For the case study, the PHPP EE Software Tool (EEST) was used to evaluate the embodied energy and CO2 equivalent emissions of the building. This would achieve two goals, to get some 'real' data on EE and ECO2e, but secondly, to allow the assessment and evaluation of the software tool itself.

The project industrial contact – the architect of this building, had kindly provided both the schematic building designs and plans alongside the PHPP software analysis. This was very beneficial for both analysis and understanding of the construction. Therefore from this data, an accurate model was compiled (PHPP-EEST) utilising as much available information as possible. Both the integrated and stand-alone software applications were used, to allow different types of analysis to be undertaken. For assessing the inter-relationship between the EE and the primary Operational Energy (OE), the first type was used, while in the assessment of the component parts of the build, the second application was used.

For the modelling, boundaries need to be specified for doing the analysis, these were set as standard with LCA and are listed below:

- For this study we are only concerned with the main envelope of the building. Fittings, fixtures, services, surface finishes, external access and ground-works are not included.
- The thermal conductivity of each insulation type was considered 'not that significant' while calculating the EE and ECO2e. A separate study of this was carried out.
- The embodied CO2 equivalent emissions were taken over the reasonably standard 100 years GWP period. However it is worth bearing in mind that these 'perceived' relative impacts can be misleading.
- It was decided to use the more up to date measurement standard of CO2 equivalent (CO2e) emissions rather that the older CO2 emissions metric for analysing the global warming impact. This metric shows a much closer relationship to reality and is becoming the most relevant standard.

- For the LCA analysis the typical lifespan of a building was taken as 50 years. This is a commonly taken standard in the UK.
- The passive houses primary operational energy (OE) can be measured in two different ways. Firstly as the primary energy required for all the buildings hot water, heating, auxiliary and consumer appliances or secondly without the consumer appliances. For the purposes of this analysis both values were included.
- For the main case study modelling, all construction materials are taken as locally supplied. A separate analysis of the impact of non-local 'freighting' was however also undertaken.
- All Total EE and ECO2e calculations have included an added 10% for construction site material waste.

It was decided that it would be useful to begin by modelling the whole build using the PHPP Embodied Energy Software Tool. This would hopefully give an overview of the project, before delving further into areas of interest for more insight into the building performance. This would also provide a baseline for further evaluation and help develop an understanding of the process to aid, and perhaps streamline data gathering.

From the background reading and evaluation of the key areas for this study it was found that the selection of base data can be highly influential on both the way the analysis should be conducted and the final results obtained. Therefore it was decided to assess several sources of base data, with the view that their comparison would provide a better understanding of embodied energy and emissions. Another benefit of using this strategy is that it allows an assessment of the base data too, and by doing this it was hoped to achieve both a more 'fuller' comprehension of the subject and more robust analysis and conclusions.

Once this first, initial, complete model of the building was finished, simulations were carried out with each of the three different base data sets. The results of these are compiled in the table below.

	BASE DATA				
	ICE		IBO		EBM
	Project Total Embodied Energy	Project Total Embodied Emissions	Project Total Embodied Energy	Project Total Embodied Emissions	Project Total Embodied Emissions
	(kWh)	(kg CO2e)	(kWh)	(kg CO2e)	(kg CO2e)
Case Study Base Case	246611	42440	216814	8259	39157

Table 13: Modelling results for Farmhouse.

The next stage of analysis was to break this 'total build' data down into its constituent parts. For this the stand-alone software tool was used. Again, this was assessed for each of the base data sets. The results of this are shown in the tables and charts that follow.

		BASE DATA											
Structure Type		ICE				IBO				EBM			
Timber Joist Walls and Concrete Floor		Embodied Energy		Embodied CO2 Equivalent		Embodied Energy		Embodied CO2 Equivalent		Embodied Energy		Embodied CO2 Equivalent	
		kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total
Individual Construction Element	Structural Materials	67074.0	27.2%	9064.0	21.4%	36249.891	16.72%	-19179.5	-232.2%	-	-	8136.883	20.8%
	Climatic Materials	45602.4	18.5%	9864.1	23.2%	69906.017	32.24%	10596.9	128.3%	-	-	9301.09	23.8%
	Surface Materials	119601.4	48.5%	20717.0	48.8%	96325.027	44.43%	14046.85	170.1%	-	-	18924.34	48.3%
	Windows	14333.3	5.8%	2795.0	6.6%	14333.333	6.61%	2795	33.8%	-	-	2795	7.1%
	Project Tot	246611.1	100.0	42440.1	100.0	216814.27	100	8259.229	100	-	100	39157.31	100

Table 14: Structural build-up with elemental breakdown for each data set.

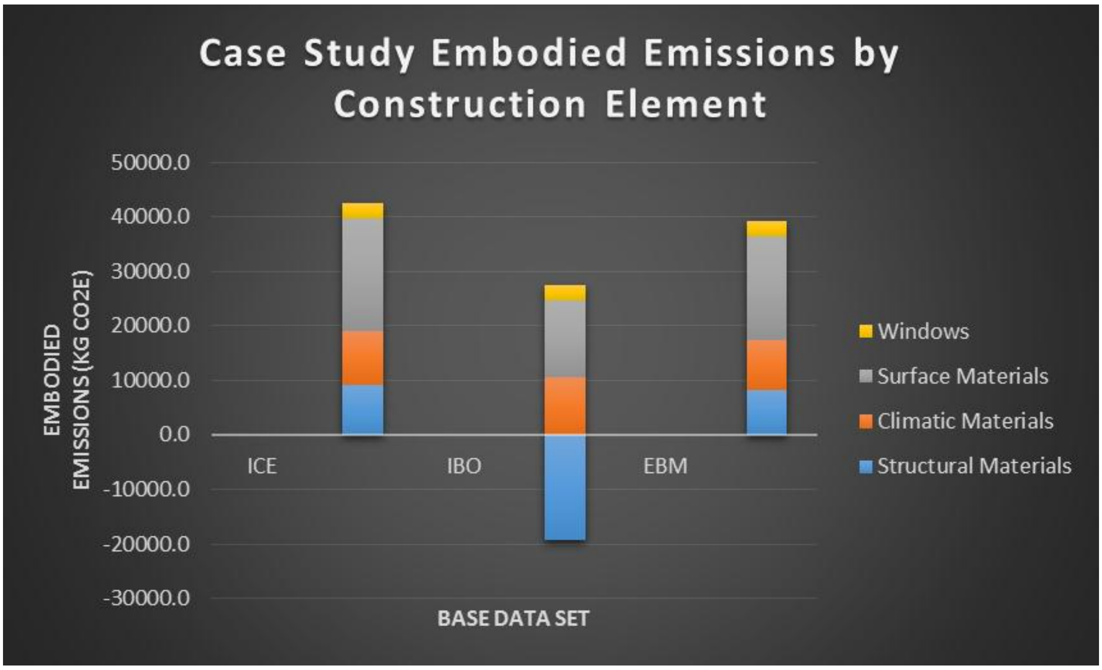


Figure 37: CO_2e emissions breakdown, notice the impact of the higher IBO timber-based CO_2 emission offsetting.

		BASE DATA											
Structure Type		ICE				IBO				EBM			
Timber Joist Walls and Concrete Floor		Embodied Energy		Embodied CO2 Equivalent		Embodied Energy		Embodied CO2 Equivalent		Embodied Energy		Embodied CO2 Equivalent	
		kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total
Individual Construction Area	Foundations	1060.0	0.4%	239	0.6%	880.8	0.4%	161	1.9%	-		161	0.4%
	Floor - Ground	29551.4	12.0%	5502	13.0%	27602.8	12.7%	3878	46.9%	-		10638	27.2%
	Floor - First	9868.1	4.0%	1343	3.2%	6921.9	3.2%	-1984	-24.0%	-		-111	-0.3%
	External Walls	76648.1	31.1%	11008	25.9%	67827.2	31.3%	-4413	-53.4%	-		10506	26.8%
	Internal walls	4320.8	1.8%	678	1.6%	3495.0	1.6%	-314	-3.8%	-		204	0.5%
	Roof	110829.7	44.9%	20875	49.2%	95753.3	44.2%	8137	98.5%	-		14965	38.2%
	Windows	14333.3	5.8%	2795	6.6%	14333.3	6.6%	2795	33.8%	-		2795	7.1%
	Project Total	246611.4	100	42440	100	216814.4	100	8260	100	0	100	39158	100

Table 15: Structural build-up with area breakdowns for each dataset used.

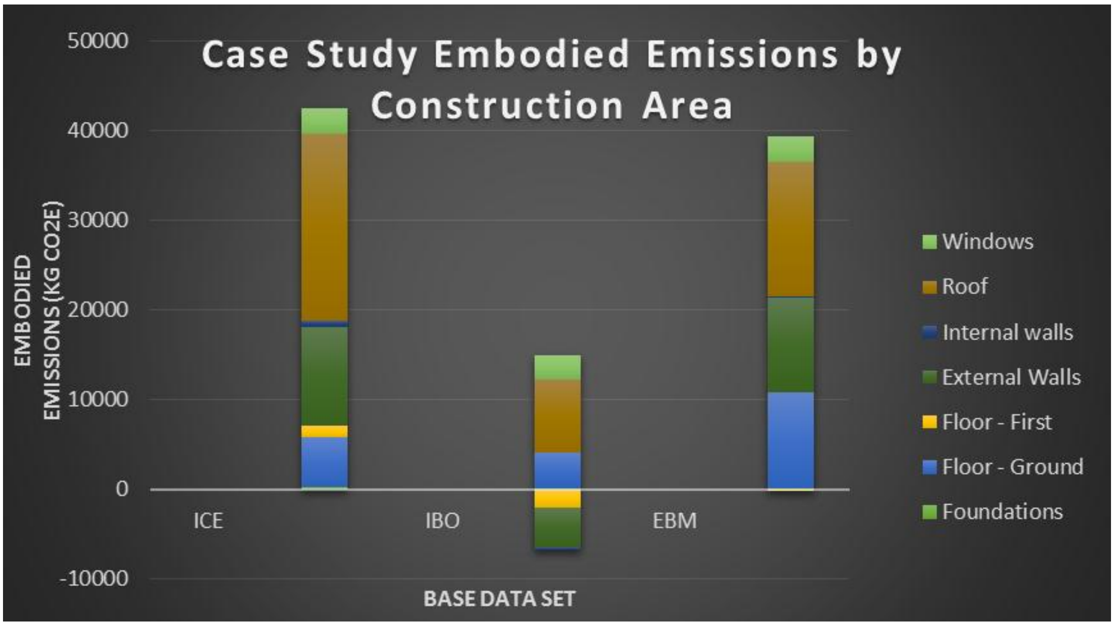


Figure 38: CO2e emissions breakdown by area. The IBO data includes higher timber-based CO2e emission off-setting.

The next stage was to begin focusing in on some of these key areas, and conducting more detailed analysis on them. Areas highlighted for initial investigation were opened up for discussion with the buildings architect to allow their better understanding of the energetic properties and quantification of the build.

From this feedback the first key area chosen was the construction insulation. This is a very important area to look at for many reasons. Firstly it is one of the biggest, by bulk area of the construction. Secondly this climatic membrane is crucial to both the passive house standard and to meeting the operational energy requirements of the build. Thirdly, as can be seen from the initial analysis it comprises a large percentage of the total build EE for our case study.

It was decided to undertake a comparative analysis of different insulation types, and to assess their relative energetic and GWP impact on the build itself. From this it was hoped a better understanding of both the range and variability, but also the relative variation in impact to the total build would be gained. Additionally, and in line with the earlier experiments the protocol of using several base data sets would be continued.

The cross-section below shows the typical insulation levels of the base case wall build-up:

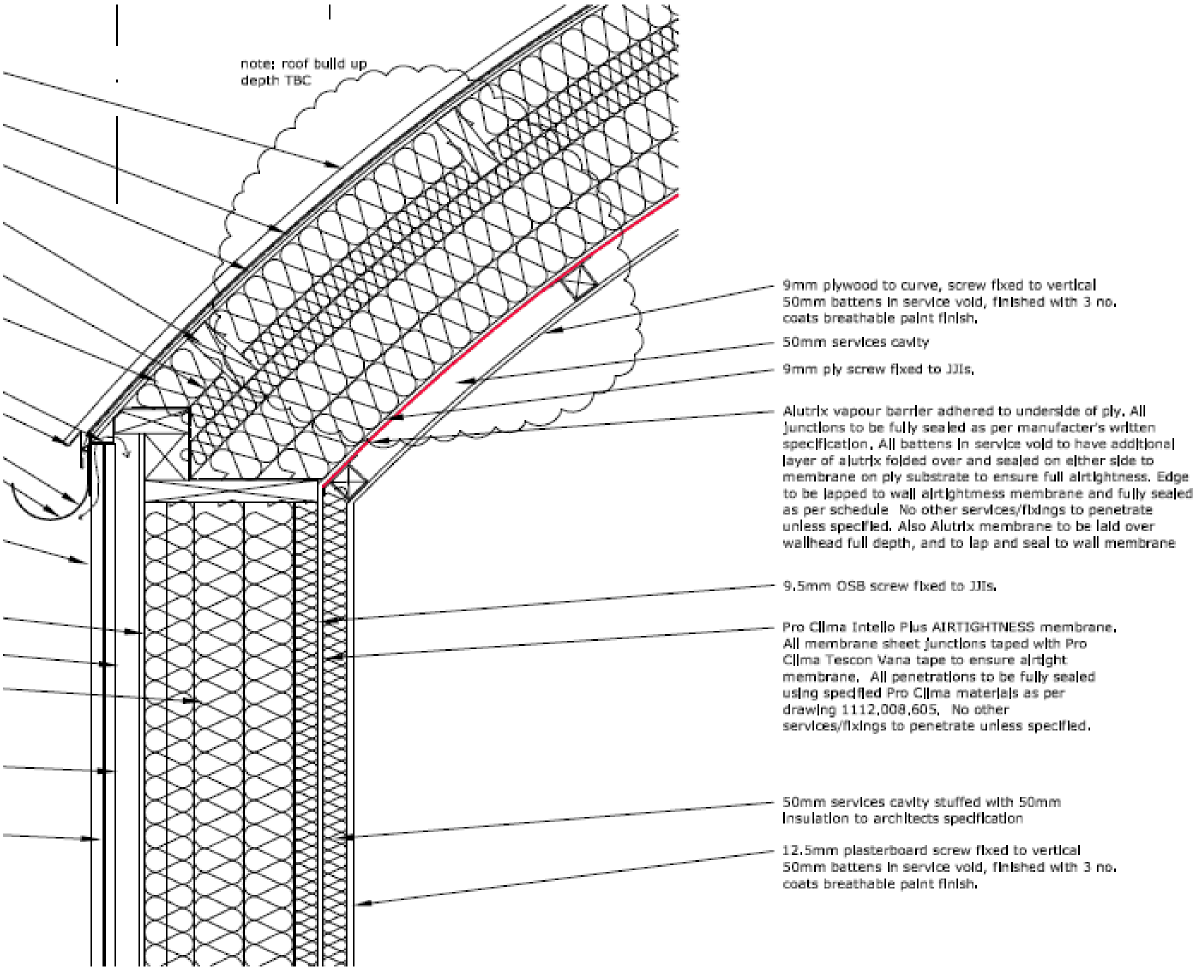


Figure 39: Base case construction external wall and roof build-ups showing insulation (Kirsty MaGuire Architects, 2012)

Table 16 shows insulation embodied CO2e and thermal conductivities from each of the three datasets. While in table 17 the analysis results for the case study insulation totals are given. These EE and ECO2e GWP results are case study insulation totals only.

	BASE DATA					
	ICE		IBO		EBM	
Insulation Type	CO2e Emissions	Conductivity (W/mK)	CO2e Emissions	Conductivity (W/mK)	CO2e Emissions (kg	Conductivity (W/mK)
Mineral Wool (base case)		0.032		0.036		0.038
	1.28		2.26		1.8	
Cellulose		0.04		0.04		0.042
	-		-0.907		-0.5	
Hemp Matting		-		0.04		0.045
	-		-0.133		0.9	
Sheeps Wool		0.038		0.04		0.04
	-		0.045		0.7	
Polystyrene		0.035		0.038		0.038
	3.43		3.35		7	
Rockwool		0.034		0.04		0.038
	1.12		1.6		1.7	

Table 16: Insulation key data from each of the base data sets.

	Newhouse Construction Total Insulation Results					
	BASE DATA					
	ICE		IBO		EBM	
Insulation Type	EE (Mj)	ECO2e (kg CO2e)	EE (Mj)	ECO2e (kg CO2e	EE (Mj)	ECO2e (kg CO2e)
Mineral Wool (base case)	111617	6637	236893	10451	-	7418
Cellulose	69236	-	89072	-2607	-	-1239
Hemp Matting	-	-	190725	1500	-	5420
Sheeps Wool	349562	-	117920	2290	-	3955
Polystyrene	357311	14538	417054	14484	-	22807
Rockwool	109841	5903	166442	10099	-	9637

Table 17: Comparison of insulation types and corresponding embodied properties for three base data sets.

To further clarify this area, an additional analysis was undertaken of the relative thermal conductivities of each of the insulation materials alongside their EE values. This was to further illustrate their differences, in terms of EE, while simultaneously highlighting their similarity of thermal conductivity. Again all three data sets of base data are included for comparison.

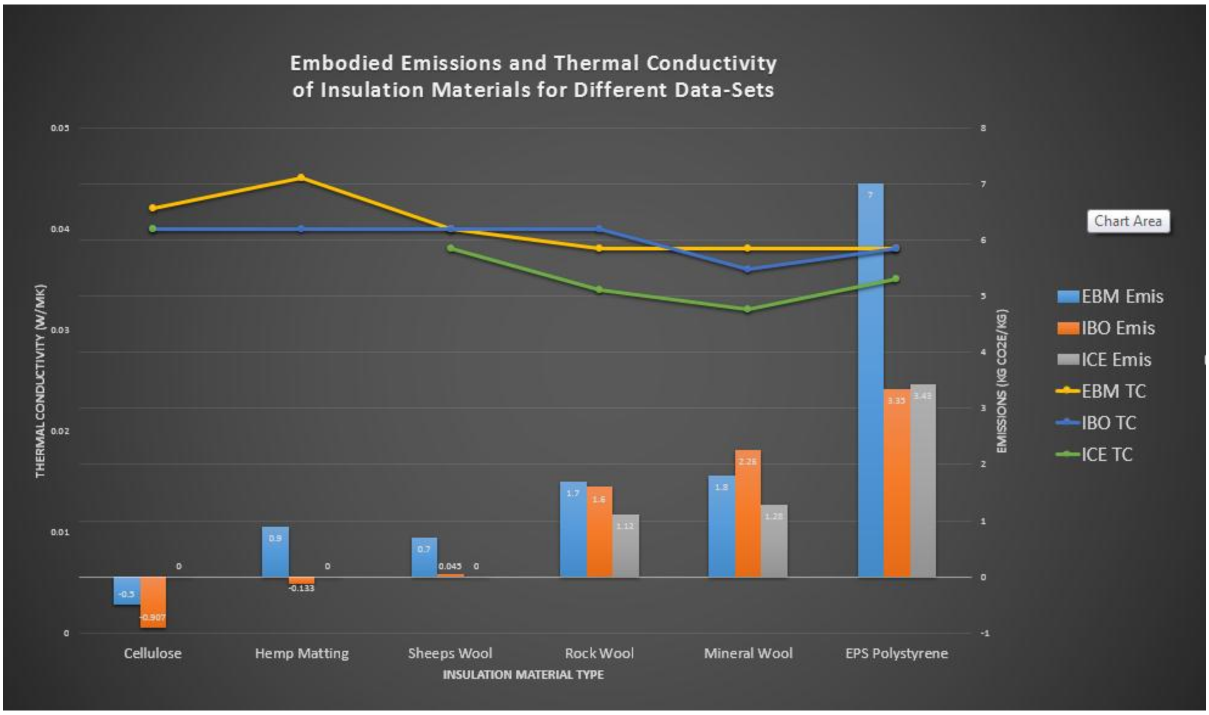


Figure 40: Analysis and comparison of insulation properties of interest for different materials and data sets.

Next, the focus would be shifted to a second area of interest – the structural element of the construction. Initially the study would be further focussed, looking specifically at the wall structural elements. This was again highlighted as an obvious candidate for further study due to its sheer size and relative contribution to total EE and ECO2e GWP. Discussion was undertaken with the case study project architect to appreciate both the structural design, variations and options before an experimental approach was decided. Again, by using the PHPP-EEST it was easy to re-design the model and to conduct an evaluation study with multiple variations.

Again, for this analysis we were interested in evaluating the EE and ECO2e GWP of the different structural designs and material choices.

For the case study building, 'the New Farmhouse', the construction is of a timber joist wall build-up, with a concrete floor and timber-joist, barrel roof, as illustrated in figure 35, 36, and 39. Table 18 and 19 highlights the relative impact of these choices, in terms of the project specific metrics with each of the evaluation data sets. They are looked at individually, alongside their relationship to the build' as a whole.

Next, and for a comparison against this base case, a second structural build-up was modelled for the case study building. The alternative wall structure is shown below in figure 41.

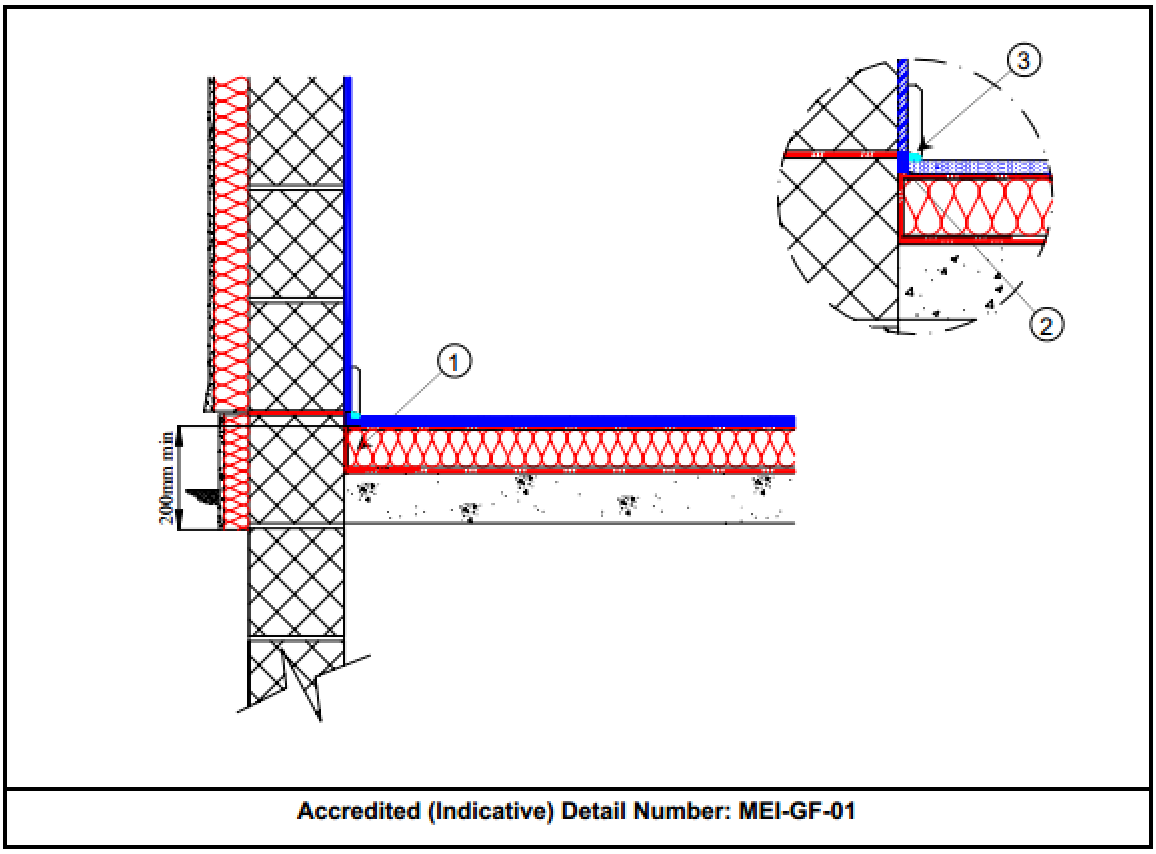


Figure 41: Alternative wall structure detail. Concrete structure with plasterboard on the inside and external insulation (Planning Portal, 2013)

The modelling results from the EEST for this study are shown in tables 20 and 21:

Again, both the individual building element metrics and the relationship to the build in total are shown.

Next, the key area of the floor and foundation would come under closer study. As can be seen from table, this represents a significant portion of the base case EE, and to a lesser extent the ECO2e GWP. Again the analysis would involve the assessment of the base case study example before a secondary, alternative construction type would be assessed and compared.

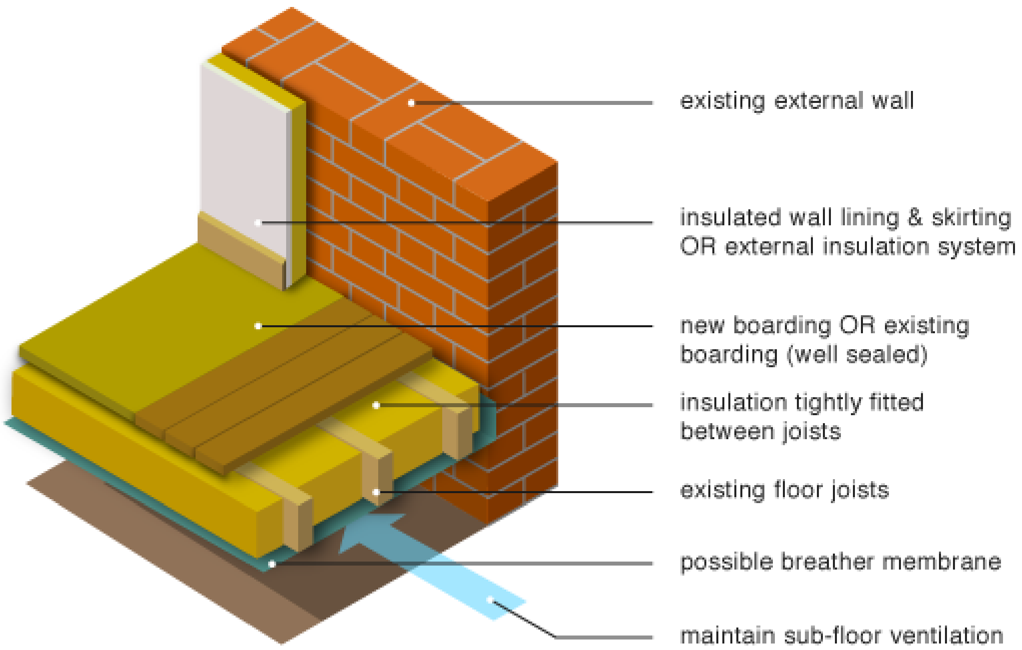


Figure 42: Typical suspended timber floor build-up (Greenspec, 2013)

After key briefings with the buildings architect it was decided to go with a dropped timber joist floor as the alternative. An example of this is illustrated in figure 42 above. Models were then created with the EEST and these were again analysed.

A second piece of analysis was also conducted into the combination of different wall and floor structures. The overall results are shown in table 22 below. This highlights the comparative impacts of the different structural builds, in terms of the case study for total EE and ECO2e GWP values.

		BASE DATA											
Structure Type		ICE				IBO				EBM			
Timber Joist Walls and Lowered		Embodied Energy		Embodied CO2 Equivalent		Embodied Energy		Embodied CO2 Equivalent		Embodied Energy		Embodied CO2 Equivalent	
		kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total
Individual Construction Element	Structural Materials	74679.7	31.8%	9298.9	0.2	48276.5	23.9%	-30551.9	139.5%	-	-	1665.7	6.0%
	Climatic Materials	28864.3	12.3%	7341.1	0.2	51791.2	25.6%	2772.5	-12.7%	-	-	4387.5	15.8%
	Surface Materials	117153.4	49.8%	20513.7	0.5	87611.7	43.4%	3082.1	-14.1%	-	-	18857.6	68.1%
	Windows	14333.3	6.1%	2795.0	0.1	14333.3	7.1%	2795.0	-12.8%	-	-	2795.0	10.1%
	Project Total	235030.7	100.0	39948.6	100.0	202012.7	100.0	-21902.2	100.0	-	100.0	27705.8	100.0

Table 18: Alternative structural build-up with lowered timber joist floor, again with each of the data sets.

		BASE DATA											
Structure Type		ICE				IBO				EBM			
Timber Joist Walls and Floor		Embodied Energy		Embodied CO2		Embodied Energy		Embodied CO2		Embodied Energy		Embodied CO2	
		kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total
Individual Construction Area	Foundations	1060.0	0.5%	239	0.6%	880.8	0.4%	161	-0.7%			161	0.5%
	Floor - Ground	17970.8	7.6%	3011	7.5%	18062.8	8.9%	-8442	38.5%			-814	-2.7%
	Floor - First	9868.1	4.2%	1343	3.4%	7349.2	3.6%	-2147	9.8%			-111	-0.4%
	External Walls	76648.1	32.6%	11008	27.6%	62746.7	31.1%	-16094	73.5%			10506	34.5%
	Internal walls	4320.8	1.8%	678	1.7%	3558.1	1.8%	-854	3.9%			204	0.7%
	Roof	110829.7	47.2%	20875	52.3%	95081.9	47.1%	2679	-12.2%			14965	49.1%
	Windows	14333.3	6.1%	2795	7.0%	14333.3	7.1%	2795	-12.8%			2795	9.2%
	Project Total	235030.8	100	39949	100	202012.8	100	-21902	100		100	30476	100

Table 19: Alternative structure build-up with construction area breakdown.

		BASE DATA											
Structure Type		ICE				IBO				EBM			
		Embodied Energy		Embodied CO2 Equivalent		Embodied Energy		Embodied CO2 Equivalent		Embodied Energy		Embodied CO2 Equivalent	
Concrete Walls and Floor		kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total
Individual Construction Element	Structural Materials	45260.5	17.6%	10613.8	22.0%	36854.9	0.2	-1141.5	-3.8%			18032.1	35.0%
	Climatic Materials	86775.6	33.8%	14198.7	29.4%	97380.2	0.4	14856.9	49.9%			15805.7	30.6%
	Surface Materials	108847.0	42.4%	20335.6	42.2%	83243.0	0.4	12998.4	43.6%			14959.6	29.0%
	Windows	15766.7	6.1%	3074.5	6.4%	15766.7	0.1	3074.5	10.3%			2795.0	5.4%
	Project Total	256649.8	100.0	48222.7	100.0	233244.9	100.0	29788.3	100.0		100.0	51592.4	100.0

Table 20: Alternative structural build-up with concrete walls – Elemental breakdown with each data set.

		BASE DATA											
Structure Type		ICE				IBO				EBM			
		Embodied Energy		Embodied CO2		Embodied Energy		Embodied CO2		Embodied Energy		Embodied CO2	
Concrete Walls and Floor		kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total	kWh	% Total	kg CO2e	% Total
Individual Construction Area	Foundations	1166.0	0.5%	262.9	0.5%	968.9	0.4%	177.1	0.6%	-	-	161	0.3%
	Floor - Ground	32506.5	12.7%	6052.2	12.6%	30363.1	13.1%	4265.8	14.5%	-	-	10638	20.6%
	Floor - First	10854.9	4.3%	1477.3	3.1%	7614.1	3.3%	-2182.4	-7.4%	-	-	-111	-0.2%
	External Walls	69690.5	27.3%	13647.7	28.5%	69359.0	29.9%	15848.8	53.7%	-	-	22941	44.5%
	Internal walls	4752.9	1.9%	745.8	1.6%	3844.5	1.7%	-345.4	-1.2%	-	-	204	0.4%
	Roof	121912.7	47.8%	22962.5	47.9%	105328.7	45.4%	8950.7	30.3%	-	-	14965	29.0%
	Windows	14333.3	5.6%	2795	5.8%	14333.3	6.2%	2795	9.5%	-	-	2795	5.4%
	Project Total	255216.8	100	47943.4	100	231811.6	100	29509.6	100		100	51593	100

Table 21: Same alternative structural build-up, this time with construction area breakdown.

	BASE DATA				
	ICE		IBO		EBM
	Project Total Embodied Energy	Project Total Embodied Emissions	Project Total Embodied Energy	Project Total Embodied Emissions	Project Total Embodied Emissions
Building Structure	(kWh)	(kg CO2e)	(kWh)	(kg CO2e)	(kg CO2e)
Timber Joist Construction Concrete Floor	246611	42440	216814	8259	39157
Timber Joist Construction Lowered Timber Joist Floor	235031	39949	202013	-21902	30476
Concrete Walls Concrete Floor	255216.8	47943.4	233245	29788	51592

Table 22: Overall data results for the embodied energy and CO_2e emissions with structural change.

Other key areas looked at, but perhaps considered less significant were the windows. Although in the case study these were found to be fairly low impact. Analysis was conducted on whether this was always the case. Alternative window choices were made, with some interesting changes. Results are shown below of the outcomes.

	ICE Embodied Data					
			Krypton Filled		Xenon Filled	
Window Type (Air or Argon Filled)	Energy (Mj per window)	Emissions (kgCO2 per window)	Energy (Mj per window)	Emissions (kgCO2 per window)	Energy (Mj per window)	Emissions (kgCO2 per window)
Aluminium Framed	5470	279	5980	305	9970	508
PVC Framed	2150-2470	110-126	2660-2980	136-152	6650-6970	339-355
Aluminium Clad - Timber Framed	950-1460	48-75	1460-1970	74-101	5450-5960	277-304
Timber Framed	230-490	12-25	740-1000	38-51	4730-4990	241-254

Table 23: Base embodied energy and emissions data for passive house window constructions.

Assembly No.	Building Assembly Description
5	Windows

	Type	Number	[Mj/Window] Min	[Mj/Window] Max	[kgCO2/Window] Min	[kgCO2/Window] Max	[kgCO2e/Window] Min	[kgCO2e/Window] Max	[Mj - Total] Min	[Mj - Total] Max	[kgCO2 - Total] Min	[kgCO2 - Total] Max	[kgCO2e - Total] Min	[kgCO2e - Total] Max
1	PVC Framed (Air or Argon Filled)	43	2150	2470	110	126	117	134	92450	106210	4730	5418	5014	5743
2	PVC Framed, Krypton Filled	43	2660	2980	136	152	144	161	114380	128140	5848	6536	6199	6928
3	PVC Framed, Xenon Filled	43	6650	6970	339	355	359	376	285950	299710	14577	15265	15452	16181
4	Aluminium Framed (Air or Argon Filled)	43	5470	5470	279	279	296	296	235210	235210	11997	11997	12717	12717
5	Aluminium Framed, Krypton filled	43	5980	5980	305	305	323	323	257140	257140	13115	13115	13902	13902
6	Aluminium Framed, Xenon filled	43	9970	9970	508	508	538	538	428710	428710	21844	21844	23155	23155
7	Aluminium Clad - Timber Framed (Air or Argon Fillec	43	950	1460	48	75	51	80	40850	62780	2064	3225	2188	3419
8	Aluminium Clad - Timber Framed, Krypton filled	43	1460	1970	74	101	78	107	62780	84710	3182	4343	3373	4604
9	Aluminium Clad - Timber Framed, Xenon filled	43	5450	5960	277	304	294	322	234350	256280	11911	13072	12626	13856
10	Timber Framed (Air or Argon Filled)	43	230	490	12	25	13	27	9890	21070	516	1075	547	1140
11	Timber Framed, Krypton filled	43	740	1000	38	51	40	54	31820	43000	1634	2193	1732	2325
12	Timber Framed, Xenon filled	43	4730	4990	241	254	255	269	203390	214570	10363	10922	10985	11577

Lowest Total Embodied Energy:	9890	Mj	Highest Total Embodied Energy:	428710	Mj
Lowest Total Embodied CO2:	516	kgCO2	Highest Total Embodied CO2:	21844	kgCO2
Lowest Total Embodied CO2e:	547	kgCO2e	Highest Total Embodied CO2e:	23155	kgCO2e

Figure 43: The case study EEST window embodied calculation field table.

Another area not considered in this investigation but highlighted from the results as significant is the design/material choice for the roofing (outer shell) of 5mm zinc cladding. This had a significant impact on project total EE and ECO2e. Therefore this is another area where possible ECO alternatives should be considered.

However, having recorded all this useful case study data. It would be useful to take a step back and to briefly review, and establish what has been covered so far?

There is now some useful data on the total EE and ECO2e GWP for the case study passive house. Several key, component areas have been evaluated and alternative constructions considered and what their relative impacts would be. This has all been done using several base data sets, therefore enabling a more accurate picture to develop.

So, this has provided a better understanding of the EE and ECO2e emissions, and calculated possible ranges for these values (in terms of both base data sets and material choices). This allows insight into the impacting factors on these for the construction of this case study passive house.

Now that detailed analysis of each of these keys areas has provided useful data-sets, these can now be used, that is to say all these individual elements of the case study build-up can now be applied to the study of assessing both an ECO alternative passive house build-up, and an INTENSIVE energy alternative passive house build-up.

The overall project embodied CO2e emissions for these two build-ups and the case study results are graphed below, again for all three of the base data sets:

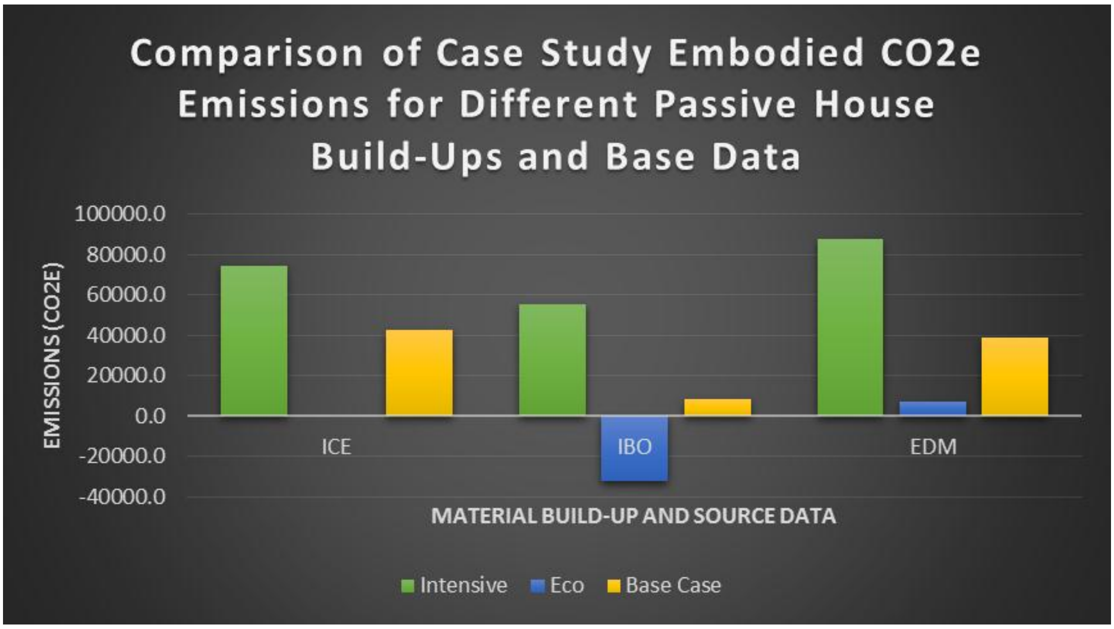


Figure 44: Project total embodied emissions for three different passive house builds, modelled with the EEST

Each of these build-ups was based on the key elements – insulation, wall structure, floor type and window structure. As can be seen here, there is quite a marked difference between the different build-ups, but also consistency between all three data-sets.

This chart provides some evidence of just how big an impact the material choices can actually have. For example taking the EBM base data set for the base case study the project total embodied CO2e emissions is 39157 kg CO2e. However if for example you chose more energy intensive products or building materials in your passive house design choices then this can rise up to 87941 kg CO2e (+125%). While conversely, if the material and product choices are of the low energy variety then the total project embodied emissions drops to 6872 kg CO2e (-82%)!

These findings suggest that passive house building material choices are significantly important to the project CO2e emissions, for all three base data sets used.

This data, useful in of itself could perhaps be more useful if its relationship with the primary Operational Energy (OE) use of the building, over its expected lifetime is studied. And by combining the data of both of these metrics you have a reasonable estimate for most of the significant energy inputs (and consequent CO2e emissions) into the building for its predictable lifetime, therefore a first step towards a full LCA of the passive house building:

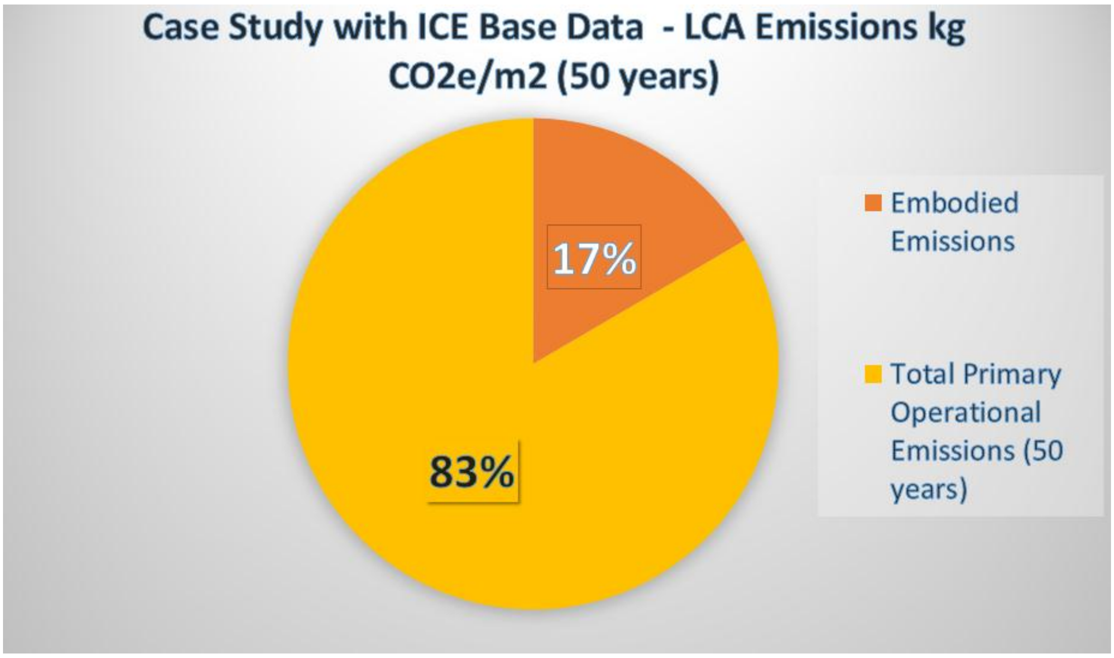


Figure 45: EE impact on the Life Cycle emissions using total primary operational energy emissions data.

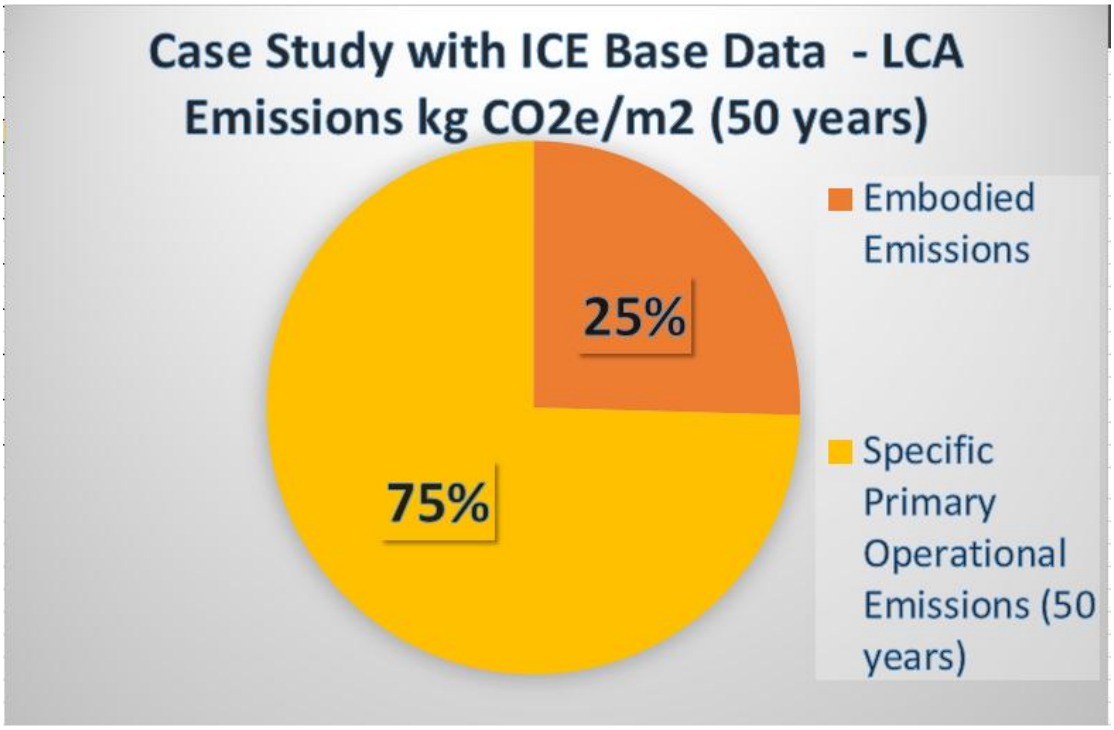


Figure 46: EE impact on the Life Cycle analysis using the Specific Primary Operational Energy Emissions data.

Further questions that now arise are:

How do the construction build-up alternatives impact on the LCA emissions total?

To answer this question and perhaps others, further analysis is required. But first some details on the software:

By using the PHPP analysis software for the case study we can evaluate numbers for the expected lifetime operational energy (OE) values. Likewise by using the developed PHPP-EEST integrated tool we can simultaneously evaluate and compare the embodied construction build energies. This is illustrated below in figure 47.

Specific Demands with Reference to the Treated Floor Area						
Treated Floor Area:	162.5	m²				
	Applied:	Monthly method			PH Certificate:	Fulfilled?
Specific Space Heating Demand:	**13**	**kWh/(m²a)**		**15**	**kWh/(m²a)**	**Yes**
Heating Load:	**9**	**W/m²**		**10**	**W/m²**	
Pressurization Test Result:	**0.2**	**h^{-1}**		0.6	h^{-1}	**Yes**
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	**101**	**kWh/(m²a)**		120	kWh/(m²a)	**Yes**
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	58	kWh/(m²a)				
Specific Primary Energy Reduction through Solar Electricity:		kWh/(m²a)				
Frequency of Overheating:	0	%	over	25	°C	
Specific Useful Cooling Energy Demand:		kWh/(m²a)		15	kWh/(m²a)	
Cooling Load:	0	W/m²				
Total Embodied Primary Energy:	1655	kWh/(m2)				
Total Embodied Emissions - CO2 Equivalent:	281	kg/(m2)				
Total Operational Primary Energy (no household applications):	58	kWh/(m2a)				
Total Operational CO2 Equivalent (no household applications):	15	kg/(m2a)				
LCA - Total Primary Energy Use (50 year life, no microgen, no household applications):	4577	kWh/m2				
LCA - Total Emissions CO2 Equivalent (50 year life, no microgen, no household applications):	1045	kg/(m2)				

Figure 47: The PHPP Verification sheet with integrated embodied software tool outputs.

Significantly, the integrated tool allows both these values to not only be compared but to be immediately analysed with respect to building material adjustments and design changes. This capacity should allow for both easier design decision-making and provide a basis for a LCA modelling strategy for passive house.

In the next, and final stage of analysis, the aim is to investigate the relationship between the case study's construction envelopes thermal insulation thickness, and the building's 'lifetime' energy efficiency. That is to say, the overall energy use shall be evaluated in terms of both the embodied energy, and the lifetime specific space heating demand (SSHD). It will be interesting to see if there is an optimum thickness for minimising this building's energy needs, and if so, then further what this insulation level calculates out at. Similar to the work earlier in this study, there shall also be further evaluation of the base data sets used in this analysis. To achieve this a comparative analysis approach will be used comprising of just two data sets – the Inventory of Carbon and Energy (ICE), and the IBO book of passive house standards (IBO). The Ecology of Building Materials database (EBM) however does not include EE values, therefore this was excluded.

This study used the original case study building design (as built), the external walls, roof, and ground floor are detailed below in figure 48, 49, and 50:

Assembly No.	Building Assembly Description
1	External Wall

Heat Transfer Resistance [m²K/W] interior R_{si} : 0.13 exterior R_{se} : 0.04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	gypsum plasterboard	0.210					13
2.	air gap	0.306	timber battons	0.130			50
3.	OSB	0.130					18
4.	mineral wool insulati	0.032	sw JJI end	0.130	OSB flange	0.130	45
5.	mineral wool insulati	0.032			OSB flange	0.130	260
6.	mineral wool insulati	0.032	sw JJI end	0.130	OSB flange	0.130	45
7.	OSB	0.090					10
8.							
			Percentage of Sec. 2	25.0%	Percentage of Sec. 3	10.0%	Total 44.0 cm

U-Value: 0.116 W/(m²K)

Figure 48: The external wall build-up.

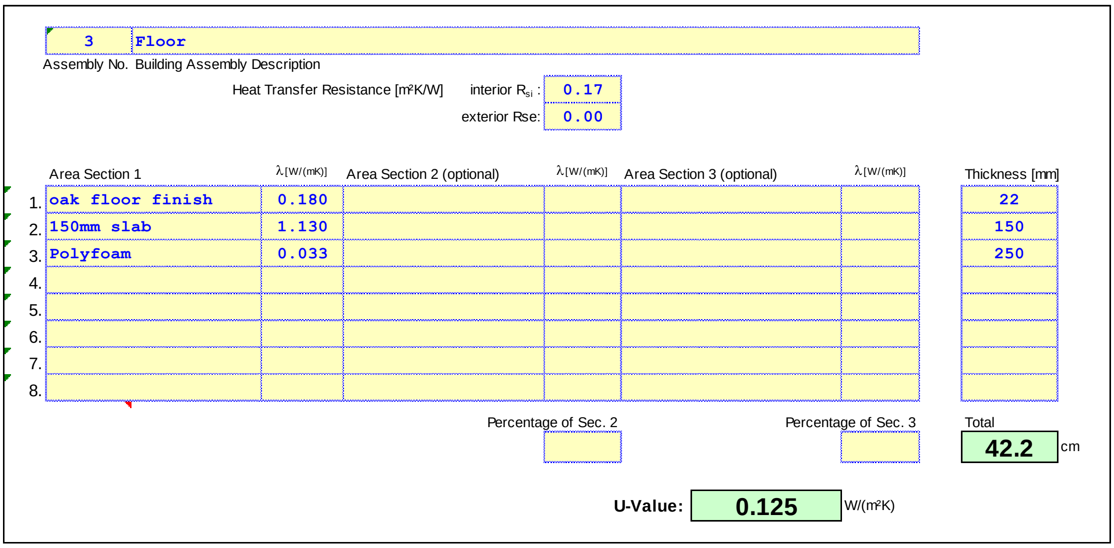
Assembly No.	Building Assembly Description
2	Roof

Heat Transfer Resistance [m²K/W] interior R_{si} : 0.10 exterior R_{se} : 0.04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	gypsum plasterboard	0.210					13
2.	air gap	0.306	50mm sw battens @ 6	0.130			50
3.	ply	0.130					9
4.	mineral wool insulati	0.032			115mm glulam	0.180	205
5.	mineral wool insulati	0.032	100mm sw battens @	0.130	115mm glulam	0.180	100
6.	mineral wool insulati	0.032	100mm sw battens @	0.130	115mm glulam	0.180	100
7.	2 x 9mm ply	0.180					18
8.	zinc cladding	50.000					5
			Percentage of Sec. 2	25.0%	Percentage of Sec. 3	8.0%	Total 50.0 cm

U-Value: 0.115 W/(m²K)

Figure 49: The roof build-up.



3 Floor
Assembly No. Building Assembly Description
Heat Transfer Resistance [m²K/W] interior R_{si} : 0.17
exterior Rse: 0.00

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	oak floor finish	0.180					22
2.	150mm slab	1.130					150
3.	Polyfoam	0.033					250
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2 | Percentage of Sec. 3 | Total 42.2 cm

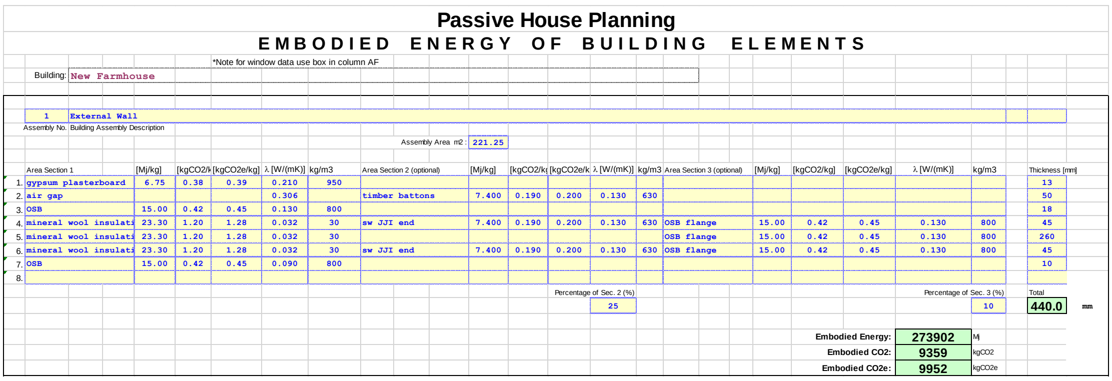
U-Value: 0.125 W/(m²K)

Figure 50: The floor build-up.

Initially this evaluation would focus on the project design insulation type - mineral wool. However further research would be carried out into other alternative insulation types.

This analysis was made possible (in practice), by the PHPP-EST that was designed earlier in this project. For this specific task the 'integrated tool' design was found to be most helpful in simultaneously allowing both embodied and operational energy results to be calculated from the same passive house construction design and data. However, additionally the tool also allowed for the relatively easier analysis involving different base data sets.

The user interface of the tool is shown below:



Passive House Planning
EMBODIED ENERGY OF BUILDING ELEMENTS
*Note for window data use box in column AF
Building: New Farmhouse

1 External Wall
Assembly No. Building Assembly Description
Assembly Area m2 : 221.25

	Area Section 1	[Mj/kg]	[kgCO2/k	[kgCO2e/kg]	λ [W/(mK)]	kg/m3	Area Section 2 (optional)	[Mj/kg]	[kgCO2/k	[kgCO2e/k	λ [W/(mK)]	kg/m3	Area Section 3 (optional)	[Mj/kg]	[kgCO2/kg]	[kgCO2e/kg]	λ [W/(mK)]	kg/m3	Thickness [mm]
1.	gypsum plasterboard	6.75	0.38	0.39	0.210	950													13
2.	air gap				0.306		timber battons	7.400	0.190	0.200	0.130	630							50
3.	OSB	15.00	0.42	0.45	0.130	800													18
4.	mineral wool insulati	23.30	1.20	1.28	0.032	30	sw JJI end	7.400	0.190	0.200	0.130	630	OSB flange	15.00	0.42	0.45	0.130	800	45
5.	mineral wool insulati	23.30	1.20	1.28	0.032	30							OSB flange	15.00	0.42	0.45	0.130	800	260
6.	mineral wool insulati	23.30	1.20	1.28	0.032	30	sw JJI end	7.400	0.190	0.200	0.130	630	OSB flange	15.00	0.42	0.45	0.130	800	45
7.	OSB	15.00	0.42	0.45	0.090	800													10
8.																			

Percentage of Sec. 2 (%) 25 | Percentage of Sec. 3 (%) 10 | Total 440.0 mm

Embodied Energy: 273902 Mj
Embodied CO2: 9359 kgCO2
Embodied CO2e: 9952 kgCO2e

Figure 51: The integrated EE software tool – Build-up spreadsheet.

Specific Demands with Reference to the Treated Floor Area						
Treated Floor Area:	162.5	m²				
	Applied:	Monthly method			PH Certificate:	Fulfilled?
Specific Space Heating Demand:	**9**	**kWh/(m²a)**		**15**	**kWh/(m²a)**	**Yes**
Heating Load:	**8**	**W/m²**		**10**	**W/m²**	
Pressurization Test Result:	**0.2**	**h⁻¹**		0.6	h⁻¹	**Yes**
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	**93**	**kWh/(m²a)**		120	kWh/(m²a)	**Yes**
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	51	kWh/(m²a)				
Specific Primary Energy Reduction through Solar Electricity:		kWh/(m²a)				
Frequency of Overheating:	15	%	over	25	°C	
Specific Useful Cooling Energy Demand:		kWh/(m²a)		15	kWh/(m²a)	
Cooling Load:	0	W/m²				
Total Embodied Primary Energy:	1655	kWh/(m2)				
Total Embodied Emissions - CO2 Equivalent:	281	kg/(m2)				
Total Operational Primary Energy (no household applications	51	kWh/(m2a)				
Total Operational CO2 Equivalent (no household applications):	13	kg/(m2a)				
LCA - Total Primary Energy Use (50 year life, no microgen, no household applications):	4184	kWh/m2				
LCA - Total Emissions CO2 Equivalent (50 year life, no microgen, no household applications):	942	kg/(m2)				

Figure 52: Validation sheet of the PHPP with embedded EE and ECO2e functions.

From these simulations it was then possible to model different envelope insulation levels using a linear scaling from 50 to 600mm. The building envelope, for this study comprised of the floor, walls and roof. From these key metrics, alongside the EEST tool and aligned with each of the base data sets, the following information set could begin to be built up.

	Typical Insulation Thicknesses - Walls, Floor and Roof (mm)	BASE DATA					BASE DATA	
		ICE		IBO		PHPP	ICE	IBO
		Total Embodied Energy	Total Embodied CO2e Emissions	Total Embodied Energy	Total Embodied CO2e Emissions	Specific Space Heating Demand (SSHD)	Total EE and SSHD (Over 50 year period)	Total EE and SSHD (Over 50 year period)
		kWh/m2	kg CO2e/m2	kWh/m2	kg CO2e/m2	kWh/m2a	kWh/m2	kWh/m2
Mineral Wool	50	1139	209	1084	-2.6	116	6939	6884
	100	1256	224	1152	7.5	58	4156	4052
	150	1349	237	1221	17.6	36	3149	3021
	200	1466	252	1290	27.7	28	2866	2690
	250	1569	266	1359	37.8	21	2619	2409
	300	1662	279	1427	47.9	17	2512	2277
	350	1779	294	1496	58	14	2479	2196
	400	1881	308	1565	68.2	12	2481	2165
	450	1974	321	1633	78.3	11	2524	2183
	500	2067	334	1702	88.4	10	2567	2202
	550	2170	348	1771	98.5	9	2620	2221
	600	2287	363	1839	108.6	8	2687	2239
						Minimum	2479	2165

Table 24: Evaluation of optimum insulation thicknesses.

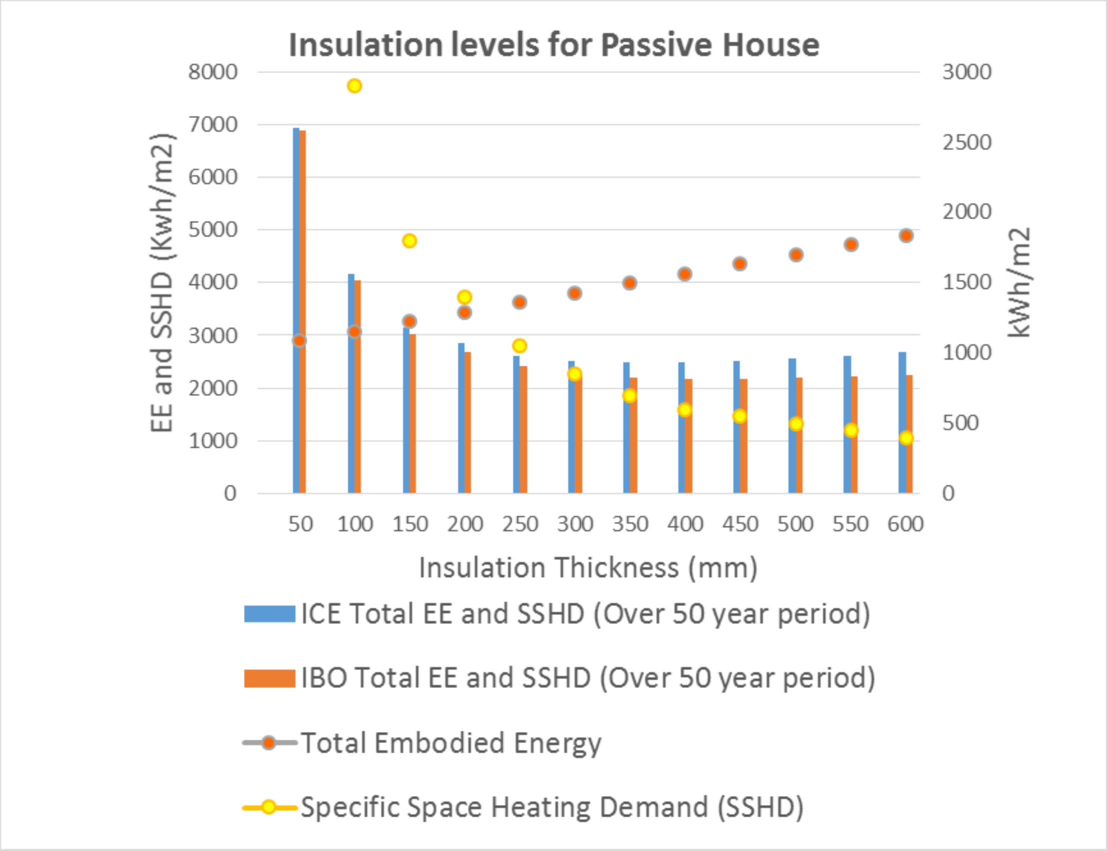


Figure 53: Calculated expected building EE and SSHD energy use with mineral wool insulation used throughout.

Another important reason for carrying out this analysis was to also evaluate the software tools performance at different tasks. This approach methodology has been key to the 'design approach' for assessment and development, and the tool has 'evolved' through several concepts and design layouts under this method.

Chapter 7 - Discussion

Design Tool

The project outcome has included two different software designs for different applications. The first - a PHPP integrated embodied energy and emissions calculating tool. And the second - a more comprehensive ‘stand-alone’ embodied energy and emissions calculation tool that gives a greater detail of results breakdown.

Another great reason for making two separate tools is for the purposes of de-bugging. And this proved very useful during the case study analysis.

An extended and updated software application tool, inclusive of material transportation analysis was designed and complete. However this ‘latest version’ was not used for the case study project energy modelling analysis results presented here.

Case Study

For all three datasets considered there was a reasonable correlation on material choices for the ecologically optimised and energy intensive alternatives.

There are a few topics that although not investigated here, are nevertheless equally important for sustainable passive house material choice and building design. Therefore it is vital that these aspects are fully considered alongside EE and ECO2e. It might be that the least energy intensive and lowest emitting option, could well have serious other negative consequences. Or conversely the highest emitting option may well be the best, overall choice for the wider environment.

In 2010 the University of Bath initiated a benchmarking program for the embodied energy and CO2e emissions for a typical range of UK residential housing, based on 2006 building standards (Appendix B). Based on an application and comparison of final results methodology, results were found to be within 1% (EE) and 10% (ECO2) of BRE validation data (Jones, 2011). Therefore the case study total project EE and CO2e emission results (ICE) were compared with these for general validation purposes.

For a detached residential house with a total floor area of 162.5 square metres (case study), the benchmarking chart suggests a typical total project embodied energy of around 850GJ, with 63 tonnes of CO2 emissions.

The case study results from this project were:

ICE Database: 783GJ (ECO) up to 1458GJ (INTENSIVE) EE, and 42.4 tonnes (ECO) up to 74.6 tonnes (INTENSIVE) of CO2e emissions, depending on material choices.

Therefore with a similar dataset and boundary conditions the benchmarking results seem reasonable.

A different study has estimated that the manufacture, maintenance and renewal of materials for a conventional building, over 50 years requires 2000-6000 MJ/m^2 (Thormark, 2007). With the broad variation, again representing construction material choices.

A comparison of the case study total ECO2e against the PHPP estimated 50 year operational CO2e emissions, shows 17% embodied CO2e against the total CO2e emissions and 25% against the specific operational CO2e emissions, that is for the ICE dataset. For the EBM dataset, the values are similar at 15.5% (total) and 23.9% (specific).

However the IBO data-sets with greater CO2e off-setting values gives much lower embodied carbon emissions at 3.7% (total) and 6.2% (specific) of the total CO2e emissions.

Then when you consider the impact of material choices with the optimised ECO alternative and INTENSIVE options, and again compare with the PHPP estimated typical 50 year operational values the significance of embodied CO2e was calculated, for the three base data sets:

ICE Embodied CO2e Emissions: Rises to 26% (total OE) and 38% (specific OE) of total CO2e emissions with INTENSIVE (materials).

IBO Embodied CO2e Emissions: Drops to -17.9% (total OE) and -35.2% (specific OE) of total CO2e with ECO (optimisation). And rises to 20.6% (total OE) and 30.8% (specific OE) of total CO2e emissions with INTENSIVE (materials).

EBM Embodied CO2e Emissions: Drops to 3.1% (total OE) and 5.2% (specific OE) of total CO2e with ECO (optimisation). And rises to 29.2% (total OE) and 41.4% (specific OE) of total CO2e emissions with INTENSIVE (materials).

These results suggest that embodied CO2e emissions are significant, compared with the PHPP estimated typical 50 year operational energy totals.

And in terms of a life cycle energy analysis (LCEA) these initial, findings can be taken as conservative. When you consider the boundaries involved and areas omitted such as transportation, services, fittings and demolition/disposal, then these figures are only going to rise.

Chapter 6 – Conclusion

A method to both assess and analyse embodied energy and CO2e emissions has been found and developed. Investigating this area has also revealed some useful insights into life-cycle energy analysis for passive house. Based on these findings a concept has been put forward on how best to approach this area in future.

When applying life cycle energy analysis (LCEA) techniques as part of an environmental life cycle analysis (LCA) evaluation of passive housing, by definition the embodied energy and emissions/pollution needs to be included. This methodology is consistent with the ISO international standard practice and structure (ISO 14044:2006). However this is not just a theoretical requirement, nor just a best practice approach. The embodied energy and emissions/pollution for passive house is actually quite significant. Therefore when designing and building towards near zero-carbon homes it would be necessary to include the embodied emissions in the analysis. But this is not just for the purposes of good environmental accounting. If applied at the design stage then this approach can help to minimise the embodied impact and therefore support achieving this target.

It is important when discussing this decision making process however to include a wider spectrum of analysis. Issues such as embodied pollution, resources, waste and recyclability must all be included. This could be done through either a single instrument, or a combination of PHPP EEST and an overarching sustainability assessment system like BREEAM or CSH.

Results from this study suggest that although difficulties lie in the accuracy of comparative EE assessment, these are not insurmountable. Instead a focus should be placed on the quality of the data set and a conscious preferred choice should be made based on the requirements/preferences of the individual. Then the general results can be useful along with the corresponding optimised eco material choices. From the three, widely differing datasets used for this study, although all gave numerically different individual results, by adopting a more systematic approach typical ECO friendly or INTENSIVE material choice variations showed all datasets to be reasonably close in agreement.

Therefore by a careful process of choosing a credible and appropriate dataset and a good understanding of the system in use, EE assessment can be a useful tool for minimising embodied CO2e emissions. And by integrating this analysis into a wider more systemic approach, the most sustainable and ecological passive house designs may be achieved.

Recommendations for the Future

- **Climate Neutral Housing -** Further development towards an understanding of 'Climate Neutral' or genuine zero carbon design requirements through LCEA of passive house with distributed renewable energy systems and their associated embodied energy content. Along with the developed EEST, this could provide a good basis for further case study analysis of passive houses for the purposes of assessing the potentials, requirements and material choices/limits for 'Climate Neutral' or genuine zero carbon design standards.
- **LCA -** Further development towards a full LCA of passive house by assessment of sustainability of material choices and design. For example recyclability, embodied toxicity and acidification potential. This may be a combined approach using the EEST software with the EBM database or in combination with BREEAM or CSH systems.
- **Energy Optimised Resource Use (EORU) -** The continuation of passive house optimised resource material use by the modelling of life cycle optimised energy efficiency levels for all insulation types and then developing into full build analysis. Possibly then looking at a 'design for salvageability' or recyclability concept.
- **CBA -** A comparative cost analysis of different resource materials and optimised against the life-cycle optimised resource use levels, as a complete cost benefit analysis.
- **EnerPHit** – More detailed evaluation of passive house refurbishment design. With an embodied energy and carbon emission analysis included in life cycle energy efficiency evaluation of renovations. And an associated CBA.

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Appendix A

Examples of Creative Design Concept Solutions – Sustainable and Innovative

The multiple award winning London 2012 Velodrome. This was a construction concept that had sustainability at the core, with an integrated, holistic approach, the design pushed standards and surpassed targets. Both operational and embodied carbon were considered at the design stage (GBC, 2013). Used 10 times less materials than the Beijing velodrome (Green Building Council, 2013). Used only 100 tons of steel (30 times less than the equivalently sized Olympic swimming arena). The arena has a 5000 square metre roof that used an innovative design and construction approach involving minimal resources (steel cabling – halving the weight), minimised embodied carbon, optimised for daylight use, and designed to collect rainwater for flushing toilets and irrigation. This low roof design also enabled 100% natural ventilation and with reduced indoor space the heating requirements are also minimised.

Figure 54: The London Olympic velodrome (UKGBC, 2012).

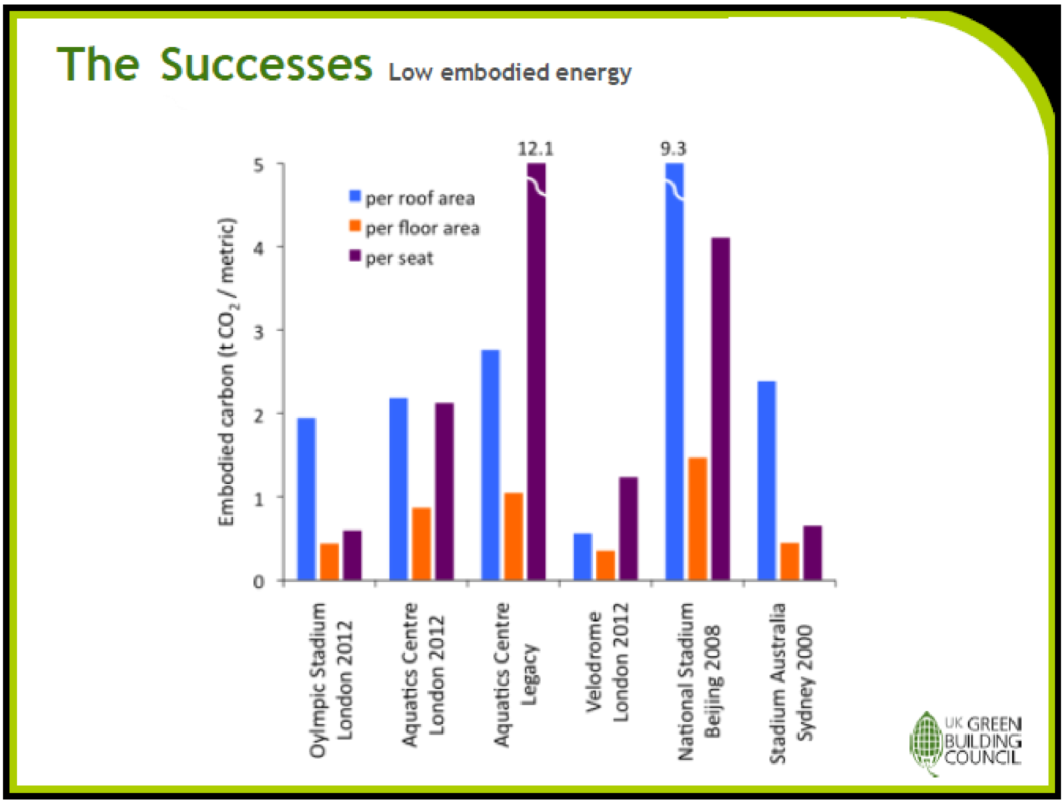

Figure 55: The Olympic velodrome embodied energy data with comparisons (UKGBC, 2012).

Successes

Exceeding targets

Environment and Sustainability Indicator	Target	Actual
Recycled aggregate by weight	25%	20.2%
Healthy materials low VOC/water based	80%	82%
BRE Green Guide Rating	A+ to C	ALL
Biodiversity- invasive species management	100%	100%
BREEAM permanent venues	Very Good	EXCELLENT
Considerate Constructors Scheme	4 per section	Average 4.47 per section

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Successes

Exceeding targets

Environment and Sustainability Indicator	Target	Actual
Efficiency Energy better than part L	15%	31%
Potable Water reduction	40%	75%
Waste – reused or recycled construction	90%	95.5%
Timber from Legal and sustainable sources	100%	100%
Key materials responsibly sourced	80%	98%
Recycled content by value (using WRAP tool kit)	20%	29%

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Figure 56a and 56b: Top and Bottom: London Velodrome sustainability construction performance (UKGBC, 2012).

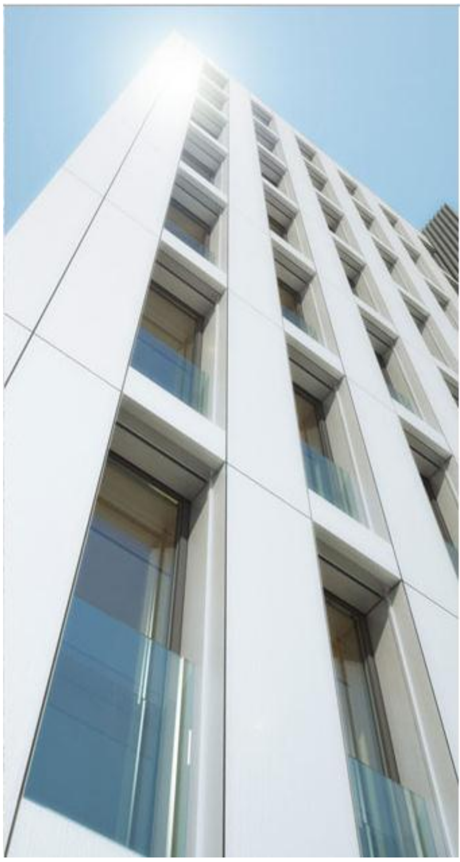
Recyclable Building – The end of life deconstruction of this building was taken into account at the design stage.

Figure 57: Recyclable building – Stuttgart Germany, 1999 (OECD, 2012).

This ‘Lego’ house concept is a four storey building that is modular constructed and designed for re-use. It is assembled by mortice-and-tenon joints and bolted joints, providing functional assembly, and dismantling for re-usable options.

The Life-Cycle Tower (LCT) is a multiple award winning passive multi-storey office block that was built in Dornbirn, Austria - completed in August 2012. It is a hybrid timber construction supported by the Austrian Research Promotion Agency (FFT) and the Ministry for Transport, Innovation and Technology (BMVIT) under the Buildings of Tomorrow Program.

Figure 58: The LCT One (Cree, 2013).



The most important details of the LCT ONE

- **Dimensions:** 8 stories, Height 27 m, Width 13 m, Length 24 m
- **Floor space:** individual rentable areas 50 m^2 - 1.600 m^2
- **Architecture:** designed by Hermann Kaufmann, facades constructed from recycled composite metal, visible wooden supporting structure inside, reception area
- **Energy standard:** passive house technology
- **Windows:** triple glazed
- **Operating costs:** Optimised by automatic energy consumption monitoring
- **Room temperature:** heating/cooling panels incorporated in ceilings, window contacts to prevent energy loss
- **Air quality:** comfort ventilation system with highly efficient heat recovery, automatic control via CO2 measurement, intelligent control of building services: shutters with automatically controlled motor drive, presence-dependent lighting control
- **Equipment:** electronic access system, personnel lift, Cat. 7 cabling for feed to each storey
- **Lighting:** basic lighting of general areas, individual office lighting, floor structure: sound-optimised double floor system
- **Room division:** individually configurable in dry construction or with system partition walls
- **High safety standards:** automatic fire extinguishing system and fire alarm system
- **Storage areas:** on every floor

Figure 59: The LCT One (Cree 2013).

Appendix B

Data Validation – Case Study Buildings

Work by the Sustainable Energy Research Team at Bath University in 2010 (Hammond and Jones), concentrated on the validation of the ICE dataset specific to both residential and non-residential buildings. This was conducted through application and comparison of final results, with BRE data. Based on UK 2006 Building Regulations, the results were normalised to the average floor area in metres squared.

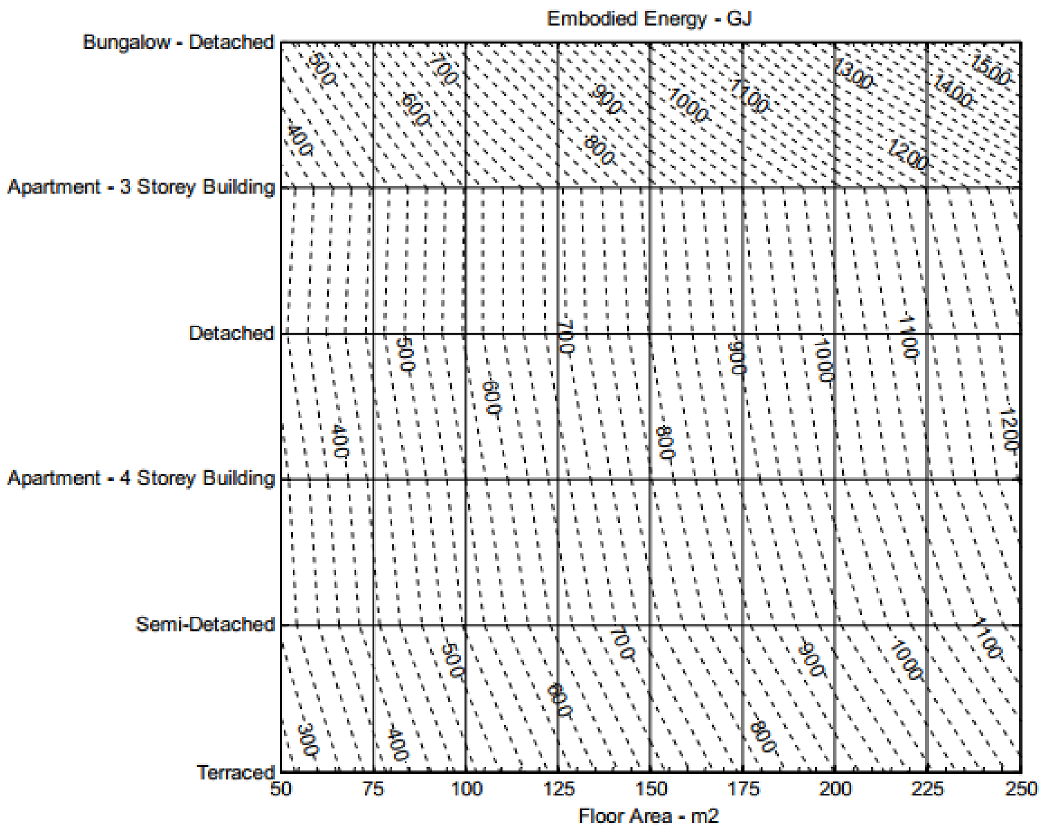


Figure 60: SERT Benchmarking for Embodied Energy (Jones and Hammond, 2010)

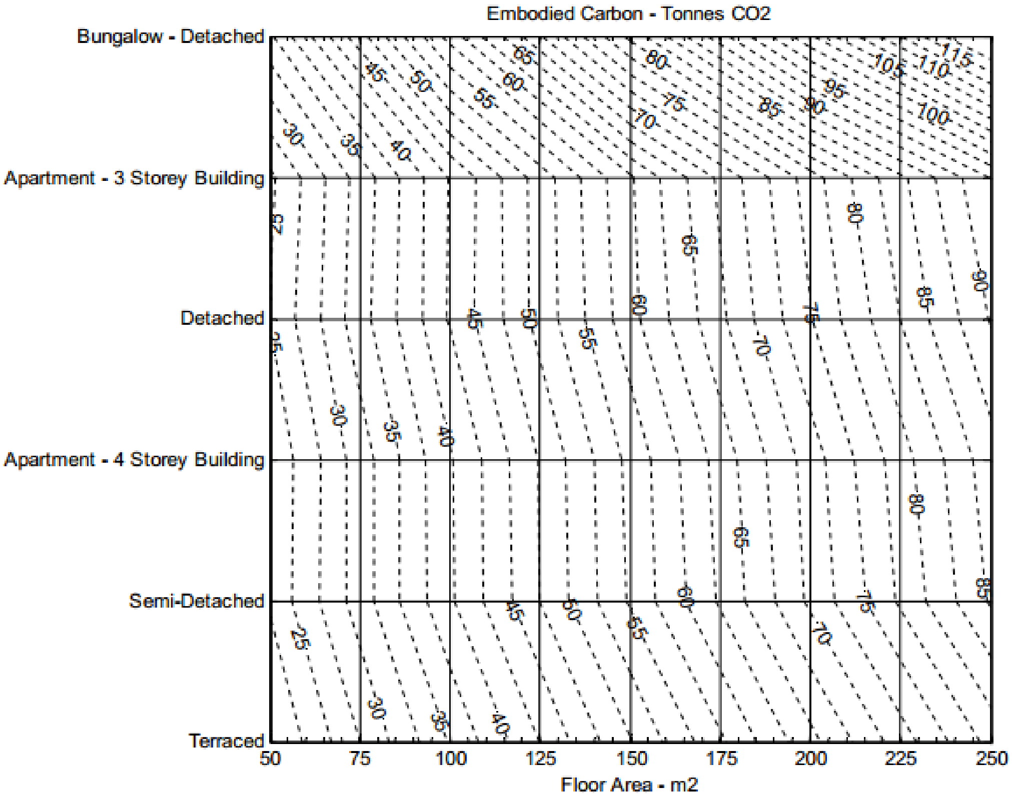


Figure 61: SERT Benchmarking for Embodied CO2 (Jones and Hammond, 2010).