Opportunities for the demand and supply of regional resources to reduce the embodied impact of domestic thermal insulation

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Abstract

The demand for insulation is expected to rise in the UK to achieve National and International energy targets, such as the 2016 Paris Agreement. The majority of products currently installed in UK housing are manufactured from mineral and fossil resources. Research indicates that biomass-based products have lower embodied impact than most conventional products. The drivers and barriers associated with a large-scale shift to biomass-based products, such as the socio-economic impact and the availability of local resources, are yet to be explored. To do this, the supply and impact of insulation products will be investigated with a long-term and large-scale perspective focusing on the case of Wales, UK.

The embodied environmental impact of mineral, fossil and biomass-based products is estimated using process-based life-cycle assessment. A forecast of demand for insulation from new and retrofitted dwellings is used as basis for future supply scenarios modelling different combinations of products. Baseline and alternative scenarios are built to model overall changes of environmental impact brought about by product substitution over time. The quantity of materials required to manufacture biomass-based products is compared to the regional capacity to supply such levels of resources. The socio-economic impact of products is investigated by surveying market prices and performing input-output life-cycle assessment. Multiplier effects for UK industry sectors are obtained via economic input-output analysis. Product prices and multiplier effects of the relative industry sector are used to estimate embodied work and gross value added associated with the various insulation products.

The research shows that biomass-based products have better cradle-to-gate environmental and socio-economic impact than fossil-based products, whilst benefits are less defined in comparison to mineral-based products. However, the good environmental performance of biomass product is tied to the carbon sequestered in their material. If the products are incinerated at the end-of-life stage, the embodied carbon savings biomass products can be lost. Demand for biomass-based products in Wales could be sustained with local resources and bring environmental and socio-economic benefits, although capital investment and policy intervention would be required to establish local supply chains and lower product price.

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ADP	Abiotic Depletion Potential
AP	Acidification Potential
BRE	Building Research Establishment
CE	Circular Economy
CERT	Carbon Emissions Reduction Target
CESP	Community Energy Saving Programme
CML	Centrum voor Milieuwetenschappen (Institute of Environmental Sciences, Leiden University)
CtG	Cradle-to-Gate
CtGr	Cradle-to-Grave
CtS	Cradle-to-Site
DECC	Department for Energy & Climate Change
DEFRA	Department for Environment & Rural Affairs
EC	European Commission
EE	Ecological Economics
EEI	Embodied Environmental Impact
EIA	Environmental Impact Assessment
EoL	End-of-Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene
EU	European Union
EWI	External Wall Insulation
FAME	Financial Analysis Made Easy (database)
FES	Future Energy Scenarios
FSC	Forest Stewardship Council
FU	Functional Unit
GB	Great Britain (England, Scotland and Wales)
GBC	Green Building Council
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GQL	General Qualification Level
GRI	Global Reporting Initiative
GVA	Gross Value Added
GWP	Global Warming Potential
HD	High-Density
I-O	Input-Output
IBU	Institut Bauen und Umwelt (Institute for Building and Environment, Austria)
IEA	International Energy Agency
IES	Institute for Environment and Sustainability
INCA	UK National Association of Insulation Manufacturers
IWI	Internal Wall Insulation
JRC	Joint Research Council
LCA	Life-Cycle Assessment

LCC	Life-Cycle Costing
LCI	Life-Cycle Inventory
LCWE	Life-Cycle Working Environment
LD	Low-Density
LI	Loft Insulation
LUC	Land Use Change
LWHS	Living in Wales Household Survey
MFA	Material Flow Analysis
NEED	National Energy-Efficiency Database
ODP	Ozone Depletion Potential
OFT	Office for Fair Trading
ONS	Office for National Statistics
PEU	Primary Energy Use
PIR	Polyisocyanurate Rigid foam
POCP	Photochemical Ozone Creation Potential
PUR	Polyurethane Rigid foam
SIA	Social Impact Assessment
SLCA	Social Life-Cycle Assessment
SW	Solid Wall
SWI	Solid Wall Insulation
UNEP	United Nations Environment Programme
UK	United Kingdom (England, Scotland, Wales and Northern Ireland)
WG	Welsh Government
WIOD	World Input-Output Database
WRAP	Waste and Resource Action Plan
XPS	Extruded Polystyrene

1 Introduction

This chapter introduces research context, aim and methods, and describes the structure of the thesis.

1.1 Research context

The built environment and the related economic sector are responsible for a significant share of resource consumption and environmental pollution across the globe (UNEP, 2008). This is due partly to the energy that is consumed by building services during operation and partly to the activities necessary to construct and demolish buildings, including the manufacture of building products. The environmental impact caused through construction is ‘embodied’ and is generally considered smaller than impact due to the use of energy in buildings (NHBC Foundation, 2014; Steele et al., 2015). However, it is acknowledged that as efforts are made to reduce “operational” energy use and the relative carbon emissions, embodied energy and emissions become more significant (Ibn-Mohammed et al., 2013). Other environmental pressures such as acidification or ozone layer depletion also exist and should be considered together with global warming (Rockstrom et al., 2009; Burger et al., 2009).

The building industry in its broadest sense constitutes a significant part of the economy and provides thousands of workplaces in the fields of design, manufacture, construction and maintenance. Its social impact lies not only in the employment generated, but also in the consequences that the physical reality of the built environment has on human health, safety and sense of community (Pearce, 2003). As a responsible part of society, the building industry needs to acknowledge the environmental and social crisis, accept the challenges of sustainability and contribute actively towards its implementation.

In response to these issues and to the wider sustainability dilemma, the use of ‘alternative’ products (locally manufactured and based on renewable biomass resources) is being advocated in construction and other industry sectors. This is supported by theoretical approaches such as ecological economics (Costanza et al., 1997a; Veen-groot and Nijkamp, 1999), bioregionalism (James and Cato, 2014) and localisation (North, 2010; Frankova and Johanisova, 2011; Erickson et al., 2013; Hines, 2014). Scholars argue that substantial benefits could be gained in environmental, social and economic terms if more sustainable products are used:

- Products based on renewable resources, i.e. biomass, are considered to have lower environmental impact than products based on mineral and fossil resources, due to raw materials and manufacturing processes.
- Local manufacturing is considered to reduce environmental impact, due to fewer emissions from transportation, and having a positive effect on local economy and society, due to business development and employment generation.

It is reasonable to question to what degree it is possible to substitute current building products with “more sustainable” alternatives. It can be argued that technical constraints, for example the need for high tensile strength or fire protection, can pose limits to product substitution, as well as constraints related to the effective capacity of the local natural resources of sustaining a high supply of materials. There is a need for evidence that product substitution at a large scale could provide significant benefits and offsets potential negative impacts.

Several studies and Life-Cycle Assessments (LCA) have been conducted to assess the environmental impact of thermal insulation products (Anastaselos et al., 2009; Zhou et al., 2010; Murphy and Norton, 2008; Kymäläinen and Sjöberg, 2008; Schmidt et al., 2004; Asdrubali et al., 2015; Jagruthi et al., 2014; Densley Tingley et al., 2015; Mazor et al., 2011; Intini and Kühtz, 2011; Pargana et al., 2014). Insulation products are an essential technology for energy efficiency in buildings, and their overall life-cycle balance is generally positive at least in term of carbon emissions, because the emissions avoided through the adequate thermal insulation of buildings largely offset the emissions caused by the manufacture of insulation products (Schmidt et al., 2004). Two main drivers are encouraging researchers to study the LCA of insulation products:

- There is a large number and variety of products on the market, thus research in this field can reflect on the differences in embodied impact associated to the use of different primary materials (biomass, mineral or fossil) and manufacturing processes (Huijbregts et al., 2003);
- The demand for thermal insulation products can be expected to rise, due to the necessity to increase energy efficiency in buildings (Giesekam et al., 2014), and therefore their environmental and socio-economic impact needs to be evidenced.

Most LCA studies on insulation products are conducted at single-product scale, i.e. comparing few products for a specific application (Schmidt et al., 2004; Murphy and Norton, 2008; Intini and Kühtz, 2011; Densley Tingley et al., 2015). This research looks at product substitution at a larger scale and on a longer term. It starts from the idea that the embodied impact of the future supply of insulation can be projected on the basis of current conditions and future trends in construction, and used as a baseline to measure changes brought about by different products. It aims to provide a holistic sustainability assessment by including socio-economic aspects as well as more typical environmental ones.

1.2 Research aim and method

This research investigates the demand and supply of insulation products for domestic buildings at the regional scale of Wales over a period of 30 years, focusing on the resulting embodied impact and demand for natural resources. The research is inspired by a reflection on theoretical approaches to sustainability and is shaped by the following questions:

- What savings in Embodied Environmental Impact (EEI) are achievable in Wales through a large-scale substitution of conventional insulation products with biomass products?
- Do biomass products have better embodied socio-economic impact than conventional products?
- To what extent could regional resources meet the demand for biomass insulation products generated by the domestic sector in Wales?

The research aims to provide evidence in a regional case study to support a significant substitution of the currently used insulation products with biomass-based alternatives, considering their embodied environmental and socio-economic impact, and the potential to meet the demand for biomass products with local resources. The research looks for quantitative evidence of the benefits and drawbacks brought about by a large-scale market uptake of biomass products together with a progressive decrease in the use of conventional ones.

Wales has been selected as case study for this research due to its clear regional identity, the potential of its natural resources and the ambition towards a more sustainable model of development which is embedded in its legislative framework (Welsh Government, 2009) together with the need to increase the energy efficiency of its dwellings to reduce fuel poverty.

The research follows three main objectives, which divide the research process into three ‘components’, each one employing different quantitative methods to pursue the related objective:

1. generate scenarios to assess the Embodied Environmental Impact (EEI) of the total domestic supply of insulation in Wales between 2020 and 2050 under different product combinations;
2. assess the embodied socio-economic impact of individual insulation products;

3. evaluate the capacity of the Welsh territory and economy to meet the demand for biomass products with local natural resources.

The overall methodological framework follows the principles of Material Flow Analysis (MFA) to generate demand and supply scenarios. The latter provide the basis for the EEI assessment of the supply of insulation products in the first component of the research, and for the evaluation of the capacity to meet the demand for biomass in the third component. Process-based LCA is used in the first component of the research to assess the EEI of insulation products. Market prices and Input-Output (I-O) analysis are used in the second component to assess the socio-economic impact of insulation products, focusing on the aspects of affordability, labour intensity and wealth generation. This combination of techniques was developed for this research, as no single method was considered appropriate to conduct the research in its entirety. Thus, this work is also an exploration of different methods and their potential. The availability of data and resources was also a decisive factor for the selection of techniques.

1.3 Structure of the thesis

This thesis is structured into seven chapters:

1. Introduction;
2. Literature Review;
3. Research Design
4. Environmental Impact Assessment – method and results;
5. Socio-economic Impact Assessment – method and results;
6. Demand and Supply of Natural Resource – method and results;
7. Summary, Discussion and Conclusions.

After this Introduction, studies relevant to this work are discussed in the Literature Review (chapter 2). The theoretical approaches to sustainability forming the basis of the research are presented in part 2.1. Existing methods to assess environmental and socio-economic impact, with particular focus on construction products, are reviewed in part 2.2. The use and environmental impact of insulation products used in the UK are discussed in part 2.3.

The Research Design (chapter 3) explains the combination of methods used in the research and provides the rationale for their choice, allowing the reader to understand the overall research process. Each of the three following chapters (4, 5 and 6) describes in detail the methods used and presents the results of the three components of the research separately.

This enables the reader to follow more easily the steps leading to the results of each component. Chapter 4 focuses on the assessment of environmental impact and describes the method used to forecast insulation demand, build supply scenarios and perform product LCA. Chapter 5 focuses on the assessment of socio-economic impact and describes the method used to survey product prices and conduct I-O analysis. Chapter 6 focuses on the assessment of demand and supply of regional resources, and describes the method used to estimate the potential availability of local resources for biomass insulation. In chapter 7, the outcomes of the three research components are analysed and commented on as a whole. The thesis is concluded with a discussion of the research value and its potential developments.

2 Literature review

This Literature Review is divided into three parts:

- (2.1) theoretical background on sustainability;
- (2.2) review of methods to assess environmental and socio-economic impact, focusing on construction products;
- (2.3) insulation products, their use in the UK and the assessment of their environmental impact to date.

2.1 Sustainability theories

This first part of the Literature Review introduces the theories that inspired the approach to sustainability taken in this research. It begins with an overview of the concept of sustainability and the challenges it poses to the contemporary world. After presenting the concept of sustainability, mainstream and alternative approaches are discussed. The review of approaches to sustainability is concluded with a summary and the identification of the 'principles' which inform this research and provide the rationale for its formulation.

2.1.1 The concept of sustainability

The necessity for a more sustainable society has been acknowledged as one of the great current global challenges (WCED, 1987). The consequences of climate change forecasted by scientists and the recurring energy supply issues are pushing governments and industry to act. A large share of energy consumption and GHG emissions are associated with the built environment (UNEP, 2008; IEA, 2009). Due to rising concerns of energy scarcity and climate change, policies and initiatives often focus on the abatement of energy consumption and Green House Gas (GHG) emissions (Ibn-Mohammed et al., 2013). A strategy for a sustainable development should also address issues besides climate change, for example resource scarcity and pollution (Allouche, 2011). Sustainability integrates social and economic dimensions with the environment, and all three are considered essential and complementary (UN Assembly, 2005).

Sustainability and sustainable development are neither widely understood nor accepted, and have been criticised for lack of clarity and objectives. ~~In its simplest meaning *sustainability* refers to the *capacity to endure*, namely the capacity to continue life, but the word is often used to refer to human activity and its impact on ecosystems (Oxford Dictionaries, 2017). The concept of *sustainable development* is more debated.~~ The definition by the Brundtland

Commission states that: “*sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”* (WCED, 1987) This definition is not universally agreed upon, especially because sustainable development is seen to imply a *weak approach* to sustainability.

Natural capital can be defined as material resources and ecosystems services provided by nature, while human capital as goods, infrastructures and utilities produced by human activity (Costanza et al., 1997a). The *weak approach* to sustainability assumes that natural and human capitals are interchangeable, and therefore as long as the sum of the two stocks remains constant, inter-generational equity is ensured. The *strong approach* denies that the two kinds of capital can be interchanged or compared (van den Bergh, 2001a; DEFRA, 2012), because natural materials can hardly be substituted by man-made products and ecosystem services cannot be replaced by any human activity (Costanza et al., 1997a).

The Brundtland definition of sustainability is based on the existence of *human needs*, and states the unavoidable *demand* for those goods that are necessary for human life and wellbeing (Benoit and Mazjin, 2009). Advocates of the strong sustainability approach argue that scientific understanding shows that all human needs are provided ultimately by nature as material resources and ecosystem services. These natural inputs sustain people and their economies, but limitations exist for renewable and non-renewable sources (Costanza et al., 1997a). Since ecosystems can only provide a *limited supply*, it follows that human demand for resources must remain below the natural capacity in order to ensure the long-term stability of the system (Daly, 1990; Costanza et al., 1997a).

In biology, the *carrying capacity* of a territory is the maximum population of a species that can be sustained indefinitively on a defined area of land (Hui, 2006). For the human species, the carrying capacity is determined by the available resources and the rates of human demand. The latter depends on the size of the population, its specific needs and the technological means that are used to meet these needs (Costanza et al., 1997a). These dynamics are expressed in the IPAT equation as formulated by Alcott (2010):

$$I = f(P,A,T)$$

where I = Impact on the environment, P = Population number, A = Affluence (consumption per capita), and T = Technology. The equation implies that environmental impact is a consequence of the interaction between the P-A-T factors. Since the environment has limited resources and ability to absorb pollution, it follows that the population needs to regulate its growth, its demand for affluence and its technological means to avoid overloading ecosystems with unsustainable pressure (Costanza et al., 1997a). Thus sustainable development implies development within the natural limits of resource availability: a society is sustainable when the rates of extraction and pollution are kept within the ecosystem potential for regeneration (Daly, 1990).

There is growing evidence that environmental pressure caused by human activity has already overloaded the natural capacity in some areas (IPCC, 2013) According to the Millennium Ecosystem Assessment (MEA Board, 2005), the current world-wide demand for renewable resources and ecosystem services is well beyond the planetary capacity of regeneration. As a consequence, every year more resources are consumed than regenerated at world level, and the ecological deficit increases (MEA Board, 2005). Rockstrom et al. (2009) proposed boundaries for nine planetary dimensions of ecological pressure which, if surpassed, will lead to ~~non-linear~~ environmental changes with significant consequences for humanity. Seven of these dimensions were quantified, with atmospheric CO_2 concentration, nitrogen cycle and biodiversity loss already passing the estimated safety thresholds (Rockstrom et al., 2009). In addition, developed countries are exploiting territories outside their national borders to sustain internal consumption and externalise the environmental risks (OECD, 1991 in Costanza et al., 1997a; Giljum and Hubacek, 2001; Giljum and Eisenmenger, 2003).

Many developed countries have acknowledged their responsibility to address environmental pressure. In the *Government of Wales Act 2006,* the Welsh Government is given a duty to promote and implement sustainable development through a dedicated scheme. *One Wales One Planet* is the strategic plan for sustainable development adopted by the Welsh Government (2009). This plan declares a vision for Wales to progress towards “using only its fair share of the Earth’s resources” within a generation (WG, 2009, p.32), though no specific target is given. Two other significant targets are the annual 3% reduction in GHG emissions from areas of devolved competence (such as Building Regulations) and the aim to stabilise “the housing ecological footprint by 2020, then reduce.” (WG, 2009, p.33).

2.1.2 Theoretical approaches to sustainability

This section proceeds by firstly presenting approaches closer to widely-accepted positions and successively exploring more ‘radical’ ones. The ‘mainstream’ economic approach has a large influence on policy choices, but it is criticised by many advocates of sustainability. Alternative or ‘radical’ approaches developed in contrast with mainstream economics are often put under the name of *heterodox* economic theories (Lee, 2014). A comprehensive discussion on this topic is beyond the scope of this review, thus only the ideas that directly inspired this research are presented here. The common themes found across these radical approaches to sustainability constitute the theoretical background for the combined environmental and socio-economic assessment of insulation products conducted in this research.

Mainstream economics and decoupling

The mainstream economic theory provides the primary lens through which economic dynamics are interpreted and is adopted as framework for policy and governance in a large part of the contemporary world. Adam Smith (1723-1790), acknowledged as the father of modern economics, saw the main driver for industrial activity and trade in *self-interest*, and theorised that the ultimate but unconscious effect was the achievement of public interest, i.e. the creation of national wealth. This principle implies that if there is an increase in the economic activity of people and firms, we can expect a consequent increase in the national wealth (Costanza et al., 1997). Adam Smith was also the first to introduce the concept of *comparative advantage* (i.e. when a country can produce goods at a lower cost than other countries; OECD, 2011), which was later developed by David Ricardo in 1817. Though some may argue that the importance of comparative advantage has declined in the globalised economy (Porter, 1985), the OECD claims that "comparative advantage remains the underlying principle the policy makers can place their faith in to guide economies" (OECD, 2011, p.3).

The ideas of Smith and Ricardo grew with the industrial revolution and laid the foundations of what can be referred to as *mainstream economics*, i.e. the set of theories and models used to interpret the economy and which defines policy in the majority of developed countries. Economic growth, measured as Gross Domestic Product (GDP) increase, stands at the core of the model of wealth proposed by mainstream economics (van den Bergh, 2001b). Although wealth may be initially concentrated in a few hands, a 'trickle-down' effect will ensure some form of distribution among the population (Aghion and Bolton, 1997). It follows that policies aiming at increasing wealth and wellbeing should primarily address economic growth, seen as necessary condition for development. Any theory of sustainability that accepts economic growth as the mean to ensure wealth must propose a model in which growth can be sustained without limits over a long term period (van den Bergh, 2001b). The *Limits to Growth* model provided some evidence that unlimited growth of population and economic activity in a finite world results in 'overshooting', a rising deficit, and then crisis and collapse (Meadows et al., 2004). The consequences of overshooting are already observed in sectors of the natural world (MEA Board, 2005), and the rising deficit in natural capital might sooner or later have an impact on the ability to produce human capital, driving the entire system into crisis.

To combine growth with sustainable development, mainstream economics relies on the concept of *decoupling*, i.e. the capacity to feed economic growth whilst progressively reducing environmental impact (Jackson, 2009, p.48). Decoupling is measured as the decline of ecological pressure per unit of economical output and has been observed in many developed countries as a *dematerialisation* of the economy, where activity moved from the production of goods to the production of services. In the last decades 'relative' decoupling (i.e. decoupling measured within national boundaries) has improved in developed countries, whilst 'absolute' (world-wide) decoupling has decreased, because the global average rates of resource extraction and pollution have continued to rise (Jackson, 2009).

It is argued that relative decoupling has been achieved because developed countries started sourcing the majority of material needs outside national borders, while domestic economies shifted to the production of services (Amann and Fischer-Kowalski, 2001). Environmental pressure has been moved out of the boundary of the calculation, and therefore absolute decoupling still needs to be proved as a realistic way to enable long term economic growth and sustainability at the same time (Jackson, 2009). Sustainability might require a 'balanced' economy, which can ensure wellbeing and social fairness without being fuelled by economic growth (Meadows et al., 2004; Jackson, 2009).

Circular economy and industrial ecology

The concept of *Circular Economy* (CE) provides a framework to reduce environmental impact via technical improvements. Its focus on the quantification of physical flows and on the refinement of manufacturing processes is adopted in this research as a guiding principle to model, assess and improve the environmental impact of insulation products.

Resources are extracted from the natural environment, entered in the economy and transformed by human activity into goods. At the end of their life-cycle, most goods become waste and exit the economy returning to the environment. The latter is used as a *source* of useful materials and a *sink* for useless waste (Hammond, 2009). This pattern of production and consumption can be described as operating largely in a linear way. The capacity of the planet to provide natural capital is limited, as is the capacity to absorb pollutants back into the ecosystem. Therefore the higher the material flows that are needed to sustain a linear economy, the higher the resulting pressure on the environment.

Proponents of CE envision a system where products are recycled at the end of their life, and re-enter the system as resources for new products (Ellen MacArthur Foundation, 2012). This reduces the need to source new materials and to produce waste, decreasing the environmental pressure while maintaining a steady flow of goods. Such a system implies more than a simple increase in recycled materials, and requires changing the way products are designed, produced and consumed. Dawkins et al. (2010) explain that CE relies strongly on the use of exergy analysis and LCA; a cradle-to-cradle approach to design; a *lean-production* system; and the establishment of *closed-loop* supply chains. To implement CE it is necessary to achieve a deep understanding of the interactions inside and between industrial and natural processes to maximise the production of human capital while limiting the impact on the environment. This multidisciplinary research stream has been called *industrial ecology* (Røine, 2000) since it aims to replicate the efficiency achieved in natural ecosystems (where all materials are recycled and there is virtually no waste) into the industrial world, enabling waste of a process to become resource for another process (Garner and Keoleian, 1995).

The principles of CE have started to be accepted and implemented in some areas of the world (Yong, 2007; COM/2014/0398; Com/2015/0614; Winans et al., 2017). In the UK, the publicly-funded Waste and Resource Action Programme (WRAP) has adopted CE as its driving philosophy (WRAP, 2014b). CE can offer considerable economic benefits and potential for new business (Rainwald and Wallace, 2012), but these are secondary effects rather than explicit objectives. Generally, the focus of CE remains on scientific and technological aspects more than economical ones. Regarding growth, there are ultimate thermodynamic limitations to the degree of efficiency that industrial processes can possibly achieve (Kjelstrup and Zvolinschi, 2008), and it is arguable that continuous economic growth contrasts with the equilibrium of the ecosystems which industrial ecology aims to emulate.

The main limitation of CE appears to be the lack of engagement with the social dimension of sustainability, although a number of different approaches have included societal aspects (Pomponi and Moncaster, 2017). Proponents of more radical approaches to sustainability have pointed out that CE presents an unclear position towards the issue of overconsumption, relies strongly on technological optimism, and seeks technological advancements only to allow developed countries to maintain their high level of consumption (Huesemann, 2003). Rourke et al. (1996) criticised industrial ecology for being poorly defined and presenting methodological weaknesses. They pointed out a lack of focus on energy flows and on indications for socio-technical transition, and a simplistic view of the free-market mechanisms (Rourke et al, 1996). However, CE can provide sound techniques for the progress towards more environmentally sustainable technologies, and could contribute to economical sustainability by developing feasible ways to achieve modern standards of living with lower environmental pressure through less financially expensive means.

Ecological Economics

Ecological Economics (EE) is based on the study of physical flows and represents the most explicit effort to translate the “strong” approach to sustainability into an economic model.

EE differs from *environmental and resource* economics, which focuses on the monetary quantification of environmental assets and their depletion through the assumption that a monetary value can be assigned to natural capital (van den Bergh, 2001a). EE by large rejects this assumption, on the basis of the strong approach to sustainability. What significantly distinguishes EE from mainstream economics is the understanding of the economic system as embedded in and absolutely dependent from the natural ecosystem (Costanza et al., 1997a). Therefore technological and economic policy "should be designed to increase the productivity of natural capital and its total amount, rather than to increase the productivity of human-made capital and its accumulation" (Costanza et al., 1997a, p.92).

EE advocates an inter-disciplinary approach to economic matters to achieve an efficient allocation of resources, a fair distribution of wealth and a sustainable scale of material throughput (Costanza et al., 1997a, p.89). Ecological economists argue that unregulated international trade prevents these objectives because it "conflicts sharply with the basic national policies of: getting prices right, moving toward a more just distribution, fostering community, controlling the macro-economy, and keeping scale within ecological limits." (Costanza et al., 1997a, p.176). EE highlights the difference between economic growth, as a phenomenon that brings monetary wealth to a population as well as potential environmental impacts, and the actual wellbeing and standard of living enjoyed by a population (Costanza et al., 1997a). *Pigouvian taxation* (i.e. taxes on pollution) and market mechanisms on environmental goods are advocated as pragmatic solutions for their protection (Costanza et al., 1997b). EE adopts a position of prudent scepticism on the capacity of technology to ensure decoupling without limits (Costanza et al., 1997a). The 'rebound effect' indicates that efficiency alone does not ensure reduction of consumption (Alcott, 2008). EE distinguishes between low and high entropy technology. Low entropy technologies have "a high ratio of human intelligence and information to material and energy", while high entropy technologies present the contrary (Costanza et al., 1997a, p.196).

The approach of EE is criticised by mainstream economists, who developed *environmental and resource economics* to internalise environmental pressure, which is seen as a market failure. Sagoff noted that some developments in ecology (Drury, 1998; Lawton, 1999; Simberloff, 2004; cited in Sagoff, 2012) have questioned the theory that ecosystems are regulated by principles and tend towards a symbiotic equilibrium between species. This undermines the very basis of EE, which looks at ecosystems as examples of stable and self-regulating systems (Sagoff, 2012). EE is also criticised for being close to Malthusian positions, or for being too moderate and uninterested in tackling social injustice (Kovel, 2002). However, ecological economists have acknowledged the connection between social, environmental and economic issues as well as the necessity to maintain a dialogue with the mainstream approach, since EE is trans-disciplinary, "methodologically pluralistic and accepts the framework of analysis of neoclassical economics along with other frameworks" (Costanza et al., 1997a ,p. 78). Despite the critiques, EE plays an essential role in the attempt to embed the economy into the natural system, and its development has also opened economic studies to diverse and innovative approaches.

Appropriate technology

The concern over quantitative and qualitative aspects of human labour as a factor of production expressed by many alternative approaches to sustainability can be traced back to the concept of *appropriate technology* introduced by Schumacher (1973).

Schumacher (1973) claimed that the problem of the modes of production has not been resolved in our times, but on the contrary, modern production exacerbated social injustice while depleting natural resources. Schumacher (1973) made a distinction between *tools* and *machines* as means to achieve an end. Tools are low-energy and low-cost artefacts which reduce the fatigue of manual work while increasing the skill and creativity of the worker, while machines are energy-intensive and expensive artefacts which reduce the fatigue but also the creativity and the quantity of manual work, and require less skill. In other words, tools are labour-intensive whilst machines are capital-intensive (Schumacher, 1973, p.50). Schumacher argued that the increase in productivity that was achieved due to the availability of capital and machines has caused a degradation of human work and effectively diminished opportunities for employment.

Schumacher (1973) proposed the notion of *appropriate development* for a country based on the principle of *appropriate technology*, a technology which maximises employment while reducing the initial capital and the environmental pressure through the use of tools instead of machines (Schumacher, 1973, p.136-141). The issue of scale is particularly important, as appropriate technology should enable the establishment of low-cost, small scale and localised units of production which are appropriate for their regional context (Schumacher, 1973, p.53-68, 164). Essentially, Schumacher invited to question technological choices and advocated for social and environmental consequences to have a central role in the design of technology and the establishment of economic activities.

Despite the widespread diffusion of Schumacher's ideas – at least among advocates of sustainability – these have had little consequences on the real world, partly because of their incompatibility with mainstream economics (Pursell, 1993). The concept of appropriate technology conflicts with mainstream economics on two main aspects: scale of production and labour intensity. Increasing the scale of production is generally a positive factor for mainstream economics, as it increases output while decreasing marginal cost. For Schumacher, increasing the scale of production indiscriminately can have negative consequences, and therefore the scale of production needs to relate to the local context. In mainstream economics, economic growth is often achieved moving from labour-intensive to capital-intensive production (Ross, 2010), using technological innovations to substitute human labour with capital, with the purpose of reducing cost (salaries) while increasing output.

Localisation

Radical approaches to sustainability are mostly critical of globalisation, while attributing positive value to the use of local resources and the development of local economies. Globalisation of the free-market economy is one of the dominant phenomena of the contemporary world and has developed side-by-side with an unprecedented rise in international trade. The International Monetary Fund (IMF) states that “economic globalisation is a historical process, the result of human innovation and technological progress. It refers to the increasing integration of economies around the world, particularly through trade and financial flows.” (IMF, 2000, p.1) However, the IMF acknowledges that the term also refers to:

- Movement of goods (trade);
- Movement of capital;
- Movement of workforce;
- Movement of knowledge and technology (2000).

Globalisation is seen as the consequence of the expansion of neoliberalism over protectionist policies. The opening of national economies to international free trade was institutionalised and regulated at world level with the progressive application of the General Agreement on Tariffs and Trade (GATT) in 1947 and the creation of the World Trade Organisation (WTO) in 1995.

The transition to a globalised society and economy met strong opposition from intellectuals to grassroots movements who support the re-localisation of the economy, following the principle that “economic decisions should focus not on profit maximisation and economic efficiency to the exclusion of all else, but on meeting needs as locally as possible” (North, 2010, p.9). Hines (2000) argues that globalisation has brought the following consequences:

- Exploitation of the natural resources and workforce of underdeveloped countries;
- Decreased employment in developed countries;
- Increased international transportation, resulting in increased GHG emissions;
- Diminished controls on source and quality of materials and products, and increase in health problems;
- Loss of economic diversification, security and democratic control (Hines, 2000).

Hines (2000) proposes a transition from the current unregulated regime of global competition controlled by transnational corporations to a system based on local competition between small businesses and international cooperation through free flow of knowledge and technology. The main argument of localisation is to localise and downscale companies to bring together the places of production and consumption (Frankova and Johanisova, 2011).

Advocates of localisation argue that a regime of fair competition between local businesses would maintain product choice and quality in the local economy, whilst international cooperation would enable innovative knowledge and technology to be exchanged across countries.

A localised economy does not imply an autarkic economy (North, 2010), where all trade with the outside is intentionally excluded for political reasons. Society and the environment motivate the exchange of goods which can be produced internally by region and nations (North, 2010). A re-localisation policy should allow for flexibility, taking into account natural and cultural features, and creating economies localised from the urban scale to groups of regions (Frankova and Johanisova, 2011).

Mainstream economists are largely opposed to localisation, seen as an obstacle to efficiency, maximisation of profits and economic growth (Frankova and Johanisova, 2011). Left-wing politicians and eco-socialists criticise the localisation agenda for potential risks of fostering localist and nationalist ideas, cultural closure, and geographical limitations to the applications of rights (North, 2010). A more subtle critique to the "local trap" of localisation is voiced by social geographers, who argue that there are no ensured benefits in localising production because the local scale does not directly imply the best outcomes for the economy, and therefore scale should be intended as a strategy and not an aim itself (North, 2010; Frankova and Johanisova, 2011). There are examples where lower GHG emissions could be achieved through transport and better conditions of production in foreign countries, therefore justifying international exchange (North, 2010). Furthermore, the re-localisation agenda raises important questions of social justice in relation to the disparity of resources in different regions, and to migration due to scarcity itself and climate change (North, 2010).

Bioregionalism

The concepts of *place* and *scale* are often seen as playing an essential role in a sustainable society (Daly, 1992; Jordan, 2002; Plummer, 2005; Wilbanks, 2007). While sustainability is a global problem, it is acknowledged that the solutions need to be implemented at regional, urban and community scales. The regional scale of policy and administration can assume particular importance for the delivery of sustainability through local control of resource use and pollution. Graymore et al. (2008) believe that the regional scale should be the primary level for the assessment and delivery of sustainability, because at this scale conflict between human demand and natural supply becomes explicit and governance and community have most potential for action. A 'sustainable region' is capable of sustaining the population without depleting the natural resources of its territory by assuming environmental protection as the primary objective and constraining human activities within regional limits (Graymore, 2005).

However, conflict might exist between regional policy and sustainable development, since regional policy was originally devised as an instrument to foster economic growth (Costanza et al, 1997a, p.236; Sedlacek and Gaube, 2010).

The theory of *bioregionalism* (developed in the US in the 1970's) focuses on the region as the appropriate scale for life. A distinctive feature is for political boundaries to match 'bioregions' to ensure a coherent administration of natural resources. The neologism *bio-region* can be translated simply into "life-place", though Berg and Dasmann (1977) specify that the term "refers both to a geographical terrain and a terrain of consciousness - to a place and the ideas that have developed about how to live in that place. Within a bioregion the conditions that influence life are similar and these in turn have influenced human occupancy.*"* (Berg and Dasmann, 1977, p.399).

In recent years, bioregionalism was revitalised by Cato (2009; 2011; 2013) developing the vision for a bioregional economy and synthesising the positions of Schumacher, EE, localisation, bioregionalism, the Permaculture movement and others. 'Bioregional economics' advocates the necessity to shift from a free-trade regime to one of *trade subsidiarity*, through which regional economies would achieve a high level of *self-reliance* (Cato, 2009; 2011; 2013). This implies limitations of long-distance trade to few particular goods, and the recovery, development and stewardship of regional resources to meet the local demand. In Table 2. 1, Cato (2011) categorises goods within a trade subsidiarity approach through two parameters: local availability of raw materials and labour intensity.

Table 2. 1 – Trade subsidiarity framework (source: Cato, 2011)

		Raw materials	
		Local	Global
Labour	Non-intensive	Products which can be obtained from local materials and do not require complex labour input.	Products which do not require complex labour input but need non-local materials and/or climate.
	Intensive	Products which can be obtained from local materials and require complex labour input.	Products which require complex labour input and need non-local materials and/or climate.

The objective of trade subsidiarity is to achieve a high level of regional self-reliance, meaning that the majority of goods consumed to meet the basic needs are sourced and produced within the region. In theory, this enables the local population to gain control of local resources and to limit the dependence on goods produced abroad. Such a localised economy would be more resilient, more capable of ensuring long term prosperity (Cato, 2013). There is a difference between self-reliance and *self-sufficiency*. The latter is a more radical stage, where the economic system is capable of sustaining itself autonomously and does not need exchange with the outside. Self-reliance is a more flexible principle, and the categories of the trade subsidiarity framework – local/global and non-intensive/intensive – are the poles of a continuum rather than separated entities (Cato, 2011).

In a self-reliant bioregional economy, taxes would focus on resource use and pollution (i.e. Pigouvian taxation), with a shift in taxation from 'goods' to 'bads', i.e. waste and pollutants. Cato argues that the bioregional theory addresses the three pillars of sustainability, and a transition towards a bioregional economy could bring significant benefits in environmental, social and economic terms (Cato, 2013).

Bioregionalism has been criticised for exaggerating the democracy and the efficiency of smaller units of governance (Newton, 1982), for not providing clear parameters for the establishment of bioregions, and for being detached from reality (Kovel, 2007). Ethnic and cultural variations seldom overlap clearly with natural boundaries (Hall, 1935, in Meredith, 2010, p.89) and that issues of political viability, citizen engagement, property rights discussion, change of production systems pose considerable barriers for the adoption of bioregionalism as practical approach (Simonis, 1997). It should be clarified that re-localisation and bioregionalism do not advocate autarky nor the end of global trade. The aim is not traditional protectionism, but responsible policies to avoid the environmental damage and the social exploitation caused by the externalisation of pollution and goods production.

2.1.3 Conclusion from the review of sustainability theories

This first part of the literature review has provided an overview of the theoretical approaches informing this research. The main points are summarised as follows:

- Global environmental pressure is rising and developed countries have a significant responsibility to address this issue;
- There is a variety of theoretical approaches to the concept of sustainability;
- Mainstream economics supports decoupling as the main way to reduce environmental pressure while ensuring economic growth;
- Radical approaches consider mainstream economics to be an inadequate theoretical framework to address the systemic challenges of sustainability. The spread of globalisation and neoliberal policies is regarded as a main driver of global environmental pressure and social injustice. Alternative pathways are necessary to address environmental and social issues.

Although diverse approaches to sustainability exist, common themes can be found throughout the theories which have been reviewed so far. Firstly, the strong approach to sustainability is a common foundation of many approaches. It implies a focus on the physical evaluation of the interactions between society and the environment, in the awareness of the fundamental difference between human and natural capital and the necessity to conserve the latter. Circular economy provides a useful framework to assess the environmental impact of human activities in physical terms and reduce it through technical developments.

The impact that technological choices have on the quantity and quality of human labour required for production is highlighted by many of the radical approaches to sustainability. Labour intensity is used to classify products in the concept of trade subsidiarity, and the distinction between tools and machines posed by Schumacher (1973) is similar to the distinction between low and high entropy technology introduced by ecological economists. The positive connotation attributed to labour intensity and the inclusion of qualitative aspects contrast with the position of mainstream economists, who consider human labour as a factor of production to be minimised.

The radical approaches to sustainability also highlight the necessity to reconnect production and consumption at the local scale as a necessary step to decrease environmental pressure and support local economies by generating employment and wealth. An increase in the use of locally-sourced renewable materials is considered instrumental to achieve higher self-reliance and resilience at the regional scale.

These ideas might provide solutions to the challenges of sustainability, but their implementation raises many questions in terms of feasibility and wider consequences. Would a shift towards ‘bioregional products’ generate more employment? Would this shift be economically viable within current conditions? To what extent a region would be able to achieve self-reliance in a specific sector? What would be the consequences on existing economic activities? These issues are explored in this research by focusing on the supply of thermal insulation products in Wales as a case study. Socio-economic aspects such as price, labour intensity and wealth generation are investigated together with environmental aspects to provide a more holistic assessment. The next part of the literature review discusses the impact assessment methods considered for the research.

2.2 Impact assessment methods

Impact assessment methods are presented in this part of the Literature Review, focusing on Life-Cycle Assessment (LCA). The general approach to environmental impact assessment is discussed in section 2.2.1. Main LCA techniques are described in section 2.2.2. Approaches and techniques for the assessment of social and economic impact are discussed in sections 2.2.3 and 2.2.4. Novel LCA approaches such as hybrid and integrated LCA are presented in section 2.2.5. EU and UK policy instruments related to product impact assessment are briefly discussed in section 2.2.6.

2.2.1 Assessing environmental impact

Several frameworks have been developed to assess sustainability using different indicators, with most frameworks focusing on environmental sustainability (Paloviita, 2004). Indicators of environmental impact are used to measure environmental performance, while other types of indicators assess environmental management or conditions (Kolk and Mauser, 2002). If environmental sustainability is intended as the capacity to maintain natural capital (Goodland and Daly 2015), one way to assess the sustainability of a product or a service is to identify its effect on the natural capital, i.e. its environmental impact. This can be defined as "any alteration of environmental conditions or creation of new conditions, adverse or beneficial, caused or induced by the action or actions under consideration" (Agricultural Document Library, 2011). A distinction can be made between primary or direct impacts, caused directly by the "action", and secondary or indirect impacts, caused at a later stage by consequences of the action. Indicators can assess sustainability at the macro level, for examples a national economy, and at the micro level, for example a single company or plant site (Helminen, 1998). The former are often derived from large scale sources such as national accounts, while the latter are built with data specific to the object of the assessment (Warhurst, 2002).

Environmental accounting

Environmental accounting, which can be conducted with physical or monetary units, can be used to measure environmental impact and produce indicators (Veleva and Ellenbecker, 2001). Accounting with physical units might be considered more accurate as physical flows bear higher relation with environmental impact than monetary flows (Paloviita, 2002). The OECD (2008) defines Material Flow Analysis (MFA) as a family of techniques used to quantify the physical flows that enter and exit a system (i.e. inputs and outputs). MFA can be performed at different scales, from the whole economic activity of a country to the production process of a single item, and can focus on different types of material flows. The scale, the focus and the purpose of the analysis determine the specific combination of techniques used in each MFA (OECD, 2008). Several methods have been developed for different functions: some are widely accepted and have been formalised into standard procedures, such as economy-wide MFA (Eurostat, 2013). MFA can be used to produce a variety of indicators, but the literal accounts on which are based are always expressed in physical units (OECD, 2008). Thus MFA differs from conventional economic accounting because it measures flows in units of mass instead of currency. Therefore those material flows which do not usually have economic value and are left out of conventional accounts make a large part of MFA studies. However, due to limited data availability, material flows accounts of physical units are often partially built on monetary accounts such as national Input-Output (I-O) tables (Hoekstra and van den Bergh, 2006), as currency is the unit most widely used to record purchases and sales, and revenue, tax, income, etc. Flows expressed as currency are transformed into mass units through price per unit values, revealing the physical base of the exchanges.

The capacity of MFA to provide indicators of environmental impact is limited, because the *effects* that physical flows have on the environment are not assessed. Nonetheless, environmental accounting is a necessary step to produce indicators of impact. Physical flows can be then aggregated according to a categorisation of environmental impact, as done in the LCA methodology (EC-JRC-IES, 2010). Several categories of environmental impact are identified to evaluate the effects of human activities on the environment. ~~While some categories, such as global warming, are relatively easily measured and modelled, others, such as the loss of biodiversity, are more difficult to measure and model, and therefore to assess. Environmental Impact Assessment (EIA) is a procedure quantifying the environmental impact caused by a specific “action”, for example an urban plan or a manufacturing process. An EIA is usually conducted to forecast the consequences of a planned action before the action takes place (IAIA, 1999), and therefore it makes use of predictive models and measurements of environmental impact from existing activities. LCA is a form of EIA, specifically developed to assess the impact associated with a product or service across its life-cycle.~~

2.2.2 Life-Cycle Assessment

LCA is one of the most commonly adopted and accepted method for the assessment of environmental impact. Since the appearance of the first studies in the 1960’s, different techniques have been developed to perform LCA. The *process-based* technique is the most practiced (Matos and Hall, 2007; Ortiz et al., 2009), its methodology is defined in the ISO 14000 standards and is used to produce Environmental Products Declarations (EPD) and GreenGuide profiles (see section 2.2.6). A relatively less common technique for LCA is based on Input-Output (I-O) analysis. The process-based technique traces the resource use and emissions associated with each process contributing to the final product. The I-O technique uses tables describing flows (physical or monetary) between economic sectors in combination with data on resource use and emissions to estimate the impact associated with final products (Matthews and Small, 2000). Each technique presents benefits and limitations, and researchers have attempted to combine the two techniques into a hybrid method (see section 2.2.5).

LCA is defined as procedures aimed at “the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (International Organisation for Standardization, 2006). An LCA (EC-JRC-IES, 2010) comprises four stages:

1. Definition of goal and scope;
2. Life-Cycle Inventory (LCI) analysis;
3. Impact assessment;
4. Interpretation.

In the first stage the purpose of the LCA is established, a “system boundary” is drawn and the *Functional Unit* (FU) is defined. The FU is the unit of product or service which serves as basis for the impact assessment, depending on the purpose and subject of the LCA. For example the functional unit can be expressed in kilograms, in the case of timber, or watt-hour, in the case of energy, or passenger-per-km, in the case of public transport.

Purpose of LCA

LCA studies can be conducted for different purposes (International Organisation for Standardization, 2006). In its simplest form, the LCA of a product (or service) is carried out to measure its environmental impact. Since the results of a LCA express environmental impact on a functional unit basis (for example GHG emissions per kg), LCA can be used to provide environmental performance indicators to measure ‘impact intensity’, following the definitions of indicators by the Global Reporting Initiative (2002). A detailed analysis can be performed on LCA results to identify “hotspots”, i.e. stages which have the most impact. Sensitivity analysis and testing alternatives can be used to predict the variation in environmental impact and investigate the effects of changes in manufacturing processes. LCA can be used to compare the impact of different products as well as to estimate the impact of “composite” products, such as estimating the impact of a building by summing the impact of its components. LCA studies can be undertaken for experts in academic or industrial contexts or for informative purpose within a public context.

The purpose of the LCA study should, in theory, determine which modelling approach is adopted in the LCI stage (UNEP, 2011). There are two main modelling approaches to LCA:

- the *attributional* approach “attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle)” (UNEP, 2011, p.47) by attributing quantities of physical flows to the functional unit on the basis of normative rules.
- the *consequential* approach “attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product)” (UNEP, 2011, p.47).

The difference between the two approaches can be compared to the difference between the economic concepts of average and marginal cost, as the two approaches answer two different questions:

- attributional approach: what is the average environmental impact associated with one unit of product?
- Consequential approach: what is the environmental impact caused by demanding one additional unit of product? (Consequential-LCA, 2015).

The attributional approach “uses data on actual suppliers or average data, and commonly uses allocation as a means to deal with multifunctional processes or systems”, while the consequential approach “uses data on actual supplier as long as this supplier is not constrained (i.e., insofar as it can respond to an increase in demand with an equal increase in supply), otherwise uses data representing marginal technology (i.e., suppliers that will actually respond to a change in demand), and uses a system expansion approach to deal with multifunctional processes to expand the analysed system with additional processes.” (UNEP, 2011, p.74). It has been acknowledged that LCA practitioners often do not clearly separate the two approaches, as for example attributional models are ‘incorrectly’ used to inform decisions which would be better served by consequential studies (UNEP, 2011). Moreover, the guidance on the matter provided in the International Reference Life-Cycle Data System (EC-JRC-IES 2010b) can be considered outdated and inconsistent (Ekvall et al., 2016).

The capability of consequential LCA (i.e. LCA using the consequential approach) to answer questions about policy changes more appropriately than attributional LCA is a matter of debate among researchers (Zamagni et al., 2012; Suh and Yang, 2014; Plevin et al., 2014). This is exemplified by the case of LCA for biofuels and the inclusion of Land Use Changes (LUC). Yang (2016) explained that a number of attributional LCA studies published before 2008 (Farrell et al., 2006; Hill et al., 2006; Wang et al., 2007) found corn ethanol having lower GHG emissions than gasoline over the life-cycle, concluding that replacing gasoline with corn ethanol would reduce overall GHG emissions. However, two studies in 2008 (Fargione et al., 2008; Searchinger et al., 2008) investigated the direct and indirect LUC as a consequence of increasing the use of corn ethanol. This included, for example, grassland cleared to cultivate corn (direct LUC) as well as LUC caused by rises in market prices of other crops being replaced by corn. The studies concluded that GHG emissions from these LUC offset the benefits of corn ethanol over its life-cycle.

Yang (2016) noted that the LCA studies published before 2008, although technically correct, had not taken into account the limitations of the attributional approach when comparing the *average* GHG emissions of corn ethanol *in the current conditions* with those of gasoline, and assumed that one *additional* MJ of corn ethanol would generate the same amount of emissions while entirely offsetting the emissions of 1 MJ of gasoline. In reality, agricultural and industrial processes are not linear, as different amount of resources per unit of product are required depending on the scale of production. Furthermore, products cannot be expected to replace each other with a one-to-one ratio. For example, choosing to consume one additional MJ of corn ethanol does not automatically decrease the production of gasoline by 1 MJ. Consequential LCA aims to take into account these and other factors, such as the effects of price changes due to changes in demand and supply, and future trends which might affect production. However, Suh and Yang (2014) argued that it is hardly possible for consequential LCA to take into account all factors in real practice, and that the economic models used in consequential LCA (such as the ‘partial equilibrium’ model) come with their own set of assumptions and limitations. Moreover, there are examples of attributional LCA which include consequential aspects (such as scenarios modelling), and therefore the attributional and consequential approaches to LCA should be seen as part of a continuous spectrum rather than a dichotomy (Suh and Yang, 2014).

To address the limitations of the traditional attributional LCA, Yang (2016) proposed a two-steps method to assess the impact of product. Firstly, attributional LCA should be used to assess the average impact under the current conditions of production. Secondly, a study of how this value might change should be performed, taking into account ‘marginal coefficients of production’ (to reflect the non-linear nature of production), ‘displacement ratios’ (to reflect partial substitution of existing products), as well as possible effects of price changes and future trends. The results would be a series of scenarios representing possible conditions, providing a range of estimates rather than a single impact value. The extent of this range would also provide an indication of the uncertainty associated with the results (Yang, 2016).

The number of LCA studies adopting the consequential approach is generally increasing (Zamagni et al., 2012), but these constitute the minority among studies which focus on construction products. This preference for the attributional approach might be explained by the additional complexity and resource demand of consequential studies as well as by the prevalence of attributional models in LCA databases. The methodology established for the production of Environmental Product Declarations (EPD, see section 2.2.6) is also based on the attributional approach.

Process-based LCA

In the second stage of the LCA (i.e. the LCI analysis), the inputs and outputs of every phase of the product life-cycle are listed and quantified (EC-JRC-IES, 2010). The methodological difference between process-based LCA and I-O LCA is fundamental to this stage. The LCI of a process-based LCA is compiled by collecting data for each of the process taking place during the life-cycle, for example, the quantity of fuel used in the transportation of timber. The data collection can be time-consuming depending on the adopted system boundary, which determines where the process-based LCI is truncated. This 'cut-off' excludes from the accounting all the upstream processes considered not sufficiently significant to the overall impact. For example, the energy used to manufacture the truck used in the transportation of timber might be left out of the LCI. As a result of cut-off boundaries, process-based LCA can underestimate environmental impact due to the exclusion of indirect effects (Dixit et al., 2010), with resulting errors found to reach the range of 50% (Lenzen, 2000).

Impact categories

In the LCA stage of *impact assessment*, the inputs and outputs collected during the inventory analysis are grouped and converted into impact indicators, either at *midpoint* or *endpoint*. Midpoint indicators relate to environmental issues, e.g. the release of toxic substances into freshwaters, whilst endpoint indicators quantify the actual environmental damage, e.g. the subsequent increase in fish mortality (EC-JRC-IES, 2010). A series of different Life-Cycle Impact Assessment (LCIA) methods have been formulated to present these indicators in a standardised way. Among the most common are CML 2001, Eco-indicator 99, EDIP 2003 and ReCiPe 8 (Hischier and Weidema, 2010; Acero et al., 2014). Their differences lie in the choice between midpoint and endpoint indicators, in the choice of impact categories, in the grouping of LCI flows and in the final presentation of results. Results can be aggregated and weighted through scoring systems or left as separate physical quantities. In addition, some LCIA allow the *normalisation* of results through an average impact reference on a country basis (Acero et al., 2014). Most LCIA methods (Acero et al., 2014; Anderson and Thornback, 2012) take into consideration the following impact categories:

- Abiotic resource depletion, i.e. the consumption of non-biological resources such as fossil fuels;
- Acidification, i.e. the concentration of acid gases responsible for phenomenon of acid deposition, or ‘acid rain’;
- Eco-toxicity, usually divided by freshwater, seawater and land;
- Energy use (i.e. consumption);
- Eutrophication, i.e. the excessive growth of plants carrying damage to the rest of the environment;
- Global warming;
- Human toxicity;
- Land use;
- Ozone layer depletion, i.e. the thinning of the stratospheric ozone layer;
- Photochemical oxidation, i.e. the creation of ozone at ground level, which is detrimental to human health;
- Water use.

The *interpretation stage* happens in parallel with the other three stages to ensure a solid and coherent study (EC-JRC-IES, 2010). The critical perspective of the practitioner is essential to understand the results of the LCA and use them in accordance with the initial purpose. A significant issue in attributional LCA studies is *allocation*, namely the problem of attribution of flows in a production process resulting in more than one product (EC-JRC-IES, 2010). For example, the manufacture of steel also produces fly ash, which is used as additive in concrete mixes. The issue of allocation is about the share of resources use and emissions that should be attributed to the production of fly ash. Two main procedures can be used to allocate this energy (and any other flow): mass-based and economic-based. The mass-based attributes flows to each product on the basis of their mass, whilst the economic-based on the basis of their economic value. A different way to address allocation, more adequate to the consequential approach (UNEP, 2011), is to “expand the system”, namely enlarging the scope of the LCA until it includes all the products resulting from the manufacturing process (EC-JRC-IES, 2010).

Embodied and operational impact of buildings

With regards to the built environment, process-based LCA is the most common method used to assess the environmental impact of construction products as well as whole buildings (Anderson and Thornback, 2012). LCA studies in the built environment often focus on energy use and global warming (especially in cases where a whole building is assessed) and distinguish between embodied and operational phases when referring to energy and GHG emissions (expressed as CO_2 equivalents). This distinction can be also applied to any other impact category that is assessed. Therefore, it is possible to make a general distinction between the Embodied Environmental Impact (EEI) of a product (or a whole building, or a service) and its operational impact. ~~Though sometimes the term “embodied” can refer to the whole impact of a building during its life-cycle, including the operational phase, in this thesis the term is always intended to exclude the latter.~~ The boundary between the two phases is not always straight-forward, for example the impact of building maintenance happens during the operational phase but is often considered part of the embodied impact, together with the impact resulting from end-of-life of a building, comprising demolition and waste disposal (Dixit et al., 2013).

Product life-cycle

In order to regulate LCA studies on construction products and buildings, the CEN Technical Committee 350 (TC350) developed a series of standards to assess the ‘sustainability of construction works’. The TC350 uses a framework to describe the building life-cycle in separate stages which has become a reference for researchers and institutions (Moncaster and Symons, 2013; RICS, 2012; Monahan, 2014). This framework is also used to produce Environmental Product Declarations (EPD). Figure 2. 1 shows the TC350 framework dividing the building life-cycle into the stages of Production, Construction, Use and End-of-Life. It is common to use the expression *cradle-to-gate* to indicate phases from A1 to A3, *cradle-to-site* for phases from A1 to A4, and *cradle-to-grave* to address the whole life-cycle of the building, though the inclusion of phases B1 toB7 needs to be specified (Moncaster and Symons, 2013).

Building Life Cycle														Beyond building life cycle
Production			Construction		Use					End of life				
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacture	Transport	Construction - installation process	Use	Maintenance	Repair	Replacement	Refurbishment	De-construction	Demolition	Waste processing	Disposal	Reuse/ Recovery/ Recycling potential
					B6	Operational energy use								
					B7	Operational water use								

Figure 2. 1 - Stages of a building life-cycle according to the TC350 (source: BS EN 15978:2011)

Generally, several options for disposal are available at the end of the life-cycle of a product, such as landfilling, incineration or recycling. The impact of this stage can be included by assessing each disposal option and choosing one as representative (e.g. the most popular practice or the one with the lowest impact) or establishing an ‘average’ End-of-Life impact by weighting the impact of each option on the basis of typical shares in practice (e.g. 20% recycling and 80% landfilling). The results of the assessment of the End-of-Life stage are strongly affected by the method adopted to account the impact of recycling/reusing and incineration with energy recovery. A methodological choice is necessary because recycling and reusing offset the demand for primary materials to be consumed, while incineration with energy recovery offsets the demand for energy generation from other sources (e.g. fossil fuels or renewables). There are different approaches to the attribution of ‘benefits and loads’ (i.e. positive and negative environmental impact) created by these disposal practices:

- attribution to the product which is being assessed, i.e. the ‘avoided burden’ approach (EC-JRC-IES, 2010b);
- attribution to the ‘next’ product, i.e. the ‘recycled content’ approach (EC-JRC-IES, 2010b);
- attribution partly to the product which is being assessed and partly to the ‘next’ product, on the basis of economic criteria or a weighting formula (Wolf and Chomkhamsri, 2014; Allacker et al., 2017).

The ‘avoided burden’ approach takes into account both benefits and loads. For example, if a product is incinerated with energy recovery, the product will be attributed the pollution caused by the incineration process but also the positive impact of avoiding energy generation. The ‘recycled content’ approach entails a smaller system boundary and takes into account only the environmental loads. Thus, if a product is incinerated with energy recovery, the product will be attributed the pollution caused by the incineration process but not the positive impact of avoiding energy generation. The ‘avoided burden’ approach might be considered more appropriate for a consequential LCA, while ‘recycled content’ approach for an attributional LCA (EC-JRC-IES, 2010b; Brander and Wylie, 2011). However, there is a substantial debate among LCA practitioners on this issue, and the European Commission has established the objective to provide a univocal method to assess the End-of-Life stage within the Product Environmental Footprint and Organisational Environmental Footprint initiative (EC-JRC-IES, 2012.). This resulted in an ‘End-of-Life formula’ which attributes benefits and loads of recycled content equally between products. However, this formula has also received criticism (Weidema, 2015; Allacker et al., 2017; Vincent-Sweet et al., 2017) as it appears to penalise recycling.

Embodied energy in buildings

Although embodied energy is not a direct measure of environmental impact, its calculation is essential in LCA studies to estimate GHG and other emissions from the use of fuels and electricity during manufacturing stages. It is acknowledged that embodied energy is more complex to measure than operational energy and that methodological differences can produce significantly different results (Dixit et al., 2010). Dixit et al. (2010; 2012) have identified the causes for the variations and inconsistencies noted in embodied energy studies with regards to buildings and construction products:

- The first group of factors is inherent to the object of the assessment, for example when differences are caused by diversity in manufacturing process or geographic location.
- The second group of factors is associated with methodological differences, for example when different system boundaries or allocation methods are chosen.
- The third group of factors is related to data issues. The calculation of embodied energy relies on existing databases describing the energy consumed during manufacturing stages. This type of data is not always available, or it can be incomplete or outdated, or refer to a different geographic location or to different production systems.

All these factors can affect the result of LCA calculations and make comparisons between studies less reliable (Dixit et al., 2010; 2012). Pomponi and Moncaster (2018) reviewed the embodied carbon resulting from several LCA studies of construction materials and noted large variations in methods adopted and resulting figures. While some of these variations can be attributed to technological geographical differences, large deviations (up to two orders of magnitude) must be affected by methodological difference and data issues. This lack of a unified approach makes comparison between LCA less reliable, and may lead to a significant 'performance gap' between LCA results and the actual impact (Pomponi and Moncaster, 2018).

Limitations of process-based LCA

Methodological diversity and the need for reliable data are considered the main drawbacks of process-based LCA (Kviseth, 2011). The issue of cut-off due to boundary definition is particularly significant (Giesekam et al., 2014). On one hand, the system boundary should be large enough to include all major causes of environmental impact; on the other hand, the data collection necessary for a detailed LCI becomes more difficult and time-consuming with the enlargement of the boundary. Once completed, LCA results can only indicate how 'bad' a product is, and further work is necessary to model potential improvements (Kviseth, 2011). The reliance on generic data contained in the main LCA databases is also considered to be a source of error (Giesekam et al., 2014).

The cumulative effect of the uncertainties of the process-based LCA method can lead to errors up to 50% (Lenzen, 2001b). Besides diversity in methods and data sources, comparison of LCA results is hindered by differences in the weighting systems used in LCIA methods (Kviseth, 2011). The complex requirements for data and resources pose an obstacle to the large uptake of process-based LCA, particularly in the case of developing countries and Small and Medium Enterprises (SME) (Ortiz et al., 2009). Partial solutions to these issues are simplified versions of the process-based method (such as the 'streamlined' LCA; Todd and Curran, 1999) and the attempts to integrate it with I-O analysis (see section 2.2.5).

As mentioned above, researchers have noted a variety of methods being used in the context of LCA of buildings and related materials (Pomponi and Moncaster, 2018). This is aggravated by a tendency to rely on generic data from LCA databases and a lack of attention towards the evaluation of data quality and uncertainty, which have an impact on the accuracy and usefulness of the LCA results (Giesekam and Pomponi, 2017; Pomponi et al., 2017).

Process-based LCA data sources

Process-based studies can be conducted using generic LCI data, i.e. data available in various databases, and/or specific LCI data, i.e. data collected on site, for example surveying a manufacturing plant. Studies using specific data will rely on generic data to model certain 'standard' processes, such as transportation via truck. Generic LCI data has been collected into a number of databases, which can be accessed for free or through the purchase of a licence. Publicly-available LCI databases include:

- ELCD (European reference Life Cycle Database), published by the European Commission Joint Research Centre (EC-JRC, 2018), contains 509 processes for various industrial sectors;
- Agribalyse (Ademe, 2018), published by Ademe (the French Environment and Energy Management Agency), contains 116 agricultural processes in the French context;
- BioEnergieDat (BioEnergieDat, 2018), published by the BioEnergieDat project, contains processes for energy for biomass in the German context;
- NEEDS (ESU Services, 2018), published by ESU-Services, contains processes for future electricity supply systems;
- USDA LCA Commons (USDA, 2018), published by the US Department of Agriculture, contains agricultural processes in the North American context;
- Oekobau.dat (Oekobaudat, 2017), created by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety of Germany, contains 1,006 processes mostly for construction products in the German context.

The main databases published by private companies and accessible through the purchase of a licence are:

- GaBi Professional Database, published by Thinkstep (2016a), contains 3,560 processes for various industrial sectors and can be extended to include additional datasets for particular sectors;
- Ecoinvent, published by the Ecoinvent centre, contains 27,950 processes for various industrial sectors.

To be able to access the datasets in these databases and produce results, practitioners often rely on LCA software developed for this purpose. Popular LCA software are GaBi, SimaPro, Umberto and openLCA.

Input-output analysis and LCA

Input-Output (I-O) analysis was developed initially by economist Wassily Leontief, awarded the Nobel prize for its formulation in 1973. This technique can be used to account for physical as well as monetary units, and it is closely related to MFA (Bouman et al., 1999). Most I-O studies are conducted in monetary units, and thus referred to as economic I-O analysis. This method is widely used because most countries compile *supply and use tables* of the national economy as basis for accounting and generation of indicators such as GDP. The time frame of I-O analysis in most cases is one year, as national supply and use tables are compiled annually. These tables quantify product output by industry sector (*supply tables*) and product consumption by industry sector (*use tables*) and are converted into the *I-O table* through mathematical operations (Miller and Blair, 2009). An economic I-O table is a description of the monetary flows between economic sectors over a period of time within a defined boundary (Leontief, 1986). This is usually a national border, but I-O tables can be produced also for smaller or larger boundaries, as well as for more than one ‘region’, thus forming a multi-regional model (Tukker et al., 2009).

Economic I-O analysis

I-O tables can be generated in two formats:

- product-by-product, describing the value of products which are used in the creation of final products, thus monetary flows are categorised by product type.
- industry-by-industry, describing the value of industrial output used as input in other industries to create their own final outputs, thus monetary flows are categorised by industry sector, using classifications such as the UK Standard Industry Classification (SIC) codes.

Industry-by-industry is the most used format for I-O tables as it makes the data compatible with datasets using industry sector classification, thus enlarging the potential of the I-O analysis (Thage, 2007). The level of detail for industry classification used in the I-O table is particularly important as it determines the ‘granularity’ of the analysis.

In industry-by-industry I-O tables, outputs are organised in rows and inputs in columns. Industrial outputs which are turned into inputs for other sectors form the *matrix of intermediate consumption*. This matrix describes all the flows between industry sectors which are necessary to meet the *final demand*, i.e. demand from households, government, etc. (Miller and Blair, 2009). At the bottom of this matrix, employment compensation, taxes and Gross Value Added (GVA) are shown in rows following the same industry classification. Optionally, additional rows can be used to associate any physical quantity to the industry sectors. These quantities can be, for example, hours worked or energy used or GHG emissions. Whether these are technically inputs, as in the case of energy use, or outputs, as in the case of GHG emissions, they are mathematically treated as inputs in order to calculate *multiplier effects*, which are among the outcomes of I-O analysis (Miller and Blair, 2009). The EIO-LCA model (Lave et al., 1995) is an example of a set of economic I-O tables (US data) which have been extended with rows for physical flows to perform I-O LCA.

I-O analysis uses matrix algebra to manipulate the I-O table and generate its outcomes (Miller and Blair, 2009). The first step of the I-O analysis is the generation of the *matrix of technical coefficients*. This matrix describes the proportion between the total output of each industry sector and the inputs from all other sectors. The next step is the generation of the *Leontief inverse matrix*. At the bottom of this matrix, each industry sector is associated to its *output multiplier* (also called *Leontief total*) which quantifies the output generated across all sectors as a consequence of one unit of final demand (Miller and Blair, 2009). If rows of physical quantities have been added to the I-O table, multiplier effects can be calculated for these quantities, performing an I-O LCA. For example, the GHG multiplier effect for industry sector “A” describes how many GHG are emitted across all sectors as a consequence of one unit (for example, one pound) of final demand in sector A. Multiplier effects allow quantifying the cumulative impact resulting from the supply of products (or services) from a specific industry sector A, taking into account direct and indirect effects. Direct effects are caused directly by sector A to generate its output, while the indirect ones are caused by purchases of sector A from other sectors necessary for its production (Miller and Blair, 2009). For example, the energy used by a steel manufacturer for its production is a direct effect, while the energy used in the extraction of iron ore (which belongs to a different industry sector) is an indirect effect. It must be noted that while I-O analysis allows producing multiplier effects in a top-down manner, multiplier effects can be estimated also for specific economic activities and geographical areas through local case studies (Domański and Gwosdz, 2010).

I-O LCA studies

Overall, the number of studies using I-O analysis for LCA is smaller than those using the process-based method (Khasreen et al. 2009). Most of the studies focusing on the construction sector are conducted at the macro scale, as a significant advantage of I-O LCA over the process-based technique is that it can be more directly use to investigate the environmental impact of whole economic sectors. A few examples are presented here.

Chang et al. (2010) used a 24 sectors I-O model of the Chinese economy in 2002 to estimate that the energy embodied in the construction sector is about one sixth of the national energy consumption. Acquaye and Duffy (2010) used Irish I-O tables and energy data to estimate the carbon emission intensity (espressed in CO_2/€) of the Irish construction sector. The I-O technique allowed Acquaye and Duffy (2010) to determine that only 17% of the emission intensity can be associated with direct emissions from construction activities, while the remaining 83% can be attributed to indirect emissions from other industry sectors. About half of these indirect emissions occur outside Ireland (Acquaye and Duffy, 2010). Similarly, Beidari et al. (2017) conducted I-O analysis to calculate and compare the multiplier effects for 18 macro-sectors of the South African economy in 2012. The results showed construction to be the 13th sector in terms of direct and indirect carbon emissions. 1.56 kg of CO2 were emitted as a consequence of one US dollar of 'purchase' from the construction sector in South Africa in 2012, with over 98% of these emissions due to indirect effects (Beidari et al., 2017).

The integration of environmental and economic variables in I-O LCA allows using the technique for assess economic sectors at the macro scale to inform policy choices. Giesekam et al. (2014) used a multi-regional I-O model to analyse the GHG embodied in the UK construction sector from 1997 to 2011. Throughout this period about half of emissions occurred in sections of the supply chain located outside the UK. However, transportation only contributed to about 10% of total emissions from the construction sector. The largest contribution (about half of total emissions) was attributed to the manufacturing stage of construction products. Although total emissions decreased by about 30% from 2008 to 2011, Giesekam et al. (2014) linked this decline to the reduced output of the construction sector in this period due the economic recession, and noted that embodied emission can be expected to rise due to the need to renew and enlarge the UK housing stock. Giesekam et al. (2014) also noted that while savings in embodied emission are immediate and can be directly monitored, savings in operational emissions occur over time and are often overestimated. Since climate change is more directly affected by cumulative emissions than by annual emissions (Matthews et al., 2012), Giesekam et al. (2014) concluded that focusing on the reduction of operational emissions will not be sufficient to achieve national carbon reduction targets.

Pomponi and D’Amico (2018) used a multi-regional I-O model to investigate and compare the carbon emission intensity (on a monetary basis) of construction activity types (residential, commercial, infrastructure, etc.) and manufacturing sectors of building-related materials in the UK (concrete, plaster, steel, bricks and timber). The study revealed that construction activities and timber products manufacturers are less carbon intensive than manufacturers of concrete, plaster, steel and bricks. The less carbon intensive sectors are also the most economically profitable if a maximum admissible level of carbon emissions is taken into account. Pomponi and D’Amico (2018) noted that the capacity of I-O LCA to include indirect effects is essential to produce results which are fully representative of the overall impact of the subject of the assessment. For example, the brick manufacturing sector appears to have low carbon intensity if only direct emissions are taken into account, but a much higher value is obtained once indirect emissions are included.

Not all I-O LCA studies on the construction sector are conducted at the macro scale. Cellura et al. (2013) used I-O analysis to investigate the energy use and carbon emissions associated with energy retrofit measures on existing dwellings in Italy in 2007. Cellura et al. (2013) identified prices for four types of retrofit measures and estimated the energy use and carbon emissions directly avoided by each measure (i.e. direct operational energy and carbon savings). By associating these expenditures and savings with the relative industry sectors, Cellura et al. (2013) conducted I-O LCA to calculate:

- Direct and indirect energy use and carbon emissions due to the realisation of the measure (i.e. embodied energy and carbon);
- The energy use and carbon emissions indirectly avoided as consequence of the missed production of operational energy (i.e. indirect operational energy and carbon savings).

Taking into account the expected life-span of the retrofit measures and the number of measures delivered in 2007, Cellura et al. (2013) concluded that the installation of condensing boilers was the most effective measure, while wall insulation the least effective measure. However, this was due to the large number boilers installed in comparison to the small number of walls insulated. In monetary terms, wall insulation was slightly more effective than boiler installation, as 3.5 kg of CO_2 were avoided for each Euro spent for wall insulation against the 3.4 kg of CO_2 avoided for each Euro spent for condensing boilers (Cellura et al., 2013, p.105).

Limitations of I-O LCA

The I-O technique presents several sources of uncertainties (Lenzen, 2001b), which can be the cause of less accurate results than those obtained through process-based LCA (Treloar and Love, 2000):

- Firstly, I-O analysis relies on an assumption of *fixed technology* between industries (Miller and Blair, 2009) which ignores the effects of economies of scale, price variations and structural changes (Lenzen, 2001a). Essentially, it is assumed that industry A buys its inputs from other industries always at a fixed ratio, independent from the volume of its output.
- When rows of physical units are added to extend the I-O tables, proportionality between monetary and physical flow is also assumed. This is problematic as a variation in price results in a change in physical flows, which are unlikely to be real (Gronow, 2001). For example, the price of one barrel of crude oil may vary significantly without any correlation with the energy embodied in its production.
- A significant limitation of I-O analysis is the aggregation of diverse industries, which is determined by the system adopted for industry classification (Giesekam et al., 2014). A “coarse” resolution of the industry aggregation leads to a coarse resolution of the results of the analysis. Any difference between products of the same industry sector and between manufacturers of the same product is lost due aggregation, and all processes within an industry sector are considered homogenous.
- Another limitation is the exclusion of the use and disposal phases in I-O tables, which effectively makes the I-O LCA viable only for cradle-to-site assessment (Suh and Huppes, 2005).

A basic I-O analysis provides a static model of the economy, as I-O table are a snapshot of economic activities during one time frame. However, I-O outcomes can be analysed in time-series if I-O tables for different years are available. This allows advanced dynamic models to be built if changes in technical coefficients are estimated. If only one year of data is available, I-O analysis can be used for comparison between industries. The temporal validity of I-O tables is important, since in most cases data becomes available for I-O analysis over time. Some researchers pose a limit of five years, while others allow for 10 to 15 years of validity (Paloviita, 2004). The validity of the analysis is affected by changes in the technical coefficients over time, which can be significant and lead to a cumulative impact on the outcomes of the analysis. However, a study on changes of multipliers over a decade in the US concluded that variations were within 10%, and therefore a minor concern (Conway, 1977).

I-O LCA data sources

A few datasets have been developed into I-O models by compiling national supply-and-use tables with environmental and socio-economic accounts. Except for the EIO-LCA model, I-O datasets are generally available as files to be manipulated with software such as Excel, Matlab or Phyton. The following datasets are freely accessible to academics:

- The EIO-LCA model (Hendrickson and Horvath, 1998) is an online tool based on US data for for 1992, 1997 and 2002. The model is divided into 428 industry sectors;
- The OpenEU dataset (Hertwich and Peters, 2010) is a multi-regional database containing data for 2002, 2003 and 2004. The model is divided into 113 world regions and 57 industry sectors;
- The WIOD dataset (Timmer et al., 2015) is a multi-regional database containing data from 2000 to 2014. The model is divided into 43 countries and 56 industry sectors;
- The EXIOBASE dataset (Tukker et al., 2013; Wood et al., 2015), is a multi-regional database containing data for 2000 and 2007. The model is divided into 43 countries and 163 industry sectors. Recently a new version has been published as EXIOBASE v.3 (Stadler et al, 2018).
- The EORA dataset (Lenzen et al., 2012; Lenzen et al., 2013) is a multi-regional database containing data from 1990 to 2013. The model is divided into 187 countries and 512 industry sectors;

Moran and Wood (2014) investigated the reliability of these I-O datasets by comparing the results of four models (EORA, WIOD, EXIOBASE and OpenEU) in terms of carbon emissions. They found discrepancies to be less than 10% and noted that though these models may present "quantitatively different results, but in general, we have qualitatively similar outcomes" (Moran and Wood, 2014, p.259).

Comparing process-based and I-O LCA results

A comparison of process-based and I-O LCA methods and results was made by Hendrickson et al. (1997) by assessing steel and aluminium production with process-based GaBi database (using early 90's data for the EU) and EIO-LCA (using 1987 data for the US). The research found that the two sets of results were comparable despite differences, which were caused by geographic and chronological reasons, as well as by different levels of comprehensiveness between the two techniques. It is generally acknowledged that the I-O technique is more comprehensive than process-based one, as all upstream processes are included, with no boundary cut-off (Lenzen, 2001b; Crawford, 2008). The I-O technique enables to assess any product or service if economic I-O tables are available and extended with environmental inputs, because only price and industry sector of the product are required to conduct the LCA. This makes I-O LCA less time- and resource- intensive than process-based LCA (Lenzen, 2001b).

Nässén et al. (2007) used I-O multipliers obtained from Swedish national accounts for the year 2000 to calculate the energy embodied into residential buildings. Results (expressed in GJ/m^2 of residential floor area) were compared to average process-based values based on 18 previous LCA studies. The value for total embodied energy obtained via the I-O technique was about twice the value obtained via the process-based technique. While the energy embodied in the manufacturing stage as assessed by I-O technique was 'only' 20% higher than the process-based result, the I-O technique produced much higher values for the energy embodied in other sections of the supply chain, such as transportation and services. Nässén et al. (2007) explained this difference as a consequence of the cut-off boundary of process-based LCA.

Säynäjoki et al. (2017) conducted both process-based and I-O LCA to assess the carbon embodied in a residential case study in Finland. As expected, the I-O results (expressed in kgCO$_2$/m^2 of residential floor area) were significantly higher (about 75%) than the process-based results. This difference was mainly the consequence of higher I-O results for specific elements, such as structural frames, finishes and on-site works. As Nässén et al. (2007), Säynäjoki et al. (2017) considered this difference a result of the cut-off in process-based LCA.

Giesekam et al. (2016) developed a unique method to bridge the difference between process-based and I-O results. Process-based figures of embodied carbon in different building typologies (expressed in CO$_2$eq/m^2 of building area) were taken from the WRAP Embodied Carbon Database, which collects data from LCA practitioners in the UK. Taking these figures as representative values, Giesekam et al. (2016) estimated the total carbon embodied in UK buildings from 2001 to 2012 on the basis of construction statistics. This 'bottom-up' estimation was calibrated to match a 'top-down' estimation obtained via I-O analysis. As expected, bottom-up results were smaller than I-O results, with discrepancies ranging from 20% to 40%. Giesekam et al. (2016) used the calibrated embodied carbon figures to build several scenarios and explore the potential to achieve 2050 carbon reduction targets, thus connecting project-level assessment to large scale objectives. The results show that significant improvements in design and manufacture will be required to keep the cumulative carbon embodied in future buildings within targets. In a best-case scenario, where new constructions are limited, the electricity grid is decarbonised and carbon capture and storage technologies are effectively deployed, the average improvement required in embodied carbon at the project-level (i.e. for a single building) is 7%. In a worst-case scenario, where new constructions are increased, the electricity grid remains as it is and carbon capture and storage technologies are not deployed, the average improvement required in embodied carbon at the project level is 67% by 2027 (Giesekam et al., 2016, p.8). Thus Giesekam et al. (2016) concluded that only a combination of project-level improvements, construction demand reduction and low-carbon technologies can achieve carbon reduction targets.

2.2.3 Assessing social sustainability

Social sustainability is the least clearly defined among the three dimensions of sustainability (Assefa and Frostell, 2007). Generally, social sustainability is related to maintaining society and pursuing social well-being, intended as the "fulfilment of basic needs and the exercise of political and economical freedom" (Magis and Shinn, 2009, p.1). There is a range of different interpretations (Vallance et al., 2011), with some focusing on employment and education, some on health, gender and aging issues, and others on democratic governance and participation (Omann and Spangenberg, 2002). Vallance et al. (2011) identified three perspectives corresponding to three concepts of social sustainability:

- *Development*: strongly connected to the wider sustainability debate and concerned with meeting human needs, with most studies focusing on issues of developing countries. The *development* perspective relates to the concept of balance between human demand and natural supply and can be argued to be the most comprehensive of the three approaches to social sustainability.
- *Bridge:* concerned with identifying and promoting ethics and social behaviours necessary to ensure environmental sustainability and establish a link to nature. The *bridge* perspective conceives social sustainability largely as means towards environmental sustainability, thus socially sustainable practices are those which have the least environmental impact. This perspective appears to subordinate social aspects to environmental ones and to ignore strictly social issues such as civil rights or security.
- *Maintenance:* concerned with maintaining cultures, traditions, communities, life-styles and natural landscapes (Vallance et al., 2011). The *maintenance* perspective intends social sustainability as an end in itself, but its concept of social sustainability is rather limited in scope and also excludes strictly social issues.

Vallance et al. (2011) believe that the lack of clarity associated with social sustainability can be attributed to potential conflicts between these perspectives:

- the needs of the people (development) versus the needs of the environment (bridge);
- the needs of the people (development) versus people's desires and habits (maintenance);
- the needs of the environment (bridge) versus people's desires and habits (maintenance) (Vallance et al., 2011).

A detailed discussion is beyond the scope of this review, however this is a significant issue that demonstrates the difficulty of developing comprehensive tools for the assessment of social sustainability.

Social sustainability indicators

As a consequence of the multiplicity of perspectives on social sustainability, a wide range of criteria and indicators are used in practice. For example, Omann and Spangenberg (2002) developed a method to assess social sustainability which includes a list of criteria for a socially sustainable development:

- self-determined life-style;
- satisfaction of basic needs;
- reliable and sufficient social security;
- equal opportunities to participate in a democratic society;
- enabling of social innovation;
- inter-generational equity (Omann and Spangenberg, 2002).

While some of these criteria can be assessed through indicators, others are more difficult to quantify, due to the qualitative nature of the data. Social indicators have not always been included in sustainability assessments (Veleva and Ellenbecker, 2000). However, there is a growing body of research attempting to identify social indicators adequate to the scale and object of the assessment (Renn at al., 2010). Social Impact Assessment (SIA), derived from EIA, includes "analysing, monitoring and managing the intended and unintended social consequences, both positive and negative, of planned interventions (policies, programs, plans, projects) and any social change processes invoked by those interventions. Its primary purpose is to bring about a more sustainable and equitable biophysical and human environment." (Vanclay, 2003, p.2). Vanclay (2003) identifies several categories of social impact included the SIA framework:

- way of life—how people live, work, play;
- culture—shared beliefs, customs, values;
- community—stability, cohesion, services, and facility;
- political systems—participation in decisions;
- environment—availability, quality, and access;
- health and well-being;
- personal and property rights—human rights;
- fears and aspirations—perception of safety, and future (Vanclay 2003).

Along SIA, Palme (2011) lists the other main methods to assess social sustainability: the standard Social Accountability 8000; the standard ISO 26000 for Social responsibility; the Global Reporting Initiative; and the UN Global Compact and the Social Life Cycle Assessment (SLCA), developed into a framework methodology for the United Nations Environmental Programme (UNEP) by Benoit and Mazjin (2009). SLCA "aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; distribution; use; re-use; maintenance; recycling; and final disposal" (Benoit and Mazjin, 2009, p.37). SLCA integrates LCA with social and socio-economic aspects, and presents the same four-stage procedure and large need for data of the process-based LCA method (Benoit and Mazjin, 2009). SLCA takes a more holistic approach and requires both quantitative and qualitative data. The method for SLCA developed by Benoit and Mazjin (2009) allows two complementary ways to classify social impacts. The first uses impact categories such as human rights, working conditions, health and safety, etc.; the second is based on stakeholder categories, of which five main types are identified:

- workers;
- local community;
- society;
- consumers;
- Value chain actors.

Each stakeholder group is associated with sub-categories of impact, for example for *workers* - fair salary, child labour, working hours, etc. – and for *local community* - local employment, access to material resources, cultural heritage, etc. (Benoit and Mazjin, 2009). The methodology for SLCA remains flexible and not fully detailed, thus UNEP released "Methodological sheets for sub-impact categories in SLCA" (Benoît-Norris et al., 2013) to provide further guidance.

The interest around SLCA has increased in the last decade, however there is currently no standard set of indicators being used in SLCA and practitioners often develop their own set based on the focus of the assessment, (Siebert et al., 2018). For example, Siebert et al. (2018) conducted a review of SLCA standards and literature and a series of stakeholders interviews in order to develop their own set of indicators for a SLCA of wood-based products in Germany.

Benoit and Mazjin (2009) acknowledge a series of limitations for SLCA. As with LCA, SLCA alone cannot provide the basis for decision on the manufacture of a product nor indicate more sustainable alternatives. The amount of data required to perform SLCA represents a significant obstacle, especially due to the qualitative nature of data requirements and the few databases.

Social impacts are not only difficult to quantify but also hard to fully understand and foresee. Due to this complexity, the ‘use phase’ of a product life-cycle has been left out of the SLCA scope in the current guidelines (Benoit and Mazjin, 2009).

Embodied work

With regards to social sustainability, the review of radical approaches to sustainability (section 2.1.3) has highlighted an interest in local work generation and labour-intensity in relation to the concepts of localisation and appropriate technology. The generation of skilled work and employment opportunity is a significant social theme in the assessment of products and technology (Renn et al., 2010). The labour intensity of production is a controversial issue in the sustainability debate. In the context of development of the Global South, there are examples in African countries where labour-intense manufacturing and construction methods have been considered positively and actively pursued as a mean to increase employment (McCutcheon, 2008). The publication of best practice guidelines for labour intensive construction works by the Construction Industry Development Board of South Africa (CIDB, 2005) in collaboration with government departments, universities and industry associations shows that these initiatives have not been limited to particularly underdeveloped countries. However, McCutcheon (2008) noted that there are significant cultural obstacles towards labour-intensive methods, as they are perceived as contrary to the idea of ‘progress’.

Human labour associated with economic activities can be estimated via I-O analysis in terms of correspondent salary as well as hours of work required. However, it is also possible to use a process-based method to estimate embodied work. The Work Environment Life-Cycle Assessment is a procedure to evaluate the quality of the work environment within the context of product manufacture, and can be seen as a SLCA with a narrow scope (Benoit and Mazjin, 2009). An example is the Life-Cycle Work Environment (LCWE) methodology, developed to quantify the impacts of a product in terms of hours of labour, levels of skills required and working conditions (Barthel et al., 2005). The LCWE procedure is derived from the process-based LCA and can be conducted in combination with it, and some process-based LCA databases, such as the GaBi Professional, contain LCWE data. Three indicators of impact are included in this method:

- hours worked by level of skills;
- total hours worked;
- number of fatal and non-fatal injuries (Barthel et al., 2005).

To calculate embodied work, data can be collected on site or, if figures for value added is available for each step of the manufacture, macro-level industry data can be used to estimate embodied work on the basis of industry sectors average figures for hours of labour per value added (Barthel et al., 2005).

2.2.4 Assessing economic sustainability

The concept of economic sustainability is debated and can be approached in different ways, as introduced in section 2.1.2. Within a business perspective, economic sustainability is intended as the capacity of a company to stay in business without losing capital (Doane and Macgillivray, 2001; Construction Products Association, 2007). More generally, any entity - a household, a company, a government, etc. - can be seen as economically sustainable if it is able to perform its function and its income is larger than its spending. This perspective focuses on the capacity to operate within an existing economic system and is not concerned with the sustainability of the system itself, i.e. the capacity of the system to sustain its activity. In the debate on sustainability, economists tend to think of economic sustainability strictly as inter-generational equity and “no more than one element of a desirable development path” (Stavins et al. 2003, p. 340). In the plan of action towards sustainable development “Agenda 21” (UN, 1993), economic sustainability is to be achieved through the neo-classical principles of growth, development, productivity and trickle-down effect (Kahn, 1995).

From the perspective of ecological economics, economic sustainability is intended as the capacity of the economic system to sustain itself without damaging the social and environmental systems (Spangenberg, 2005), i.e. without depleting economic, social and environmental capital. Economic sustainability is seen as an instrument to achieve human development, not as the objective of development (Sachs, 1999). Differently, social sustainability is considered both as an instrument and objective of human development (Harris and Goodwin, 2001). Ecological economics focuses on understanding how economic development can sustain human development (Anand and Sen, 2000). Economic sustainability is still intended as the capacity to maintain a *Hicksian income* (i.e. maintaining capital stock intact and consuming only the production surplus), but this principle is applied to the totality of the economic system and in a long-term perspective of ensuring inter-generational equity (Anand and Sen, 2000; Goodland and Daly, 2015). The economy is not seen as an independent entity regulated by invariable arithmetic rules, but as a more complex system of interactions. Spangenberg (2005) argued that the assumptions and mathematical models of mainstream economics are not adequate to represent the complexity of the interrelations between economy, society and environment. Systems theory and modelling can provide new criteria to evaluate the sustainability of the economic system, such as:

- diversity and redundancy of the economic process;
- balanced exchanges with the other economies;

- innovation potential;
- capacity to provide and improve quality of life, viability of institutions, social cohesion, sound environment (Spangenberg, 2005).

This 'systemic' approach to economic sustainability is critical of mainstream economics, and stresses considerably on the necessity to intervene at the macro-economic scale in order to steer the economy to more sustainable ends (Jackson, 2009). It is argued that the lack of capacity of the current economic system to prevent negative social and environmental impacts is a direct consequence of the incorrect assumptions of the neo-classical economic theory (Spangenberg, 2005; Jackson, 2009).

The different perspectives on economic sustainability discussed above can be viewed potentially in contrast to each other, which is similar to the conflicts between interpretations of social sustainability as identified by Vallance et al. (2011), In particular, economic sustainability as the capacity to *stay in business within the existing economic context* might conflict with economic sustainability as the capacity of the economic system to sustain itself without depleting social and environmental capital. If an economic system enables a company to stay in business while polluting the environment and exploiting its workers, it can be argued that the economic system itself is not sustainable. More precisely, the *conditions* posed by the economic system are not sustainable, and therefore need to be improved. Pigouvian taxation, i.e. taxing externalities, is advocated by ecological economists (Costanza et al., 1997b) as a way to create more sustainable conditions of the economic system. An extended discussion of this issue is beyond the purpose of this review, nonetheless it is important to bear in mind these contrasting views and the question on the sustainability of the economic system itself when discussing possible indicators of economic sustainability.

Economic sustainability indicators

Although a number of economic indicators have been used in sustainability initiatives, Veleva and Ellenbecker (2000) complained that "most frameworks attempt to address economic performance but they still use traditional economic indicators that are not true measures of sustainability (e.g., market share, sales, stock price, profitability)" (~~Veleva and Ellenbecker, 2000~~, p.523). To obtain indicators at the level of single products, a process-based approach can be adopted (such as life-cycle costing) or more traditional economic indicators can be used, such as Gross Value Added (GVA).

Life-cycle costing

Life Cycle Costing (LCC) is a process-based method that can be used to assess economic sustainability from a business perspective at the level of production. LCC is essentially a compilation of all the costs related to a product over its life cycle (Benoit and Mazjin, 2009). Its methodology is not as formalised as process-based LCA, but the standard ISO 15686-5 provides guidelines to conduct LCC for buildings. LCC is usually performed from the perspective of one economic actor (e.g. the manufacturer) and the measure of economic impact is the aggregate cost itself (Swarr et al., 2011). Financial estimates of the externalities of production, e.g. pollutants and waste, are not in the scope of conventional LCC. *Environmental LCC* is being developed in relation to LCA and SLCA methodologies to establish an overall framework for life-cycle sustainability assessment (Zamagni et al., 2013). However, it is argued that there is limited compatibility between LCC and LCA, as LCC and LCA are often conducted separately and monetary values used in LCC are influenced by currency exchange and time (Bierer et al., 2014). Material Flow Cost Accounting (MFCA) may be considered a more adequate technique to integrate economic analysis into the LCA framework. MFCA "is a flow-oriented accounting approach which aims at the identification and monetary valuation of material inefficiencies in production processes" (Bierer et al., 2014, p.6), and its method is set in the standard ISO 14051. It is performed by quantifying material inputs and outputs in physical units and associating monetary values (Sygulla et al., 2011). Thus MFCA can use the same inventory as LCA and does not take the perspective of one stakeholder (Bierer et al., 2014).

The main drawback of the process-based methods such as LCC and MFCA is data availability. Little information is contained in LCA databases and it not consistent due to geographical and chronological diversity. Collecting specific data from the industry would be cumbersome and figures such as cost, added value and employment compensation at the product level are business-sensitive. In comparison to process-based methods, I-O analysis requires less time and resources to generate economic indicators, because data is more readily available (see section 2.2.2) and less demanding to work with.

Gross value added

Gross Value Added (GVA) is a term used in national and regional economic accounts to compare economic activity (Wainman et al., 2010). Technically, it indicates the difference between gross product and intermediate consumption, that is:

GVA = gross product + intermediate consumption (ONS, 2016)

Net value added is simply GVA minus the consumption of fixed capital, i.e. the decline of fixed asset values (Eurostat 2016). At the national level, GVA usually makes up over 90% of GDP, as:

GDP = GVA + taxes - subsidies (ONS, 2016)

GVA can be calculated using three different 'approaches': production, income and expenditure. GVA is estimated in the UK using all three approaches by the ONS through the compilation of national supply and use tables (Wainman et al., 2010). GVA is measured at *producer prices* or *basic prices*. Producer price is the amount received by the producer excluding deductible VAT and subsidies on products, but including taxes on products (for example, import duties). Basic price is the amount received by the producer excluding taxes on products but including subsidies.

GVA can be calculated at the level of a single company or industry sector as well as for whole regional and national economies. At the macro level, GVA is used as an indicator of economic activity (Wainman et al., 2010). At the business and sector level, it represents the contribution to the economy (Wainman et al., 2010). GVA is a measure of the value that has been added to the final product in addition to the combined values of all the components that constitute the product. A company pays employment costs and taxes on production out of its GVA, and what remains is its profit. Therefore GVA is seen as an indicator of positive economic impact in terms of wealth creation, because GVA represents the additional wealth that a company has been able to produce by combining several elements (raw materials, energy, labour, expertise, innovation, etc.) into a final product.

2.2.5 Hybrid and integrated LCA

Previous sections indicate that LCA theory and practice can be distinguished by method (process-based or I-O) and by subject of assessment (environmental, social or economic dimension). However, researchers have developed ‘hybrid’ and ‘integrated’ (or ‘extended’) LCA to attempt to bridge these divisions. A few examples of studies adopting these techniques are reviewed here.

Hybrid LCA

A group of new techniques has been purposely created to combine the accuracy of process-based LCA and the comprehensiveness of I-O analysis (Crawford, 2008; Lenzen and Treloar, 2009). These hybrid techniques are still in development and have not been standardised into a single procedure. For example, Suh and Huppes (2005) distinguished three different ways to perform a hybrid LCA. Due to their novelty and experimental nature hybrid LCA studies are considered to be time consuming and resource intensive (Giesekam et al., 2014). Nonetheless, the interest around hybrid LCA is increasing together with the debate around its viability and accuracy in comparison to process-based LCA (Pomponi and Lenzen, 2018).

In the last two decades a number of hybrid LCA studies have been published. Treloar et al. (2001) provide an example of hybrid LCA in the context of construction by assessing the energy embodied in Australian residential building. The results show values over two times higher than those obtained by process-based studies. Their hybrid technique uses I-O data as a basis, and integrates process-based information when available. They concluded that this method improves the completeness of the LCA results, but acknowledged that using I-O data at the product level can be problematic (Treloar et al., 2001). Another example of hybrid LCA focusing on construction products is by Dadhich et al. (2005), who assessed the carbon emissions across the supply chain of plasterboards products in the UK and identified the manufacture and transportation stages as the most impacting stages.

Sharrard et al. (2008) developed a hybrid LCA method to be used in conjunction with the EIO-LCA model. This method was applied to assess the environmental impact of seven construction case studies across five impact categories (energy use, GWP, air pollutants and toxic releases). For each case study, the results of the hybrid LCA were compared to the results of the unmodified EIO-LCA. Sharrard et al. (2008) found that in most cases the hybrid LCA produced higher impact figures than the unmodified EIO-LCA, concluding that the hybrid LCA provides a more accurate assessment.

A singular example of hybrid LCA is provided by Nagashima et al. (2017), who assessed the impact of wind power generation system in Japan, extending the research scope beyond environmental impact to include socio-economic aspects such as production output and added value.

Integrated LCA

There is an official initiative to integrate and harmonise the methodologies for process-based LCA, LCC and SLCA to provide a general framework for life-cycle sustainability assessment (Valdivia et al. 2012). Since SLCA is the least defined of the three methods, some researchers have chosen to narrow down the social impact assessment to the working environment, integrating LCA and LCC with LCWE (Albrecht et al., 2013). Others prefer to leave the social dimension out, focusing on the integration of LCA and LCC (Brandão et al,. 2010).

Another approach to the integrated assessment of sustainability looks at the environmental impact in relation to social and economic impact. In the case of Batalla et al. (2014), GHG emissions from sheep farming are divided by man-hours and net profit margin to produce indicators of impact intensity such as GHG emissions per unit of work and GHG emissions per unit of economic profit (Batalla et al., 2014). Similarly but with more detail, Clift (2003) proposed to analyse the proportion between environmental impact and added value during each stage of the life-cycle of a product in order to identify the critical stages which have a high environmental impact and low added value (Clift, 2003). It can be argued that MFA and I-O analysis can integrate the three dimensions of sustainability more directly than process-based methods, as any type of multiplier effect can be calculated from the same model once data is available. However, the outcomes of I-O analysis cannot describe qualitative aspects of social impact assessment.

2.2.6 Assessment methods in EU and UK policy

This short section introduces European and British policy instruments which focus on the assessment of sustainability at product level, particularly for construction products.

European policy

The European Commission has reinstated the necessity for a common framework of indicators across EU countries to tackle consumption and pollution from buildings (European Commission 2017). The European Committee for Standardisation (CEN) established Technical Committee 350 (TC350) to develop European framework and methodology for assessing the sustainability of buildings. Three main standards regulate the assessment of environmental, social and economic performance with quantitative indicators:

:

- *EN 15978:2011. Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.* This standard describes the methodology to calculate the environmental impact of a building, based on process-based LCA (BRE 2016).
- *EN 16309:2014+A1:2014. Sustainability of construction works - Assessment of social performance of buildings - Calculation methodology*. This standard focuses mostly on the social impact happening during the operational stage of buildings, with criteria such as accessibility, adaptability, health and comfort, safety and security, and stakeholder involvement, although sourcing of materials and services is also a criterion (BRE 2016).
- *EN 16627:2015. Sustainability of construction works - Assessment of economic performance of buildings - Calculation methods.* This standard focuses on the economic performance of building over its life-cycle, but does not include economic risk assessment or the economic impact of the building beyond its site (BRE 2016).

In parallel with the framework to assess whole buildings, the TC350 has contributed to the development of the methodology regulating the production of *Environmental Product Declarations* (EPD). An EPD is a certificate declaring the environmental impact of a construction product across it life-cycle. EPD are instruments which certify and communicate the environmental impact of products which allow comparison of product impact. EPD are conceptually similar to Energy Performance Certificates (EPC), but are not a mandatory requirement. The *EPD International* initiative has extended the concept of EPD to all types of products beyond those used in construction and promotes its adoption across Europe and the world (EPD International 2017).

EPD are defined as 'type III' environmental indicators, i.e. instruments for industry-to-industry communication. Four standards provide the methodology to produce EPD:

- *ISO 14025:2006. Environmental labels and declarations - Type III environmental declarations - Principles and procedures.*
- *CEN/TR 15941:2010. Sustainability of construction works - Environmental product declarations - Methodology for selection and use of generic data.*
- *EN 15804:2012+A1:2013. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*
- *CEN/TR 16970:2016. Sustainability of construction works - Guidance for the implementation of EN 15804.*

The EPD methodology follows process-based attributional LCA. The assessment of different product types – for example, bricks or cement or insulation – is regulated by specific *product category rules*. These rules describe the details of the methodology required for the LCA and how information is to be presented on the certificate. To produce the EPD for a product, a company commissions the study to a LCA practitioner and the results are verified by an approved independent party, for example BRE. Some researchers acknowledge EPD as a valid source of information on the environmental impact of products (Sariola and Ilomäki, 2016).

British policy

Although no British policy currently regulates the EEI of construction products, the *GreenGuide* for product specification developed by BRE (2018b) in relation to the Code for Sustainable Homes has affected how this field is addressed by the industry. The *Code for Sustainable Homes* (CSH) was an assessment framework issued by the UK Government to enable local authorities to set clear requirements for new dwellings with good environmental performance. The CSH was withdrawn in 2015 as consequence of the review on housing standard and the intention of limiting regulations., and only a few requirements, mostly voluntary, have been integrated into Building Regulations (BRE, 2017). The CSH framework featured material sourcing and embodied impact among its criteria, although these had a very limited weight on the final score of the assessment (Giesekam et al., 2014). Points awarded for low impact products were calculated on the basis of BRE GreenGuide ratings. These ratings were a set of labels, from E to A+, determined on the basis of "environmental profiles" of products, obtained through process-based LCA. The Alliance for Sustainable Building Products (ASPB), an association of designers and manufacturers promoting low impact construction products, argued that the GreenGuide rating methodology was not adequate for several reasons:

- products were combined into typical building elements (e.g. a ventilated roof system) which did not allow differences in construction systems and specific products to be considered;
- carbon sequestration into biomass was not taken into account;
- the presentation of a rating as a single score encompassing all categories of environmental impact made the assessment rely on a set of hidden assumptions (ASBP 2013).

The ASBP proposed to use EDP certificates to rate environmental performance, as this methodology is more transparent, widely used across Europe and allows the combination of certificates to assess building elements (ASBP, 2013).

2.2.7 Conclusion on assessment methods

This review of impact assessment methods showed a variety of approaches:

- Most studies focus on the environmental rather than the social and economic dimensions of sustainability. This might be explained by the quantitative and univocal nature of environmental impact assessment, whilst social impact assessment takes into account different stakeholders and qualitative aspects, and economic impact assessment depends on the interpretation of economic sustainability. Nonetheless, there are examples of studies attempting to integrate the assessment of the three dimensions of sustainability.
- Most LCA techniques are either process-based or use I-O analysis, with few examples of hybrid methods. The process-based method is widely adopted, as the technique is standardised and is acknowledged by EU and UK policies. This method requires a bottom-up accounting of physical flows, and existing studies and databases can provide generic data and benchmarks. The I-O method is less popular but its use is growing. I-O analysis can be conducted in different ways and can be based on physical units, though in most cases monetary flow accounts are used. This method requires national I-O tables extended with satellite accounts, which are available in a few datasets.

To identify an appropriate method for the purpose of this research, a number of factors were considered:

- Due to their recent development, hybrid and integrated LCA techniques are not standardised and lack a consistent background of literature and data sources. A study on product assessment based on these new LCA techniques would require a large data collection and focus mostly on methodological issues.

- Process-based LCA is the most established method for the assessment of environmental impact at the product level, thus new research can build on existing literature and access several data sources.
- The variety of methods for the assessment of social and economic impact is a consequence of the diverse interpretations that can be made of these two dimensions of sustainability. In comparison to environmental aspects, socio-economic aspects of sustainability have a more subjective nature and require the researcher to adopt specific perspectives.
- Using the process-based technique to assess socio-economic impact is time- and resource-intensive, whilst the I-O technique is less demanding and can be considered more suitable to express socio-economic indicators.

As will be discussed in chapter 3 (Research Design), using the process-based technique to assess the EEI of insulation products and the I-O technique to assess their socio-economic impact is considered an appropriate combination of methods for the purpose of this research.

2.3 The use and impact of domestic insulation products

Application, manufacture and embodied impact of thermal insulation products are discussed in this part of the literature review. Properties and use of thermal insulation in buildings are introduced in section 2.3.1. The data collected to identify products in the UK insulation market is reviewed in section 2.3.2. Manufacture and application of products are discussed in sections 2.3.3. Resources and supply chain for biomass-based products in the British and Welsh context are discussed in section 2.3.4. LCA studies on insulation products are reviewed in section 2.3.5. The last section (2.3.6) concludes the literature review by presenting a summary and highlighting the opportunities for research.

2.3.1 Properties and applications of thermal insulation products

The application of insulation products to the envelope of domestic buildings is undertaken to increase their thermal resistance. *Building envelope* refers generically to any solid or transparent surface which encloses a space of the building and is therefore in contact with the outdoor environment on one side and with the indoor on the other. The solid envelope can be divided into different elements:

- pitched and flat roof;
- external wall;

- ground floor, either in contact with foundations/soil or exposed to an unheated space, such as a basement.

Insulation can be installed on a lightweight structural frame (e.g. timber frame) or on heavyweight solid elements (e.g. brick masonry), as well as a combination of the two structures. Insulation products can be applied to the envelope during construction as well as added as part of a retrofit at later stage of its life-cycle, with differences in installation techniques, architectural detailing and performance requirements. The following pages introduce the different types of existing insulation products the main factors affecting performance and application range: thermal conductivity, vapour resistance, density and physical format. Table 2. 2 shows typical values for insulation products which can be commonly found on the UK market.

Table 2. 2 – Typical properties of commercially available insulation products (source: Pfundstein et al., 2007; AEA Technology plc, 2010; Duijve, 2012; Pargana, 2012; Wilde and Lawrence, 2013; Black Mountain, 2016b; 2017b)

Group		Product	Conductivity	Density	Vapour resistance factor	Compressive strength	Specific heat capacity	Fire class	Physical format	
			W/mK	kg/m^3	μ	kPa @10%def	J/kgK	NEN-EN12501	Panels	Batts & rolls
Conventional	Mineral	Stone wool	0.03-0.04	15-200	1 - 5	40-200	600-1000	A1 - A2	x	x
		Glass wool	0.035-0.044	10-150	1 - 5	negligible	600-1000	A1 - A2		x
	Plastic	PUR	0.018-0.028	30-160	50 - 100	120-150	1400-1500	D - F	x	
		EPS	0.029-0.045	10-80	20 - 100	60-200	1500	E - F	x	
		XPS	0.025-0.04	15-85	80 - 300	150-700	1300-1700	E - F	x	
		Phenolic	0.02-0.021	35 40	30 - 50	120-130	1500	B - D	x	
Alternative	Innovative	Aerogel	0.013-0.021	100-150	2 - 5.5	/	/	A1		x
		Aluminium multifoil	0.038-0.045	17 g/m^2	68,000	/	/	F		x
		Vacuum panels	0.008	180-210	(barrier)	/	/	A2	x	
	Recycled	Recycled paper	0.038-0.04	30-70	2 - 3	negligible	1700-2150	E		x
		Recycled textiles	0.038	18	1 - 5	negligible	840 1300	E		x
	Biomass	Hemp fibre	0.038-0.04	30-42	1 - 2	negligible	1500-2200	E		x
		Wood fibre	0.037-0.058	50-270	5	20-250	1600-2100	E	x	x
		Flax fibre	0.035-0.04	28	1 - 2	negligible	1300-1640	C		x
		Sheep wool	0.035-0.04	25-60	1 - 2	negligible	960-1300	E		x
		Cork	0.037-0.043	90-140	5 - 30	100-200	1700-2100	E	x	

Types of insulation products

Insulation products can be categorised in different ways depending on their popularity, physical structure and origin of primary material (AEA Technology, 2010; Jelle, 2011; Pargana 2012; Duijve, 2012; Asdrubali et al., 2015). A simple distinction based on popularity can be made between 'conventional' and 'alternative' products. Conventional products have been on the market for several years and are manufactured and used in large numbers. In the UK, these conventional products are either mineral-based such as stone wool and glass wool, or forms of plastic foams derived from fossil sources, such as polystyrene, polyurethane, polyisocyanurate and phenolic foam.

Alternative or 'unconventional' products (Asdrubali et al., 2015) have been developed more recently and are manufactured and used in small numbers or are still in the development stage. These products can be sub-divided into three broad groups: technologically innovative, recycled, and biomass-based. Technologically innovative products are based on new materials and techniques, for example vacuum panels, multi-foil aluminium, or phase-changing materials (Jelle, 2011). Recycled products are based on different waste resources, such as paper (Schmidt et al. 2004), textiles (Pokkyarath et al., 2014) or polyester (Intini and Kühtz, 2011). Biomass-based products generally use organic fibres from plants (e.g. flax) or animals (e.g. sheep wool), though there can be exceptions such as cork, which has a cellular structure. The following is a non-exhaustive list of biomass materials which can be used for thermal insulation (Yates, 2006; Van Dam Wageningen, 2009; Menet and Gruescu, 2012):

- Flax fibre;
- Straw;
- Reed;
- Kenaf fibre;
- Hemp fibre;
- Cotton fibre;
- Coconut fibre;
- Wood fibre, also called wood wool;
- Sheep wool;
- Expanded rye;
- Cork, either virgin or recycled.

For simplicity of terms, these insulation products are referred to as 'biomass products', though not all of their components are necessarily manufactured from biomass sources.

The manufacture of organic fibres is expected to release fewer GHG emissions than artificial fibres due to the carbon stored in their mass, but it is also considered more work intensive and expensive (Van Dam Wageningen, 2009). Specific advantages of organic fibres are the ability to act as moisture buffers and the higher heat capacity in comparison to mineral fibres (Cripps et al., 2004). Despite the potential benefits of biomass products, their penetration on the market is very limited. This can be attributed to a combination of factors: a scattered and conservative market; the limits posed by standardisation and regulations (Van Dam Wageningen, 2009); and the high price in comparison to conventional products. Even in countries such as Germany and Austria, where the use of biomass products is supported by financial incentives, these products occupy only 3-5% of the market (Cripps et al., 2004).

Thermal conductivity

The physical property describing the capacity to allow the passage of heat is *thermal conductivity*, measured in watts per meter per Kelvin (W/mK) and usually indicated with *k* or λ (lambda). Good insulating materials have low thermal conductivity, and vice-versa. Thermal conductivity is affected by material density and heat capacity, and is determined not only by conduction through the solid body, i.e. the transfer of heat at atomic level, but includes minor contributions from radiation, convection, leaks and other phenomena that can increase the passage of heat through the material (Jelle, 2011). The inverse of conductivity is called thermal *resistivity*. Thermal *conductance*, usually called *U-value*, describes the capacity to conduct heat across a layer of a certain thickness. It is calculated dividing conductivity by the layer thickness. The inverse of conductance is thermal *resistance*, usually called *R-value*, and measured in m^2K/W.

The specific heat capacity of a material (i.e. the capacity of the material to store thermal energy and thus act as thermal buffer) also affects the performance of the insulation layer. Generally, a high heat capacity improves the performance, as the material not only ‘obstructs’ the passage of heat but also delays it.

Vapour resistance

The amount of heat that can pass through a layer of material depends primarily on the conductivity of the material and the thickness of the layer. However, thermal conductivity is not constant but can change in response to variations in moisture and temperature difference between outdoor and indoor (Jerman and Černý, 2012; Wilde and Lawrence, 2013). The capacity to delay the passage of moisture is also a relevant property of insulation products, and can be measured either as *vapour resistivity* (MNs/gm, mega-Newton seconds per gram-meters) or as *water vapour resistance factor* in comparison to the property of air (also called μ–value). In certain conditions, products with a high resistance to the passage of vapour can cause the accumulation of moisture, which can lead to a loss of thermal performance as well as damage from condensation.

Density

Most insulation products can be produced with different densities. The density to which the material is manufactured affects the weight of the final product as well as its thermal conductivity, although not with a linear relationship (Kymäläinen and Sjöberg, 2008). Density and the inner structure of the material determine the format in which insulation products can be manufactured. For example, fibrous products such as mineral wools have generally lower rigidity and compressive strength than cellular products such as plastic foams. These properties affect the range of applications suitable for each product (Jelle, 2011).

Finally, other properties such as fire resistance or acoustic insulation need to be taken into account in order to satisfy legal performance requirements (Jelle, 2011). To enable comparison on equal terms, the declared values for conductivity and other properties of insulation products found on the market are the results of measurements in standardised conditions.

Physical format

Application techniques depend on the ‘physical format’ of the product and the components of the envelope. Formats such as panels, batts (i.e. semi-rigid panels) and rolls can be laid on a surface, encased in a frame, glued, nailed, fixed with ad-hoc rails, etc. Loose products need to be cast into the envelope, such as plastic granules or sprayed foam. Insulation materials can be integrated into composite envelope elements at the manufacturing stage. The composite nature of these products makes it difficult to compare them with ‘simple’ insulation products on an equal functional basis, because composite products can also serve structural and weather-protective functions beside thermal insulation. This multifunctional nature can be an advantage, but one of the drawbacks of composite products is the difficulty to recycle and reuse them without extensive re-working (Denison and Halligan, 2009; Job et al., 2016). For this reason, composite products are excluded from the scope of this review.

2.3.2 Domestic insulation products in the UK

The UK market of insulation products for domestic building (i.e. national demand) was valued at £700-800 million in 2010, with about 70-80% of the market represented by retrofits and the rest by new constructions (Office for Fair Trading, 2012a). Demand in this sector is driven by Governmental schemes (such as ECO, CERT and CESP), with a smaller proportion of the demand from private ownership focusing on the less expensive interventions such as cavity wall and loft insulation (Office for Fair Trading, 2012a). In the early 2010's demand was expected to increase, aided by low carbon targets (Office for Fair Trading, 2012a). However, demand decreased by about 7% partially as a consequence of the end of the CERT and CESP schemes together with the lack of success of the new scheme *GreenDeal* (AMA Research, 2015b). AMA Research (2015b) reported that demand has risen since 2014 due to a steady increase in domestic construction and a limited uptake of GreenDeal and ECO measures. Energy prices are expected to rise over the long term and indirectly increase demand and price of insulation (AMA Research, 2015b).

Demand for domestic insulation is also influenced by changes in Building Regulations. Welsh Building regulations were updated in 2012 after being devolved to the Welsh Government in 2011, meaning that the Government can set different requirements in Wales in respect to England. In terms of environmental impact, these regulations focus on the operational phase of the building (i.e. energy consumption and related GHG emissions) through the requirements set out in *Part L - Conservation of fuel and power*. For new dwellings, *Part L1A* poses a limit to GHG emissions and maximum values of thermal transmittance (U-value) to be ensured in envelope elements.

Table 2. 3 shows that U-values required in Wales are lower than those in England, and thus more insulation is needed. For the renovation of an existing dwelling, *Part L1B* requires certain levels of thermal transmittance to be achieved through additional insulation only if it is technically and economically feasible. A payback of no more than 15 years is the criterion adopted to determine economic feasibility.

Table 2. 3 - Comparison of maximum U-values required in Building Regulations Part L in Wales and England (source: HM Gov, 2016a; HM Gov, 2016b; WG, 2014a; WG, 2014b)

	Envelope element	Maximum U-values (W/m^{2}K) required by Building Regulations	
		Wales	**England**
New dwellings	Ext walls	0.21	0.3
	Roof	0.15	0.2
	Floor	0.18	0.25
Retrofitted dwellings	Ext. and Int. wall insulation	0.3	0.3
	Roof	0.16 -0.018	0.16 -0.018

Supply chain of insulation products

The supply chain of domestic insulation products can be divided in:

- manufacturers – purchasing primary materials and manufacturing products;
- distributors and retailers – purchasing products from manufacturers and selling them through their distribution network;

- contractors and installers – purchasing products from retailers and installing them on domestic buildings (Office for Fair Trading, 2012a).

Insulation manufacturers

There is a high degree of *market concentration* in the manufacturing sector for insulation, i.e. relatively few large companies occupy most of the market, which has the potential for anti-competitive behaviour (Office for Fair Trading, 2012a). Existing companies also have the advantage of economies of scale, as a high capital cost is required to open new manufacturing plants (Office for Fair Trading 2012a) and a large demand is needed to make production profitable (Pokkyarath at al., 2014). The total value of conventional insulation products manufactured in UK in 2010 (i.e. national production) was around £760 million, with about 60% being plastic products and the rest mineral products (Office for Fair Trading, 2012a). Mineral products have been available on the insulation market for over 50 years, while plastic products have been introduced more recently (Longsdale, 2012). In the last ten years there has been a shift of preference from mineral products to plastic ones (Longsdale, 2012; AMA Research 2015b). Table 2. 4 reports business indicators relative to the industry sector associated with conventional insulation products. The UK manufacturing sector of mineral products is dominated by Rockwool, Knauf, Saint Gobain and SuperGlass (Office for Fair Trading, 2012a; AMA Research, 2015b). The manufacture of stone wool is part of the non-metallic mineral products sector, and insulation represents about one quarter of the total revenue of this sector (Mak, 2017). The manufacture of glass wool is part of the glass fibres sector. Two research reports have indicated that mineral products have gained an unfair advantage over other products by being preferred in Governmental schemes for loft insulation and sold at subsidised rates in do-it-yourself stores (Hayward et al. 2013; Pokkyarath at al., 2014). The raw materials of mineral products are either quarried (basalt rock, silica sand, coke) or recycled from waste or industrial processes (recycled aggregates and glass, steel slag).

Kingspan, Quinn, Knauf, Jablite and Kay-Metzeler are the largest manufacturers of plastic insulation in the UK (Office for Fair Trading, 2012a; AMA Research, 2015b). Plastic insulation products are part of the primary forms plastic sector. The raw materials for plastic products are various organic compounds produced after the extraction of fossil materials, i.e. oil and natural gas.

There is a number of small manufacturers of alternative products in the UK, and significant potential for research and development of innovative insulation products based on advanced materials or biomass resources (Longsdale, 2012). A lack of competition between UK certifying bodies (e.g. BRE) has been identified as a barrier to innovation in the sector (Office for Fair Trading, 2012a; Hayward et al. 2013). More generally, the uptake of low-carbon construction materials (such as biomass and recycled insulation, but also timber, recycled aggregates, etc.) in the UK is hampered by a number factors. Giesekam et al. (2015) investigated the view of the UK construction sector on low-carbon materials and identified several barriers to their uptake, for example a lack of technical knowledge and training, negative perceptions from other professionals, concerns about durability and low availability of materials. Among other outcomes, Giesekam et al. (2015) noted that high price was often perceived as a barrier rather than being experienced as one, while professionals engaged in low-carbon project reported a link between embodied carbon reductions and cost reductions.

Table 2. 4 – Business indicators of industry sector associated with conventional insulation products

Insulation products	**Stone wool**	**Glass wool**	**PUR, EPS and phenolic**
Product manufacturing sector	Manufacture of other non-metallic mineral products	Manufacture of glass fibres	Manufacture of plastics in primary forms
SIC2007 code	C23.99	C23.14	C20.16
Sector stage	Mature	(not available)	Mature
Capital intensity	Medium	(not available)	High
Technological change	Low	(not available)	Medium
Barriers to entry	High	(not available)	Medium
Source	Mak, 2017		Breeze, 2015
Primary material sector	Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate	Quarrying of stone, sand and clay	Extraction of crude petroleum and natural gas
SIC2007 code	B08.11	B0.8.12	B06
Sector stage	Mature	(not available)	Decline
Capital intensity	High	(not available)	High
Technological change	Low	(not available)	Medium
Barriers to entry	Medium	(not available)	High
Source	Breeze, 2016		Clutterbuck, 2016b

A survey of the FAME database (Bureau van Dijk, 2016) and companies' websites was conducted to collect data on the number and location of insulation manufacturers and retailers in relation to Wales. Contractors and installers were not investigated as the installation phase is outside the scope of this thesis. It was not possible to obtain a fully comprehensive list because insulation manufacturing companies are not grouped under a single category, and insulation retailers fall under the larger category of builder's merchants.

Table 2. 5 shows the main British and Irish manufacturing companies, ranked by operating revenue. Several companies have plants located close to Wales or in Wales, as Rockwool (Bridgend), Knauf (Cwmbran and Chester) and Kingspan (Herefordshire). Main manufacturers of biomass products are Thermafleece (Eden Renewable Innovations) and Black Mountain, both located in England. No evidence of any wood fibre insulation manufacturer located in the UK was found.

Table 2. 5 – Manufacturers of thermal insulation products in the UK (source: Bureau van Dijk 2016)

Company name	Product	Location	Latest Operating Revenue (1000£)	Latest No of Employees	SME
Gortmullan Holdings Limited	PIR (Owner of Quinn companies)	Northern Ireland	554,792	2,630	No
Knauf Insulation Limited	stone wool, glass wool, XPS	North Wales, South Wales	148,881	591	No
Kingspan Insulation Limited	PIR, phenolic foam, XPS	England (Herefordshire)	117,003	385	No
Vita Cellular Foams (UK) Limited	PUR, EPS (Kay-Metzeler)	England (Liverpool, East Anglia)	111,335	520	No
Recticel	PIR	England (Birmingham)	110,208	629	No
Xtratherm UK Limited	PIR, phenolic foam	North Wales	96,665	122	No
Leanort Limited	(owner of Xtratherm)	/	91,507	284	No
Saint Gobain Celotex	PIR, glass wool (Isover)	England (East Anglia)	90,374	175	No
Rockwool Limited	Stone wool	South Wales	79,703	443	No
IKO PLC	PIR	England (Liverpool)	70,084	276	No
Icopal Limited	PIR (Thermazone)	England (Manchester)	42,287	131	Yes
Ecotherm Insulation (UK) Ltd	PIR	England (East Anglia)	40,572	61	Yes
Novostrat Limited	Multifoil	Ireland	27,803	292	No
Jablite Limited	EPS	England (London)	27,429	77	Yes
Springvale EPS Limited	EPS	England (Kent, Yorkshire)	23,731	105	Yes
Superglass Holdings PLC	glass wool	Scotland	23,507	158	Yes
Superglass	glass wool	Scotland	23,429	156	Yes
Owens-Corning Veil U.K. Ltd.	glass wool	England (Yorkshire)	19,970	82	Yes
Eurobond Laminates Limited	Stone wool composite panels	South Wales	19,094	82	Yes
Quinn Building Products Limited	PIR	Northern Ireland	17,370	190	Yes
Ballytherm Limited	PIR	Ireland	16,921	34	Yes
Styrene Packaging & Insulation Limited	EPS	England (Yorkshire)	14,750	90	Yes
S And B EPS Limited	EPS	England (Yorkshire)	12,937	46	Yes
Moulded Foams Limited	EPS	South Wales	12,665	80	Yes
NMC (UK) Limited	EPS	South Wales	12,121	54	Yes
Sundolitt Limited	EPS, XPS	Scotland	11,060	56	Yes
Cellecta	XPS	South England	9,143	29	Yes

Company name	Product	Location	Latest Operating Revenue (1000£)	Latest No of Employees	SME
Aerobord Limited	EPS	Northern Ireland	7,145	26	Yes
Ursa U.K. Limited	Glass wool	England (London)	3,134	7	Yes
Sips Frames UK Ltd	EPS structural insulated panels	Scotland	3,019		Yes
Kevothermal Limited	vacuum panels	England (Birmingham)	1,444		Yes
KdB	multifoil	N.Ireland	912	7	Yes
Plant Fibre Technology Ltd	Hemp fibre	Welsh company relying on French manufacturer	n/a	n/a	Yes
Eden Renewable Innovations	Hemp fibre, sheep wool	England (Cumbria)	n/a	n/a	Yes
Ciur (UK) Limited	Cellulose (Warmcel)	Wales	n/a	n/a	Yes
Eccleston & Hart Limited	EPS	England (Birmingham)	n/a	n/a	Yes
Thermal Economics Limited	EPS, PIR, multifoil	England (Luton)	n/a	n/a	Yes
Airpacks Limited	EPS (KORE)	Northern Ireland	n/a	n/a	Yes
Quinn Therm Limited	PIR	N.Ireland	n/a	n/a	n/a
YBS insulation	Multifoil	England (Sheffield)	n/a	n/a	n/a
NaturePRO	Sheep wool, hemp fibre, wood fibre (owned by SIG, unclea if manufacturer or retailer)	(not avaiilable)	n/a	n/a	Yes
Black Mountain	Hemp fibre, sheep wool	England (East Anglia)	n/a	n/a	Yes

Insulation retailers

Direct sales of insulation products from manufacturers to installers are small, with most products delivered to the market via general *builders' merchants* or specialist distributors (Office for Fair Trading, 2012a; AMA Research, 2015b). There are some national large companies in the distributor and contractor sectors but most firms are small and operate at a regional scale (Office for Fair Trading 2012a). In an industry report by IBISWorld (Clutterbuck, 2016a) the UK construction retail sector is considered to be at the 'mature' stage, i.e. with limited opportunities for expansion in the future. IBISWorld considered this sector to have a low degree of capital intensity and technological changes, and a medium level of barriers for new companies (Clutterbuck, 2016a). Imported products have been estimated around 10% of the UK market in 2011 (Office for Fair Trading 2012a). Importing insulation is considered expensive as the bulkiness of products results in high transportation cost (Office for Fair Trading 2012a). However, raw materials are often imported, and UK manufacturers have reported increasing costs in recent years (Longsdale, 2012). Table 2. 6 shows retailers and distributors of insulation products with at least one branch in Wales or just across the border in England, ranked by operating revenue. Both large national companies and local small businesses operate in the region. Most retailers supply a range of mineral and plastic products.

Sheep wool insulation can be purchased from some of the large retailers (such as Minster), but specialised small firms (such as Ty Mawr) have a wider range of biomass products. Thermafleece and Black Mountain products can also be purchased directly from manufacturers.

Table 2. 6 – Retailers of thermal insulation products located in Wales or near Wales (source: Bureau van Dijk 2016)

Company name	Products sold	Main branch locations	Operating Revenue (1000£)	Latest No of Employees	SME
Travis Perkins	Plastics, minerals	several branches across Wales	6,217,200	24,656	No
Jewson Limited (Minster)	Plastics, minerals, cellulose, sheep wool	several branches across Wales	1,763,035	8,504	No
Keyline		Cardiff, Camarthen	392,303	929	No
CCF Limited	Plastics, minerals	Cardiff, Liverpool	261,853	497	No
Encon Insulation Limited	Plastics, minerals, sheep wool	Cardiff, Liverpool	182,750	463	No
LBS Builders Merchants Limited	Minerals	Several braches in South Wales	31,302	216	Yes
Robert Price & Sons Limited	n/a		25,737	220	Yes
Robert Price (Builders Merchants) Limited	Plastics, minerals	Several braches in South Wales	21,843	195	Yes
Boys & Boden, Limited	n/a	Llandrindod Wells, Welshpool, Shrewsbury, Newtown, Chester	19,348	192	Yes
Braceys	n/a	Cardiff, Bridgend	16,577	n/a	Yes
TG (Tudor Griffiths) Builders merchant	n/a	Welshpool	13,487	69	Yes
Richard Williams	Plastics, minerals	Llandudno, Ruthin	11,263	n/a	Yes
Nationwide Drywall & Insulation Limited	Plastics, minerals	Cardiff, Liverpool	n/a	n/a	Yes
TY Mawr Lime Limited	Sheep wool, hemp fibre, recycled PET	Brecon	n/a	n/a	Yes
A & A Insulation Services Limited	Plastics	Cardiff	n/a	n/a	Yes
AIS Insulation Supplies Limited	Plastics, minerals	Camarthen	n/a	n/a	Yes
SIG Insulations Limited	Plastics, minerals, sheep wool, hemp fibre, wood fibre	Cardiff, Leominster, Liverpool	n/a	n/a	Yes
Seconds And CO Limited	Plastics	Llandrindod Wells	n/a	n/a	Yes
GC Insulation supplies	n/a	Cardiff	n/a	n/a	Yes
J and A Phillips	Plastics, minerals	Newport	n/a	n/a	Yes
Whitchurch builder supplies	Plastics, minerals	Cardiff	n/a	n/a	Yes
Celtic sustainables (3P Technik UK Limited)	Sheep wool, hemp fibre, recycled PET	Cardigan	n/a	n/a	Yes

Market shares of conventional insulation products

Industry and market research reports have been reviewed to establish the market shares occupied by insulation products in the UK, as this type of data is not typically available in academic literature. When reviewing industry and market research, it should be taken into account that these source do not necessarily comply with academic standards. Most market research is only available for a high fee. Data from the *Building insulation products market report UK – 2015-2019 analysis* (AMA Research, 2015a) has been purchased for this research and used, among other sources, to determine the market shares occupied by insulation products in retrofitted lofts flat roofs of new dwellings. Precise figures from this source cannot be disclosed due to legal restrictions, however they indicate a large prevalence of glass wool in lofts and of PUR in flat roofs (AMA Research, 2015a).

Comparison between data sources on market shares is difficult, as some sources refer to national production (i.e. supply, which includes exports) while other to national consumption (i.e. demand, which includes imports and excludes exports). However, only about 10% of insulation used in the UK is imported (Office for Fair Trading, 2012a). Furthermore, some sources quantify shares of the insulation market in monetary terms, such as UK pounds of insulation sold, while others make use of physical units, such as square meters of insulation installed. Data on the EU market for insulation products helps understanding this distinction:

- Figure 2. 2 shows the product mix in the insulation market at the European level in monetary units as insulation sold. Plastic products occupy about 50% of the market, while glass wool and stone wool have respectively about 20% and 30%. 'Other products' are given about 5% of the market. The source does not specify to which products this category refers to, it is reasonable to assume that it includes 'alternative' products, such as biomass and those based on aerogel, vacuum panels and recycled materials. Most sources tend to group these products into one category of 'other products' due to their very small shares of the market, though not every source includes this category.
- Figure 2. 3 shows product mix in the insulation market at the European level in physical units, as insulation installed, and does not feature a category for 'other products'. Glass wool occupies the relative majority of the market with about 40%, while EPS takes the second largest share (about 30%). Overall, mineral products occupy around 60% of the market.

Differences between Figure 2. 2 and Figure 2. 3 can be explained by the fact that the latter quantifies products in cubic meters, while former refers to Euro. Since glass wool is cheaper than PUR and phenolic foams (as will be shown in section 5.1), glass wool occupies a smaller share of the market when monetary units are used instead of physical ones.

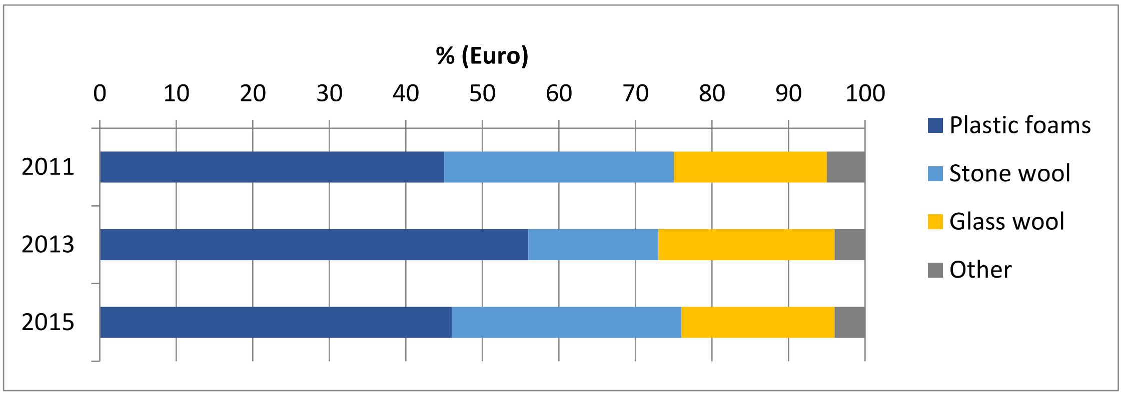


Figure 2. 2 – Share (%) of European insulation market, Rockwool data based on monetary units (€ of insulation sold) (source for 2011: Rockwool, 2014; source for 2013: Rockwool, 2015a; source for 2015: Rockwool, 2015b)

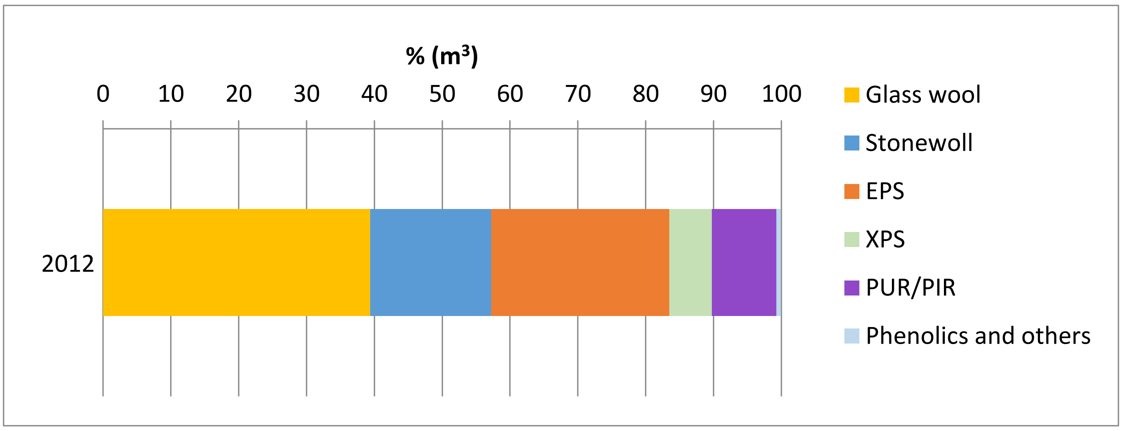


Figure 2. 3 – Share (%) of European insulation market in 2012, based on physical units (m3 of insulation sold) (source: IAL Consultants, 2013)

The following two graphs describe the UK market for insulation products, including products used in domestic and commercial buildings as well as industrial applications. Figure 2. 4 quantifies the insulation manufacturing sector of the UK in cubic meters of insulation produced. The manufacturing output in 2010 is shown to be largely occupied by PUR and glass wool, with smaller productions of EPS, stone wool and XPS. Figure 2. 5 describes the UK market in terms of pounds of insulation sold. In both 2005 and 2010 over 40% of the market was occupied by mineral products, while the share of PUR increased from about 20% in 2005 to about 30% in 2010, at the expense of EPS and XPS.

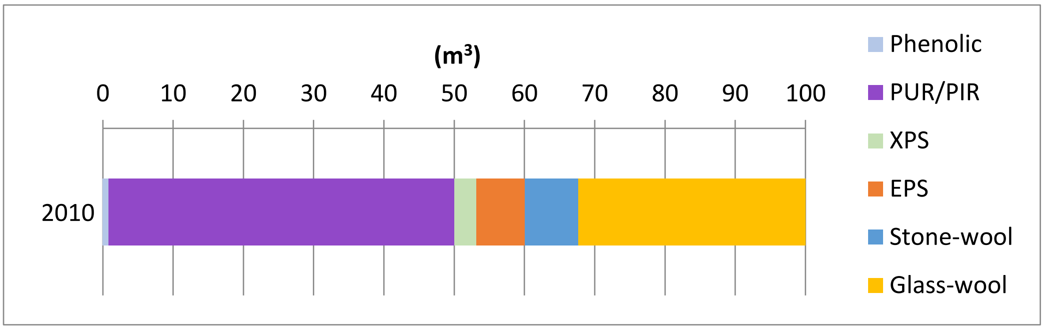


Figure 2. 4 – Share (%) of the manufacturing sector of domestic insulation in the UK in 2010, based on physical units (m3 of insulation produced) (source: IAL Consultants, 2009 ; 2011; cited in Office for Fair Trading, 2012a.)

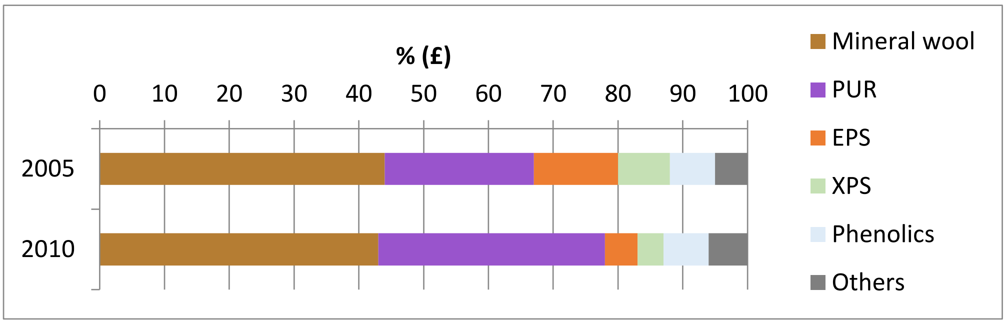


Figure 2. 5 – Share (%) of UK Insulation market by insulation type, based on monetary units (£ of insulation sold) (source: AMA Research, 2006, cited in Market Transformation Report on insulation (BNIW01, v.1.3), 2007; and BRUMFA, 2010, cited in Longsdale, 2012)

Although the previous graphs indicate the prevalence of conventional products, little information is provided on what products are used to insulate specific envelope types in domestic buildings. A report by the Office for Fair Trading (2012b) and an annual survey made by the Insulated Render and Cladding Association (INCA, 2015) provide more detail on the sub-sectors of the insulation market in the UK, but do not clearly distinguish between new and retrofitted dwellings (Figure 2. 6 and Figure 2. 7). Both publications can be considered as reliable sources of information, and together with the AMA Research report (2015a) are the most detailed available data on product mixes in different sub-sectors of the insulation market. The data in Figure 2. 6 is given in the technical report *Anticipated acquisition by Saint-Gobain (BPB United Kingdom Limited) of Celotex Group Limited* by Office for Fair Trading (2012b) and expresses shares of the market in monetary units. PUR and PIR occupy the majority of the floor and flat roof sub-sector, and glass wool is mostly used in pitched roofs. In Figure 2. 6 the solid wall sub-sector is occupied for almost 40% by phenolics, while this product occupies only about 10% in Figure 2. 7, where EPS largely dominates the external wall sub-sector with over 70%. Figure 2. 7 expresses shares of the market in physical units. Differences between the two graphs can be attributed to the units used, as well as to the fact that the data in Figure 2. 7 refers to external wall insulation, while Figure 2. 6 refers to solid wall insulation. Although there is an overlap, these two categories are different. “Solid wall insulation” refers to the insulation of solid masonry walls (usually in retrofits) and can be applied externally or internally. External wall insulation is by definition applied externally, on masonry as well as other wall types.

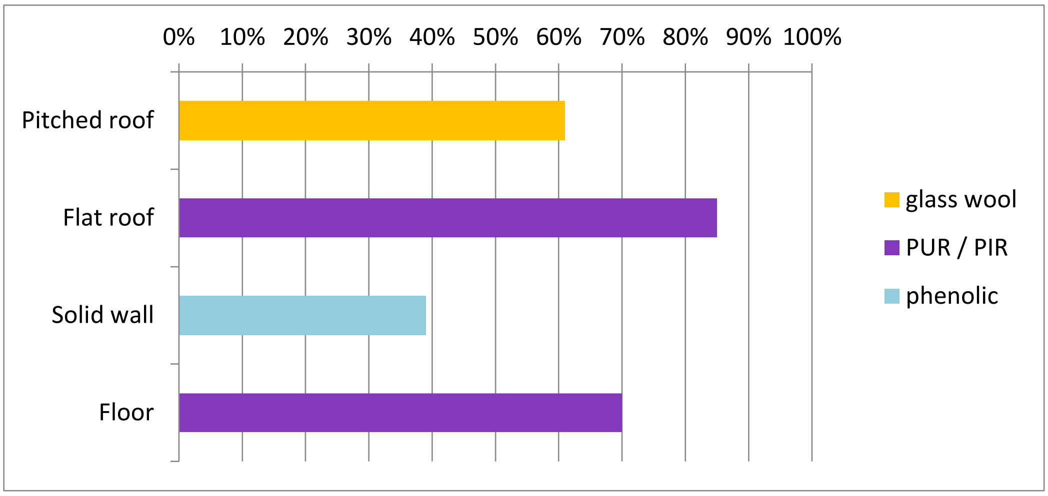


Figure 2. 6 – Share (%) of specific products in UK insulation market sub-sectors in 2012, based on monetary units (£) (source: Office for Fair Trading, 2012b)

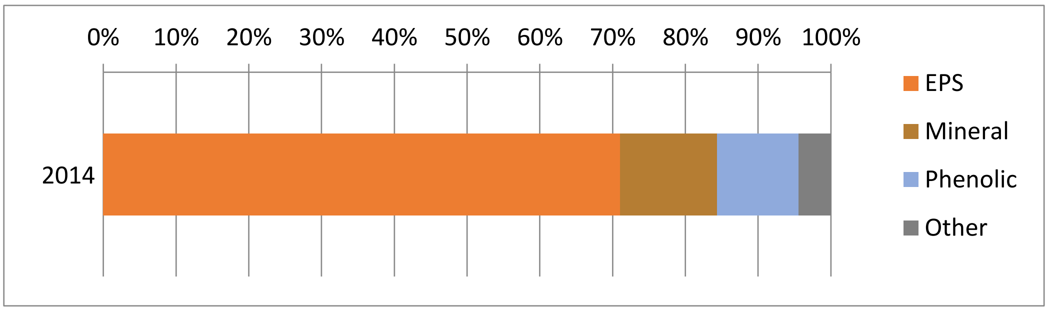


Figure 2. 7 – Share (%) of external wall insulation installed in new and retrofitted dwellings by installers members of the Insulated Render and Cladding Association (INCA) in 2014, based on physical units (m2 of insulation installed) (source: INCA, 2015)

2.3.3 Manufacture and application of insulation products

This section describes manufacture and application range of eight types of insulation products. Five of these products were identified in the previous sections as the 'conventional' products in the UK, i.e. products which occupy the majority of the market:

1. Stone wool;
2. Glass wool;
3. Polyurethane Rigid and Polyisocyanurate foam (PUR and PIR);
4. Expanded Polystyrene;
5. Phenolic foam.

The other three products are based on biomass resources which are currently produced in Wales or have the potential to be:

6. Hemp fibre;
7. Sheep wool;
8. Wood fibre.

Therefore these eight insulation products were selected on the basis of regional relevance, being either products which are widely used in Wales (as part of the UK market) or products which can be manufactured from regionally-appropriate materials. In a different geographical context, other products would have been selected on the basis of the relative conditions of the market and the regional resources.

The choice to limit the scope of this review to biomass products and exclude recycled ones is not a judgement on the superiority of the former type to the latter, but a consequence of the author's interest in exploring the links between natural resources and human demands in the regional context, as discussed in the first part (2.1) of this Literature Review. Recycled products show the potential to be low-impact alternatives to conventional products, as they have a clear affinity to the principles of circular economy and are associated with low embodied impact (Schmidt et al., 2004; Intini and Kühtz, 2011; Pokkyarath et al., 2014).

Mineral insulation products

Stone wool and glass wool have been commercialised as insulation products for several decades. Though their primary materials are different, the manufacturing processes are very similar (EURIMA, 2012). Both stone wool and glass wool are fibrous products produced from naturally available mineral resources and recycled mineral materials. In comparison to fossil-based products, mineral insulation products are flexible, vapour permeable, non-combustible and do not release toxic substances when exposed to flame (Stec and Hull, 2011).

Stone-wool insulation

Stone wool is made of basalt rock, slag (by-product of the steel industry), coke and inert waste briquettes. These materials are melted together in a furnace and spun into fibres while a binder material is added. The loose fibres are cured (i.e. heated), compacted and cut into the format required for the final product (EURIMA, 2012). Any waste is re-used as input in the manufacturing process. The product does not require further additives as it is naturally water-repellent and fire resistant. Stone wool is classified as non-hazardous waste and therefore at the end of its life-cycle can be land-filled or used as material for road fill (Duijve, 2012). Recycling in the manufacture of new stone wool represents a better option because it reduces the need for virgin material (Schmidt et al., 2004), however this requires an infrastructure for waste collection and reception at the manufacturing plants.

In terms of EEI, stone wool is generally acknowledged as a product with medium-low impact (Schmidt et al. 2004). Its main primary materials are minerals, which can be considered 'renewable' in so far as they are produced by volcanic activity (Denison and Halligan, 2009).

Stone wool can be manufactured at different density, resulting in different stiffness and conductivity. Low-density products are usually between 30 to 60 kg/m^3 with conductivity between 0.035 and 0.038 W/mK, while high-density products can reach 200 kg/m^3 with conductivity up to 0.04 W/mK. High-density products are more expensive and used mostly in the format of rigid panels when stiffness and compressive strength are required. Both low- and high-density products are considered to be vapour permeable. Fire resistance is classified between A1 and A2 (Stec and Hull, 2011), following the European classification system (EN 13501-1). Stone wool is produced in panels (the high-density type), batts, mats and rolls. Due to its ease to cut, flexibility and adaptability to rough surfaces, stone wool has a wide range of applications in walls, roof and floors of both new and retrofitted buildings.

Stone wool is better known as *Rockwool*, the company name of the original developer and largest manufacturer in the UK and Europe (Rockwool, 2015). Rockwool manufactures a product with high alumina and low-silica, which is a modification to the traditional stone wool. This composition is considered not to be carcinogenic and dissipates from the lungs much faster than traditional stone wool (Kamstrup et al., 2001). During the installation process is it recommended that workers wear protective gloves, as stone wool fibres can irritate the skin (EURIMA, 2012). The binder material in stone wool (generally about 5% of the product) is usually phenol-formaldehyde, whose potential emissions have raised health concerns, although there is little evidence on negative effects in the indoor environment (Salthammer et al., 2010). Nonetheless, in recent years a biomass-based binder has been developed and used in the manufacture of stone wool by Knauf to replace phenol-formaldehyde (Knauf, 2015).

Glass-wool insulation

The manufacturing process of glass wool is very similar to stone wool, although with different primary materials. Glass wool can be produced from different mixes of silica sand, soda ash and recycled glass cullets, with the share of recycled glass which can reach up to 80% of the product (Denison and Halligan, 2009). A binder is necessary to make the material more cohesive. Phenol-formaldehyde is generally used but biomass-based alternatives (such as ECOSE) are available (Knauf, 2015). Besides skin irritation (avoided via masks and glove) and the potential emissions of phenol-formaldehyde (if present), there are no significant concerns for health arising from the production and installation of glass wool (Isover-Saint Gobain, 2014.). As in the case of stone wool, glass wool waste is non-hazardous and can be landfilled, but the best disposal option is recycling it in the manufacture of new glass wool.

Glass wool is produced mostly at low-density, usually between 10 and 30 kg/m^3, with a thermal conductivity between 0.3 and 0.44 W/mK. In comparison to stone wool, glass wool is cheaper but its range of application is more limited, as the product has little stiffness and compressive strength. As for stone wool, glass wool is considered vapour permeable and its fire resistance is classified between A1 and A2 (Stec and Hull, 2011). A typical application for glass wool in the UK is the insulation of existing lofts.

Plastic insulation products

The insulation products based on fossil resources reviewed here are panels of PUR, EPS and phenolic foams. All three types are synthetic organic foams with a cellular structure (ether closed or open), manufactured by increasing the volume of a mix of hydrocarbons through a blowing agent. In comparison to mineral products, plastic foams are rather rigid, lack vapour permeability, and are associated with higher emissions of toxic substances when exposed to flame (Stec and Hull, 2011).

Polyurethane and Polyisocianurate Rigid foam (PUR/PIR) insulation

Polyurethane (PUR) is a thermoset plastic with closed cell structure (AEA Technology, 2010) which was originally developed as replacement for rubber (Denison and Halligan, 2009). Polyisocyanurate (PIR) is very similar to PUR. The difference between the two products lies only in the ratio of polyoil and isocyanate polymers used in the manufacturing process (AEA Technology, 2010). For this reason, they are commonly considered as one type of product (PU Europe, 2006), and are henceforth referred to as PUR for simplicity. Though PUR can also be sprayed on-site, this review focuses on rigid PUR panels, which use and format are comparable to the other insulation products.

The manufacturing process of PUR is the last stage of a long production chain of oil and natural gas derivates. The production flowchart by Plastics Europe (2011) shows the main "'ingredients" of PUR to be methylene diphenyl diisocyanate and polyoils. Pentane is the most common blowing agent, though carbon dioxide can also be used (PU Europe 2006). Before the advent of specific regulations to control ozone depletion, hydrofluorocarbons were used as blowing agent (Mazor et al., 2011). Pentane is considered to have low GWP (US EPA, 2011) but it is classified in the European hazard system as extremely flammable (F+), harmful to humans (Xn) and dangerous to the environment (N) (European Chemicals Bureau, 2003). The end-product comes in panels of various thicknesses (up to 20 cm), which are often finished with rigid or flexible facings (usually aluminium) to add specific properties (PU Europe, 2006).

The composite nature of many PUR panels makes straight-forward recycling very difficult. 'Clean' panels can be crushed and mechanically recycled into pressed boards (not for insulation purposes). Chemical recycling is also possible, but technically more difficult especially at a large scale (Yang et al., 2012). Composite panels can only be landfilled or incinerated for heat recovery (Denison and Halligan, 2009). A study published in 2008

(Consultic, 2008, in Hobbs an Ashford, 2013) provides data on the shares of the typical disposal practices in the UK for PUR waste arising *from manufacturing and installation*: landfilling (71%), incineration (20%), re-use (7%) and mechanical/chemical recycling (2%).

The typical thermal conductivity of PUR products is 0.022 W/mK (Kotaji and Loebel, 2010) but can range between 0.018 and 0.028 W/mK. PUR can be manufactured with densities between 30 and 160 kg/m^3, with little impact in the conductivity of the material (PU Europe, 2006). PUR is not vapour permeable and is also very resistant to water absorption, which makes it particularly adequate for applications where there is a high risk of flooding (PU Europe, 2006). Among insulation products, PUR has a high specific heat capacity, comparable to wood fibre (PU Europe, 2006). The fire resistance of most PUR and PIR products is between classes D to F (PU Europe, 2006) with PIR having a slightly better performance than PUR (Stec and Hull, 2011). In comparison to EPS and phenolic products, PUR releases more toxic substances when exposed to flame (Stec and Hull, 2011).

Expanded Polystyrene (EPS) insulation

Polystyrene is a thermoplastic product initially developed by BASF and commonly used for its thermal insulation property but also as light packaging and shock-absorbing material (Denison and Halligan, 2009). Expanded Polystyrene (EPS) is produced from granules of expandable polystyrene containing a blowing agent. Waste EPS can be recycled into the production via re-granulation. The manufacture process generally consists in a pre-expansion stage where the granules are heated with steam up to 100°C, which forces the blowing agent to expand. The granules are then stored into ventilated silos for cooling and ‘seasoning’, allowing the blowing agent to be replaced by air. The loose material is then expanded into moulds and ‘fused’ through heat (CITEPA, 2004). In recent years the use of EPS as insulation has been improved by the addition of graphite in the formula, which results in a grey coloration of the product, while traditional EPS is simply white. The addition of graphite reduces the thermal conductivity of EPS but increases its price.

The primary resources used to produce of EPS are crude oil and natural gas, both non-renewable fossil sources. However, the EPS industry claims that only 0.1% of the world oil consumption is used to produce EPS (British Plastics Federation, 2007). The production of styrene is problematic because the compound is toxic and possibly carcinogenic. However, the EPS industry claims that the levels of residual styrene in EPS panels are below concern (EUMEPS, 2010). The blowing agents used in past EPS production were ozone depleting gases, but now pentane is mostly used (CITEPA, 2004). Alternatives to pentane also exist (US EPA, 2011).

Polystyrene can be also "extruded" to produce Extruded Polystyrene (XPS), which generally has slightly higher density and thermal conductivity than EPS. Thus XPS is preferred to EPS when robustness and compressive strength are required. Carbon dioxide and other co-blowing agents are used to inflate the polystyrene foam in the XPS manufacturing process. LCA studies suggest that XPS has generally a higher environmental impact than EPS, due to its higher density and its manufacture process. In the Green Guide by BRE (2008) XPS is awarded an "E" rating, whilst EPS is awarded "A+" for densities between 15 and 30 kg/m^3 and "A" for density 40 kg/m^3. However, the GWP declared by the Green Guide for XPS is extremely higher than results from other studies such as Hammond and Jones (2008). This might be explained considering that the product assessed by the Green Guide uses hydrofluorocarbons (which have high GWP) as blowing agent.

EPS is a low-density material (generally between 10 and 35 kg/m^3), with 98% of its volume occupied by air (EUMEPS, 2010). Its low density makes it an effective insulation material capable to achieve thermal conductivity between 0.034 and 0.038 W/mK. However, there are different versions of EPS on the market, and higher density products can offer increased robustness but also an increase in conductivity, thus a loss in thermal performance. Resistance to vapour also depends on the density of the material, though in comparison to mineral products, EPS can be considered as not permeable to vapour. In terms of fire resistance, EPS and XPS are classified E and F (Stec and Hull, 2011).

At the end of its life-cycle, EPS can be recycled into production if the material is clean, which is possible when EPS panels are used as insulation in buildings, though a careful demolition process is necessary in order to recover the panels in good conditions. The presence of fire retardants in EPS used for insulation requires additional re-processing to allow recycling (EPS Industry Alliance, 2013). The recovery of EPS from composite products such as structurally-insulated panels becomes more difficult due to the presence of chemical binders. It is possible to incinerate EPS waste in order to recover the calorific value of the material. Though the industry claims that the process only produces carbon dioxide and non-toxic ash (British Plastics Federation, 2007; Wang et al., 2003). Landfilling of EPS waste is an option, as the material is completely inert. ~~Polystyrene does not biodegrade, and therefore it is possible for flakes to be ingested by animals~~. Landfilling probably represents the worst end-of-life scenario for the product, as both the material use and the calorific value are lost. Background information from an ongoing research project on EPS recycling (LIFE-PSLOOP, 2017) provides data on typical disposal practices for EPS insulation at European level: incineration with energy recovery (52.5%), landfill or incineration without energy recovery (40%) and recycling (7.5%).

Phenolic foam insulation

Phenolic foam is the least documented conventional insulation, as very few studies focus on its production and environmental impact (Densley Tingley et al., 2014). Phenolic foam is a thermoset plastic produced from a mix of phenolic formaldehyde resin, a blowing agent and an acid catalyst. The blowing agent is usually pentane, though a mix of pentane and isopropyl chloride can also be used (Densley Tingley et al., 2014). Other chemicals are added for specific functions, such as powdered urea to decrease thermal conductivity and increase structural strength or surfactants to stabilise the cellular structure (Densley Tingley et al., 2014). As for PUR, the final product is often complemented with facings in aluminium (or other materials), thus re-use and recycling are problematic. Phenolic foam can be land-filled or incinerated to recover its calorific value (Densley Tingley et al., 2014). The thermal conductivity of phenolic products ranges from 0.018 to 0.023 W/mK, with a typical density of 35 kg/m^3. In terms of fire resistance, phenolic products are classified between B and D (Stec and Hull, 2011).

Biomass insulation products

Manufacturing processes of hemp fibre, sheep wool and wood fibre products are presented here. The next section (2.3.4) investigates the associated supply chains in the British and Welsh context. The potential for using biomass products for construction in the UK has been explored for several years as a way to reduce the EEI of buildings (Cripps et al., 2004; Yates, 2006; Denison and Halligan, 2009). Yates (2006) identified sheep wool, hemp fibre and flax fibre as having the potential to be manufactured and used in UK as thermal insulation products. Timber products were excluded from Yates' analysis (2006), which explains the lack of mention of wood fibre.

Hemp fibre, sheep wool, and wood fibre insulation have been identified to have high potential in terms of local resource availability in the context of Wales. Sheep wool insulation is made from low-quality wool, which is currently produced in Wales as by-product of the sheep meat sector. The main manufacturers of sheep wool insulation in the UK (Eden Renewables and Black Mountain) are partially supplied by producers in Wales (Norton, 2008; Black Mountain, 2016b). Hemp and wood fibre products are not currently manufactured in Wales (Table 2. 5) but the potential exists. Hemp fibre insulation is made from *industrial hemp*, which could be cultivated in Wales (Allen, 2016). Wood fibre insulation is made from softwood chips, which are produced in Wales as a secondary product of the timber industry. These three biomass product types are sold in the UK with the brand *NaturePro* by of Euroform Ltd. Sheep wool and hemp fibre are also manufactured and sold in the UK as *Thermafleece* by Eden Renewables Ltd and as *NatuWool* by Black Mountain Ltd (the latter company is in liquidation (Companies House, 2017a)). These two companies are located in England and claim to source the majority of their primary materials in the UK. It should be noted that while this review focuses on biomass products in their present form, there are examples of new products being developed, as shown by Pennacchio et al. (2017).

Straw and flax have been considered as relevant products for this research, but were dismissed for the following reasons:

- Straw fibre insulation has a narrow range of application due to its physical format, and the Welsh production of straw is very limited. Straw is imported in Wales from England to be used as livestock bedding and feeding (Copeland and Turley, 2008). Therefore it is sufficiently clear that Welsh resources could not sustain any significant demand for straw fibre to be used as insulation product.
- Although flax is cultivated in the UK for several purposes, flax fibre insulation is currently not manufactured in the UK and can only be imported from abroad, whilst there are examples of hemp fibre insulation sourced, manufactured and sold in the UK. Flax and industrial hemp are relatively similar crops and the manufacturing processes of flax fibre insulation and hemp fibre insulation are also similar. In fact the two fibres can be combined into a single insulation product (Norton, 2008). For the purpose of this research, reviewing and modelling two similar products such as flax and hemp fibre was considered to introduce a duplication of efforts. Thus, it was preferred to exclude flax fibre products from the scope of this research while including hemp fibre.

Besides low EEI, some researchers have pointed out the ‘superior’ performance of biomass insulation products in terms of heat capacity and moisture control (Cripps et al., 2004). In comparison to mineral and plastic products, the higher specific heat capacity of biomass products enables a longer delay in heat transfer and increases the overall thermal mass of the envelope. The capacity of biomass products to allow the passage of water vapour as well as to absorb and release a higher quantity of moisture compared to mineral and plastic products is considered to be an advantage in specific application such as for example historical buildings or vapour permeable envelopes. Although the conductivity of biomass insulation increases when large quantity of water vapour is absorbed, thus causing a loss of performance, it has been shown by Padfield (1998) to be no different than in mineral products. Nonetheless, the hygrothermal and moisture sorption characteristics of biomass products have continued to be the subject of research (Norton, 2008; Zach et al., 2013; Latif et al., 2014)

There is a concern about the possible growth of microbes in biomass products and the emission of organic and inorganic particles. A study by Koivula et al (2005) included several samples of flax fibre, hemp fibre and recycled wood fibre (in loose format) and detected the presence of fungi at various extents in all samples. Samples of the commercially available products displayed lower values, since these products are treated with anti-fungi. However, significant emissions of microbes were measured only in conditions of relative humidity above 90%. Negligible emissions of bacteria and volatile organic compounds were recorded for all samples, with the exception of high VOC emissions from recycled wood fibre. Koivula et al. (2005) noted that a much lower quantity of such emissions from a similar material had been identified in previous study.

Hemp fibre insulation

Hemp (*Cannabis sativa*) is a *bast fibre* plant which can be grown in temperate climates with relatively low agricultural inputs and high yield (Kymäläinen and Sjöberg, 2008). The term *industrial hemp* indicates the variety of Cannabis sativa that contains insufficient amounts of psychoactive compounds to be used as a recreational substance (Carus and Sarmento, 2016). Several countries, including the UK, allow growing industrial hemp as an agricultural crop for commercial purposes. The straw of industrial hemp can be separated from the other parts of the plant to produce a fibre which has been put to different uses throughout history (Cromack, 1998). In 2013, 57% of the industrial hemp fibre produced in Europe was used by the pulp and paper industry, and 26% for insulation. The rest was used in the production of bio-plastics and technical textiles (Carus and Sarmento, 2016). Industrial hemp is also grown for the shives (i.e. the core of the straw) and the seed oil (Springdale Crop Sinergies, 2006).

Hemp fibre displays variations in physical and chemical properties due to the influence of external factors such as climate, time of harvest, and exposure to humidity. This makes the material less easily standardised than products manufactured entirely with industrial processes (Springdale Crop Sinergies, 2006; Kymäläinen and Sjöberg, 2008). However, there is sufficient evidence that hemp fibre is a suitable raw material for insulation products if the growth of microbes is kept under control by adequately *retting* the hemp straw, avoiding the exposure to moisture during the manufacturing process and treating the final product with additives (Kymäläinen and Sjöberg, 2008). Retting is a microbial process which breaks the chemical link between fibres and core, allowing an easier *decortication* process (Norton, 2008). Miscalculating the time for retting the straw leads to lower quality fibres. Retting on the field is the traditional method, but is it very dependent on weather conditions (Garstang et al., 2005).

Industrial hemp is a resistant crop which can be grown with none or very low amounts of pesticides and herbicides (Garstang et al., 2005; Latif et al., 2010; Haufe and Carus, 2011). However, the plant “requires nutrient rich, moist, well structured and drained soils” (Haufe and Carus, 2011, p.5). It is sown in spring and harvested about three to four months later, with an average yield of 6 tonnes of dry straw per hectare, which can reach up to 12 tonnes per hectare in particularly favourable conditions (Garstang et al., 2005; Haufe and Carus, 2011).

Norton (2008) described a typical manufacturing process of hemp fibre insulation, based on a product sold in the UK. The industrial hemp is grown in Hertfordshire, UK, left to ret on the field for several weeks and then baled and transported to a decortication plant to separate the fibre. Once the fibres are separated and cleaned, the manufacturing stage of the insulation product takes place. The fibres are immersed or sprayed with a fire retardant and mould repelling solution, usually based on sodium borate or ammonium phosphate (Norton, 2008; Zampori et al., 2013). The loose dried fibres are then blended with a binder material, lied to from a fleece, thermally bonded and cut into the required format. Hemp fibres can be mixed with compatible fibres such as flax or cotton, but this is not necessary. The binder material is needed to ensure the cohesiveness of the fleece. About 15% of the mass of most hemp fibre insulation products on the market consists of PET fibres (polyesther teraphtalate) which serve as a binder (Norton, 2008; Zampori et al., 2013; Zach et al., 2013), although Black Mountain (2017b) claim that 95% of their hemp fibre insulation is made of "natural fibres". The plastic fibres contribute significantly to the EEI of the product and pose an obstacle for recycling it at the end of its life-cycle. An alternative organic binder based on polylactic acid has been developed to replace the PET fibres (Norton, 2008; Haufe and Carus, 2011). Possible disposal options for hep fibre insulation are landfilling, incineration (with or without energy recovery) and composting (Norton, 2008). While incineration and, to a lesser extent, composting hemp fibre insulation release a large share of the carbon sequestered in the fibre, landfilling retains large part of it, and therefore represents a better disposal option, at least in terms of GWP (Norton, 2008).

Hemp fibre insulation products are comparable in physical format and application range to low density mineral products and particularly glass wool, though they have generally a higher density (Haufe and Carus, 2011). The typical conductivity (0.036 – 0.04 W/mK) is comparable to the range displayed by glass wool. In comparison to mineral products, hemp fibre insulation has much lower resistance to fire (class E), higher specific heat capacity and a different interaction with humidity. Experiments by Latif (2013) showed that hemp fibre has "'excellent' […] and 'good' […] moisture buffering capacity in relation to the 'Moisture Buffer Value Classes'." which enables reducing the risk of condensation (Latif, 2013, p.343). Comparing the hygro-thermal conditions measured in two samples of stone wool and hemp fibre insulation (both covered with oriented strand board), Latif et al. (2014) noted that although both samples were prone to condensation and mould growth, frequency and likelihood was lower in the case of hemp fibre. Thus the hygro-thermal performance of hemp fibre can be considered comparable to that of stone wool, if not better. However, the capacity of hemp fibre to *absorb* water in large quantities can be considered an obstacle for insulating envelopes which might get exposed to water (Zach et al., 2013).

Sheep wool insulation

Insulation products based on sheep wool have been produced in the UK and other countries for some years (Denison and Halligan, 2009) and there are examples of sheep wool used as insulation material in Welsh vernacular buildings (e.g. the *Llainfadyn cottage* at St. Fagans Museum near Cardiff). Research based on laboratory measurements by Zach et al. (2012) showed the thermal performance of sheep wool to be comparable to that of stone wool and highlighted its capacity to absorb water without significant changes in thermal conductivity. Manufacturers of sheep wool insulation are eager to stress that the hygroscopic nature of sheep wool insulation makes it particularly appropriate to be installed in old buildings, where it reduces the risk of condensation (Black Mountain, 2017a). In addition to this benefit, producers also claim that sheep wool insulation has low EEI and contributes to indoor air quality by absorbing formaldehyde (Black Mountain, 2017b).

Raw sheep wool comes in many types, especially in the UK where there is a large variety of sheep breeds (Morris, 2013). Wool quality is measured on a scale of grades related to the thickness of the wool fibre (British Wool Marketing Board, 2017), ranging from 2 (finest wool) to 7 (coarsest wool). ‘Low-grade’ wool (grades 6 and 7) is produced by hill and mountain sheep breeds, which are the large majority of breeds raised in Wales (Quigley, 2010). Insulation products are made with grade 7 wool (Mansour et al., 2014), which is also the type of wool used to manufacture carpets (Quigley, 2010).

Once wool is sheared from the sheep – in spring and early summer – it needs to be cleaned from dirt and impurities before entering the manufacturing stage. The cleaning process, called ‘scouring’, consists in a series of washes with chemical cleaning agents (Norton, 2008; Mansour et al., 2014). During this process, different batches of wool can be blended together to produce a fleece of uniform quality. A recent research project conducted in Spain has successfully developed a new dry-scouring process for wool to decrease its environmental impact. The developers claim that in comparison to traditional scouring, this new technology reduces water effluents by 70%, energy consumption by 30% and carbon footprint by 95% (LEITAT, 2016). Unfortunately, detailed documentation on this project is not available in English.

Clean wool is mixed and thermally bonded with a binder material necessary to ensure the cohesiveness of the final insulation product. Most sheep wool insulation products contain about 15% of PET fibres as binder (Norton, 2008; Mansour et al., 2014), as in the case of hemp fibre products. The fleece is then treated with fire retardant and a pesticide, usually sodium borate, and cut into the desired format (Norton, 2008; Mansour et al., 2014). Both plastic binder and pesticide can potentially be substituted with biomass-based alternatives. Polylactic acid can be used instead of PET fibres (Norton, 2008), while sodium borate might be replaced with a plant-based extract, but the technology has not been fully developed yet (Haus der Zukumft, 2016). As in the case of hemp fibre, at the end of its life-cycle sheep wool insulation can be landfilled, incinerated or composted. Landfilling represents the best option in terms of GWP, as the sequestered carbon is partially retained in the material (Norton, 2008).

Sheep wool insulation products are comparable in physical format, conductivity and application range to low-density mineral products and particularly glass wool, but have lower resistance to fire (class E), higher specific heat capacity and different hygroscopic behaviour. Measurements by Zach et al. (2012) show that in conditions of relative humidity between 30 and 80% (at 23 C), the moisture content of the fleece remains at about 20%, with minimal increase in thermal conductivity. Sheep wool products usually have higher density than glass wool, as fleece density affects significantly thermal conductivity. Sheep wool samples measured by Zach et al. (2012) show that a density of 20 kg/m3 results in 0.04 W/mK (at 20 C mean temperature), but doubling the density reduces conductivity to 0.036 W/mK.

Although studies on the traditional wool textile industry (producing garments, blankets, etc.) showed evidence of health risk associated with the inhalation of dust fibre during the manufacturing stage, Mansour et al. (2014) concluded that more research is required to investigate whether this issue might apply to the manufacture of sheep wool insulation, stressing the difference between the fine wool used for textiles and the coarse wool used for insulation. Sheep wool manufacturers recommend the use of mouth and nose masks during the installation of the product, and there is no evidence for health risks if this precaution is taken (Mansour et al., 2014).

There is some concern with the risk of proliferation of moths in sheep wool products. At the end of the 2000’s, sheep wool products installed in a number of properties in the UK were the cause of moth infestation, and had to be replaced. The problem was limited to a batch of Thermafleece insulation treated with diatomaceous earth instead of sodium borate (Jones, 2011). In fact the competitor manufacturer (Black Mountain) distanced itself from this issue and ensures that there have been no accidents related to products treated with sodium borate (Black Mountain, 2017c).

Wood fibre insulation

Wood fibre insulation was developed two decades ago in Europe by timber-producing countries to use chippings and shavings from sawmills (GreenSpec, 2017a). Wood fibre insulation is currently manufactured in several European countries (including Finland, France, Germany, Switzerland, Italy and Poland) but not in the UK. However, wood fibre insulation was raised as a potential end-product for Welsh softwood in a report on integrated strategies for timber industry in Wales (Bryans, 2011) and again in guidelines for Welsh softwood in construction (WoodKnowledge Wales, 2016). Although wood fibre insulation is not common in the UK, there are no significant technical barriers against its uptake. A unique case study on the use of wood fibre insulation in a mid-rise building in Brighton, UK, shows that despite initial scepticism among builders, on-site training and simplicity of installation enabled a successful integration of the new product (BRE and the University of Bath, 2011a).

The wood-derived ‘fibre’ manufactured for insulation purposes is similar to cellulose insulation made from recycled paper, and the two materials can also be combined into a single product (GreenSpec, 2017a). Most wood fibre insulation is manufactured from softwood chips produced by sawmills activity (GreenSpec 2017b). The material can be produced in different formats: loose flakes, low-density flexible rolls and batts, and high-density rigid panels. The wood content of rolls, batts and panels is between 80% and 95%, depending on the quantity of additives used (Gutex, 2012; Pavatex, 2014; GreenSpec, 2017b).

Wood fibre can be manufactured using a wet or dry process, though low-density material is produced only through the wet process (GreenSpec, 2017b). With this method, wood chips are ground into a pulp and mixed with water, and optionally with paraffin (to reduce hygroscopicity) or with latex (acting as a binder). Long rolls are formed by extruding and pressing the wet mix, which is then dried by compression, vacuum pumping and warm air. Finally the dried material is cut into the required format (Gutex, 2012; GreenSpec, 2017b). In the dry process, woodchips are ground into a pulp but not mixed in water. The pulp might be sprayed with paraffin, and dried with warm air. The pulp is then sprayed with a polyurethane resin which acts as a binder and accounts for about 4% of the final product. Once laid on a conveyor belt, the pulp is compressed into shape and ‘cured’ via exposure to water vapour and air. Finally, the material can be cut into the required format (Pavatex, 2014; GreenSpec, 2017b). At the end of its life-cycle, wood fibre insulation can be landfilled, incinerated (with or without energy recovery), composted or recycled. According to the classification by WRAP (2012, in DEFRA, 2012), wood fibre insulation can be considered grade ‘B’ waste, and therefore can be recycled as feedstock for industrial wood processing (e.g. chipboard manufacturing).

The density of wood fibre products ranges from 50 to 270 kg/m^3, and the conductivity from 0.037 to 0.058 W/mK. Denser products have higher conductivity, and thus lower thermal performance. While the format and consequent range of application of hemp fibre and sheep wool insulation can be compared to those of glass wool products, stone wool is a better term of comparison for wood fibre insulation. Like stone wool, wood fibre can be manufactured at high density to increase its stiffness and load-bearing capacity, and therefore can be used in specific applications such as covering a timber frame or under a floor screed. However, wood fibre has a poorer fire resistance (class E) than stone wool, but a higher hygroscopicity and vapour permeability (BRE and University of Bath, 2011b).

The conductivity, format and range of application of low-density wood fibre are similar to that of hemp fibre and sheep wool insulation. Conversely, high-density wood fibre products are manufactured for three main purposes:

- as sheating/sarking boards capable to resist rain for the duration of the construction stage;
- as panels for finishing external walls with render;
- as load-bearing panels for floor insulation below the screed (Pavatex, 2015; GreenSpec, 2017b).

To satisfy these functions, wood fibre is treated with additives and manufactured at a density generally between 140 and 180 kg/m^3, which increases conductivity to 0.04 W/mK or more.

Product application range and potential for substitution

Table 2. 7 shows the ranges of application of the insulation products reviewed above in the envelopes of new and retrofitted dwellings. The insulation needs to integrate with the technique used to construct the different components of the envelope (walls, roofs and ground floors). The range of application of a product depends mostly on the flexibility and resistance to loads allowed by its physical format, as discussed in section 2.3.1. The reviewed products can be grouped in three formats: flexible batts and rolls, rigid cellular panels, and rigid fibrous panels.

- Flexible batts and rolls, typical of low-density fibrous products, have limited stiffness and do not resist compression (nor traction) and therefore usually need to be held in place by other components of the envelope, such as a timber frame or a light mesh (Black Mountain, 2017c). Since the frame and the flexible product do not form a homogenous layer, an additional layer of insulation is necessary if a more uniform thermal resistance is to be reached across the envelope surface. This additional insulation should be sufficiently robust support itself and possibly other envelope components. Flexible products have the advantage to be lightweight, and easily cut and adapted to uneven surfaces, which is particularly beneficial in the case of retrofitted dwellings (AEA Technology plc, 2010; Duijve, 2012; Pargana, 2012).
- Rigid cellular panels, typical of fossil-based products, can have high compressive and tensile strength, with the advantage to be applicable in conditions where the insulation product can support itself as well as other envelope components (e.g. wet

render systems). This enables insulating the building envelope with fewer thermal bridges, as the products can be installed over the building structure. However, the rigidity of the panels makes them difficult to adapt to uneven surfaces and requires high-precision cutting in order to avoid gaps in the insulation layer (AEA Technology plc, 2010; Duijve, 2012; Pargana, 2012).

- Rigid fibrous panels, such as high-density stone wool and wood fibre, can provide robustness while retaining a degree of adaptability, and therefore are particularly appropriate to be used as the additional layer required in framed structures in combination with flexible products (AEA Technology plc, 2010; Duijve, 2012; Pargana, 2012; Pavatex, 2015; GreenSpec, 2017b; Gutex, 2017; Pavatex, 2017).

The categorisation above is a simplified approach to a complex issue, namely the technological integration of several products in the construction of the building envelope. The choice of an insulation product is influenced not only by its performance and cost, but also by the technique used to build the envelope.

In terms of performance, general characteristics of the insulation products reviewed above can be summarised as follows:

- Mineral products are manufactured from several types of mineral materials, have medium to high conductivity and are vapour permeable. The fibrous structure results in flexible formats, but stone wool can be also produced as high-density panels.
- Plastic products are manufactured from oil and natural gas derivates, have medium to low conductivity and are not vapour permeable. The cellular structure results in rigid panels.
- Biomass products are manufactured form plant and animal fibres, have medium to high conductivity and are particularly vapour permeable. The fibrous structure results in flexible formats, but wood fibre can be also produced as high-density panels.

Following this categorisation, it is arguable that replacing mineral products with biomass ones is technically feasible, as they have similar characteristics and therefore biomass products should generally be suitable for the same envelope types on which mineral products are currently applied. This is not to say that biomass products can replace mineral ones in every case, as there are still differences such as fire resistance and hygrothermal behaviour. On the other hand, it can be argued that replacing plastic products with biomass ones is less technically feasible, because of different characteristics. PIR and phenolic products require thinner layers in comparison to fibrous one, due to lower thermal conductivity, and their rigidity and water resistance can be necessary in certain applications. The choice between rigid and fibrous product also involves architectural detailing to ensure compatibility between the structure of the building envelope and the format of the insulation product. Though fibrous products (biomass or mineral) might not be able to replace rigid plastic products in many applications, the high-density formats of stone wool and wood fibre can provide a feasible alternative where some degree of rigidity and strength are required.

Table 2. 7 – Possible applications of insulation products across the components of the building envelopes (source: Pfundstein et al., 2007; AEA Technology plc, 2010; Duijve, 2012; Pargana, 2012; PU Europe, 2014; Kingspan, 2014; Knauf, 2015; Pavatex, 2015; GreenSpec, 2017b; Black Mountain, 2017c; Gutex, 2017; Pavatex, 2017)

			Conventional products						Biomass products			
			Stone wool		Glass wool	PUR	EPS	Phenolic	Hemp fibre	Sheep wool	Wood fibre	
			Panels	Batts &rolls	Batts &rolls	Panels	Panels	Panels	Batts &rolls	Batts &rolls	Panels	Batts &rolls
New build	Walls	inside cavity	x			x	x	x			x	
		inside frame	x	x	x				x	x	x	x
		wet render	x			x	x	x			x	
		dry clad	x	x	x	x	x	x	x	x	x	x
	Flat roof	inside frame	x	x	x				x	x	x	x
		above frame	x			x	x	x			x	
	Pitched roof	on floor	x	x	x				x	x	x	x
		below frame	x			x	x	x			x	
		inside frame	x	x	x				x	x	x	x
		above frame	x			x	x	x			x	
	Ground floor	below frame	x			x	x	x			x	
		inside frame	x	x	x				x	x	x	x
		under screed				x		x			x	
Retrofit	Walls	inside frame	x	x	x				x	x	x	x
		wet render	x			x	x	X			x	
		dry clad	x	x	x	x	x	X	x	x	x	x
	Loft	on floor	x	x	x	x		x	x	x	x	x
		below frame	x			x	x	x				
		inside frame	x	x	x				x	x	x	x

2.3.4 Resources and supply chain of biomass insulation products

In this section the review on biomass insulation products appropriate for the regional resources of Wales is expanded by investigating the conditions enabling supply of primary materials. This information allows connecting the relatively narrow topic of biomass insulation to the wider discourse on demand and supply of natural resources. Palumbo et al. (2015) provided a unique example of research connecting demand for insulation and local conditions by investigating the demand for natural fibres as thermal insulation in buildings and the available supply of fibrous by-products of crops in Spain. Firstly, Palumbo et al. (2015) estimated the demand for thermal insulation on the basis of a forecast of future construction activity. Successively, they calculated the quantity of natural fibres required to meet these levels of demand and compared it to the average annual harvest of fibrous by-products from crop cultivation (Palumbo et al., 2015). This study provides a basic method to investigate the relation between the demand for products determined by conditions of the building stock and the potential supply determined by current land use.

Hemp fibre insulation - Resources and supply chain

The cultivation of industrial hemp in the UK was legalised and regulated in 1993. Farmers require a yearly license released by the Home Office to ensure that their crop has no psychoactive potential (HM Gov 2017). The area of land cultivated as industrial hemp annually in the UK has varied significantly over the years (Haufe and Carus, 2011). After a rapid growth in the 1990's, 2,000 ha per year were reached several times until the mid 2000's, when a slow decline began. In recent years, production has been lower than 500 ha per year. The largest European producer of industrial hemp is France, where between 5,000 and 12,000 ha were cultivated in the period 1993-2012 (Haufe and Carus, 2011). In Wales, industrial hemp is grown in rather small quantities. Allen (2016) mentioned a small farmer growing hemp from 2011 to 2013 in Pembrokeshire (South-West Wales) with good results in terms of yield but poor weather conditions during the harvest. In the mid-2000's hemp was grown successfully at the Henfaes Research Centre of Bangor University (North Wales) as part of an EU-funded research project to investigate the potential for cultivating and processing flax and hemp (Loxton et al., 2013).

As an agricultural activity, industrial hemp cultivation is affected by relevant policy. The British agricultural sector receives a significant amount of subsidies. From 2003 to 2015 the majority of these were delivered through the EU-funded *Single Payment Scheme*. Under this scheme, farmers received subsidies on the basis of their land and activities at the condition of "cross compliance" with a set of environmental, food safety and animal health regulations (HM Gov, 2015). It is argued that the requirements to keep land in "good agricultural conditions" ended up favouring the removal of wild species from uncultivated land (Monbiot, 2013). Indeed the State of Nature report 2013 identified farming practices as one of the causes of habitat loss and consequent decline of 60% of animal and plants in Wales over the last 50 years (RSPB, 2013).

In 2014/2015 the average share of the income made by UK agricultural businesses from Single Payment Scheme was considerably higher than the share made from the actual agricultural output (Daneshkhu, 2016; Milne and Braham, 2016). Following changes in *Common Agricultural Policy* of the EU, In January 2015, the Single Payment Scheme was replaced by the *Basic Payment Scheme* without significantly altering the structure of the policy (HM Gov, 2015). It is probable that the current regime of subsidies will change as a consequence of the UK leaving the EU (Daneshkhu, 2016). The shape and purpose of the future policy has already become a controversial issue (Robertson, 2017). In summer 2016, the National Trust proposed a subsidy scheme prioritising environmental conservation, which was badly received by farming associations concerned with maintaining the economic viability of agriculture (Vidal, 2016). It remains unclear if and how the EU-funded subsidies will be replaced, although the Government in Westminster promised to match EU agricultural funding until 2020 (Daneshkhu, 2016).

Industrial hemp is one of many crops eligible for Basic Payment Scheme subsidies (Rural Payments Agency 2017). Until 2013 industrial hemp was also eligible for subsidies through the *Fibre Processing Aid* scheme, also part of the EU Common Agricultural Policy. It should be noted that these subsidies were paid to the fibre processor, not the farmer (COM/2008/0307 final).

It might be possible to relate the reduction in area of land cultivated at industrial hemp in the UK which began in the mid-2000's to the shift from the previous *Arable Area Payment Scheme* to the Single Payment Scheme, which reduced the overall amount of subsidies. Just before the implementation of the new scheme, a report for DEFRA (Garstang et al., 2005) analysed the economic impact of this shift on the production of flax and hemp in the UK. The study indicated that although the gross margin of hemp farmers would be halved, hemp would remain economically viable as a break crop. Changes in subsidies were also indicated as the cause for stopping the cultivation of hemp at the Henfaes Research Centre (Loxton et al., 2013). The prospect of lower profits might have contributed to the overall reduction of hemp farming in the UK. In addition to this issue, the production of industrial hemp in the UK was hampered by a lack of demand for end-products (Springdale Crop Sinergies, 2006; Loxton et al., 2013). Furthermore, a review of the UK hemp fibre supply chain in 2005 (Springdale Crop Sinergies, 2006) stressed the lack of sufficient industrial infrastructure for fibre processing. Since the crop output is concentrated in a short period and transport costs are particularly high, a viable supply chain requires deposits to store the hemp straw as well as a reasonable distance from the industrial plant were the fibres are processed (Springdale Crop Sinergies, 2006).

Currently, there are three UK companies which can process industrial hemp fibre. The output capacity of these companies is probably quite limited, since the largest of the three (*East Yorkshire Hemp*) is a family-run business (Nick Voase, 2017, pers. comm., 30 November). In 2011 the major fibre processing company in the UK, Hemcore, closed its plant in Hertfordshire and terminated its activity (Companies House 2017b). Hemcore had been active since 1993 and had made industrial hemp a profitable crop for farmers in the region. It is possible that the end of the Fibre Processing Aid scheme contributed to the conditions that drove the company to terminate its activity. The end of the scheme might also have indirectly diminished the profitability of hemp for farmers. In 2006, the proposal to extend the *Fibre Processing Aid* scheme until 2008 was supported by a report of the European Commission on the flax and hemp sector, stating that:

> *For hemp producers, removal of the aid would entail a proportional reduction in prices* [paid to producers, i.e. farmers – author's note]. *In such a case the margin for hemp producers would be squeezed considerably and would be significantly narrower than the margin obtained from cultivation of other alternative arable crops. Note that hemp cultivation is more labour-intensive than other field crops. A significant reduction in the area under hemp and a consequent fall in supplies of hemp straw to the primary processing industry would be expected.* (COM/2006/0125 final, p.9).

Given this information, it is reasonable to conclude that the end of the Fibre Processing Aid scheme and the reductions in Single Payment Scheme subsidies had a part in the reduction of industrial hemp farming in the UK.

Sheep wool insulation - Resources and supply chain

Sheep wool is one of the oldest traded goods in the world (Morris, 2013). Until the 19th century, wool production was the main purpose of sheep farming in the UK, and the selection of sheep breeds was directed by criteria of fibre quality. In the last two centuries the purpose of sheep farming has shifted towards meat production (Morris, 2013). Though the UK is one of the major European producers, British wool makes up only about 2% of the global production and is very small in comparison to the large outputs of Australia and China (Morris, 2013). About a quarter of British wool comes from sheep raised in Wales (Morris, 2013). The British Wool Marketing Board is the producers' association handling the large majority of wool produced in the UK (Morris, 2013). Wool is acquired by the Board directly from the producers at fixed prices and stored in depots to be sold throughout year to the manufacturing industry (British Wool Marketing Board, 2017). There are five depots of the Board in Wales.

Sheep shearing is necessary for the health of the animals. For many years the price of wool in the UK was so low that producers were barely able to pay for the cost of shearing their flocks. During the 2000's, prices increased sufficiently for producers to make a small profit from their wool (Mitchell Associates, 2005; Morris, 2013). The British Wool Marketing Board foresees this trend to continue in the future, as a consequence of a global reduction in wool supply and growth in the demand for natural fibres (Morris, 2013). It is argued (Norton, 2008) that under current conditions the large majority of British wool is to all effects and purposes a by-product of the sheep meat sector, as wool would not be produced at all if sheep were not raised for their meat. This is particularly applicable to Wales, where the majority of sheep belong to breeds producing the poorest wool quality.

Despite the low cost of coarse wool, sheep wool insulation products are acknowledged to be more expensive than conventional products. Corscadden et al. (2014) investigated the costs of producing sheep wool insulation in a small artisanal facility in Canada. Although UK manufacturers are already established in medium scale plants and the costs of materials, labour, energy, etc. are different, this study holds valuable information for this research. Table 2. 8 show the breakdown of the cost of producing one unit of sheep wool insulation, excluding the costs of machinery, building maintenance, rentals etc. (Corscadden et al., 2014, p.13). The cost of labour is clearly the largest component, though Corscadden et al. (2014) note that this is accentuated by the artisanal scale of the facility. Energy and materials contribute to most of the remaining costs in equal parts, with most of the energy consumption taking place during the scouring process (Corscadden et al., 2014).

Table 2. 8 - Production cost for unit of sheep wool insulation (0.4 kg) (source: author's calculations on Corscadden et al., 2014, p.13)

Component	Cost ($)	Percentage
Materials	1	18%
Labour	3.38	60%
Electricity	0.99	17%
Water	0.03	0.5%
Others	0.27	4.5%
Total	5.67	100%

Scouring facilities are an essential link in the supply chain of sheep wool used for insulation as well as traditional textile applications. Wool grease, which can be processed into lanolin, is generated as a by-product during the scouring process. However, scouring has a significant environmental impact: it requires the use of chemical detergents, consumes large quantities of energy and water, and at the end of the process the water effluents need to be treated to remove several contaminants (Mitchell Associates, 2005; Norton, 2008; Quigley, 2010).

In the UK there are two large scouring plants, both located in Yorkshire, and several small facilities, but not many medium-sized ones (Mitchell Associates, 2005; Quigley, 2010). In response to the demand for closer scouring facilities from Welsh wool producers, two reports were commissioned in 2005 and 2010 to investigate the economic feasibility to open a medium-sized scouring plant in Wales. The first report (Mitchell Associates, 2005) located a hypothetical plant in the centre of Wales (Newtown, Powys) to maximise access from across the region. The scouring company would be economically profitable under the condition of a substantial initial funding to cover for the high capital cost of the machinery. It was noted that it would be economically viable to scour the wool in Portuguese, Czech or Italian plants, though it would be questionable in terms of the environmental impact of the transport (Mitchell Associates, 2005).

The second report (Quigley, 2010) assessed the feasibility of a medium sized scouring plant - capable to process between 4 and 30 tonnes of wool per year – integrated with an anaerobic digestion facility to process the water effluents. The hypothetical plant was located in North Wales (Gwynedd) on land owned by the group of farmers which commissioned the study. The author concluded that though wool scouring facilities have high capital costs and small margin of profit, the prospective Gwynedd plant could be economically profitable thanks to its location and the additional revenue from the anaerobic digestion facility (Quigley, 2010).

Wood fibre insulation - Resources and supply chain

A relatively small portion of the land of Wales (14%) is occupied by forests, as in the other UK nations. This is clearly different in countries such as Sweden (75%) or Austria (48%) (Bryans, 2011). However, it is also recognised that Wales has one of the best environments in Europe for growing softwood (i.e. coniferous trees) and coniferous woodland is about half of the total Welsh woodland (WoodKnowledge Wales, 2016). Sitka spruce (*Picea sitchenisis*) is the most common conifer in Wales, due to its adaptability to upland conditions. About two thirds of coniferous woodland in Wales is publicly owned, while most of the broadleaves forests are privately owned (Newman et al., 2015). The Welsh Government Woodland Estate comprises about 40% of Welsh woodland and makes up around 6% of the area of Wales. The Estate is managed by the public agency Natural Resource Wales, who also holds other roles such as regulator and seller of timber produced on the Estate (Natural Resource Wales, 2018). Under the Basic Payment System scheme (introduced earlier discussing industrial hemp fibre), land occupied by trees is not eligible for subsidies, except in the case of commercial tree nurseries (WG, 2015a). *Glastir* is the scheme for sustainable land management in Wales, funded by the Welsh Government and the EU. Under this scheme, grants can be obtained for woodland management and creation (WG, 2015b).

Most of the softwood harvested in Wales, and more generally in the UK, is bought by sawmills and processed to be used in construction (Newman et al., 2015). Beside domestic production, the UK construction industry relies for over half of its supply on imported softwood (Newman et al., 2015). In the early 2010's prices were favourable to imports: a price estimate by Bryans (2011) indicated that imported softwood could be about 10% cheaper than Welsh softwood. Although between 2010 and 2015 there has been a moderate increase in the volume of domestic production – as expected by the Forestry Commission - consumption and imports have remained relatively stable (Newman et al., 2015). Future developments are unclear, especially due to the uncertainty caused by UK leaving the EU (John Clegg Consulting and Tillhill Forestry, 2016). For the moment, changes in currency exchange rates have made timber imported from Europe more expensive, and thus indirectly favoured British timber. However, it remains to see how the long-term effects of 'Brexit' and the likely change in agricultural subsidy regime might impact on the UK forestry sector (John Clegg Consulting and Tillhill Forestry, 2016).

The Forestry Commission produced a series of forecasts on the availability of softwood in the UK, extended until 2060 in the last update (Forestry Commission, 2014). This study expects an increase in the available softwood until 2030, followed by a decline and a stabilisation in 2050 to a level lower than the starting point. This trend is also forecast to take place at the level of England, Scotland and Wales. The availability of Welsh softwood in the long term is forecast to reduce to about 50% of the current level by 2045 (Forestry Commission, 2014). This decline is expected to have an impact on the existing wood-processing industry in Wales (Newman et al., 2015).

In 2010 a forestry consultancy (John Clegg Consulting Ltd) investigated the potential development in the demand of wood fibre in the UK in relation to the forecast of the Forestry Commission. In that context 'wood fibre' did not refer to insulation products but to the primary material – woodchips and shavings, but also recovered timber - used to manufacture a wide range of products, such as oriented strand boards, medium-density fibre boards as well as insulation panels and rolls. The study forecasted that demand for wood fibre would rise and surpass domestic supply, with a consequent increase in the imports of softwood. This rise in demand was expected to be an indirect but significant effect of the Renewable Obligations scheme (John Clegg Consulting, 2010). In fact the wood panel industry has been openly critical towards this policy, arguing that it indirectly subsidises companies to buy woodchips as biomass fuel, therefore allowing these companies to buy at a lower price than wood panel manufacturers (John Clegg Consulting, 2010; Europe Economics, 2010). Moreover, the demand for wood fibre as biomass fuel risks causing a rise in prices (John Clegg Consulting, 2010).

Data on 8,000 ha of woodland and farmland in central Wales was used to analyse and compare the economic performances of the forestry and sheep farming sectors in a report (Bell, 2015) commissioned by Confor, a forestry and timber industry association. The analysis showed that without taking subsidies into account, coniferous woodland can produce up to five times the economic output of sheep farming. Furthermore, although forest output is expected to decrease and stabilise in about 40 years due to tree rotation (in line with Forestry Commission forecasts), the forestry sector is still expected to remain profitable before subsidies (Bell, 2015). The capacity of the forestry sector to spend in the local economy is also considered higher than for sheep farming. In terms of employment, Welsh forestry activities currently generate almost two times the labour per area of land in comparison to sheep farming. However, the stabilisation of forest output is expected to progressively decrease this value (Bell, 2015).

2.3.5 Environmental impact of insulation products

This section reviews LCA literature assessing the environmental impact of insulation products. Firstly, comparative LCA studies focusing on insulation products are presented. Successively, results from LCA studies and other sources of information (such as EPDs) are grouped by product type (mineral, plastic and biomass) to identify typical ranges of environmental impact.

Review of comparative LCA studies

A number of studies have investigated and compared the EEI of conventional and alternative insulation products (Schmidt et al., 2004; Papadopoulos and Giama, 2007; DeBenedetti et al., 2007; Norton, 2008; Lazzarin et al., 2008; Anastaselos et al., 2009; Pargana, 2012; Duijve, 2012; PWC, 2013; Densley Tingley et al., 2015; Shrestha et al., 2014; Braulio-Gonzalo and Bovea, 2017; Kunic, 2017). Although these studies focus on the impact of the embodied stage of the life-cycle of products, some researchers stress the overall positive impact of any insulation product due to the energy saved during the operational stage of the life-cycle (Schmidt et al., 2004; PWC, 2013; Shrestha et al., 2014; Kunic, 2017). Functional units based on thermal resistance and product life-spans of 50-60 years are usually adopted to compare products with different conductivity (Shrestha et al., 2014). PEU and GWP are considered in almost every study, and AP, EP, POCP and ozone depletion potential are often part of the assessment. A selection of the comparative studies which are most relevant to this thesis is presented here.

Schmidt et al. (2004) performed LCA of three products: stone wool as representative of conventional products, recycled paper as representative of recycled products, and flax fibre as representative of biomass products. A cradle-to-grave boundary was adopted and several end-of-life scenarios (incineration, recycling in high- and low-grade applications, landfilling) were modelled, choosing the least impacting as the best option for each product. This study generated LCA results by using product LCI "established in very different ways" (Schmidt et al., 2004, p.122). Stone wool was modelled using specific LCI data for Rockwool manufactured in Denmark, recycled paper was modelled combining Swedish, Finnish and Swiss data, and flax fibre is modelled on the basis of an Austrian product, It was acknowledged that there can be significant differences in the production of flax fibres across Europe, and that LCA including agricultural processes are problematic by themselves (Schmidt et al., 2004). The results showed the flax fibre product to have a higher EEI than stone wool and recycled paper, displaying the highest impact in most categories (PEU, GWP, AP, EP and solid waste generation). POCP was the only category where stone wool had the highest impact, although its EP value was almost as high as flax fibre (Schmidt et al., 2004). Recycled paper achieved the lowest impact in all categories except hazardous waste generation, where it was the most impacting product. A significant part of the EEI of the flax fibre product was attributed to the agricultural stage, and Schmidt et al. (2004) showed that modelling a Danish version of the product (in development) resulted in a much lower EEI, due to different agricultural inputs and conditions. Schmidt et al. (2004) also looked at health-related aspects of the three insulation products, pointing out that there is more evidence for the potential negative effects (including carcinogenic) of exposure to dust released from flax fibre and recycled paper during the installation process than stone wool. The study concluded that the three products save more than 100 times the energy necessary for their manufacture, and that considering the inherent uncertainties of LCA, the most important aspect of insulation products are quality and durability (Schmidt et al., 2004).

The well-documented work by Schmidt et al. (2004) is cited in other studies, such as Lazzarin et al. (2008), where several products are compared in terms of energy savings and price on the basis thermal resistance. The research by Lazzarin et al. (2008) is an example of LCA results drawn from a variety of sources being used as inputs in a new work. Another example is the study by Densley Tingley et al. (2015), who compared the EEI of stone wool, Expanded Polystyrene (EPS) and phenolic foam using data sources such as the Ecoinvent LCA database, the Inventory of Carbon and Energy (ICE, Hammond and Jones, 2008) and their own collection of specific data to produce comparable LCA results.

Papadopoulos and Giama (2007) used the GEMIS model to assess the EEI of stone wool and Extruded Polystyrene (XPS). The results showed stone wool to have a higher impact than XPS in AP, EP and waste generation, while XPS had higher impact in GWP and PEU. The GEMIS model appears to use a combination of process-based and I-O data. English documentation for this model is very limited and no explanation of the model is given in Papadopoulos and Giama (2007), thus it is difficult to make further observations on the results and compare them to other sources.

Duijve (2012) performed an evaluation of insulation products based on both embodied and operational stages. Generic LCA results for eight products were generated by collecting data from several sources (the Ecoinvent and Oekobau databases, EPDs and LCA literature) for five impact categories (PEU, GWP, AP, EP and ozone depletion potential). By using these sources to calculate average, minimum and maximum impact values for each product, Duijve (2012) adopted the same procedure used by Hammond and Jones (2008) to generate the ICE database. Duijve (2012) also estimated the potential requirements for insulation of cavity walls in retrofitted dwellings in the Netherlands. The estimate was obtained by combining data on typical dimensions of units in the Dutch stock and the levels of insulation achieved in common practice and through the Passivhaus standard. On this basis, Duijve (2012) produced a forecast of total energy and carbon savings achievable with different levels of insulation, and compared operational and embodied impact for different materials. Though LCA results were generated for a functional unit based on thermal resistance, the final assessment was conducted for a specific cavity wall thickness, and therefore the operational performances of the products were not equivalent. When selecting the products to be included in his assessment, Duijve (2012) excluded sheep wool, recycled cotton and recycled paper on the basis of a basic estimate of the potential availability of these products in the Netherlands.

Duijve (2012) argued that it is not possible to identify an optimal insulation product, as different applications have different requirements, and the end-of-life can have a significant effect on the overall EEI. For example, Polyurethane and Polyisocyanurate Rigid foam (PUR and PIR) panels are robust products with a very low conductivity but a high EEI, which can be reduced if the panels are recycled at the end of the life-cycle. Duijve (2012) found grey EPS to have the lowest EEI and PUR/PIR the highest. With regards to biomass products, hemp and flax fibres display EEI in the same range of stone wool, glass wool and white EPS (Duijve, 2012), but have limited recyclability due to the inclusion of polyester fibres. The possibility to use biomass-based substitutes for the polyester is also mentioned. Duijve (2012) concludes that stone wool, glass wool and grey EPS are currently the most balanced options in terms of EEI and performance, with stone wool and EPS offering a large range of applications. These features and the relatively low prices have made these products the most successful on the Dutch market (Duijve, 2012).

Pargana (2012; later partially published in Pargana et al., 2014) conducted an LCA of six insulation products and compared the results across ten impact categories and one weighted score. The data used to compile product LCIs was collected through questionnaires from Portuguese manufacturers and modelled with the Ecoinvent database. The study aimed to investigate the environmental and economic performance of insulation products based on cork, which is widely produced in Portugal, in comparison to other products. Both LCA and price survey of insulation products were performed for a functional unit based on thermal resistance. Cork insulation had an overall low EEI but a high price per functional unit, while EPS emerged as the best option both in environmental and economic terms.

In 2013 PriceWaterhouseCooper (PWC) produced a report for PU Europe, the European association of PUR manufacturers and raw materials suppliers (PWC, 2013). The report is based on the LCA and LCC of hypothetical commercial and residential buildings under several scenarios, considering different climates and insulation products. Both embodied and operational stages were modelled, concluding that different insulation products do not make a significant impact on operational energy at the building level (PWC, 2013). Despite this obvious conclusion and the possible bias of the report towards its client, the methodology takes a valid approach. Most of the data used calculate the EEI of the insulation and other products is taken from EPD. For each insulation product, the results of the reference EPD used in the report are also compared to the results of the other existing EPD in order to determine the extent of possible variation in EEI. This analysis confirms that +/- 20% is a valid estimate of the possible variations in LCA results. In addition, the PWC report (2013) provides the most detailed analysis of insulation product prices on the basis of thermal resistance among publicly available sources. Prices (in Euro, excluding VAT) were collected from a number of manufacturers and a linear regression was carried out to generate average prices. Though its validity is limited to the Belgian market of 2012, it is relevant to note that for all products analysed (PUR, stone wool, glass wool and wood fibre) price per unit of thermal resistance increases as more thermal resistance is required, i.e. thick formats are more expensive than thin ones, although prices do not increase in equal measure across products (PWC, 2013, p.156).

Kunic (2017) calculated the Cradle-to-Site carbon embodied in 15 insulation products using generic Ecoinvent data and a FU based on conductivity. Low-density wood fibre resulted as the product with the lowest embodied carbon, and glass wool and recycled paper also showed low impact. Foam glass, XPS, cork, aerogel, vacuum panels and the high-density type of stone wool all presented high embodied carbon (Kunic, 2017). The time required for carbon neutrality (i.e.

carbon payback) based on typical degree-days for Slovenia was calculated and the results indicate that carbon neutrality is reached in one year for low carbon products and in about a decade for high carbon products (Kunic, 2017).

Braulio-Gonzalo and Bovea (2017) selected seven conventional and two alternative products on the basis of the Spanish market and analysed their efficiency in typical roof, wall and floor applications by varying product thicknesses. The authors concluded that *“an unlimited increase in insulation thickness does not imply better eco-efficiency in all the types of materials due to the cost factor”* and *“not all natural insulation materials are related to low environmental impacts*” (Braulio-Gonzalo and Bovea, 2017, p.538). Foam glass and cork insulation achieved the poorest performance, while the alternative products (sheep wool and recycled cotton) achieved the best performance together with stone wool.

Anastaselos et al. (2009) developed an “assessment tool for the energy, economic and environmental evaluation of thermal insulation solution” which included other elements of the envelope beside the insulation layer. The functional unit used to compare the different envelope systems is not based on thermal resistance but on the total thickness of the envelope. Though it makes sense from a construction point of view, this functional unit does not allow envelope systems to be compared on an equal basis in terms of their thermal performance, which is arguably the point of the study. Anastaselos et al. (2009) selected PEU, GWP, AP, EP, POCP and two different single scores as their EEI categories, and the cost of construction (purchase and installation) as their economic indicator.

This review of comparative LCA literature shows that there are several researchers conducting LCA of insulation products. The interest of researchers in this topic might have been stimulated by the large variety of existing products and by the diverse resources used for their manufacture. The LCA studies reviewed here use the process-based attributional method, with the partial exception of Papadopoulos and Giama (2007). No example of I-O LCA used to assess insulation products was found. The review of LCA studies also shows that it is common practice to compare LCA results from different sources, although methodological differences can lead to uncertainty. All studies assess energy and/or carbon emissions, but other categories such as AP, EP and POCP are also considered relevant. Some studies include the end-of-life stage in the impact assessment, but most are limited to the cradle-to-gate boundary. The majority of studies focus exclusively on the EEI of products, while some examples include other aspects such as operational impact (Duijve, 2012; PWC, 2013; Kunic, 2017) and cost (Anastaselos et al., 2009; Pargana, 2012; PWC, 2013; Braulio-Gonzalo and Bovea, 2017). Three of these studies (Duijve, 2012; Pargana, 2012; Braulio-Gonzalo and Bovea, 2017) chose to focus on groups of products based on regional conditions. Only one study (Duijve, 2012) chose to include a forecast of insulation demand based on insulation requirements and features of the regional building stock. Overall, there is a lack of studies looking at the sustainability of insulation products with a holistic and long-term perspective.

Environmental impact by product type

LCA results found in the literature are presented here by product type to enable identifying typical ranges of EEI values. Data sources are academic LCA studies, EPD certificates and four LCA databases: the Inventory of Carbon and Energy (Hammond and Jones, 2011), the GaBi Professional database (Thinkstep, 2016a), the German database Oekobaudat (2017) and the Austrian online database Baubook (2015). Complete references for EPD and database entries are given in Appendix I. To build a comparable set of LCA results, EEI figures found in the literature are scaled to quantify the impact of one functional unit of thermal resistance (1 m^2K/W). The comparison of EEI figures is limited to the impact categories of PEU, GWP, AP, EP and POCP. These five categories have been identified by Anastaselos et al. (2009) as the most relevant for insulation products. It must be noted that while PEU and GWP are covered in most LCA sources, the other categories are less “popular” and therefore fewer EEI figures are available for comparison.

All LCA results presented here exclude the operation stage of the life-cycle of products. Most studies adopt a Cradle-to-Gate boundary, while only a few studies adopt a Cradle-to-Site boundary (indicated as ‘CtS’) or a Cradle-to-Grave boundary (indicated as ‘CtGr’). Generally, within a product type it is reasonable to expect Cradle-to-Site and Cradle-to-Grave LCA to produce higher EEI figures than Cradle-to-Gate LCA, as more stages are included in the assessment.

Overall, the graphs in the following pages show that there can be significant differences n LCA results for products of the same type. This is the result of several factors: different materials and manufacturing processes, different energy mixes, different LCI cut-off, different secondary data sources, minor methodological differences, and errors. Nonetheless, a set of LCA results can be used to identify a range of typical values (in a similar way to the ICE database by Hammond and Jones, 2008), which can successively be used to benchmark new LCA results.

Environmental impact of mineral products

Figure 2. 8 to Figure 2. 12 show LCA results found in LCA sources for mineral insulation products. Glass wool displays slightly lower EEI values than stone wool in all categories except POCP. Given the similarity of the manufacturing processes, this might be the result of the lower density of glass wool and its higher content of recycled materials.

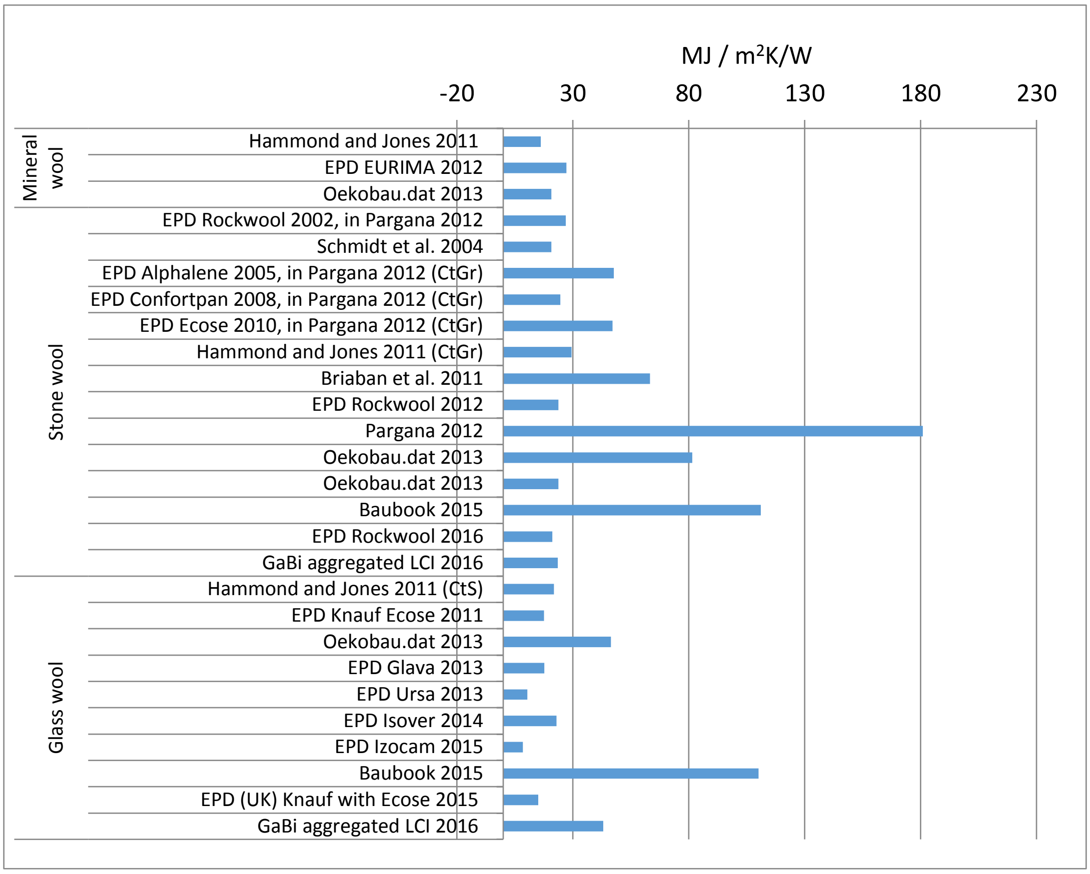


Figure 2. 8 – PEU of mineral products from the review of LCA studies (source: see Appendix I)

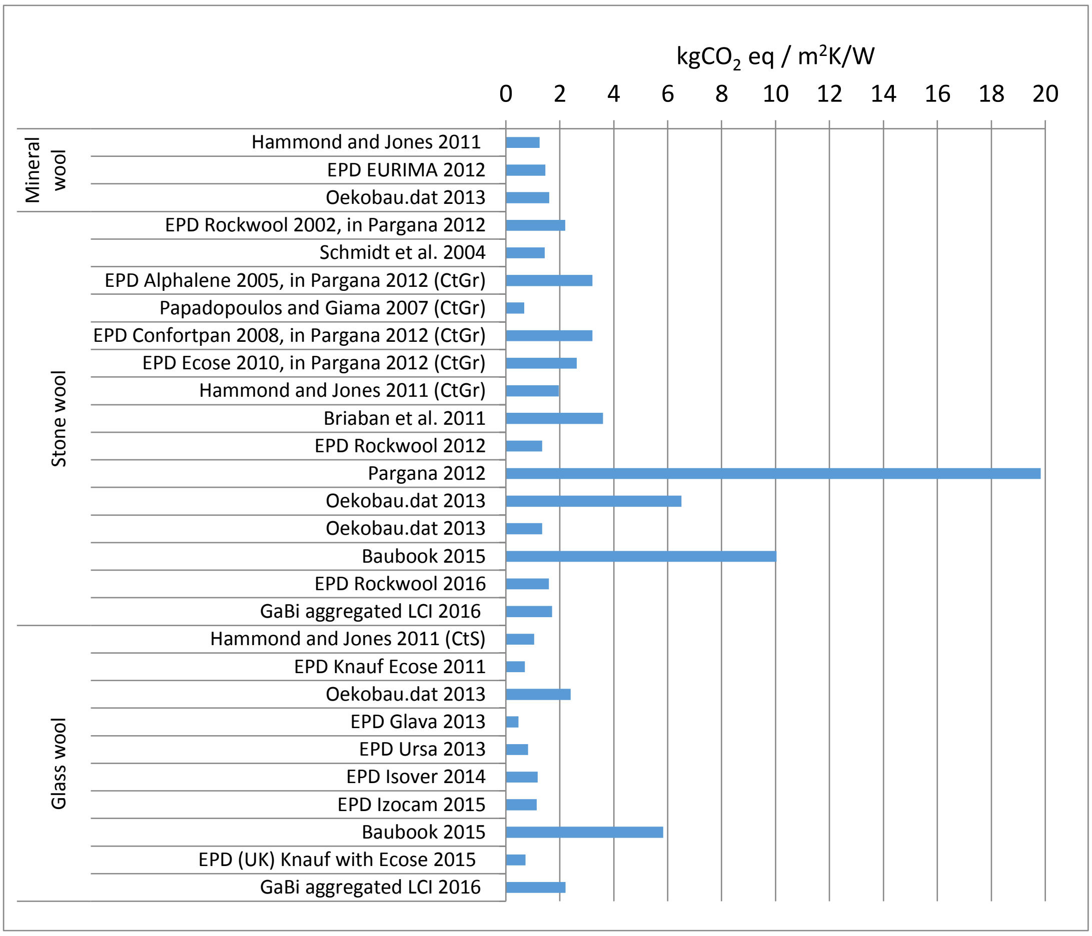


Figure 2. 9 – GWP of mineral products from the review of LCA studies (source: see Appendix I)

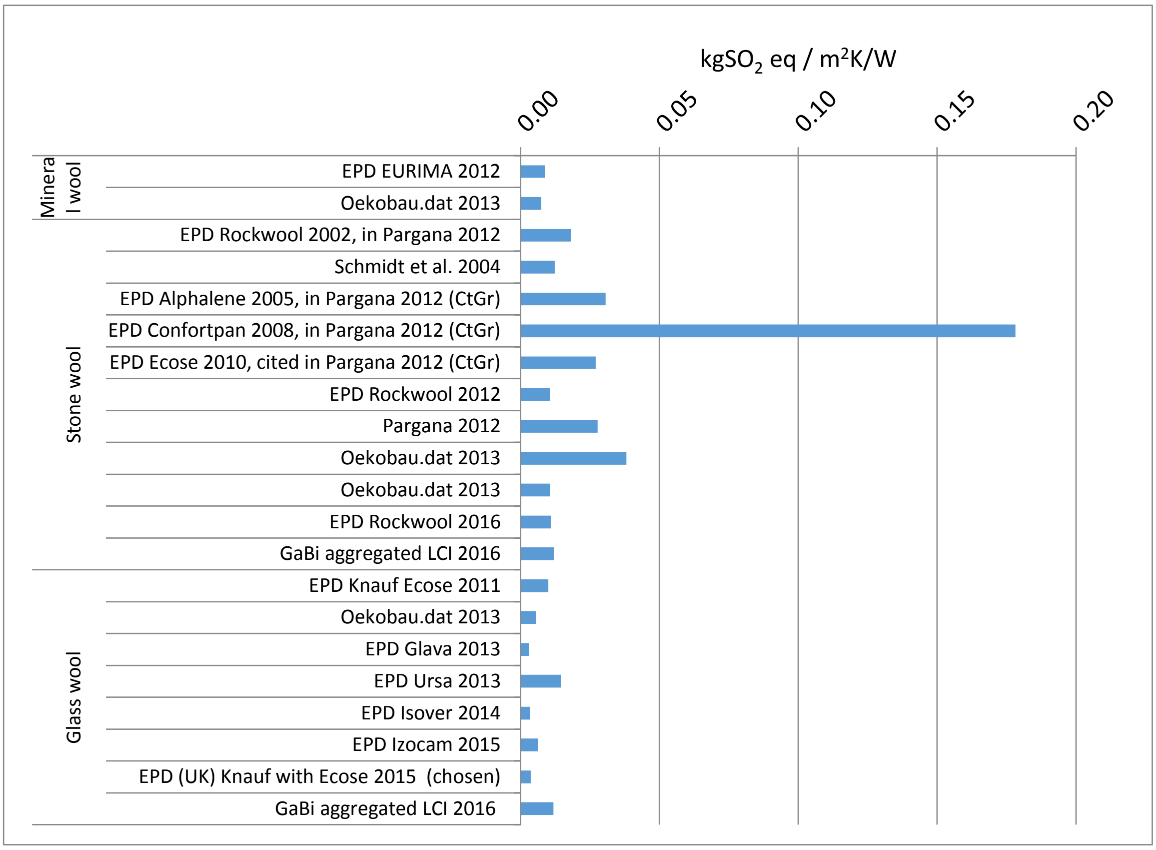


Figure 2. 10 – AP of mineral products from the review of LCA studies (source: see Appendix I)

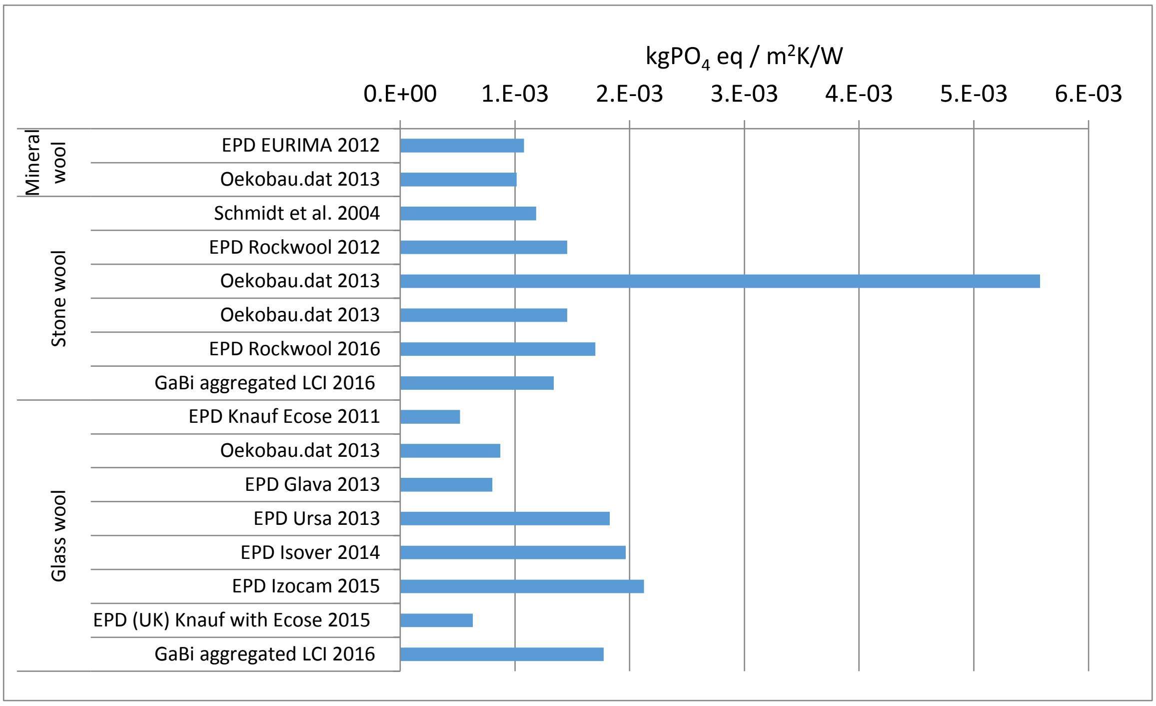


Figure 2. 11 – EP of mineral products from the review of LCA studies (source: see Appendix I)

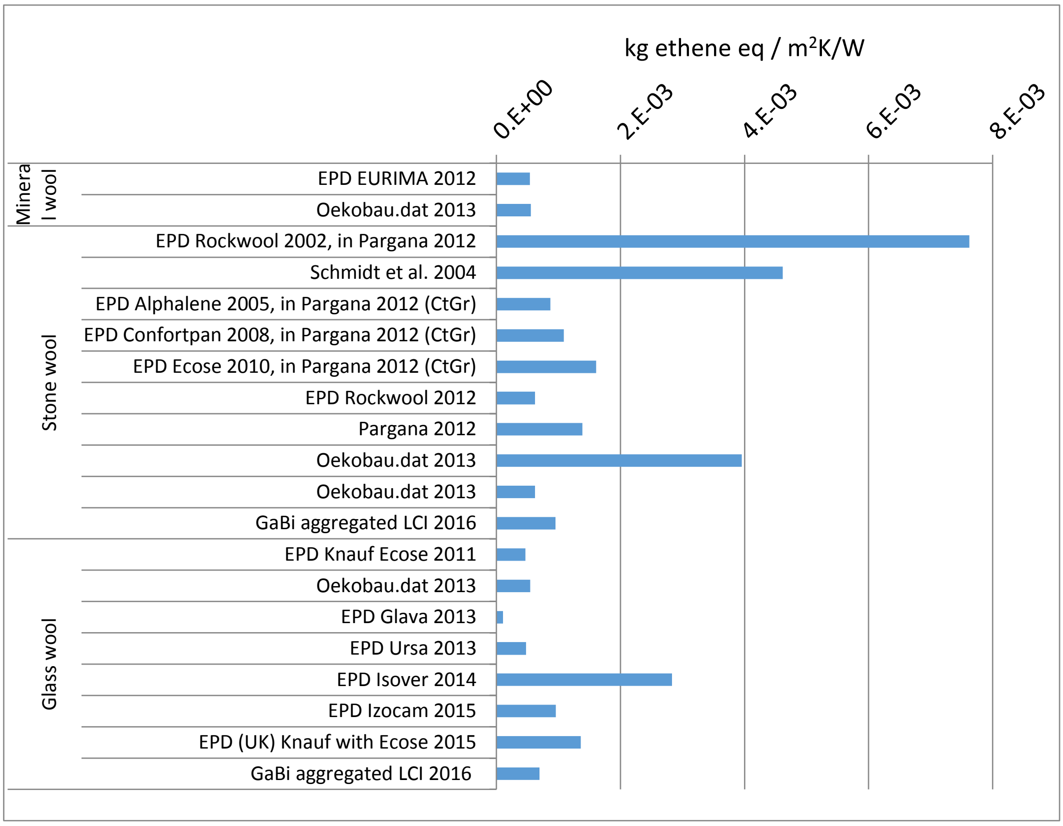


Figure 2. 12 – POCP of mineral products from the review of LCA studies (source: see Appendix I)

Environmental impact of plastic products

Figure 2. 13 to Figure 2. 17 show LCA results found in LCA sources for plastic insulation products. PUR products appear to have generally a higher EEI than EPS products in all categories except POCP. Breakdowns of LCA results by life-cycle stage indicate that emissions of POCP-relevant compounds are concentrated in the manufacturing stage of EPS rather than during the production of raw materials (EUMEPS, 2010), which in this case includes the production of styrene. This is an exception to a general trend for plastic insulation products, whose final manufacturing stage cause a minor contribution to the overall EEI (EUMEPS, 2010).

Very limited information is available on the EEI of phenolic products, as acknowledged by Densley Tingley et al. (2014), and the two available sources present significant differences. Nonetheless, the available data suggests that the EEI range of phenolic products is comparable to those of PUR and EPS products.

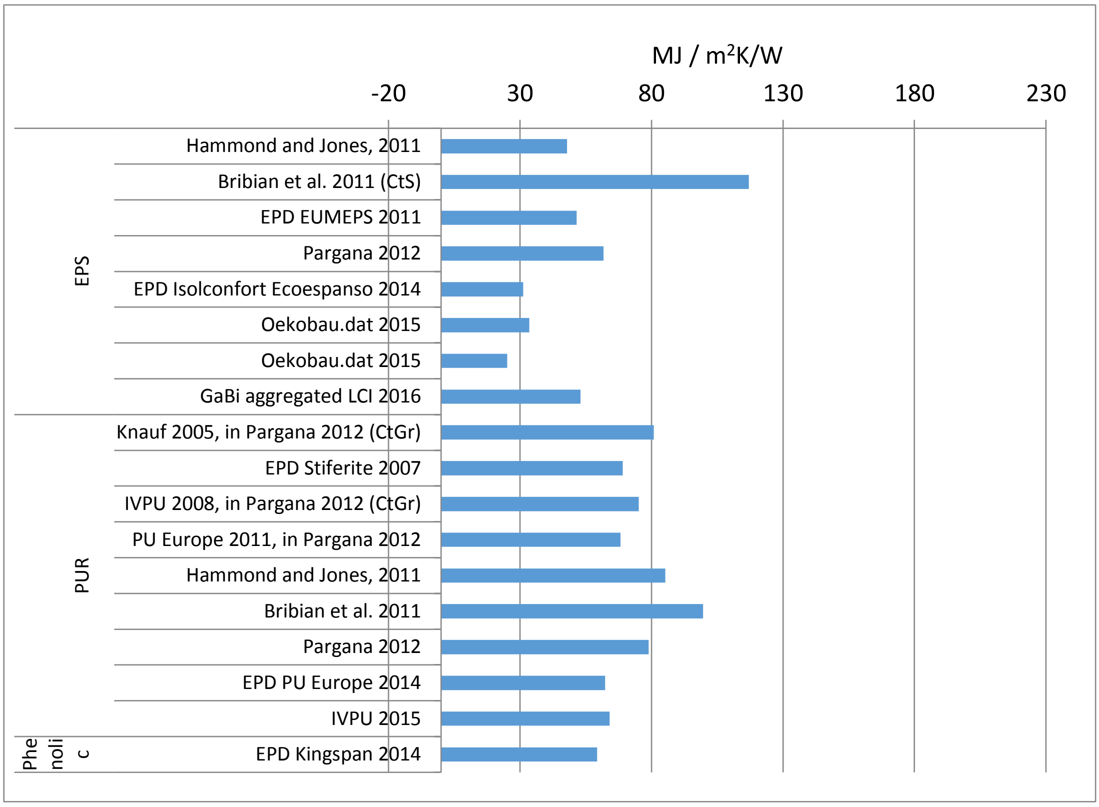


Figure 2. 13 – PEU of plastic products from the review of LCA studies (source: see Appendix I)

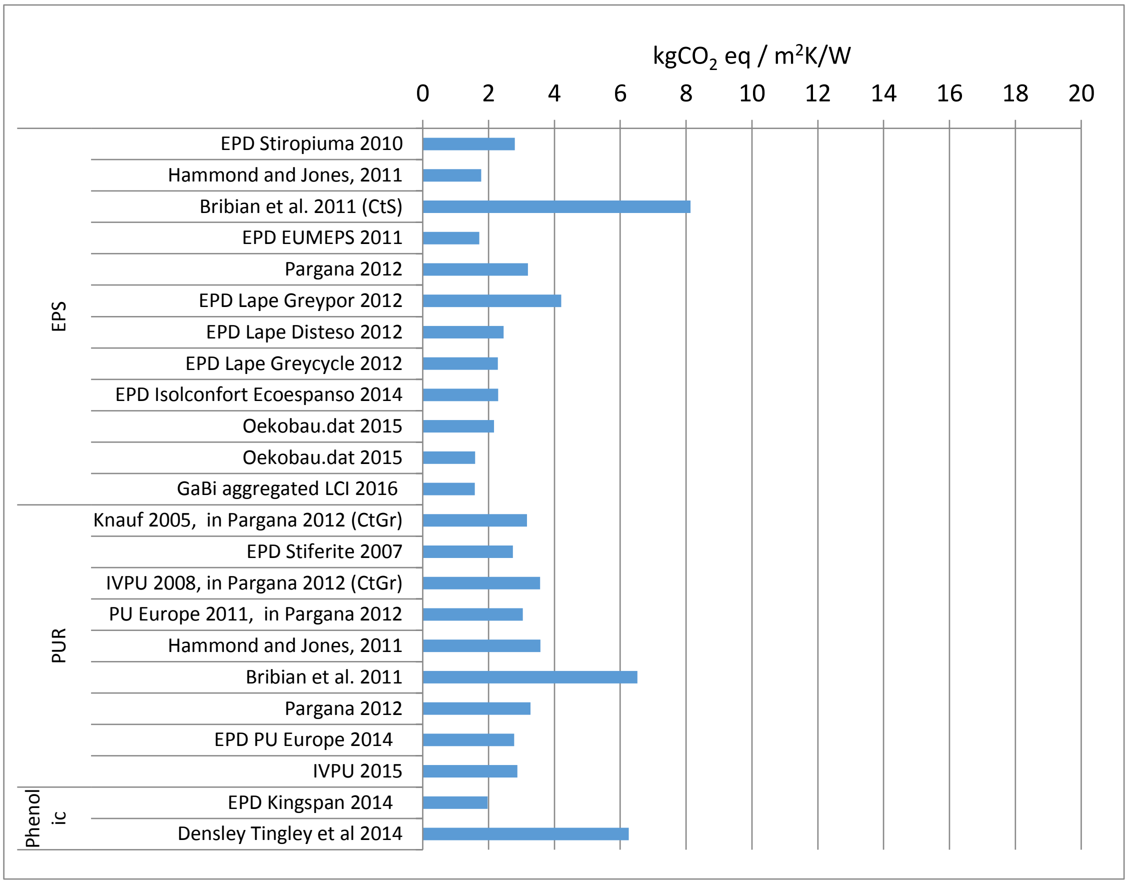


Figure 2. 14 - GWP of plastic products from the review of LCA studies (source: see Appendix I)

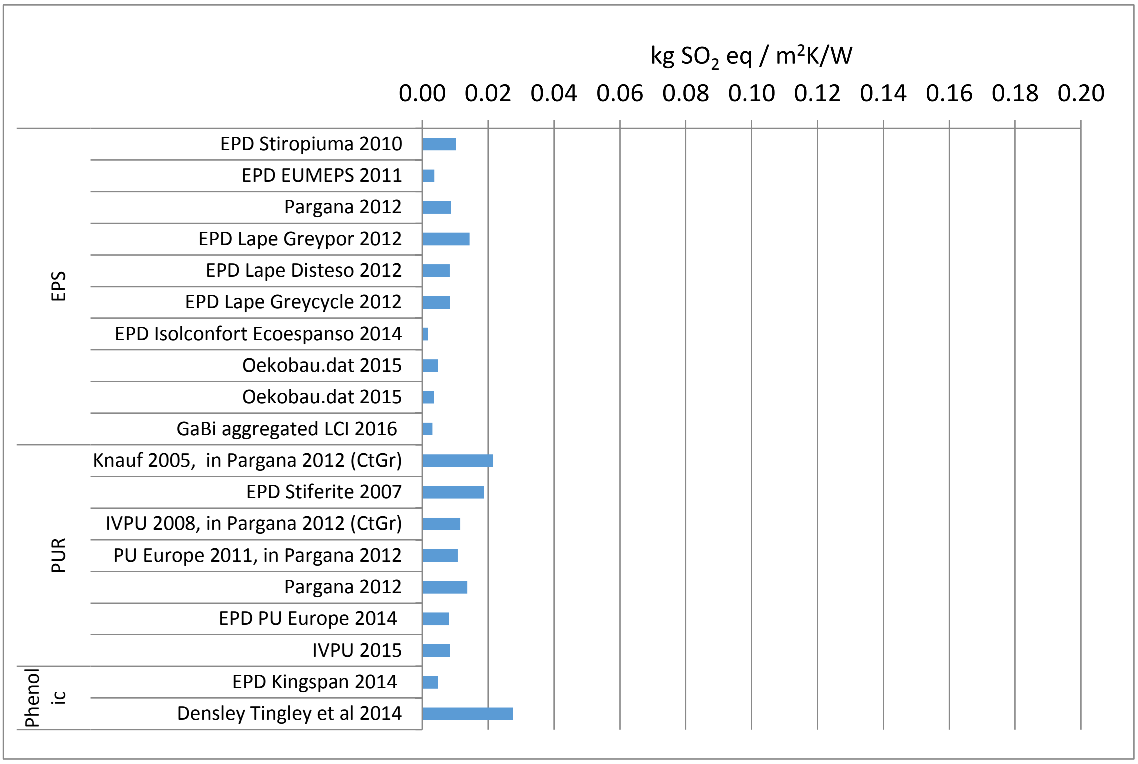


Figure 2. 15 - AP of plastic products from the review of LCA studies (source: see Appendix I)

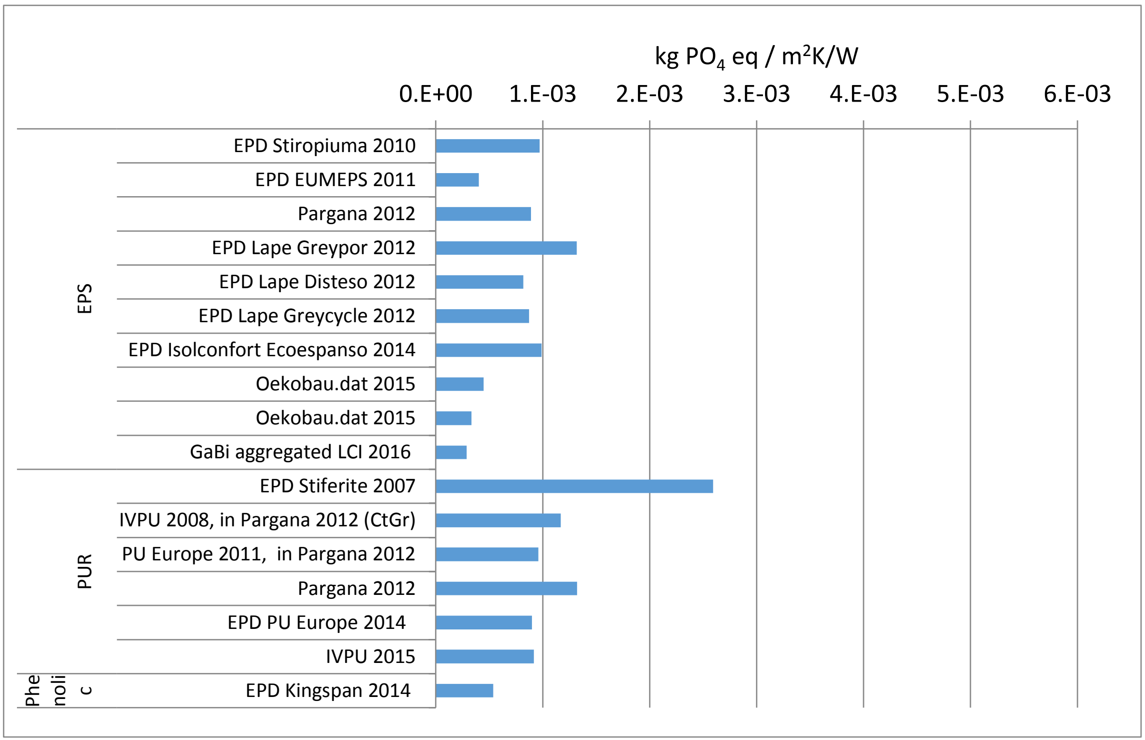


Figure 2. 16 – EP of plastic products from the review of LCA studies (source: see Appendix I)

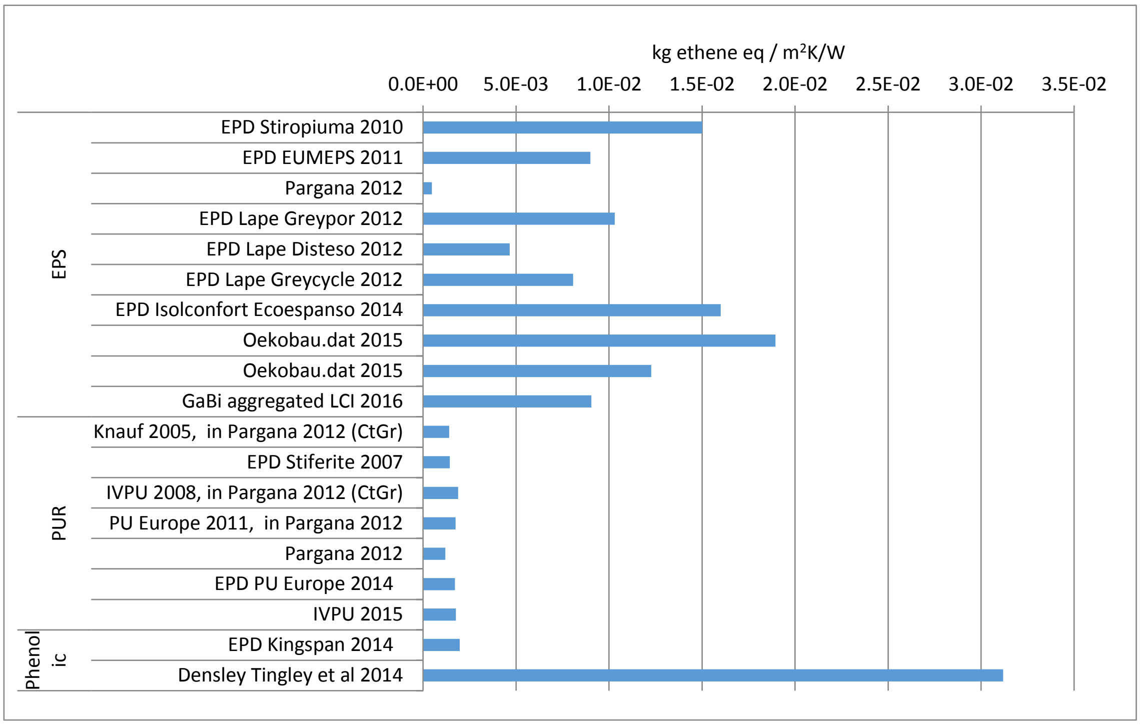


Figure 2. 17 - PEU of plastic products from the review of LCA studies (source: see Appendix I)

Environmental impact of biomass products

Figure 2. 18 to Figure 2. 22 show LCA results found in LCA sources for biomass insulation products. Firstly, it can be noted that fewer sources are available in comparison to conventional products. This might be explained by the limited popularity of biomass products and their relatively recent development. Sheep wool insulation is the product with the least number of available LCA sources, despite being a relatively well-known alternative product. Norton (2008) conducted LCA of hemp fibre and sheep wool insulation using specific data collected from British companies. These can be considered the most reliable sources for these two products in the UK context, although it must be noted that that the hemp fibre product is manufactured in France (with British hemp) due to the lack of a suitable facility in the UK. The study by Zampori et al. (2013) is also based on specific data, but for the Italian context. No detailed LCA studies were found on wood fibre insulation. The LCA results shown in Figure 2. 18 to Figure 2. 22 is found in EPD certificates by three European manufacturers, in the Baubook database and in Kunic (2017).

In terms of PEU (Figure 2. 18), wood fibre insulation appears to be the most impacting among biomass products. For GWP (Figure 2. 19), most LCA sources show negative emissions, especially for HD wood fibre. Negative emissions represent a positive impact on the environment, as more carbon is stored in the product than emitted during its manufacture. However, some sources show positive GWP values for biomass products. This might indicated that the carbon stored in the biomass is not sufficient to balance carbon emissions, or can be the consequence of the methodological choice of not accounting for stored carbon. This aspect is discussed later in further detail. In terms of AP and POCP, LCA results shows the three biomass products to have similar levels of EEI, while in the case of EP, LD wood fibre products appear to have lower EEI than the other products.

Studies on the impact of hemp fibre insulation agree that more than half of the energy embodied in the product is caused by the addition of PET fibres, which constitute about 15% of the weight of finished product (Norton, 2008; Haufe and Carus, 2011; Zampori et al., 2013). This is likely to affect sheep wool insulation as well, since the two products contain a similar share of PET fibres. Besides, the presence of this plastic fibre also complicates disposing or recycling the product at the end of its life-cycle. Both Norton (2008) and Haufe and Carus (2011) discuss the possibility to replace PET fibre with polylactic acid to reduce embodied energy. An additional way to lower embodied energy could be to decrease the density of the product without compromising stiffness and conductivity (Norton, 2008; Haufe and Carus, 2011).

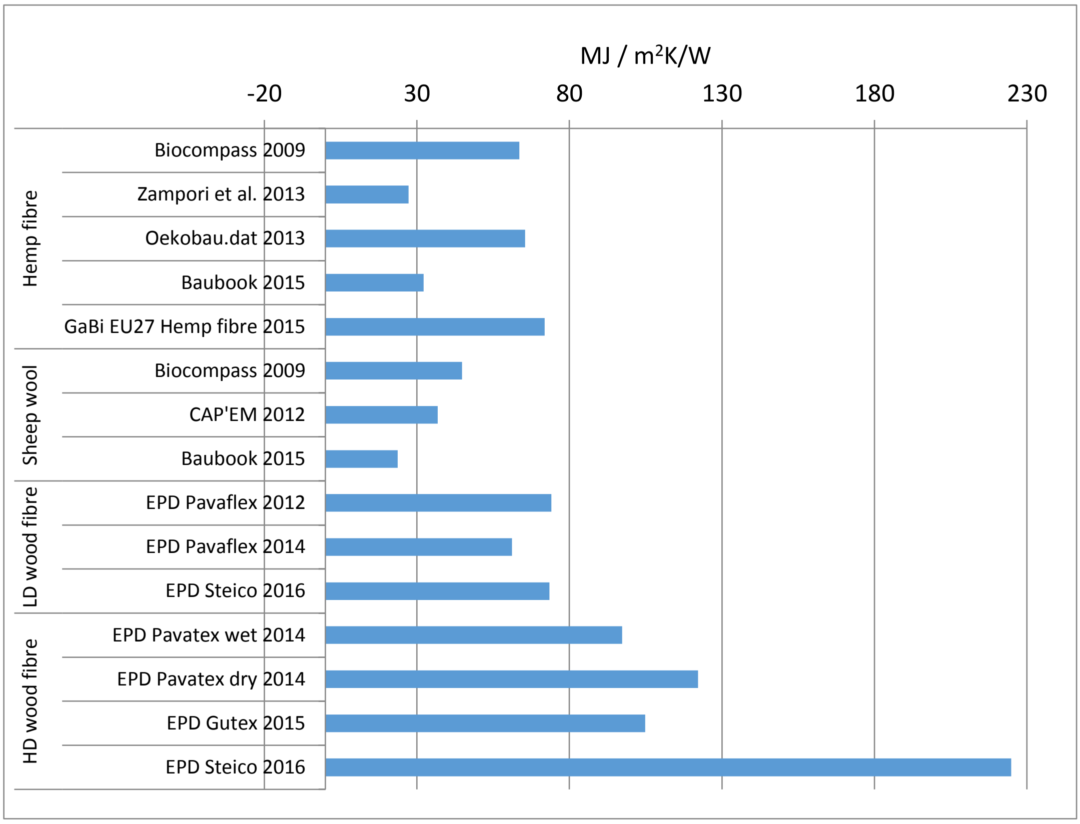


Figure 2. 18 - PEU of biomass products from the review of LCA studies (source: see Appendix I)

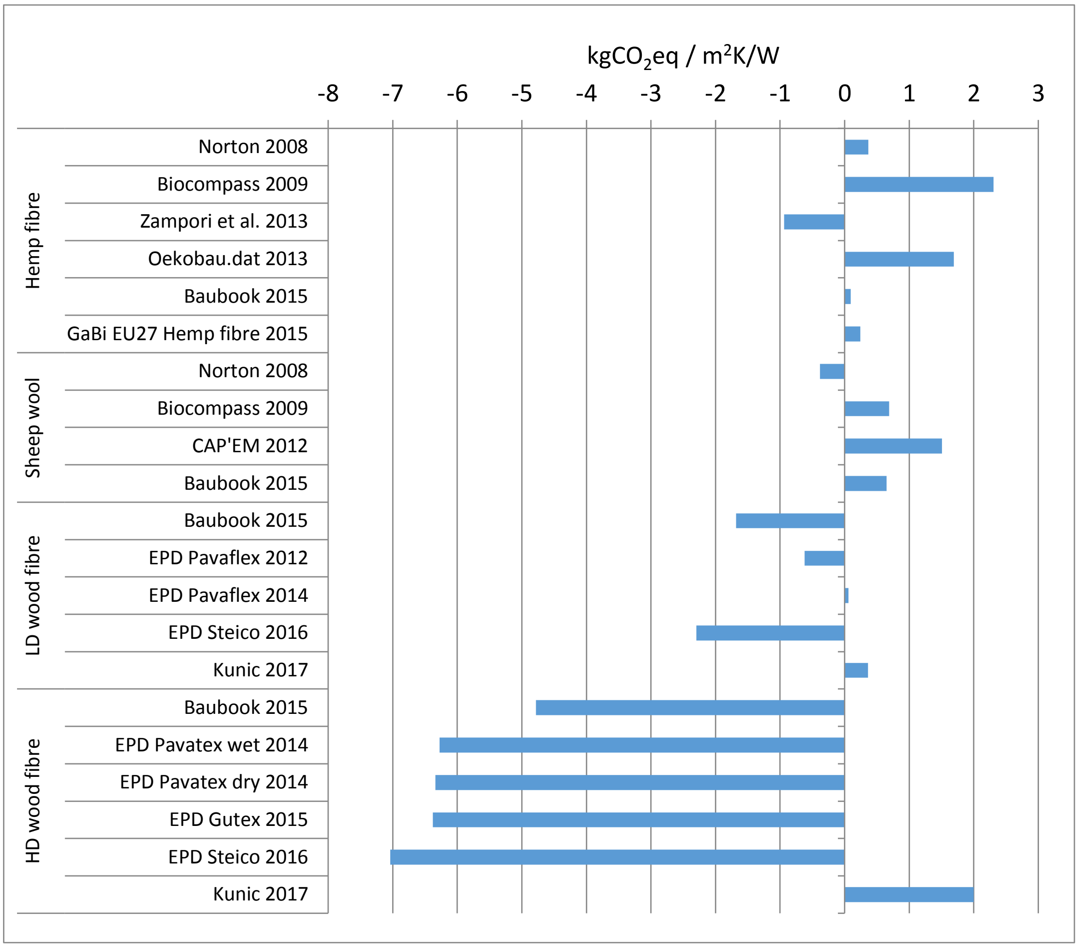


Figure 2. 19 - GWP of biomass products from the review of LCA studies (source: see Appendix I)

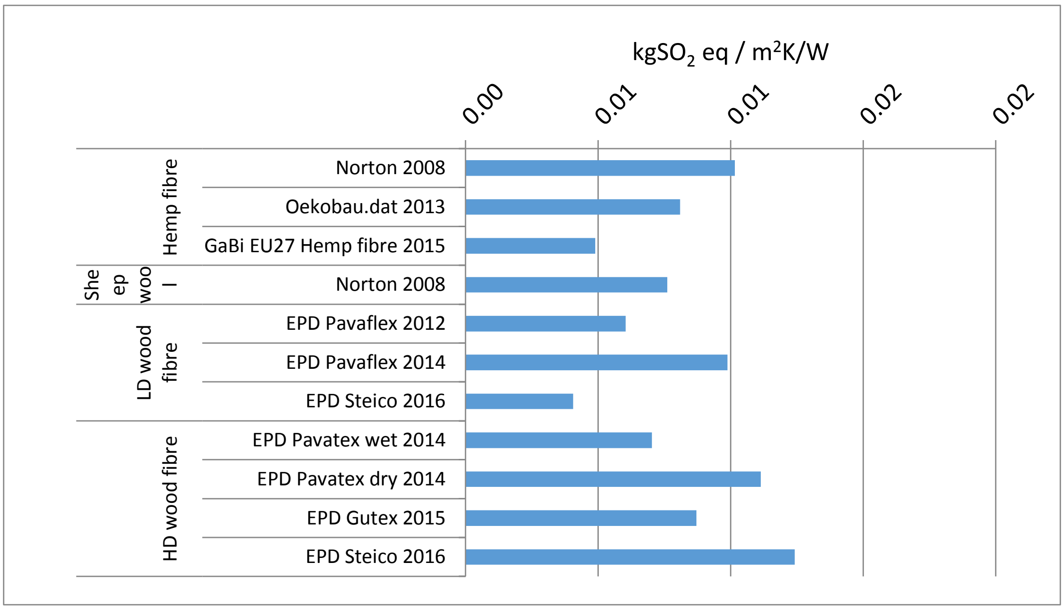


Figure 2. 20 - AP of biomass products from the review of LCA studies (source: see Appendix I)

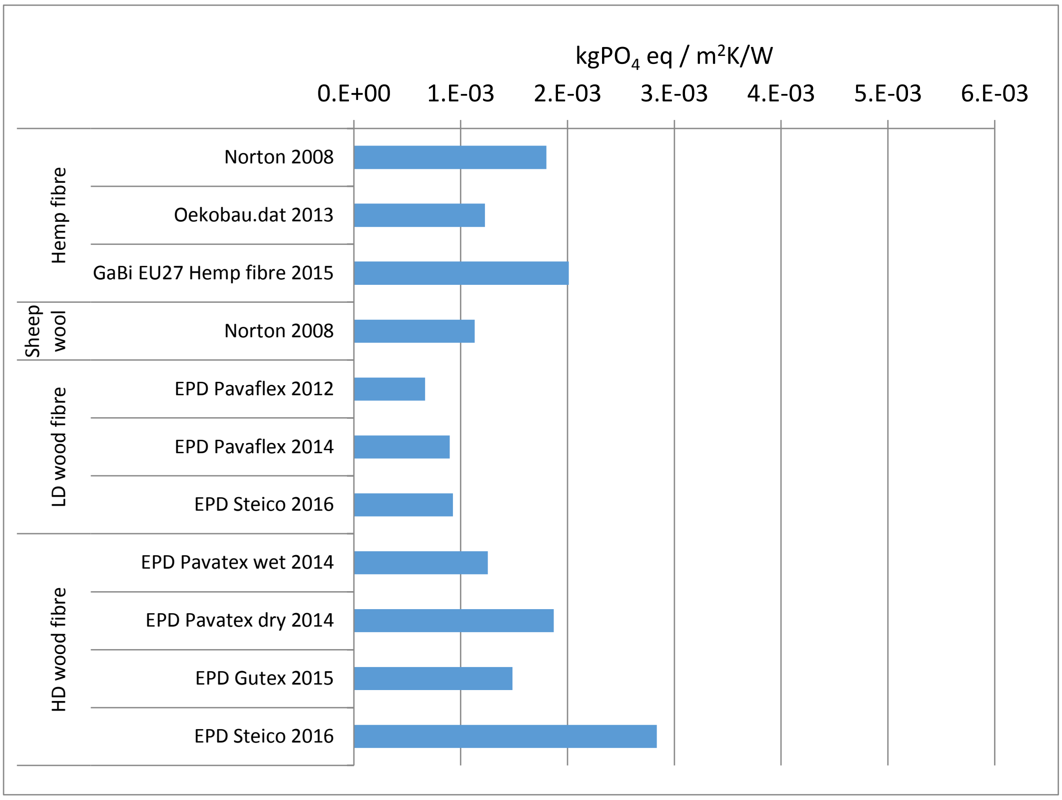


Figure 2. 21 - EP of biomass products from the review of LCA studies (source: see Appendix I)

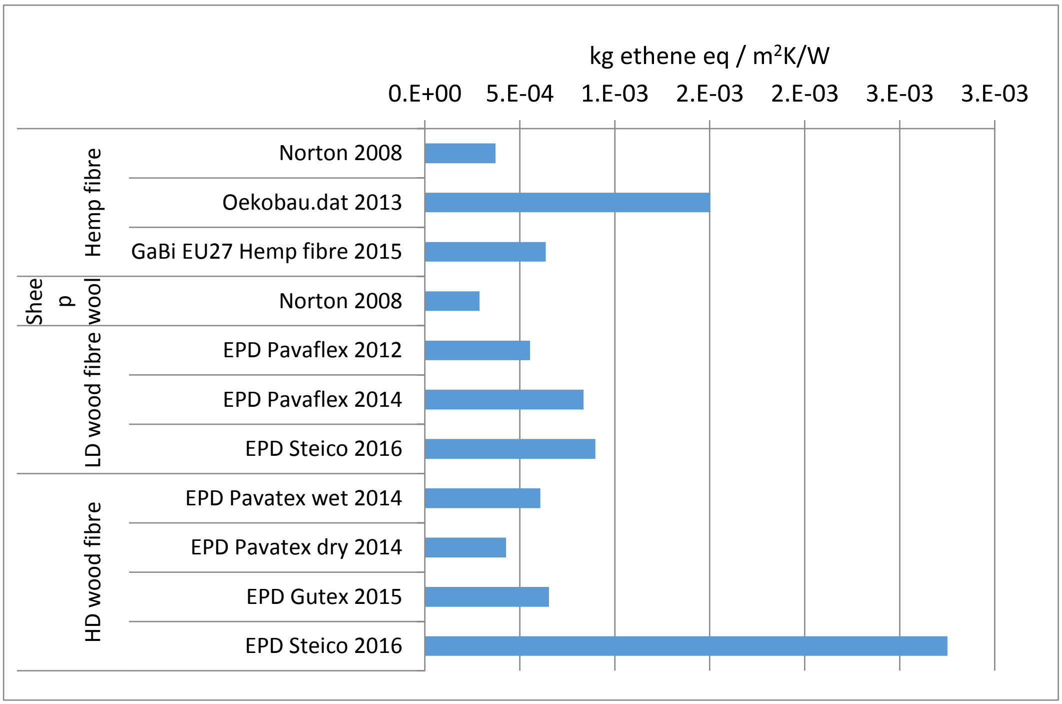


Figure 2. 22 - POCP of biomass products from the review of LCA studies (source: see Appendix I)

The complexity of agricultural stage LCA

Conducting an LCA of products based on biomass resources requires taking into account the impact of the activity leading to the 'extraction' of primary materials from the source. In the case of the three types of products studied in this research, this means modelling the impact of three 'agricultural' activities:

- industrial hemp farming;
- sheep farming;
- growing and felling of conifers.

Conducting LCA for agricultural processes is more complex than for industrial ones, as the higher complexity of agricultural LCA is due to several factors, such as the presence of many by-products, differences in crop and livestock management systems, variations in soil and climate and the large number of emission sources (Caffrey and Veal, 2013). Moreover, the sequestration of carbon in biomass due to natural processes poses the question of how to account for this carbon, which is stored in the final product for its life cycle but might eventually be released into the environment. Zampori et al. (2013) note that LCA of insulation products should include carbon sequestration since their life-cycle can be expected to be over ten years, which is the criteria for including sequestration set by ISO 14067, the standard regulating the carbon footprint methodology. Most LCA studies on insulation products include carbon sequestration (when applicable), but there are exceptions. Specific issues arising from the LCA of agricultural processes associated with biomass products are presented here.

Hemp fibre insulation - LCA of agricultural stage

Three factors affect significantly the results of an LCA of fibre produced from industrial hemp:

- the quantity of fertilisers;
- the annual yield;
- the allocation between fibres and shives.

The existing literature on industrial hemp cultivation, although agreeing on the low requirements of this crop, presents differences in the amount of fertilisers to be used. Nonetheless, detailed LCA results in Zampori et al. (2013) show that fertilisers make by far the largest contribution to carbon emissions among agricultural inputs of industrial hemp (including tillage, bailing, etc.). However, it should be noted that the relatively low requirements for pesticides and fertilisers make industrial hemp a very suitable break crop in a crop rotation process (Garstang et al., 2005).

Yield values vary depending on location and weather conditions in each year. Assuming that two fields are treated with the same amount of work and fertilisers per hectare, it is still possible that the outputs will not be equal. In this case, LCA results for a unit of hemp straw grown on the field with the higher output will show a lower environmental impact than a unit of straw from the other field, since the same impact per hectare is divided by a larger number of units.

Once the environmental impact per unit of hemp straw is calculated, it needs to be allocated between the fibre and the shives on either a mass or economic basis. While the mass method is based on an average ratio between fibre and shives, the economic method is based on prices valid within a certain area and time period, and therefore can vary between studies. The LCA by Zampori et al. (2013) compares the two options, showing that the mass method allocates the impact almost equally between fibres and shives, while the economic method allocates a higher share to fibres due to their higher market value. This is based on the conditions of the Italian market, but Carus et al. (2013) confirm that in European countries the price per kg of fibres is about twice the price of shives.

The choice as to whether to include or not carbon sequestration in LCA can have a significant impact on the resulting GWP, or embodied carbon. A review of studies by Haufe and Carus (2011) found the cradle-to-gate life-cycle of hemp fibre insulation requiring from 110% to 170% more energy than glass wool. Similar figures are obtained for embodied carbon if sequestration is not taken into account. Conversely, the LCA of hemp fibre insulation results in savings of embodied carbon from 40% to 140% in comparison to glass wool (Haufe and Carus, 2011).

Sheep wool insulation – LCA of sheep farming stage

A key factor affecting LCA results of sheep wool is allocation, as sheep farming produces meat and wool, but also milk and other products, such as manure (Henry, 2012). Studies investigating sheep wool rather than sheep farming choose to focus on meat and wool as the main outputs. Wiedeman et al. (2015) have compared LCA results for sheep wool obtained with different allocation methods for three locations: the UK, New Zealand and Australia. Four different physical methods are modelled to allocate between sheep meat and wool, resulting in the impact of sheep farming being attributed to wool at a range between 7% and 22% (Wiedeman et al., 2015). If the economic method is chosen, it is necessary to establish the economic value of the two outputs. In the UK, where most wool is a b-product of the meat sector, Wiedeman et al. (2015) allocate the impact of sheep farming on the basis that the value of wool usually amounts to 4% of farm revenue. This is not far from the 3.3% used by Williams et al (2006) to allocate economically between meat and wool in a UK-wide LCA of agricultural commodities. In Australia, where the system is managed to optimise the production of meat as well as high quality ‘merino’ wool, the economic method allocates the impact of sheep farming equally between meat and wool (Wiedeman et al., 2015). The fact that sheep wool would not be produced in the UK without the presence of the meat sector might justify the complete exclusion of the impact of sheep farming from the LCA of sheep wool, especially if the price of wool is too low to present a profit to the farmer. Norton (2008) took this approach.

While acknowledging economic allocation as the most common method used in the LCA of sheep wool, Wiedeman et al. (2015) note that it “will also cause results to vary over time in response to market fluctuations and subsidies or price interventions in addition to changes in environmental impacts, and this could complicate the interpretation of benchmarking results as the knowledge base builds.” (p.11) However, variations in sheep wool LCA due to economic factors also make the single LCA results more accurate, as no universal value can be attributed to the impact of wool, but only specific values depending on the context and level of assessment (Edwards-Jones et al. 2008).

Williams et al. (2006) have conducted a system-wide LCA to determine the environmental impact of the UK agricultural sector. Their research shows sheep meat to have a significant impact, with the highest values among all meat types in the categories of GWP and EP (Williams et al., 2006, p.4). Within a broader perspective, the extensive land use required by large scale sheep farming raises several questions in terms of its wider impacts and long-term sustainability. Monbiot (2017) pointed out that sheep grazing is largely responsible for the soil erosion and degradation in British uplands, and that while lamb is only a very small component of the average diet, the area of land used for sheep raising is equal to all the land used for food crops. Moreover, the sheep farming sector is not different from other agricultural activities when it comes to relying on subsidies. In 2015/2016, the average profit made by cattle and sheep farms in Wales included more subsidies (about £ 23,000) than revenue from meat production (about £19,000) (O’Regan et al., 2017). The current lack of clarity regarding the future of agricultural subsidies following the exit of the UK from the EU is a source of significant concern among Welsh farmers (Williamson, 2017a). Recently, the new trade deal between the UK and New Zealand together with the prospect of a ‘hard Brexit’ (i.e. no particular trade deal between UK and EU besides WTO rules) has been called by the president of the Farmer Union of Wales “a perfect storm” for Welsh sheep farmers (Williamson, 2017b). Since a large share of Welsh sheep meat is exported to Europe, Welsh farmers fear losing unrestricted access to the European market while having to compete with cheap imports from New Zealand.

Wood fibre insulation - LCA of forestry stage

In comparison to hemp fibre and sheep wool products, the agricultural component of the LCA of wood fibre products is less complex. Conifers grow in their natural environment, and fertilisers are used in small quantities only in case of man-made forests on particularly poor soils (Malcolm, 1997; Carey, 2006). Thus the first input to the life-cycle of the wood fibre insulation is the energy used to fell and transport trees. If trees are managed sustainably – for example following Forestry Stewardship Commission principles (FSC, 2017) – the carbon sequestered in timber can be accounted as negative emissions towards GWP. All EPD certificates for wood fibre insulation (Gutex, 2012; Pavatex, 2014a; 2014b; Gutex, 2015; Steico, 2016) declare that the timber used for their products is sourced from sustainable forests.

In Figure 2. 19, Kunic (2017) is the only source showing substantial carbon emissions from LD and HD wood fibre products. All other sources show negative or near zero emissions due to the carbon stored in the biomass. If Kunic (2017) is not considered, wood fibre results to be the biomass product with the highest carbon content per functional unit. As can be expected, HD wood fibre contains more carbon, as it contains more mass. To obtain wood fibre data, Kunic (2017) did not perform an LCA but used two existing aggregated LCI in the Ecoinvent database. Since no detail is given on these datasets and *carbon sequestration* is not explicitly mentioned, it is likely that sequestered carbon was not taken into account by Kunic (2017).

Wood fibre was developed to make use of woodchip 'waste' from sawmills, however from the information given in EPD (Pavatex 2014a; Steico, 2016) it appears that Pavaflex, and possilbly Steico, also process virgin timber on-site to obtain woodchips. In this case no allocation is required as woodchips are the only product. However, when woodchips are generated as by-product of sawmills, allocation is required between chips and the main product, i.e. solid timber. In Gutex (2015) the mass allocation method is chosen, while in Pavatex (2014a; 2014b) the economic method is used. However, GWP data in Figure 2. 19 indicates that the effect of the allocation method is not substantial.

Comparison of environmental impact across product types

The LCA results data found in existing sources and presented in the previous pages is summarised in Figure 2. 23 to Figure 2. 27. to allow a direct comparison between all product types. For each EEI category the impact of products is shown through the average, minimum and maximum values.

In terms of PEU, Figure 2. 23 shows glass wool to be the least impacting product on average and HD wood fibre the highest one. The other biomass products are within the range established by glass wool and PUR, which is the conventional product with the highest average impact. In terms of GWP, Figure 2. 24 shows stone wool and phenolic foams to have the highest average embodied carbon, followed by PUR and EPS. In comparison, biomass products and particularly HD wood fibre have much lower values, and the 'negative' ones actually represent a positive environmental impact thanks to carbon sequestration. In terms of AP, Figure 2. 25 shows stone wool having the highest average impact, while glass wool, EPS and the biomass products all display low impact values close to one another. In terms of EP, Figure 2. 26 shows stone wool having the highest average impact, followed closely by EPS hemp fibre and wood fibre. Phenolic foam presents the lowest impact among all products, though it must be remembered that LCA sources for this product are very limited. In terms of POCP, Figure 2. 27 shows phenolic foam having the highest average impact, followed by EPS. In comparison to these two, all other products have much lower values, with sheep woll presenting the lowest one. However, the ranges of minimum values show that phenolics and EPS can also display low impact.

The three plastic products have EEI values generally within the ranges established by other products in all impact categories except POCP, where EPS and phenolics display a much higher impact. It is difficult to identify reasons for these high values. However, looking back at the single LCA sources for these figures (Figure 2. 17), it can be noted that there are ten items for EPS and only two for phenolics, Densley Tingley et al. (2014) and the EPD by Kingspan (2014). While the entries for EPS are fairly distributed across the range, phenolics display either a very high value, by Densley Tingley et al. (2014), or a low value in line with other products, by Kingspan (2014). Given that Densley Tingley et al. (2014) admit having limited information on manufacturing process, it can be argued that the EPD by Kingspan (2014) is a more reliable source.

In the PEU and EP categories, the EEI of biomass product is generally comparable to that of conventional products. In terms of AP and POCP the EEI of biomass products is in the lower ranges, while the embodied carbon of biomass product is considerably lower than conventional products, or even negative (i.e. sequestered carbon). In terms of EEI, the capacity to provide carbon storage can be considered the most significant benefit of biomass products in comparison to conventional ones.

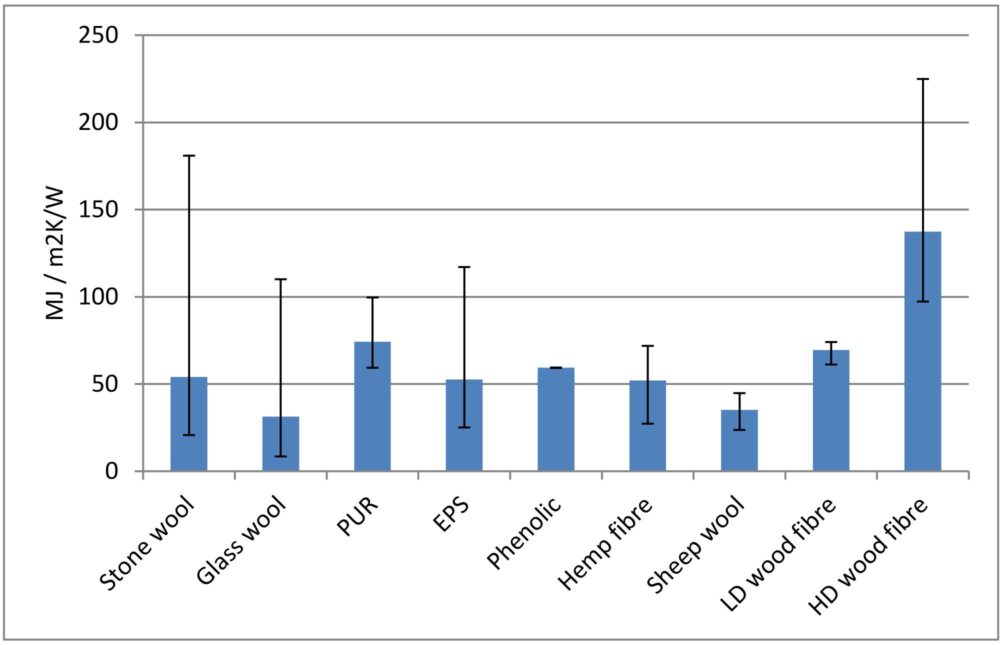


Figure 2. 23 – Minimum, average and maximum PEU of insulation products from the review of LCA studies (source: see Appendix I)

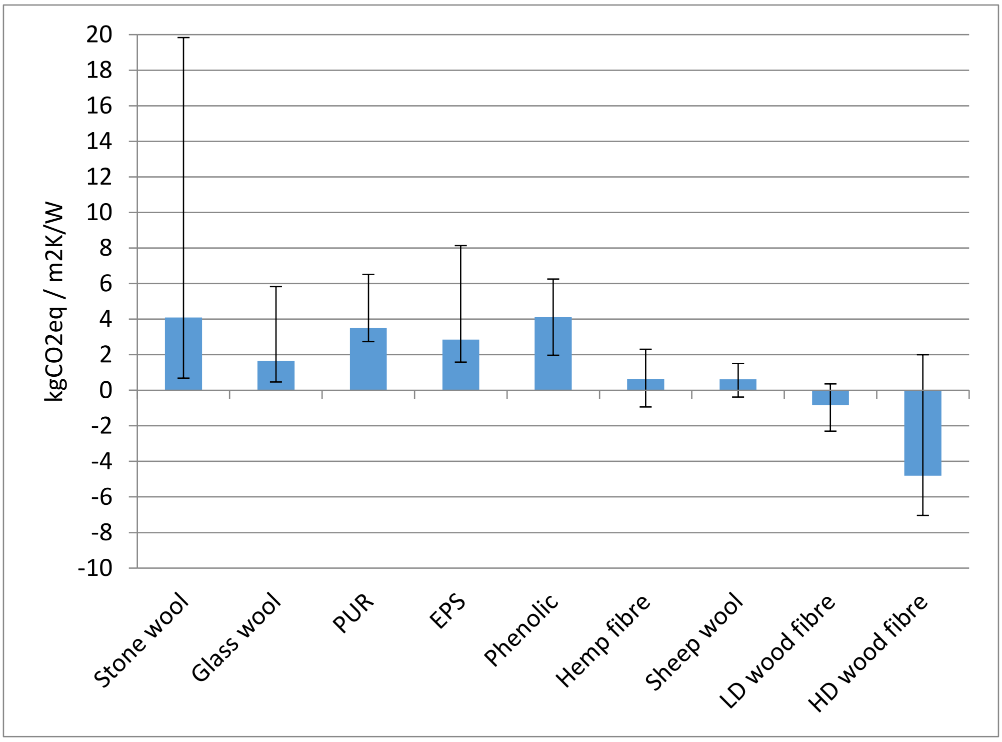


Figure 2. 24 - Minimum, average and maximum GWP of insulation products from the review of LCA studies (source: see Appendix I)

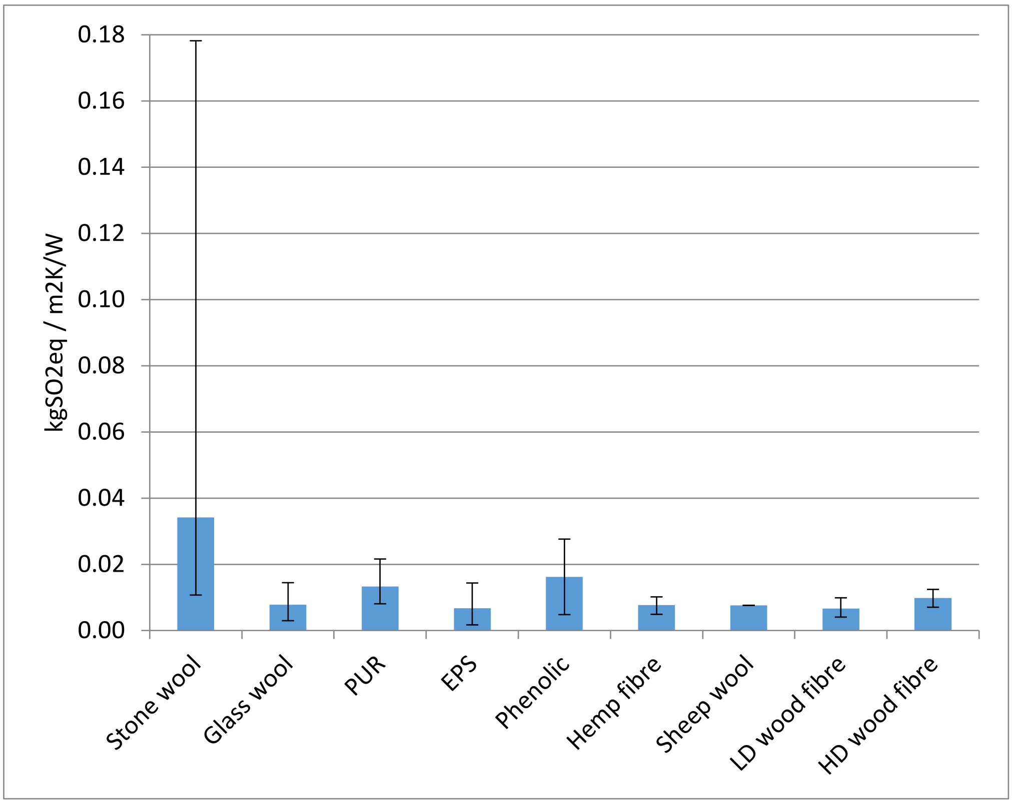


Figure 2. 25 - Minimum, average and maximum AP of insulation products from the review of LCA studies (source: see Appendix I)

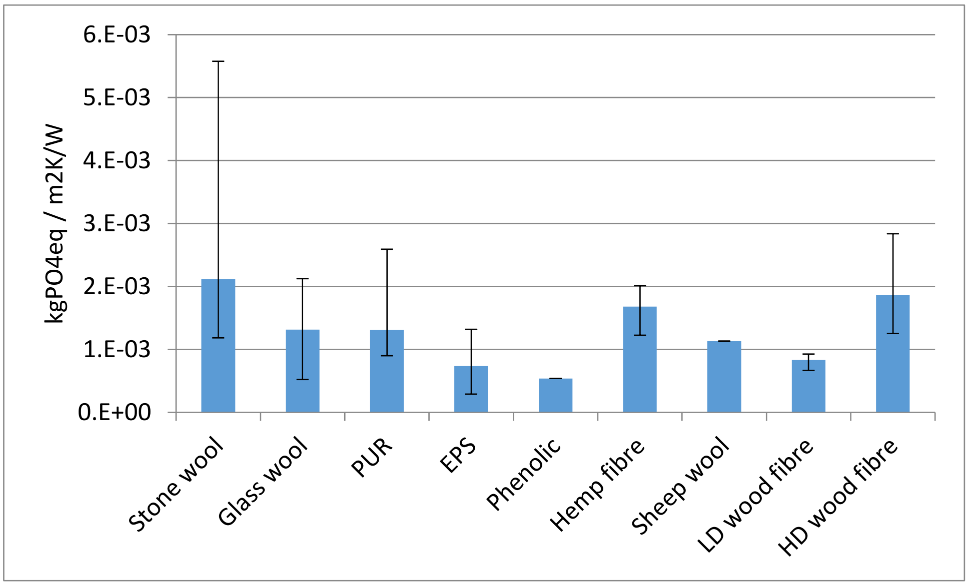


Figure 2. 26 - Minimum, average and maximum EP of insulation products from the review of LCA studies (source: see Appendix I)

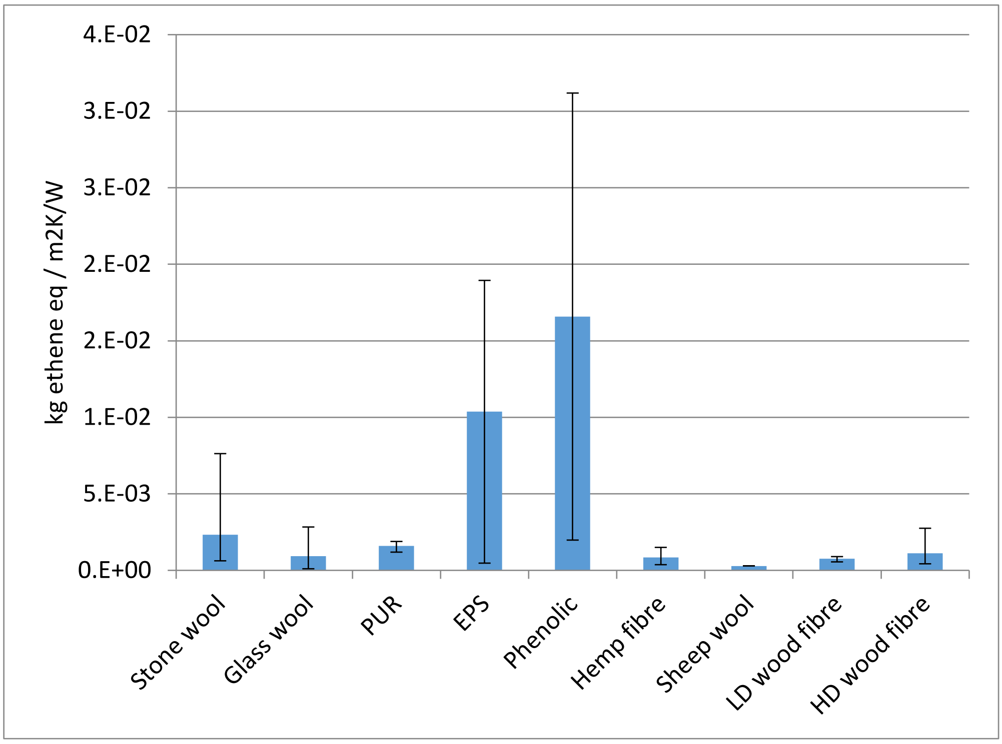


Figure 2. 27 - Minimum, average and maximum POCP of insulation products from the review of LCA studies (source: see Appendix I)

2.3.6 Conclusion on the review of insulation products

This review of literature on insulation focused on two groups of products on the basis of regional conditions for Wales. Five conventional products were identified as occupying the largest market shares in the UK:

- Stone wool;
- Glass wool;
- Polyurethane Rigid and Polyisocyanurate foam (PUR and PIR);
- Expanded Polystyrene (EPS);
- Phenolic foam.

Although these products can clearly be identified as the most popular on the market, the accessible sources did not hold sufficient data to form a complete picture of the shares occupied by each product within specific sub-sectors of the market, for example roof insulation in new dwellings. Furthermore, no information is available to determine whether the Welsh market displays significant differences in comparison to the larger UK market.

Three biomass products were identified to have the potential to be sourced and manufactured in Wales:

- Hemp fibre;
- Sheep wool;
- Low Density (LD) and High Density (HD) wood fibre.

These products are available on the UK market but occupy minimal shares. This can be attributed to high prices and limited availability, and both these factors can be related to a small scale of production. Technically, biomass products could replace conventional products in many domestic applications. Due to similar physical properties and format, biomass products are more compatible with the application range of mineral products than plastic ones. Nonetheless, annual changes in market shares occupied by different products suggest that in the choice of insulation there is a degree of freedom from strictly technical conditions. Thus it is possible to hypothesise a scenario where the market shares of conventional products are progressively reduced in favour of biomass products, possibly based on regional resources and locally manufactured. Such scenario would theoretically lower the EEI in the supply of insulation products while stimulating the local economy, according to the radical approaches to sustainability discussed in the first part of this literature review (2.1).

The review of LCA studies showed several examples of biomass products with lower environmental impact than plastic and mineral ones. However, the presence of 'natural' materials does not appear to ensure low impact in every category, therefore generalisations should be avoided. Furthermore, the large range of variations in LCA results highlights the uncertainty associated with LCA. Given the number of existing LCA sources on insulation, new research in this field should take these results into account by using them to benchmark new figures. Research on insulation products should also expand beyond the environmental dimension of sustainability. Economic aspects are often mentioned within the LCA literature on insulation products, but only few studies choose to investigate them, while social aspects are virtually absent in the literature. Only one LCA study (Duijve, 2012) takes a long-term approach by estimating future demand for insulation. As noted by Giesekam et al. (2014, p.211), "a dearth of quantitative evidence exists, not only in assessing the environmental impacts of individual construction materials and products, but in evaluating the cumulative sector wide changes that may be necessary to meet emissions reduction targets".

The unique research by Palumbo et al. (2015) provided a basic method to relate product demand to regional availability. However, no study has addressed supply on a regional scale together with the potential for reducing impact with products based on local resources. Therefore there is an opportunity to build on existing studies on insulation products by modelling large scale substitution and its consequences in terms of environmental impact, and to expand the scope of the field by investigating the socio-economic aspect of products and the availability of local biomass resources.

3 Research design

The design of the research according to the division in three ‘components’, as introduced in chapter 1, is presented in this chapter. The research components are related to the main objectives:

1. First component – Environmental impact: generating scenarios to assess the EEI of the entire supply of insulation in Wales under different product combinations;
2. Second component – Socio-economic impact: assessing the embodied socio-economic impact of individual insulation products,
3. Third component - demand and supply of regional resources: evaluating the capacity of the Welsh territory and economy to meet the demand for biomass products with local natural resources.

Methodology, and results of the three components are presented in chapters 4, 5 and 6 to help the understanding the process leading to the final outcomes. These are discussed as a whole in chapter 7, together with limitations, applications and further developments.

Several quantitative methods have been combined to achieve the research aim and objectives. The research framework is based on the general principles of Material Flow Accounting (see section 2.2.1). Demand and supply of insulation products are accounted in physical units, while economic I-O analysis is conducted in monetary units to investigate the socio-economic impact of products. This combination of methods was identified taking into consideration the research objectives and the existing context of assessment techniques, studies and data sources discussed in part 2.2 of the literature review.

The structure of the entire research process is visualised in Figure 3. 1. The first component of the research is divided into three parts (pink frames). The second component and third component are shown respectively in yellow and purple frames. In each component several steps (green boxes) are taken to produce the final outcomes (highlighted in black frames). These steps are described in brief in the following pages of this chapter, and with detail in chapters 4, 5 and 6.

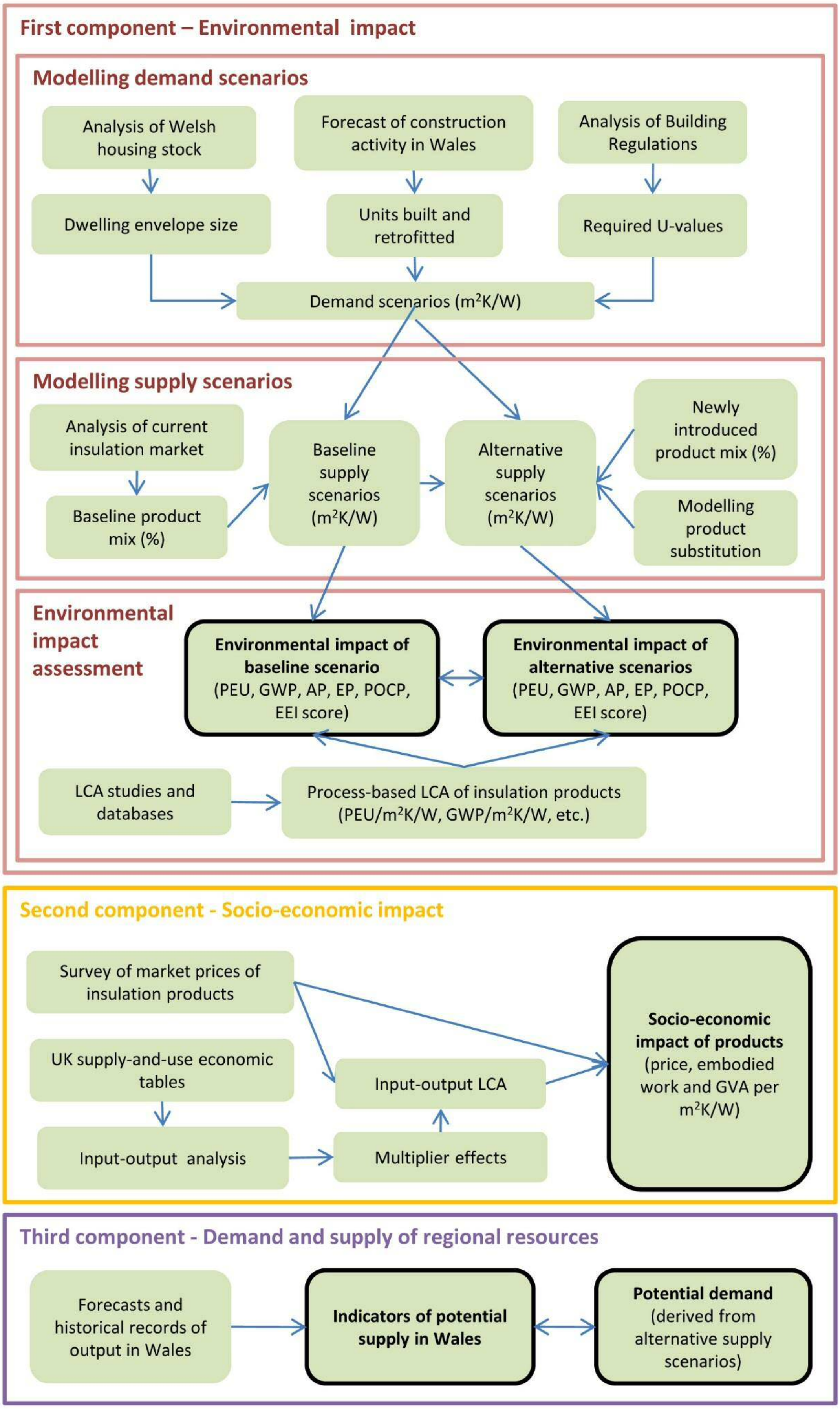


Figure 3. 1 – Diagram describing the research process

3.1 Defining demand and supply of insulation

The foundations of the research design are presented in this section. The *strong approach* to sustainability acknowledges that any decrease in natural capital will bring long-term negative consequences, as it reduces the available supply and therefore the capability to meet future human needs (section 2.1.1). The links between needs, demand and supply is a key theme of this research. *Demand* is defined as the request for goods to satisfy a specific function. The demand for thermal insulation products in dwellings is intended as the request for objects which can be applied to architectural elements of the envelope (walls, roofs, etc.) and provide thermal resistance to reduce the heat transfer across these architectural elements. In turn, the request for thermal insulation in dwellings is generated by the effort to reduce energy demand as well as to improve thermal comfort. This research does not study this aspect, but assumes the demand for insulation products as 'a matter of fact' and proceeds to investigate how this demand can be met with different combinations of products.

supply is defined as the provision of goods which can satisfy the function requested by the demand. In the case of thermal insulation, supply is intended as the provision of objects which can be applied to architectural elements to provide thermal resistance. Since there are different products which can provide the same thermal resistance, the demand can be met with several combinations of products. What matters is that products are capable to satisfy the *function* requested by the demand. This concept of need which can be satisfied by different means is loosely modelled on the theory of human needs and satisfiers formulated by Max-Neef at al. (1992).

In the case of thermal insulation, the required function to be satisfied is the capacity to provide thermal resistance (R-value), measured in square meters of surface area with absolute thermal resistance equal to 1 K/W. This physical unit of m^2K/W, which combines a unit measuring area (m^2) with a unit measuring temperature difference due to heat flow (K/W), is used to quantify thermal insulation products throughout this research and it is taken as the *Functional Unit* (FU) for product LCA. Usually thermal transmittance (U-value) is used to quantify insulation in architectural studies. However, the U-value of an insulation layer (which is assumed not to be in contact with indoor and outdoor air, thus not subject to radiation and convection) is simply the inverse of the R-value, and indeed is measured in W/m^2K. In this research the R-value is preferred to the U-value because the former is directly proportional to the quantity of insulation, which makes calculations and comparisons more intuitive.

The concept of demand and supply is also applied in this research to track the chain of manufacturing processes linking insulation products to their primary materials and the natural resources from which those are extracted (third research component).

3.2 Design of the first component: environmental impact

The first research component focuses on assessing the EEI of insulation products used in Welsh dwellings from 2020 to 2050. The component is divided into three parts, described in the following sections:

- Modelling demand scenarios, where the demand for insulation is estimated through a bottom-up model of the building stock;
- Modelling supply scenarios, where different combinations of products on the market are modelled;
- Environmental impact assessment, where product LCA is performed.

3.2.1 Modelling demand scenarios

The demand for thermal insulation generated by a single dwelling at a moment in time can be precisely quantified, because the surface areas to be insulated and the thermal resistance to be satisfied can be known with certainty. In the case of new buildings, designers and current regulations affect these variables. In the case of retrofits, a survey of the building can be conducted.

The demand for insulation generated by all the domestic construction activities within a region during several years is less easily quantified, unless an extensive survey is conducted. In the case of future construction activities, the surface areas to be insulated and the thermal resistance to be satisfied can only be estimated through hypothetical scenarios based on current conditions. To build these scenarios it is necessary to make assumptions on a number of variables, such as the total number of dwellings which will be retrofitted and built during a certain period of time, and the distribution of construction activities across this period of time. For these reasons, in this research the demand for insulation generated in Wales by domestic buildings is organised into a series of *sectors* and *demand scenarios*. Firstly, construction activities on residential buildings are is divided into:

1) retrofits and
2) new constructions.

These domestic building sectors are then subdivided by types of dwelling envelope to be insulated. The demand scenarios are based on the calculation of three main variables:

- the typical size of dwelling envelope to be insulated – estimated using existing data on the Welsh dwelling stock;
- the thermal resistance to be satisfied by the dwelling envelope - estimated using U-values requirements in Building Regulations and considering potential changes in policy;

- the number of dwellings to be insulated (both new built and retrofit) - estimated through a forecast of construction activities based on the latest available figure for the Welsh dwelling stock in 2014.

By combining the three variables, the demand for insulation is estimated in terms of total FUs (m^2K/W) per year in the period from 2015 to 2050.

Insulation demand from retrofitted dwellings

The demand sector of dwelling retrofit is subdivided into the following envelope types:

a. Solid Wall (SW), both externally and internally insulated, and
b. loft.

The insulation of external cavity walls in recent constructions and the insulation of flat roofs are excluded from the scope of this research. The latter are a very small minority of existing dwellings (see section 4.1.1), while the insulation of cavity walls has been strongly pursued in recent years in the UK. Moreover, its technique of execution (injection of loose insulation) limits the types of products which are suitable for this research. Furthermore, there are several problems associated with cavity wall insulation due to moisture issues (Kiselova, 2015), which would further increase the number of variables to be taken into account. The insulation of ground floors in domestic retrofits also presents particular technical challenges, and therefore it is not included in the scope of this research.

Insulation demand from new constructions

The demand sector of domestic new construction is subdivided into the following envelope types:

a. external walls,
b. roofs and
c. ground floors.

These envelope types cover the majority of building envelope potentially requiring thermal insulation. Less frequent applications are excluded, such as for example the insulation of intermediate floors which are exposed to the outdoor environment due to architectural features.

The demand sector of new constructions is estimated across four different scenarios, which are determined by:

- the number of new dwellings built each year (increasing or declining);
- the thermal resistance required by building regulations (remaining constant or increasing).

These four scenarios are modelled to evaluate the effect that different conditions could have on the annual demand for insulation in new dwellings.

3.2.2 Modelling supply scenarios

supply scenarios are built to model how different insulation products can be used to satisfy the thermal resistance required by the demand scenarios. Practically, supply scenarios represent different combinations of products as forecasts of the Welsh insulation market between 2020 and 2050. Since the current manufacturing scale of biomass products is small, it would be unrealistic to model alternative scenarios where the use of these products increases immediately. Instead, 2020 is the year chosen to begin the substitution of conventional products with biomass ones. Thus while being based on the 2015-2050 demand scenario previously described, only the period 2020-2050 is modelled in the supply scenarios.

For each envelope type, for example ‘new dwellings - external walls’, all supply scenarios are equivalent to each other in terms of operational performance, i.e. they provide the same thermal resistance. This allows a fair comparison between scenarios in terms of embodied impact, knowing that operational performance is equivalent.

The supply scenarios are divided into:

1) baseline scenarios and
2) alternative scenarios.

baseline supply scenarios

The baseline supply scenarios model business-as-usual conditions of the market, assuming that the future demand for insulation will be met with the same mix of conventional products that is currently in use. With ‘mix of products’ it is meant the values of percentage share that each product occupies in the market of insulation. The conventional products studied in this research (introduced in section 2.3.3) are:

Mineral products:

1) Stone wool;
2) Glass wool;

Plastic products:

3) Polyisocyanurate rigid foam (PUR);
4) Expanded polystyrene (EPS);
5) Phenolic foam.

These products have been selected because they currently cover about 90-95% of the current market (as discussed in section 2.3.2). All other types of insulation products are grouped into an additional category of 'other products'. The share that these products occupy on the market for each envelope type is excluded from the scope of the assessment by subtracting it from the total demand for insulation.

Identifying the exact mix of products used in the UK and more specifically in Wales to insulate specific envelope types proved to be a difficult task. Thus, for most envelope types a 'secondary' baseline scenario is used to model variations of the mix of conventional products. These secondary baselines allow investigating the changes in impact determined by the different product mix in comparison to the product mix used for the Primary baseline.

alternative supply scenarios

The alternative supply scenarios model conditions of the market where the use of biomass products is increased over time by progressively replacing the conventional products determined by the baseline scenarios. Biomass products studied in this research have been chosen, among existing biomass products, because they have already reached the stage of industrial scale production and they are, or could be, manufactured from biomass resources harvested in Wales (as discussed in section 2.3.4). These products are:

1) Hemp fibre;
2) Sheep wool;
3) Low-Density (LD) and High-Density (HD) wood fibre.

One additional alternative supply scenario is built to model a progressive increase in the use of mineral products. This is done to investigate the potential for reducing EEI by increasing the market share of the best performing products among conventional ones without recurring to biomass products. Stone wool (the high-density version) and glass wool are preferred over plastic products for number of reasons:

- the EEI of stone wool and especially glass wool in most categories is lower or equal to that of plastic products (see sections 2.3.5 ~~and 4.3.11~~);
- mineral products include a higher share of recycled materials;
- their virgin primary materials can be considered more renewable than those of plastics (see section 2.3.3);
- both stone wool and glass wool are manufactured in Wales at the plants of Bridgend, Queensferry and Cwmbran (see section 2.3.2).

The substitution of conventional products with biomass ones requires that the latter can replace the former without compromising performance or radically altering the way in which insulation is integrated into the envelope of retrofitted and new dwellings. As discussed in section 2.3.1, this is easily achievable for certain products in certain envelope types, for example substituting glass wool with sheep wool in loft insulation, because the products have very similar physical format, properties and installation method. It is less easily achievable for products in other envelope types, for example substituting EPS with hemp fibre in solid wall insulation, because of the differences between these two products. Essentially, soft (i.e. low-density) fibrous products such glass wool, hemp fibre, sheep wool and LD wood fibre do not resist compression and need to be held in place by a frame or mesh. Among the biomass products studied in this research, only HD wood fibre can be used as a rigid panel and resist compression. Thus to install a soft product in envelope types requiring rigidity or resistance to compression, the layer of soft product needs to be integrated with a rigid layer. The latter is provided by HD stone wool (to be used with glass wool) and HD wood fibre (to be used with biomass products). Details are presented in section 4.2.3. Products introduced by the alternative supply scenarios are shown in Table 3. 1.

Table 3. 1 - Products "newly introduced" by the alternative supply scenarios

alternative supply scenario	Newly introduced insulation products
Mineral	HD stone wool and glass wool
Sheep wool	Sheep wool and HD wood fibre
Hemp fibre	Hemp fibre and HD wood fibre
Wood fibre	LD wood fibre and HD wood fibre

Modelling product substitution

The share of products (biomass or mineral) which are 'newly introduced' in the alternative scenarios is modelled to be increased gradually through time, thus the alternative scenarios retain part of the baseline mix of conventional products. This is illustrated by Figure 3. 2 and Figure 3. 3, showing a simplified example of product substitution for generic baseline and alternative supply scenarios.

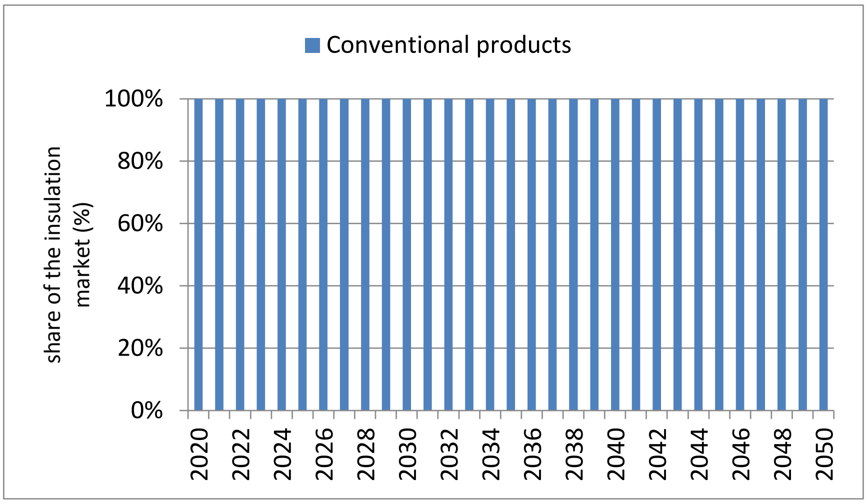


Figure 3. 2 – Generic baseline supply scenario

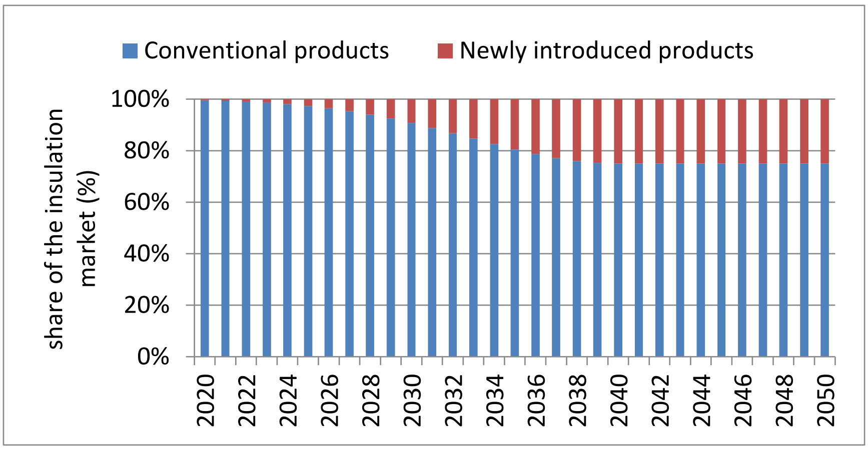


Figure 3. 3 - Generic alternative supply scenario progressively increasing the uptake of newly introduced products to 25% of the insulation market

In Figure 3. 2, all supply of insulation consists of conventional products from 2020 to 2050. In Figure 3. 3, at year 2020 the newly introduced products occupy 0.5% of the market and this share is gradually increased following an 'S' curve reaching the maximum market share of 25% in 2040. The type of 'S' curve shown here is used in all the alternative scenarios to model the progressive increase in the use of new products. This type of curve is modelled on the 'bell' curve used by Rogers (2003) to describe the diffusion of innovations within a market, and it is henceforth referred to as the 'substitution curve'. Because of the curve shape and its maximum value in 2040, the cumulative quantity of biomass products introduced over the 31 years period in Figure 3. 3 is 13.8 % of the total supply, which means that this generic alternative scenario retains 86.2% of the conventional products contained in the baseline scenario.

Beside the shape of the substitution curve, the two main parameters which determine the extent of product substitution are the maximum value reached by the curve (i.e. the maximum *market penetration*) and the year of this occurrence. Four levels of market penetration are modelled by the alternative supply scenarios to represent different levels of substitution that could potentially take place, although only the lowest of the four levels might be considered as achievable in real conditions. The levels of substitution are named as follows:

- *Small*, reaching 25% of market penetration;
- *Medium*, reaching 50% of market penetration;
- *Large*, reaching 75% of market penetration;
- *Very Large*, reaching 100% of market penetration.

Modelling these four levels of substitution enables evaluating the maximum potential changes in EEI achieved by biomass products (first research component) against potential for local biomass supply (third research component).

For all envelope types except loft, the year 2040 is chosen as the time of maximum market penetration. This is an arbitrary but reasonable choice, because while it is impossible to know when a product might reach its maximum market share, it is also logical to assume that a significant penetration cannot be reached in a short period of time, due to the slow innovation uptake which is typical of the construction sector (Reichstein et al., 2005). On the other hand, it would not be meaningful for this research to model a very slow uptake of biomass products. Thus, a period of 20 years is considered a reasonable choice within a total time frame of 31 years. For loft insulation, the year of maximum market penetration is anticipated to 2030 because there are fewer technical barriers for the substitution of the main conventional product currently in use (glass wool) with biomass alternatives.

3.2.3 Environmental impact assessment

In this research the environmental impact embodied into insulation products is quantified through the method known as process-based attributional Life-Cycle Assessment (LCA), described in section 2.2.2. The choice to use process-based LCA to assess Environmental Embodied Impact (EEI) is determined by the wide acceptance of this method and the existence of a body of studies and data sources. Accessing industry sources of specific and consistent LCI data presented obstacles in the context of this research due to the resource-intensity and the business-sensitive nature. At the same time, the review of existing LCA sources (see section 2.3.5) provides sufficient generic data to build upon.

Using integrated or hybrid LCA techniques was not deemed a feasible option due to the lack of standard methods and consistent data. A hybrid LCA would likely produce more accurate results than the process-based LCA, but the time and resources required to perform each hybrid LCA would severely limit the number of products that could be assessed and therefore hinder the overall objective of the research. To assess several insulation products, the process-based technique was preferred over both I-O and hybrid techniques as the first is more practiced and there is a larger body of studies and data to rely upon. I-O LCA could be argued to be more appropriate for a large-scale assessment because of its comprehensiveness, as suggested by the existing literature (see section 2.2.2). However, using I-O analysis at the product level can be problematic (Lenzen, 2001b), especially for environmental impact due to the assumption of proportionality between monetary and physical flows.

Although modelling product substitution at large scale involves a consequential aspect, the attributional approach is chosen to conduct process-based LCA in this research. This is due to the higher complexity of the consequential approach as well as to the lack of available data for performing and benchmarking consequential LCA for insulation products. Ideally, a large-scale assessment combining attributional and consequential aspects could be developed (following Yang, 2016), but the requirements of data collection and price modelling could not be met within the limits of this research. The most challenging aspects of such research would consist in establishing marginal coefficients of production for industrial and agricultural processes associated with insulation products, and modelling market dynamics for several primary resources and final products. Large part of the input data required for these tasks is likely to be commercially sensitive, and therefore difficult to access. Some aspects which might be present in a consequential approach are explored in the third research component, such as LUC necessary to meet the demand for biomass products and the economic consequences of increasing this demand. Nonetheless, the choice of the attributional approach to LCA remains a limitation for the results of the first research component.

The Functional Unit (FU) used to assess insulation products is based on thermal resistance, (1 m^2K/W), as introduced above. The system boundary chosen for the LCA is cradle-to-site, meaning that the stages considered in the assessment are:

1) the extraction of primary resources,
2) the manufacturing processes, and
3) all the transport taking place from when the resources are extracted until the final product is delivered on the site of construction.

These stages correspond to the boundary A1-A4 as defined in the standard CEN/TC350 – Sustainability of Construction Works (see section 2.2.2). This choice excludes the stages of operation and disposal. The exclusion of the operational stage is motivated by the fact that the products have the same operational performance, since the FU is based on thermal resistance.

The EEI of the end-of-life of the insulation products is assessed via process-based LCA separately, and investigated by evaluating the effects that its inclusion bears on the performance of the alternative scenarios in comparison to the EEI of the baseline scenario. Thus both Cradle-to-site and cradle-to-grave LCA results are produced for each insulation product. The results of the end-of-life stage are calculated by considering three main disposal options (recycling, incineration with energy recovery and landfilling) and applying a weighting factor based on typical shares for each option. This method allows avoiding the multiplication of alternative scenarios which would be necessary to evaluate each disposal option separately, but requires identifying typical shares of disposal options for each insulation product, on which there is scarce data and thus some assumptions are necessary.

The ‘recycled content’ approach (see section 2.2.2) is adopted to model the impact of the end-of-life stage. This choice is motivated by the fact that the recycled content approach is considered more appropriate for an attributional LCA (EC-JRC-IES, 2010b; Brander and Wylie, 2011) and by the significant lack of data required to produce and benchmark the EEI of recycling and incineration processes for insulation products. Since the ‘recycled content’ approach does not account the benefits of recycling and energy recovery, it can also be considered as the more conservative option. In practical terms, adopting the ‘recycled content’ approach excludes the benefit and loads associated with recycling waste insulation (which are attributed to the ‘next’ product), and the benefits associated with energy recovery (i.e. the avoided energy generation). Within this context, the choice to maintain a clear distinction between the cradle-to-site and the cradle-to-grave performances of the alternative scenarios is justified by the higher degree of uncertainty associated with the assessment of the end-of-life stage, which is highly affected by the typical shares of disposal options and by the exclusion of the environmental benefits generated by recycling and incineration with energy recovery.

Choice of environmental impact assessment method and categories

Among the available impact assessment methods for LCA, the CML method (version 2001 – April 2013) is chosen in this research to generate the results of the process-based LCA. The CML method is preferred over others because:

- it presents results at midpoint level, which are generally associated with lower uncertainties than results at endpoint level (EC-JRC-IES 2010a);
- normalisation factors are available for this method;
- it is one of the most commonly used methods (EC-JRC-IES, 2010a);
- a large part of existing LCA studies on insulation products adopts the CML method (see section 2.3.5) and thus using the same method in this research allows benchmarking the LCA results of single products against existing LCA sources.

The CML method quantifies environmental impact at the midpoint through several categories. In this research, four CML categories are chosen to be assessed and an additional fifth category not present in CML is also included: Primary Energy Use. These five Environmental Embodied Impact (EEI) categories (introduced in section 2.2.2) are:

1) Primary Energy Use (PEU), including both renewable and non-renewable sources, expressed in MJ;
2) Global Warming Potential (GWP), expressed in kgCO_2eq;
3) Acidification Potential (AP), expressed in kgSO_2eq;
4) Eutrophication Potential (EP), expressed in kgPO_4eq;
5) Photochemical Ozone Creation Potential (POCP), expressed in kg ethene-eq (C_2H_4).

The choice to consider only four impact categories from the 11 main categories provided by the CML method and to add the PEU category is justified by the need to simplify the evaluation of EEI by restricting the number of impact categories to the most relevant for construction products, especially insulation. The work of the standard CEN/TC350 was used as guidance. In particular:

- GWP, AP, EP and POCP are four of the seven environmental impact categories selected by the TC350 for the EPD methodology, the other ones being Ozone Depletion Potential (ODP) and Abiotic Depletion Potentials (ADPs) for fossil and non-fossil resources. In existing LCA studies of insulation products ODP and ADPs are rarely considered since these categories have limited significance for these products.
- PEU is often used as a proxy for environmental impact and resource use, and indeed the EPD methodology includes several categories of energy use as indicators of resource use.

One singular drawback of using the CML2001 – April 2013 method is that emissions from trucks are attributed a negative value in the POCP category, which implies a positive effect on air quality. As explained on the GaBi database website (Thinkstep, 2016b), this is caused by the CML characterisation dividing nitrogen oxides emissions into NO_2 and NO emissions. The latter “has a negative effect on the POCP since it reduces the close ground ozone formation” (Thinkstep, 2016b). However, “there is a discussion in the scientific LCA community about this taking place since the message "We drive a truck and clean the air’" is questionable” (Thinkstep, 2016b).

Calculating the impact of supply scenarios

To progress from single products to large scale assessment, process-based LCA results are scaled up to model the products included in the supply scenarios. These are based on a forecast of insulation demand from new constructions and retrofits (as introduced above). Therefore, the EEI of the supply scenarios is quantified through a bottom-up procedure, i.e. by scaling up the impact of the individual products assessed through individual process-based LCAs. This is done by multiplying the impact associated with a FU of product ‘A’ by the total number of FUs of ‘A’ featured in the supply scenario, and repeating for each product. The sum of the impact values equals to the total EEI of the scenario.

Similar procedures have been used in research. For example, Mandley et al. (2015) estimated typical quantities of main construction materials associated with each square meter of new residential and commercial buildings in the UK, and assessed its embodied carbon using the data collected in the Inventory of Carbon and Energy (Hammond and Jones, 2008), which is based on several LCA results. These quantities were scaled up on the basis of a forecast of construction activity in the UK to produce an estimate for the carbon that will be embodied in future buildings. Mandley et al. (2015) used this "model" to investigate large scale carbon savings through measures such as increased recycling rate and product substitution. ~~The limitations of this bottom-up approach to EEI are discussed in section~~

Manipulating and interpreting environmental impact results

To facilitate the interpretation of results, the EEI of the supply scenarios are manipulated by including EEI *variations* and *normalisation*, and compared on the basis of percentage changes and a score system. These techniques are introduced here and described in detail in section 4.3.

Variations of EEI are modelled by taking minimum and maximum EEI for each product and applying these figures to the supply scenarios. Thus each supply scenario has minimum and maximum total EEI values associated with each category, which represent the range of the possible changes in the total EEI due to variations in the impact of single products. This range of possible changes provides a basic indication of the uncertainty associated with the LCA results of the single products and their effect on the total impact. For conventional products and both LD and HD wood fibre, minimum and maximum values are chosen from available existing LCA studies (see section 4.3.11). The LCA results of these products are obtained from aggregated LCIs or existing EPDs, therefore it is not possible to investigate the variations in impact determined by changes in key variables. Thus existing LCA sources are used to benchmark the results obtained in this research as well as to provide minimum and maximum EEI, showing the magnitude of potential variations in the impact of each product. For hemp fibre and sheep wool products, detailed LCIs are available, and therefore the minimum and maximum impact values are determined by changing key variables in the extraction and manufacturing stages (see section 4.3.12).

Normalisation is a standard procedure in LCA practice which allows the evaluation of which impact categories are most relevant among those included in the assessment in comparison to a term of reference (EC-JRC-IES, 2010b). Impact values in each category resulting from the LCA are divided by reference figures called *normalisation factors*. These factors represent the average impact of an entity, for example a person or a country, over a period of time. Since normalisation factors are expressed in the same units as the impact values from the LCA, normalised figures are unit-less and represent the proportion between LCA results and reference values. Thus, the normalised impact values can be compared across the impact categories to identify which categories are most relevant in relation to the reference impact values. The use and reliability of normalisation factors are limited by their type and age. The latest factors for CML are based on data from 2000 (Wegener Sleeswijk et al., 2008) and can be considered relatively outdated, but no other option is available.

To allow a simplified analysis, the EEI results are also presented in an additional format by aggregating the five categories into one value, i.e. an *EEI score*. This aggregation is conducted by adding together the five normalised EEI figures, which is equal to using a weighting factor of 1 for each category, as described by EC-JRC-IES (2010b, p.282).

The comparison between changes in EEI caused by the alternative scenarios is presented in its final format in terms of percentage variations from the EEI of the baseline scenarios. Considering percentage changes in reference to baseline impact offers a more robust method to compare between alternative scenarios than using absolute figures. Evaluating the change from the baseline EEI caused by each alternative scenario in percentage terms makes the comparison between the alternative scenarios more direct and allows 'hiding' the difference in absolute figures between the EEI of the primary and secondary baseline scenarios. Absolute figures are of minor interest by themselves, because they are strictly dependent on the extent of insulation demand. The objective of the first research component is to identify which, among alternative scenarios, performs best in relation to the baseline impact, not to estimate EEI changes brought about by each alternative scenario in absolute figures.

3.2.4 Structure of the first component

The process of the first research component is summarised in the following diagrams:

- Figure 3. 4 - modelling demand scenarios;
- Figure 3. 5 - modelling supply scenarios;
- Figure 3. 6 - environmental impact assessment.

Blue boxes represent existing sources (literature, databases, etc.). Green boxes represent steps in the research process. Black frames indicate results (i.e. tables of figures, graphs, etc.). Final results are highlighted with a thick frame (in Figure 3. 6). The methodology of the first research component is presented in detail in chapter 4 together with the relative results. The next section describes the design of the second research component.

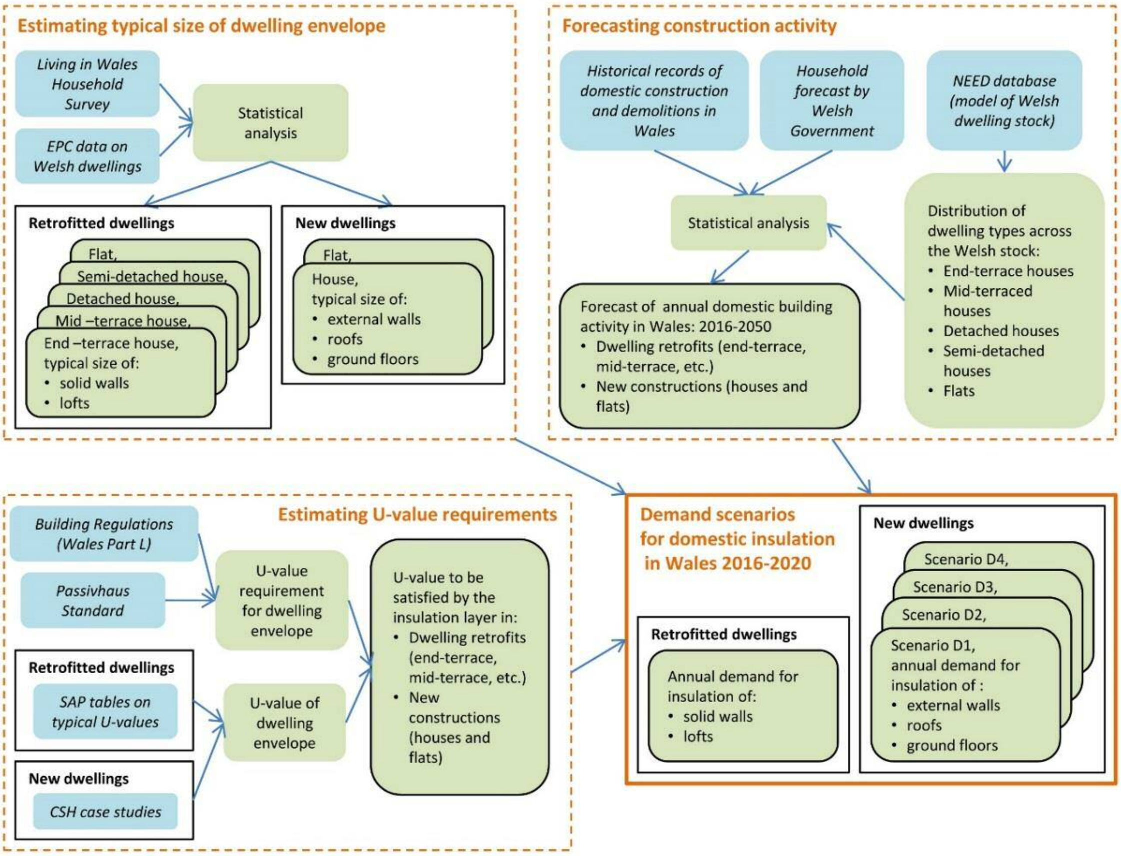


Figure 3. 4 – Diagram describing the first part of the first research component (modelling demand scenarios)

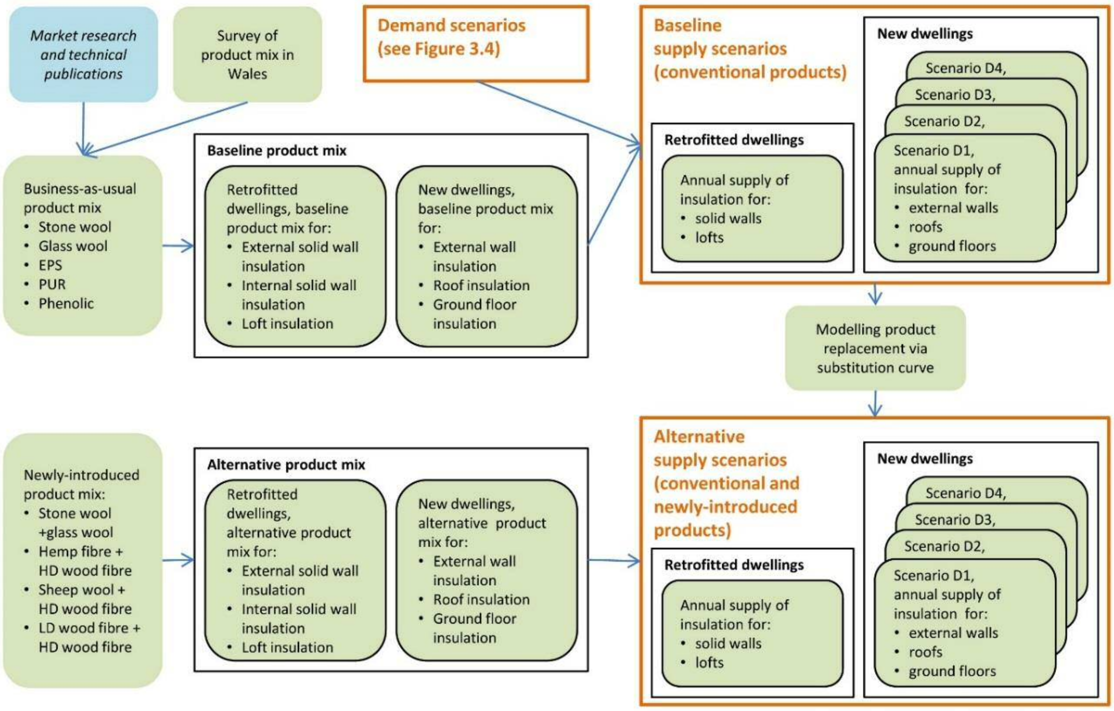


Figure 3. 5 – Diagram describing the second part of the first research component (modelling supply scenarios)

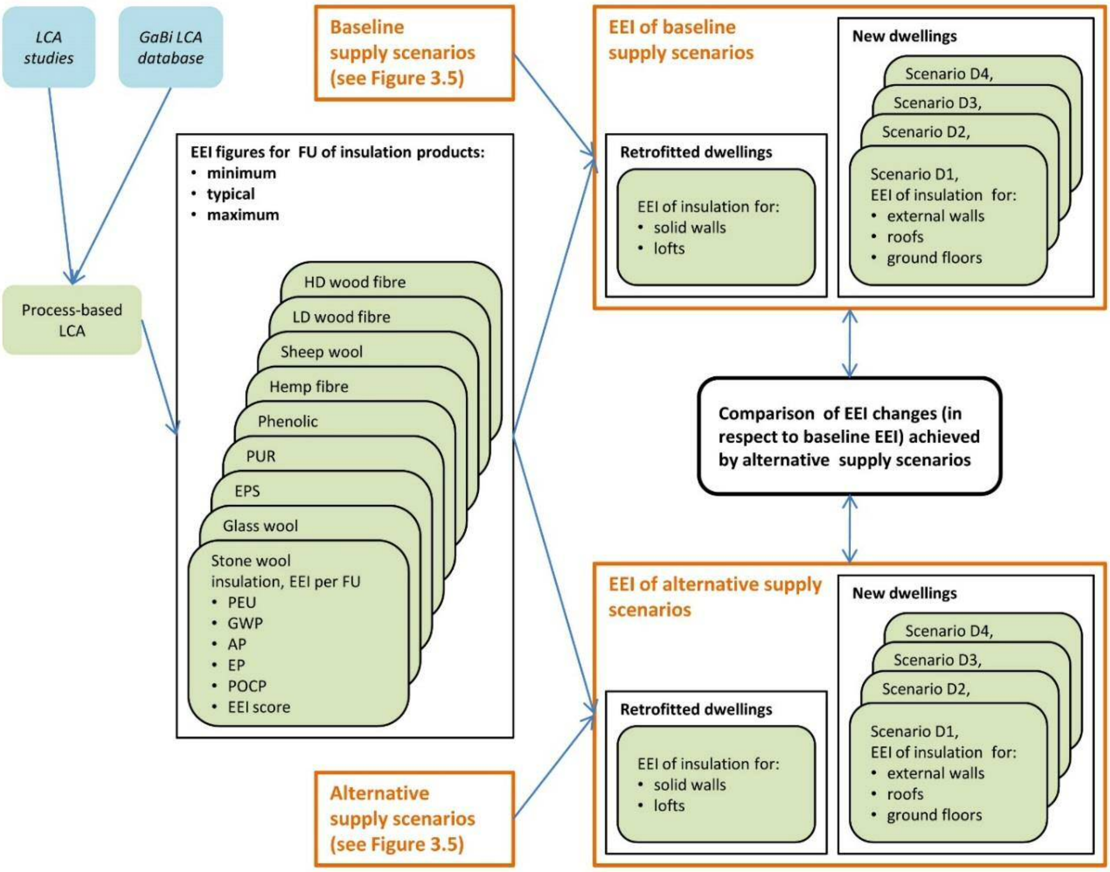


Figure 3. 6 - Diagram describing the third part of the first research component (environmental impact assessment)

3.3 Design of the second component: socio-economic impact

The second research component focuses on assessing the socio-economic impact of insulation products. The use of indicators of social and economic impact to assess sustainability implies the adoption of a specific perspective and is less established than the use of environmental impact indicators, as discussed in sections 2.2.3 and 2.2.4. Social impact is a wide topic requiring both quantitative and qualitative measurements, which are often more appropriately assessed at the level of industry and community rather than for individual products (see section 2.2.3). A variety of indicators of economic impact exist, and selecting the most appropriate entails a judgement on the validity of the chosen indicator as measure of impact within the existing economic conditions, which might not be optimal for the long-term sustainability of the economic system (see section 2.2.4). In addition, the existence and availability of relevant data influenced the selection of the method to produce indicators for the assessment of social and economic impact of insulation products. Thus, identifying an appropriate method to assess social and economic impact of insulation products via quantitative indicators required narrowing focus on a limited number of aspects. Following the radical approaches to sustainability discussed in section 2.1.3, this research focuses on three aspects of insulation products which are related to both social and economic dimensions:

- the affordability of products for a large-scale use;
- the generation of local employment opportunity due to the human work required during the extraction of natural resources and the manufacturing stages;
- the creation of wealth through the economic processes involved by the manufacture of products.

In relation to these aspects, three indicators are chosen to assess the socio-economic impact of insulation products, considering the cradle-to-gate boundary:

- product price (expressed in £/m^{2}K/W) - obtained through a survey of market prices;
- local embodied work (expressed in FTE/m^{2}K/W) - obtained through I-O analysis;
- domestic Gross Value Added (GVA, expressed in £/m^{2}K/W) - obtained through I-O analysis.

3.3.1 Survey of market prices of insulation products

A survey of products sold in the UK between 2015 and 2017 is conducted to identify maximum, minimum and average prices of insulation on a FU basis (£/m^{2}K/W). The price of a product on the market is a measure of the 'value' of the product to the seller as well as to the buyer. Within a non-monopolistic market, several actors compete to sell their products. The UK insulation manufacturing sector is dominated by relatively few large firms and presents medium to high barriers to new companies (see section 2.3.2), but cannot be considered a monopolistic market. The retailing sector is more open and populated by many firms of different size (see section 2.3.2). Clearly there are other factors affecting the choice of buyers (such as thickness, fire resistance, durability, etc.) besides the mere price per m^{2}K/W of insulation. Nonetheless, a product with a lower price per m^{2}K/W than its competitors can be considered to have positive economic impact, because it is cheaper for the buyer to purchase and more competitive for the seller to produce. Thus, comparing prices of insulation products can indicate the viability of products within the UK market, i.e. which products are more "economically sustainable" within current conditions. It must be noted that the conditions of the context affect the assessment of economic sustainability, because if conditions were to change, some products might become more viable, as discussed in section 2.2.4.

3.3.2 Input-output LCA

The I-O LCA method is used in this research to assess the socio-economic impact embodied in insulation products in terms of embodied work and GVA generation. The review of process-based LCA techniques for the assessment of social and economic impact showed that there is a variety of perspective still in development, and that existing literature and access to databases are limited (although some LCWE data is available). Collecting specific LCI data to assess several insulation products via process-based technique was not considered feasible within the limits of this research. On the other hand, I-O analysis is a robust technique which can produce quantitative indicators, such as employment and GVA multiplier effects, which are particularly relevant to the focus of the research. I-O analysis also allows an integrated assessment of the social and economic aspects, and enables focusing on the impact which takes place within the national boundary. For these reasons the socio-economic aspects of insulation products ~~(research objective 2)~~ are assessed using multiplier effects from I-O analysis as indicators of socio-economic impact. The UK I-O tables contained in the EORA dataset (Lenzen et al., 2012; 2013) are used to conduct economic I-O analysis, although Welsh tables based on physical units would have been the ideal dataset for the research.

The socio-economic impact assessment of insulation products is conducted at the level of individual products and not for the whole supply scenarios. This is done to limit uncertainty, in the awareness of two main limitations:

- Price variations: the survey of product prices undertaken for this research shows that there is s wide range of prices within the same product type (see section 5.1). These price figures are used not only as indicators of affordability but also as the numerical inputs necessary for the I-O analysis to convert the FU of insulation from a physical unit (m^2K/W) to a monetary one. Modelling scenarios with the current prices projected into a period of several years would have limited reliability, as it would not be possible to take into account potential price changes due to factors such as the increase in demand, the effects of economies of scale and developments in the manufacturing processes. Modelling future price variation would also increase complexity by introducing additional variables to the supply scenarios.
- Multiplier effects: using multiplier effects to produce a socio-economic LCA of insulation products presents the limitations of I-O analysis as assessment at the product level (see section 2.2.2). Most significantly, the level of industry classification at which it is possible to conduct the I-O analysis might not be detailed enough to reflect the specific features of some of the insulation manufacturers. The consequences of industry sector aggregation are discussed in section 5.2.

Generally, the use of I-O analysis for assessment at the product level can problematic. Lenzen (2001b) specifies that due to the limits of industry sector aggregation, I-O analysis "is (and should) not be applied to single products or processes." (p.143). However, there are examples of research (Joshi, 1999) and databases (EIO-LCA) using I-O analysis for product LCA. As stated by Lenzen (2001b), the "tiered-hybrid LCA" method uses I-O analysis at the product level for the assessment of embodied impacts, as "the direct and downstream requirements (for construction, use, and end-of-life), and some important lower-order upstream requirements of the functional unit are examined in a detailed process analysis, while remaining higher-order requirements (for materials extraction and manufacturing) are covered by input-output analysis" (Lenzen, 2001b, p.143). Therefore I-O LCA can be considered an appropriate technique to assess the socio-economic impact of insulation products within the context of this research, if its limitations are taken into account in the interpretation of results.

Embodied work

Embodied work refers to the amount of human effort necessary to generate a product, from raw material extraction to the final manufacturing stage. In this research the work embodied in insulation products is calculated in terms of Full-Time Equivalents (FTE) per FU (m^2K/W). In this way, by comparison it is possible to identify which products generating more employment upstream in the supply chain. Figures for embodied work are obtained via I-O LCA, using product prices together with employment multiplier effects from I-O analysis (see section 5.2). The employment multiplier effect takes into account the work generated as direct and indirect consequence of an increase in the final demand for products belonging to certain industry sectors (Miller and Blair, 2009). To focus on the work generated domestically (i.e. in the UK), the model excludes the work embodied in processes taking place outside UK boundaries.

Among the chosen socio-economic impact indicators, it is the one most directly related to the social sphere, because higher embodied work could represent a positive social impact, as more employment is generated. However, from the point of view of the producer, it can be argued that higher employment might mean a higher amount of money spent for salaries, which could increase the cost of a product and decrease its competitiveness on the market. As discussed in section 2.2.3, attributing positive or negative value to labour intensity implies adopting a specific economic perspective. According to the discourse on appropriate and low-entropy technology (see section 2.1.3), labour intensity can be attributed a positive value. Conversely, a mainstream economic approach might attribute a negative value to labour intensity, as long as it is considered a factor to be minimised. These perspectives are explored in this research, but solving their contrast is beyond its scope.

In addition to the figures obtained via I-O analysis, the embodied work of some products is also assessed via process-based method using LCWE data available in the GaBi Professional database (see section 5.3). The results of this assessment cannot be compared directly with I-O outcomes due to different boundaries. However, by presenting figures for embodied work broken down by skill level the LCWE data provides a basis to evaluate the quality of work besides its quantity.

Gross Value Added (GVA)

GVA can be considered an indicator of positive economic impact in terms of wealth creation, because GVA represents the additional wealth that a company has been able to produce by combining several elements into its final product, as introduced in section 2.2.4. In this research, figures for GVA associated to functional units of insulation products are obtained via I-O LCA, using product prices together with GVA multiplier effects from I-O analysis (see section 5.2). The GVA multiplier effect accounts for the GVA generated as direct and indirect consequences, excluding the GVA embodied in processes occurring outside UK boundaries.

3.3.3 Structure of the second component

The process of the second research component is summarised in Figure 3. 7. Blue boxes represent existing sources (literature, databases, etc.). Green boxes represent steps in the research. Black frames indicate results (i.e. tables of figures, graphs, etc.). Final results are highlighted with a thick frame. The methodology of the second research component is presented in detail in chapter 5 together with the relative results. The next section describes the design of the third research component.

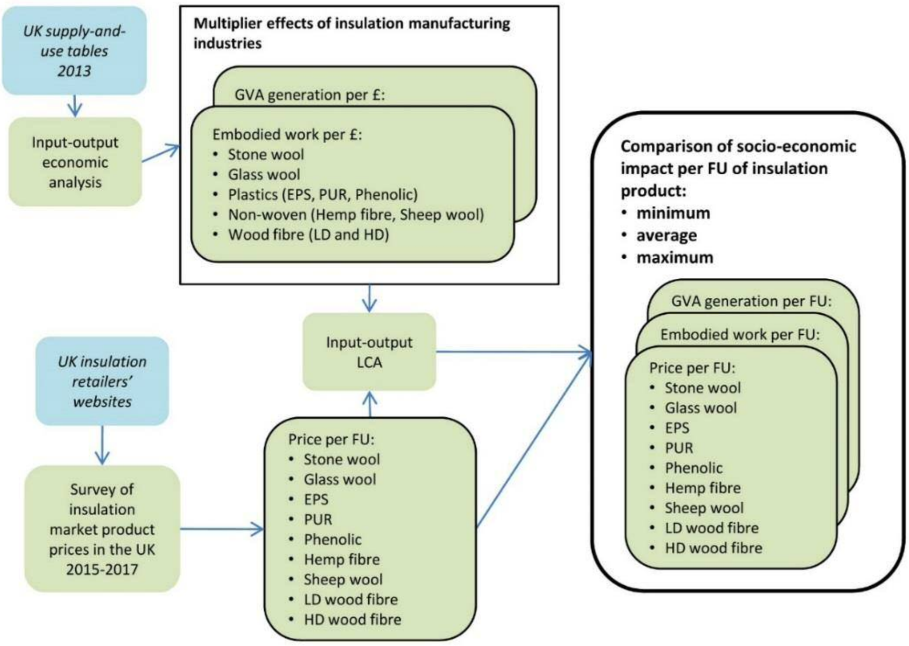


Figure 3. 7 - Diagram describing the second research component

3.4 Design of the third component: demand and supply of regional resources

The third research component investigates the regional capacity to meet the demand for regional resources determined by the alternative supply scenarios introducing biomass products. The analysis focuses on the main primary materials necessary to manufacture the biomass products, excluding those materials which do not constitute the main mass of the product (for example fire retardants). To investigate the relationship between demand and supply, two terms are compared for each biomass insulation product:

- annual demand for 'natural resource' (i.e. primary material) in Wales determined by the alternative scenarios - obtained by converting the annual FU of biomass insulation required by the alternative scenarios into the equivalent quantity of natural resource;
- an indicator of the capacity of the Welsh territory and economy to supply this resource - based on existing data on the Welsh agricultural sector.

This comparison allows discussing the potential of establishing local supply chains of biomass products, and identifying some of the consequences that an increase in the demand for natural resources at large scale might have on the wider economic context. A similar approach was taken by Palumbo et al. (2015) by comparing the availability of crop by-products in Spain and the demand for insulation.

The indicators chosen to represent regional availability are related to the economy of Wales and not only its territory because biomass is grown and harvested through economic activities (as discussed in section 2.3.5), and therefore the presence of both natural resources and their related economic sectors are necessary to make biomass available to manufacture insulation products. It must be noted that the indicators of supply capacity do not necessarily represent *fixed* constraints, as they are affected by land use and economic activity which might change over time.

Table 3. 2 shows the demand for resources and the indicator of supply capacity selected for each product. The 'natural resources' used to quantify sheep wool and wood fibre insulation are the primary materials used in the manufacture of insulation, respectively raw wool and softwood chips. The primary material used to manufacture hemp fibre insulation is industrial hemp, but this is not currently produced in Wales (see section 2.3.4). Thus, demand and supply of hemp fibre insulation are compared in terms of hectares of land that would be required to produce the necessary quantity of industrial hemp.

Table 3. 2 – Demand for natural resources and indicators of regional supply capacity

Insulation product	Demand for regional resources	Indicator of supply capacity
Hemp fibre	Agricultural land cultivated with industrial hemp (hectares)	Historical records of agricultural land in Wales cultivated with crops similar to industrial hemp (e.g. flax)
Sheep wool	Raw wool (kilograms)	Historical records of raw wool production in Wales
Wood fibre (LD and HD)	Softwood chips (kilograms)	Forecast of softwood chips by Welsh mills to wood-processing industries

The resources necessary for biomass products can be ultimately tracked down to different land uses. These are agricultural land (for hemp fibre), grazing land (for sheep wool) and forest land (for wood fibre). A comparison of products based on land requirement per FU could be made to evaluate which product requires more land. Such comparison would consider land requirement, but not the capacity of the related economic activity. This aspect is especially relevant for sheep wool and wood fibre, since both raw sheep wool and woodchips are, to different extents, by-products of specific industry sectors. Therefore a comparison based on the 'regional resources' as identified in Table 3. 2 was preferred.

3.4.1 Summary of the third component

The process of the third research component is summarised in Figure 3. 8. Blue boxes represent existing sources (literature, databases, etc.). Green boxes represent steps in the research. Black frames indicate results (i.e. tables of figures, graphs, etc.). Final results are highlighted with a thick frame. The methodology of the third research component is presented in detail in chapter 6 together with the relative results. The next chapter presents methodology and results of the first research component.

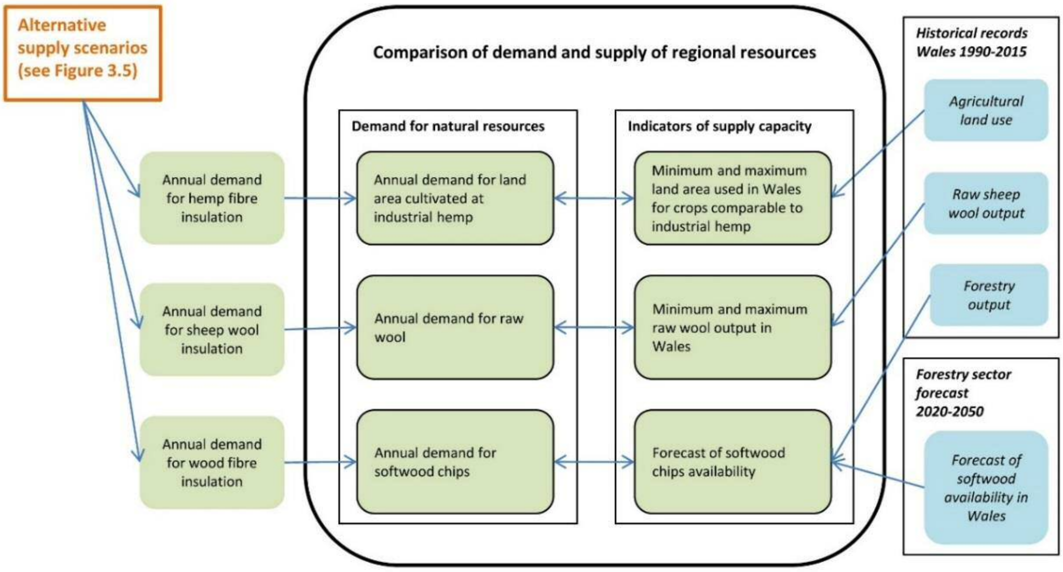


Figure 3. 8 – Diagram describing the third research component

3.5 Data collection and generation

This research is conducted by manipulating and combining different sources to produce the required information. Table 3. 3 illustrates the new data generated by combing primary and secondary data sources in the three research components.

Research component	New data	Primary data source	Secondary data source
1 - Environmental impact	1.a - Typical areas of building envelope to be insulated (wall, roof/loft and floor) for retrofitted and dwellings in Wales, categorised by dwelling type and size		NEED, LWHS and EPC data
	1.b - Typical thickness of insulation in retrofitted and new dwellings, categorised by envelope type		CSH case studies and Building Regulations
	1.c - Forecast of domestic retrofits and new constructions in Wales		NEED and construction statistics
	1.d - Typical market shares of insulation products in Wales, categorised by envelope type	Interview and questionnaire	Literature and market research
	1.e - Forecast of domestic insulation demand in Wales	1.a, 1.b, 1.c, 1.d	
2 - Socio-economic impact	2.a - UK market prices for insulation products based on FU	Survey of UK product prices	
	2.b - I-O multipliers for employment and GVA in UK		Eora dataset
	2.c - Employment an GVA generation for FU of insulation products	2.a and 2.b	
3 - Natural resource demand	3.a - Forecast of natural resource demand for biomass insulation products	1.e	Natural resource requirements per FU of biomass insulation (LCA data)

Table 3. 3 – New data generated in this research by combining primary and secondary data sources

4 Environmental impact assessment – Method and results

This chapter presents the procedure adopted to assess the EEI of insulation products and the results of this assessment. Data, variables and assumptions used to build demand and supply scenarios are described in sections 4.1 and 4.2. Data used to produce LCA figures for single insulation products is discussed in section 4.3. Intermediate research outcomes (such as single product LCA figures) are presented throughout the process, while the main results are shown in section 4.4. Section 4.5 provides a summary of the research outcomes of the first component.

4.1 Modelling demand scenarios

The method used to estimate the future demand for insulation is based on geometry, statistics and thermodynamics. The demand scenarios for retrofits and new constructions follow the same methodological approach but are built separately using different combinations of data. An early version of this work was published in Varriale (2016).

Three main variables are calculated to model the demand for insulation products:

A. The area of building envelope to be insulated, and the distribution of dwellings by type, age and size across the existing and future dwelling stock. This variable depends on the geometry of existing and future dwellings, which is quantified in square meters of surface area to be insulated, categorised by dwelling type, age and size.
B. The thermal resistance achieved by the insulation layer. This variable is determined by legal requirements set by Building Regulations in Wales and by the thermal resistance of existing envelopes (for retrofits) and of the non-insulating layers of the envelopes (for new constructions). It is quantified in m^2K/W, and categorised by dwelling type and age.
C. The number of dwellings to be retrofitted and newly built between 2015 and 2050. This variable is the result of a forecast based on existing stock conditions (for retrofits) and the rate of new constructions (for new constructions). It is quantified by total number of units built or retrofitted, and categorised by dwelling type, age and size.

The total demand for insulation is calculated by combining together variables A, B and C, and is quantified in square meters of insulation with thermal resistance of 1 m^2K/W. The estimate is based on the status of the Welsh dwelling stock in 2014, thus the forecast starts from 2015. However, only the demand from 2020 to 2050 is considered in the supply scenarios (section 4.2), since product substitution is assumed to begin in 2020.

Several sources are used in this part of the research to calculate variables A and B, due to a lack of readily available data. The two main sources are:

- the Living in Wales Household Survey 2008 (LWHS), published by the Welsh Government (2013a), containing 2,741 Welsh dwellings categorised by dwelling type, age, floor area, wall type, roof type and geometry;
- the anonymised dataset of the National Energy Efficiency Data-Framework 2014 (NEED), published by the Office for National Statistics (2014a), containing 2,747 Welsh dwellings. The units are categorised by dwelling type, period of construction, four 'floor area bands' (i.e. dwelling size), presence of Solid Wall Insulation (SWI) and thickness of Loft Insulation (LI).

The geometric information contained in the LWHS is used to calculate the areas of envelope to be insulated, categorised by building type, age and size (variable A) with a procedure adopted from the method used in the Green Deal Household Model Assumptions for a similar purpose (Tahir et al., 2011). It is not clear if the distribution of dwelling type, age and construction reported in the LWHS is representative of the actual distribution of these features across the Welsh housing stock. Conversely, the NEED has been specifically developed by the ONS to represent the English and Welsh stocks, and contains more recent data than the LWHS. Therefore the NEED is chosen to model the distribution of dwelling type, age and size for the remaining potential for insulation (variable C). Other data sources used in this part of the research are the Appendix S of the SAP2009 documentation (BRE 2011) and CSH case studies, which are used to estimate variable B together with Building Regulations for Wales.

Some adjustments are necessary in order to match the data, because the categories for dwelling type, age and size are not exactly the same in the LWHS and NEED. These adjustments are explained in the following pages together with the procedures used to calculate each of the three variables contributing to estimate the demand for insulation products.

4.1.1 Estimating insulation demand from domestic retrofits

This section illustrates the procedure used to estimate the demand for Solid Wall Insulation (SWI) and Loft Insulation (LI). SWI is divided into External Wall Insulation (EWI) and Internal Wall insulation (IWI). Table 4. 1 gives a summary of the methods used to calculate the three main variables for the insulation demand generated by retrofitted dwellings. Details are presented in the following pages.

Table 4. 1 - Summary of methods adopted to estimate insulation demand from retrofit measures

Variables		Sub-components	Depending on	Results
A	**The size of the building envelopes to be insulated**	Average areas of building envelope to be insulated categorised by dwelling type, age and size	Typical geometric features of the dwellings	Square meters of surface area to be insulated
B	**The thermal resistance required to be achieved by the insulation layer**	Thermal resistance values required by Building Regulations	Building Regulations	Thermal resistance values to be achieved by insulation
		Typical thermal resistance values of the existing envelopes	Physical composition of the existing envelope	
C	**Future insulation measures**	Number of dwellings to be insulated	Maximum potential available for the insulation type	Number of insulation measures
		Distribution of dwelling type, age and size across the stock	Conditions of the dwelling stock	

Within the LWHS, 2,741 units are divided in 8 dwelling types. ‘End terrace’, ‘mid terrace, ‘semidetached’, ‘detached’ and ‘purpose-built flat’ are considered in the calculations of this research, while “temporary, “converted flat” and “non-residential plus flat” are excluded, due to the very small number of units. In the LWHS each dwelling is described by number of storeys, external width and depth, internal ceiling height, and also the number of apartments for the “purpose-built flat” type. Figure 4. 1 shows the plan view of a generic dwelling in the LWHS. The dimensions of 83 dwellings were not fully recorded in the database, thus these units are excluded from the calculations leaving a total of 2,658 units.

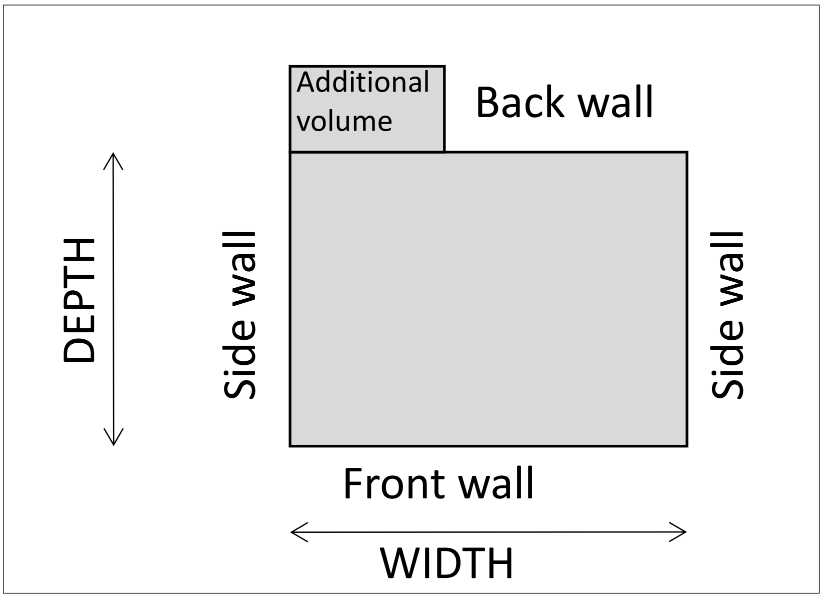


Figure 4. 1 – Diagram of dwelling dimensions as recorded in the LWHS

Calculating dimensions of solid walls (variable A)

There are different types of solid walls. The classification by the National Insulation Association reported by Longsdale (2012) includes:

- "masonry walls of 225mm thickness and other non-traditional construction types such as single leaf masonry;
- walls over 225mm thickness (e.g. thick stone walls);
- concrete walls, metal or timber panels and some mixed wall types – for example, where the ground and first floors are constructed of different materials;
- walls of high rise flats (at least 6 storeys high) – especially those built between 1953 and 1972" (Longsdale 2012, p.17).

For each of the 2,658 units contained in the LWHS, the gross area of each External Wall (EW) is calculated by multiplying the width, or depth, by the average external height, assumed to be equal to the internal height plus 0.25 cm to account for floor thickness. To obtain the total gross EW area of the dwelling, surface areas are summed excluding those which are not exposed to the outdoor environment. In 'mid terrace' units, only the front and back walls are assumed to be exposed to the outdoor, whilst in 'detached' units both side walls are also exposed and thus counted towards the EW total. In "semidetached" and "end terrace" units, only one of the two side walls is counted. The LWHS describes the geometry and position of the additional volume featured in many Welsh dwellings, which can be the result of a later addition to the original building or simply an architectural element. The walls of these volumes are included in the calculation of the gross EW areas.

In 'purpose-built flat' units, the total EW is calculated by summing all the walls and dividing the figure by the number of apartments included in the building in order to obtain an average value of EW area for each apartment. This operation is necessary because the dimensions recorded in the LWHS for flats refer to the whole building block and not to the single unit. Records with more than nine flats in the apartment block are excluded from these calculations because their features generate very small or large values for EW. This can be explained by the fact that a large apartment block may contain flats of different sizes. If the flat recorded in the LWHS is particularly small or large (in comparison to others in the same block), then the resulting EW estimate is skewed.

An estimate of window area is subtracted from the total gross EW area to obtain net EW area. Window area for each dwelling is calculated from the floor area value using the equations given in table S4 of SAP2009 (BRE 2011), where different coefficients are provided for different age of construction and dwelling type. This method to calculate the net EW area produces consistent results for all the dwelling types, except 'purpose-built flat'. Since the gross EW area of each flat is calculated as a theoretical average among all the flats of its block (which may have different sizes), assuming a window-to-wall ratio is considered more reliable than referring to the floor area of the recorded unit. A window-to-wall ratio of 25% is used to obtain net EW area for each flat, which is equal to the average window-to-wall ratio of the 'mid-terrace' units (used as a proxy for flats) resulting from the calculations with the SAP2009 equations (table S4, BRE, 2011).

The calculations described above enable associating the floor area of each unit with an estimate for the net EW area, as shown in Table 4. 2. The four floor area bands and the six dwelling types are chosen to match the categories used in the NEED. Since a distinction between detached houses and bungalows is not included in the LWHS, the figures obtained for the detached type are also used for the bungalow type, because the two are assumed to be similar in terms of architectural layout.

Table 4. 2 - Estimated average net EW area (m^2) categorised by dwelling type and floor area band

Floor area band	Detached house	Semi-detached house	End terrace house	Mid terrace house	Bungalow	Flat (inc. maisonette)
1 to 50 m^2	66.5	55.5	64.0	32.6	66.5	29.0
51-100 m^2	109.4	89.8	91.0	50.3	109.4	33.3
101-150 m^2	151.1	119.1	122.5	64.2	151.1	34.3
Over 151 m^2	214.7	160.3	161.7	86.7	214.7	41.6

Internal Wall Insulation (IWI) requires less material than External Wall Insulation (EWI) due to the thickness of internal partitions and floors. The average internal height of a single floor in a dwelling is 245 cm. as indicated by LWHS (2008), while typical floor thickness is around 25 cm. Therefore EWI is required to cover an external height of 270 cm, whilst IWI is required to cover only 245 cm (corresponding to 91% of EWI).

Calculating dimensions of lofts (variable A)

LWHS data is used to calculate gross loft area for all dwelling types, which is assumed to be equal to the building print of the unit, with the exception of flats. For the latter, only units classified as "top floor flat" in the LWHS are considered to calculate net loft area, which is assumed to be equal to the floor area of the flat.

For all dwelling types (except flats) the transition from gross to net loft area is made by applying a coefficient of 0.9, to take into account the area potentially occupied by roof structure and other elements. The data is then categorised by dwelling size and age, as shown in Table 4. 1. It must be noted that these figures are valid for horizontal surfaces, thus any insulation installed on the internal surface of a tilted roof is likely to require more material.

Table 4. 3 - Estimated average net loft area (m²) categorised by dwelling type and floor area band

Floor area band	Detached house	Semi-detached house	End terrace house	Mid terrace house	Bungalow	Flat (inc. maisonette)
1 to 50 m²	40.91	37.22	30.63	36.12	40.91	41.19
51-100 m²	67.39	46.09	44.70	43.19	67.39	65.24
101-150 m²	78.34	64.39	59.74	57.95	78.34	122.03
Over 151 m²	118.40	97.69	97.53	84.95	118.40	174.01

Calculating thermal resistance of solid walls (variable B)

The U-values shown in Table 4. 4 are typical for SW dwellings, and are selected based on table S6 of SAP2009 (BRE, 2011) and Rhodes et al. (2007) considering the following assumptions:

- All dwelling types (except 'bungalow') are assumed to be built in brick masonry, the most common type of solid wall construction in the UK (University of the West of England, 2008). Brick masonry has poor U-values in the SAP2009 tables, but research by Rhee-Duverne and Baker (2013) shows that the thermal performance of old brick walls is often underestimated. On-site measurements of 18 English dwellings provided an average U-value of 1.4 W/m^{2}K for a standard 9-inch brick wall, while the SAP2009 indicates 2.1 W/m^{2}K. However, it can be argued that most retrofits will use SAP2009 guidance rather than on-site measurements to determine the U-value of the existing EW.
- 'Bungalow' dwellings are assumed to be built with timber frames.

Table 4. 4 - Estimated U-values (W/m2K) of existing SW dwellings categorised by dwelling type and age (source: author's selection from BRE, 2011 and Rhodes et al., 2007)

Age	Detached house	Semi-detached house	End terrace house	Mid terrace house	Bungalow	Flat (inc. maisonette)
before 1930	2.1	2.1	2.1	2.1	2.2	2.1
1930-1949	2	2	2	2	1.9	2
1950-1966	2	2	2	2	1	2
1967-1982	1	1	1	1	0.63	1
Construction type	Brick masonry	Brick masonry	Brick masonry	Brick masonry	Timber frame	Brick masonry

SW dwellings built after 1982 are not considered in these calculations as it is assumed that these units will not be prioritised for SWI measures, since 1982 Building Regulations set the requirement of maximum U-value for external walls at 0.6 W/m^{2}K. The U-values shown in Table 4. 4 are used to calculate the thermal resistance, or R-value (m^{2}K/W), necessary for the additional insulation to achieve a U-value of 0.3 W/m^2K, required by the Building Regulations Part L for renovated thermal elements (Welsh Government, 2014b). The R-value of the additional insulation is calculated with Equation 4. 1:

Equation 4. 1 – R-value of additional insulation required in retrofitted dwellings

$$R_I = (1/U_B) - R_E$$

R_E = thermal resistance (m^2K/W) of the existing envelope

U_B = maximum U-value (W/m^2K) set by Building Regulations

R_I = thermal resistance (m^2K/W) of the additional insulation

Table 4. 5 reports the R-values required for SWI to satisfy the requirements of Building Regulations, resulting from Table 4. 4 and Equation 4. 1, and categorised by dwelling age and type to match the categories used in the NEED.

Table 4. 5 - Estimated R-values (m^2K/W) required for SWI measures to satisfy Building Regulations, categorised by dwelling age and type

Age	Detached house	Semi-detached house	End terrace house	Mid terrace house	Bungalow	Flat (inc. maisonette)
before 1930	2.86	2.86	2.86	2.86	2.88	2.86
1930-1949	2.83	2.83	2.83	2.83	2.81	2.83
1950-1966	2.83	2.83	2.83	2.83	2.33	2.83
1967-1982	2.33	2.33	2.33	2.33	1.73	2.33

Calculating thermal resistance of loft (variable B)

The U-values shown in Table 4. 6 are typical for lofts and have been selected from SAP2009 (BRE 2011) and Rhodes et al. (2007), assuming that all dwelling types have either pitched roof, flat roof or room-in-roof. The U-values of Table 4. 6 are used to calculate the thermal resistance necessary for the additional insulation to achieve the maximum U-value of 0.16 W/m^2K, required in the Building Regulations Part L for renovated thermal elements (Welsh Government 2014b). Equation 4. 1 is used to calculate the R-values. Table 4. 7 reports the R-values required for loft insulation to satisfy the requirements of Part L, resulting from Table 4. 6 and Equation 4. 1, and categorised by dwelling age to match the categories used in the NEED.

Table 4. 6 - Estimated U-values (W/m^{2}K) of existing lofts (source: author's selection from BRE, 2011 and Rhodes et al., 2007)

Age	All dwelling types
before 1930	2.3
1930-1949	2
1950-1966	1.5
1967-1982	1
1983-1995	0.35
1996 onwards	0.26

Table 4. 7 - Estimated R-values (m^{2}K/W) required for LI measures to satisfy Building Regulations

Age	All dwelling types
before 1930	5.82
1930-1949	5.75
1950-1966	5.58
1967-1982	5.25
1983-1995	3.39
1996 onwards	2.40

Forecasting solid wall measures (variable C)

StatsWales (2017a) reports a total of 1,400,073 dwellings in Wales in 2014. According to the NEED model of the Welsh stock, 39.1% of these units were built before 1983 using SW masonry. In 1982 Building Regulations set the requirement of maximum U-value for external walls at 0.6 W/m^{2}K, hence in this research it is assumed that dwellings built after 1982 will not be prioritised for SWI, given the relatively good thermal resistance of their EW. Therefore these units are excluded from the following estimate of the potential for SWI in Wales. The NEED indicates that 3.63% of the SW stock has already been treated with SWI, which is consistent with data from DECC (2014a) reporting that 3.2% of the entire SW housing stock of Great Britain (GB) has been insulated. Therefore it can be assumed that 527,557 dwellings remain as SWI potential in Wales.

To account for dwellings which might not be suitable for SWI, an additional 1.6% is subtracted following an estimate by DECC (2012a). A further cut on the maximum potential for SWI in Wales takes into account dwellings which will be demolished in the future rather than be retrofitted. A projection of the Welsh dwelling stock is calculated based on the current stock (StatsWales, 2017a) with a demolition rate of 0.05% (see section 4.1.2 for details). This projection indicates that only 2% of the existing dwellings will be demolished by 2050. Since it has been observed that demolition activities do not specifically target buildings in poor condition (Boardman, 2007), it is assumed that future demolitions will be distributed evenly across the Welsh stock, including SW dwellings. Thus the maximum potential for SWI measures in Wales is reduced to 508,734 units. However, it is unlikely that all these dwellings will be treated with SWI by 2050. The scenario of 80% reduction in GHG emissions by 2050 developed by the Green Construction Board (2013) for the UK, forecasts that 70% of the hard-to-treat dwellings, which include SW properties, will be insulated. The share of 70% can be considered to be an ambitious but reasonable target, and is chosen to be modelled in this research.

While market research (Purple Market Research, 2008) indicates that in the UK the split between EWI and IWI is about 60%-40%, the scenario modelled for the Energy Company Obligations (ECO) impact assessment by DECC (2414b) assumes that only around 21% of the SWI delivered through the ECO scheme will be IWI. More recently, Household Energy Efficiency National Statistics (March 2017) indicate that only 5% of the SWI measures delivered through ECO (from 2013 to 2016) have been IWI (DBE&IS, 2017). Considering these contrasting figures, a middle-ground split of 79%-21% between EWI and IWI is chosen to be modelled in this research, following DECC (2414b). Although this split may vary, its effect on the total area of envelope to be insulated is rather limited: for example, if a 60%-40% split is used, the total EW area is reduced only by 1.8%. However, this split might have more effect once different products are chosen to model baseline supply scenarios (see section 4.2.2).

The distribution of pre-1983 SW dwellings by construction age, floor area band and dwelling type as recorded in the NEED is shown in Figure 4. 2, which indicates that most units were built before 1930. By matching the distribution given in Figure 4. 2 with the average EW area in Table 4. 2 and the R-values in Table 4. 5, it results that:

- one EWI installation in Wales requires on average 94.2 m^2 of envelope to be insulated, and 265.8 m^2K/W of insulation to be provided;
- one IWI installation in Wales requires on average 85.7 m^2 of envelope to be insulated, and 241.9 m^2K/W of insulation to be provided.

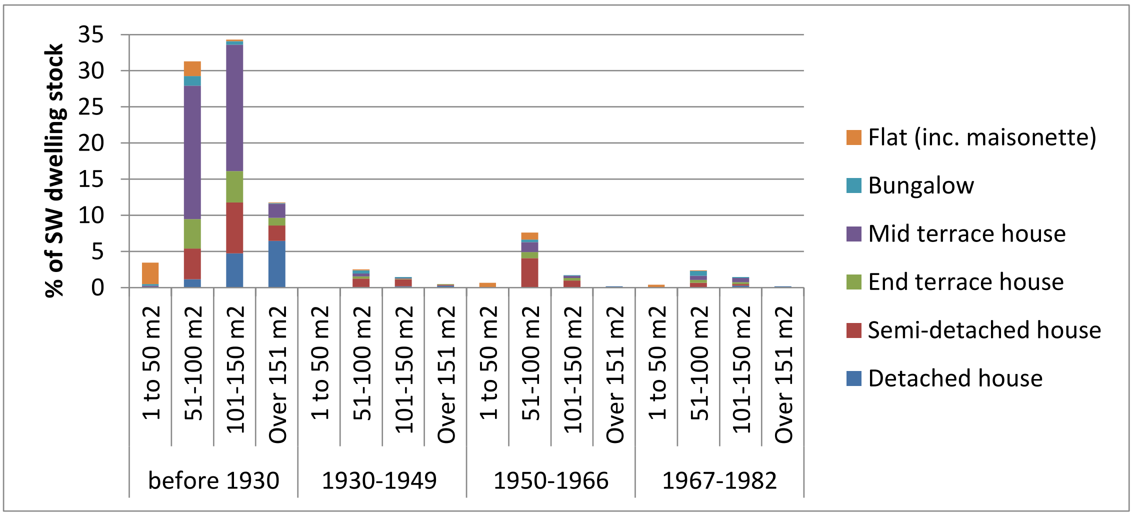


Figure 4. 2 - Distribution of SW dwellings built before 1983 in Wales divided by construction age, floor area band and dwelling type (source: NEED, ONS 2014a)

Table 4. 8 shows the steps leading to the final figure for total estimated SWI installations in Wales from 2016 to 2050. These 354,687 measures are assumed to be delivered across the next 35 years as shown in Figure 4. 3.

Table 4. 8 - Process of estimation of the Welsh SWI potential

		Units	Source
Welsh dwelling stock (in 2014)	1,400,073	dwellings	StatsWales (2017a)
Percentage of Welsh pre-1983 SW dwellings	39.1	%	NEED (ONS 2014a)
Welsh pre-1983 SW dwellings	547,429	dwellings	author estimate
Percentage of dwellings already treated with SWI	3.63	%	NEED (ONS 2014a)
Remaining Welsh SWI potential	527,557	dwellings	author estimate
Percentage of dwellings not suitable for SWI	1.60	%	DECC (2014a)
Remaining Welsh SWI potential	519,116	dwellings	author estimate
Percentage of dwellings demolished by 2050	2	%	author estimate
Remaining Welsh SWI maximum potential	508,734	dwellings	author estimate
Share of units actually treated withSWI	70	%	author assumption
Resulting SWI installations	356,114	measures	author assumption
Share treated with EWI	79	%	DECC (2014b)
Share treated with IWI	21	%	DECC (2014b)
Resulting units treated with EWI	152,620	dwellings	author estimate
Resulting units treated with IWI	74,784	dwellings	author estimate

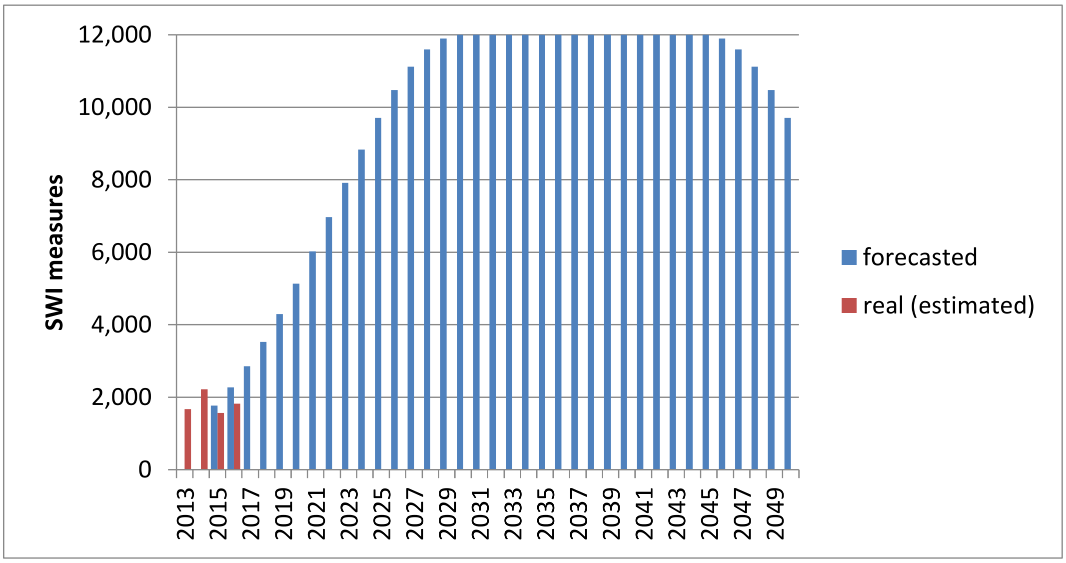


Figure 4. 3 – Annual SWI installations in Wales, estimate of real measures (source: Table 4. 9) and forecasted measures

Figure 4. 3 also shows an estimate of the SWI installations delivered in Wales in recent years through Green Deal and ECO. These figures are obtained using data from Green Deal and ECO measures in GB (DBEIS, 2017). Calculations are made by taking the total installations delivered through Green Deal and ECO in the whole of GB together with the percentages which are known

to be in Wales and known to be SWI. A rough estimate of the SWI installations in Wales can be obtained, as shown in Table 4. 9.

Table 4. 9 – Estimated SWI installations delivered in Wales

	2013	2014	2015	2016	Source
Total ECO measures in GB	519,780	750,402	410,848	360,879	(DBE&IS, 2017)
% of total ECO measures in Wales	6.1	4.5	4.8	6.1	
% of total ECO measures which include SWI	5.3	6.5	7.9	8.3	
Estimated SWI installations in Wales through ECO	1,676	2,215	1,565	1,821	Author's estimate

The forecast of SWI installations shown in Figure 4. 3 follows two rationales:

- at the start of the forecasted period, the rate of installations per year should be close to current levels;
- the rate of installations per year needs to increase considerably in order to deliver the majority of measures (and their benefits) before 2050.

Thus future SWI installations are forecasted to start just above 4,000 installations/year, and to increase each year to reach a maximum of 12,000 installations/year by 2030. This rate is sustained until 2035 and then decreased.

The annual delivery rate of SWI measures is a key factor to generate the 'demand curve' of Figure 4. 3. In recent years the lack of success of the Green Deal and ECO schemes has lowered the expectations of a sustained increment in the annual uptake of SWI installations (Platt and Rosenow, 2014). Although these installations can be delivered outside Government schemes, it can be argued that the high capital cost of SWI measures is likely to force the large majority of installations to be implemented through such schemes. Platt and Rosenow (2014) report that the targets for the ECO scheme are well below the SWI target set by the Commission of Climate Change (2013) necessary to achieve the carbon reduction targets. The CCC target assumed 2.3 million SW units to be insulated by 2022 in GB, and proposed an average rate of 240,000 installations per year over 10 years. If 6.8% of these installations are assumed to happen in Wales (as the NEED indicates that Welsh pre-1983 SW dwellings are about 6.8% of the British pre-1983 SW stock), an average of 16,368 SWI installations should be implemented in Wales each year. The 12,000 maximum annual SWI installations assumed in Figure 4. 3 is lower than the CCC figure, which aims to saturate the SW potential earlier than 2050. However, modifications to the ECO target (DECC 2014b) reduced the expectations for annual uptake of

SWI installations, as anticipated by Platt and Rosenow (2014). With these changes, only 102,000 SWI were expected to be delivered annually until 2017 by ECO and domestic Green Deal. If 6.8% of these installations are assumed to happen in Wales, 6,936 SWI would be delivered per year, which is just over one half of the maximum annual SWI installations modelled in Figure 4. 3.

Forecasting loft insulation measures (variable C)

The NEED indicates that 67.05% of the Welsh dwellings have more than 150 mm of LI. This figure is consistent with data by DECC (2014a) reporting that 68.8% of the British dwellings have more than 125 mm of LI. The NEED divides the remaining dwellings between those with less than 150 mm of LI and those with "no information". The reference annex of the NEED explains that the latter either do not have a loft, or the relevant information was not included in the Energy Performance Certificate (EPC) from which the NEED data is taken. Given that a large part of these units with "no information" are classified as flats, it is reasonable to assume that these dwellings are unsuitable for LI. Therefore dwellings with "less than 150 mm" of LI are taken as the effective remaining potential for LI in Wales, for a total of 198,484 units (14.23% of the Welsh stock, according to NEED). An additional 2% is subtracted from this total to take into account future demolitions (as described earlier) which brings the maximum potential for domestic LI in Wales down to 195,297 dwellings. As LI is relatively inexpensive and easy to install, it is assumed that 95% of these dwellings will be eventually treated with LI by 2050. The steps leading to the final figures for LI potential are reported in Table 4. 10.

Table 4. 10 - Process of estimation of the Welsh LI potential

		units	source
Welsh dwelling stock (in 2014)	1,400,073	dwellings	StatsWales, 2017a
Percentage of Welsh dwellings with less than 150mm of loft insulation in NEED	14.23	%	NEED (ONS, 2014a)
Welsh dwellings with less than 150mm of loft insulation	199,282	dwellings	author estimate
Percentage of dwellings demolished by 2050	2	%	author estimate
Estimated maximum potential Welsh dwellings suitable for lot insulation	195,297	dwellings	author estimate
Future total share of treated loft insulation potential	95	%	author estimate
Resulting loft insulation measures	185,532	measures	author estimate

The distribution by age, floor area band and type of Welsh dwellings with less than 150 mm of LI is shown in Figure 4. 4. By matching the distribution given in this figure with the average loft area in Table 4. 3 and the R-values in Table 4. 7, it results that on average one LI measure in Wales requires 62.1 m^2 of loft to be insulated, and 324.7 m^{2}K/W of insulation to be provided.

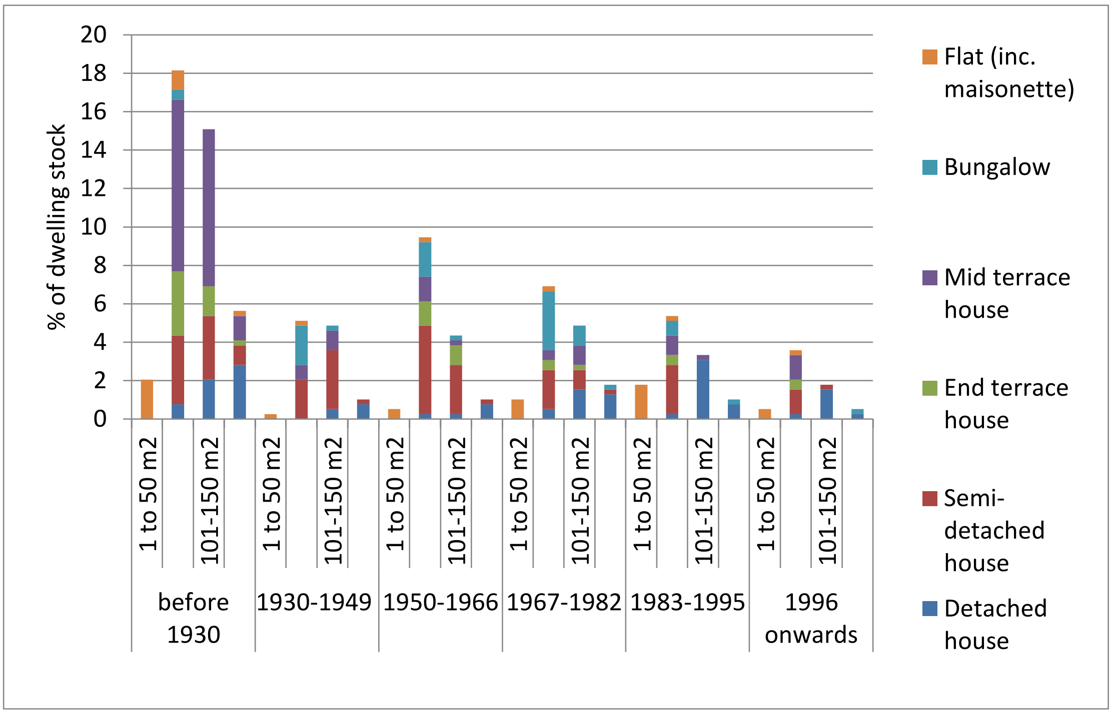


Figure 4. 4 - Distribution of dwellings in Wales with less than 150 mm of LI, categorised by floor area band, dwelling type and age (source: NEED)

Figure 4. 5 shows the forecasted rates of LI measures across the next 35 years, together with the estimated measures delivered in recent years. These were calculated in the same way as explained earlier for estimated SWI installations in Wales (see Table 4. 9). As can be seen, insulating most of the remaining potential can be achieved with a peak of 7,000 per year in 2030 without exceeding recent rates of installations per year.

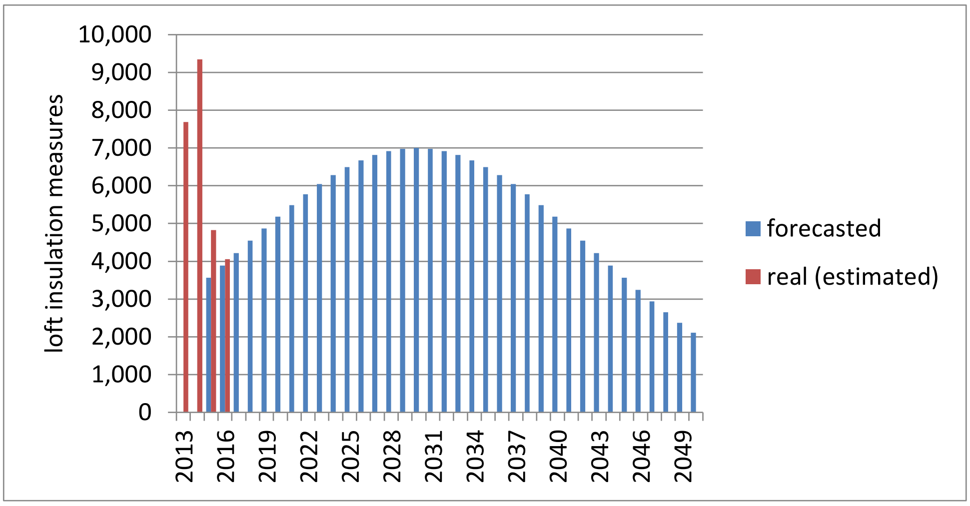


Figure 4. 5 – Annual LI measures in Wales, estimated measures (source: author's estimate on DBE&IS, 2017 data) and forecasted measures

4.1.2 Estimating insulation demand from new domestic constructions

This section describes the procedure used to estimate the demand for the insulation of external walls, roof and ground floors of future dwellings in Wales. Table 4. 11 gives a summary of the methods used to calculate the three main variables for the insulation demand generated by new domestic constructions. To calculate variables B and C, two different 'conditions' for each variable are modelled, which results in four different demand scenarios once the A, B and C variables are combined together. These four demand scenarios are produced to evaluate the changes in demand resulting from different rates of construction and policy requirements. In the presentation and discussion of results, the EEI of insulation products required in new dwellings is assessed primarily through the first demand scenario. The changes in EEI determined by the other three demand scenarios are presented in comparison to the EEI of the first scenario.

Table 4. 11 - Summary of methods adopted to estimate insulation demand from new dwellings

Variables		Sub-components	Depending on	Results
A	**The size of the building envelopes to be insulated**	Average areas of building envelope to be insulated categorised by dwelling type	The typical geometric features of new dwellings	Square meters of surface area to be insulated
B	**The thermal resistance required to be achieved by the insulation layer**	Thermal resistance values required by Building Regulations	The Building Regulations	Thermal resistance values to be achieved by insulation
		Typical thermal resistance values of the building envelope excluding the insulation layer	The physical composition of the building envelope of new dwellings	
C	**Forecast of new construction**	Number of new dwellings	Policy choices and future housing market conditions	Number of dwellings
		Distribution of dwelling type (houses/flats)	Future housing market trends	

Calculating dimensions of walls, roofs and ground floors (variable A)

All homes in Wales built since 2008 require an Energy Performance Certificates (EPC) (HM Govt, 2007). The figures for EPCs of new dwellings registered in Wales from 2009 to 2014 (DCLG 2014) are shown in Table 4. 12. These are used to calculate the average floor area of the dwellings built in Wales during this period:

- flats have average floor area of 58 m^2;
- houses have average floor area of 111.1 m^2.

The floor area of new dwellings is estimated using this EPC data, as it is assumed that the size of dwellings will not change significantly in the next 35 years.

Table 4. 12 – Floor areas of new dwellings registered in Wales from 2009 to 2014; source: Statistical Release of the Energy Performance Certificates (DCLG, 2014)

	Flats			**Houses**		
	Number of Units	Total Floor Area (m^2)	Average Total Floor Area (m^2)	Number of Units	Total Floor Area (m2)	Average Total Floor Area (m^2)
2009	2,593	135,418	52	4,187	438,101	105
2010	1,441	82,366	57	5,060	565,870	112
2011	1,740	98,319	57	4,647	508,506	109
2012	1,562	92,521	59	4,475	513,155	115
2013	1,267	76,594	60	4,375	492,764	113
2014	1,421	88,442	62	4,328	491,028	113
Average			58			111.1

Given the average floor areas of new flats and houses in Table 4. 12, the corresponding area of external walls can be estimated if the average ratio between wall and floor area is known, and the same procedure can be used for roof and ground floor areas. The LWHS data on Welsh dwellings is used for this purpose. All post-1991 dwellings recorded in the LWHS (except flats) classified as 'houses' (242 units) are analysed as a group, since these units are of recent construction and therefore are more likely to be representative of future dwellings. Only 28 "purpose-built flats" are recorded in the LWHS as post-1991 units, a figure too small to provide a significant basis for analysis. Therefore the whole set of 'purpose-built flats' of the LWHS (181 units) is used in the calculations.

The surface area of walls and roofs of dwellings is calculated with LWHS data using the same procedure detailed in section 4.1.1 for retrofitted dwellings. The area of the ground floor is assumed to be equal to the area of the roof. The correlation between floor area and EW and roof areas are shown in Figure 4. 6, Figure 4. 7 and Figure 4. 8 for houses and flats.

For the 'house' type, the EW/floor area scatter graph (Figure 4. 6) suggests a strong correlation (R^2=0.72) between the area of floor and EW. A weaker correlation (R^2=0.65) is found in Figure 4. 7 between floor and roof areas. This can be explained by the difference between a single-storey house, where the roof is about the same area as the floor, and a two-storey house, where the roof is about half the area of the floor. For the 'flat' type, Figure 4. 8 suggests a weak correlation (R^2=0.25) between floor and EW areas, which could be explained by variations in design and orientation among units within a building block. However, Figure 4. 8 also shows that most flats have net EW area between 40 and 65 m^2, indicating the overall average (55.2 m^2) as an acceptable value for the purpose of this research.

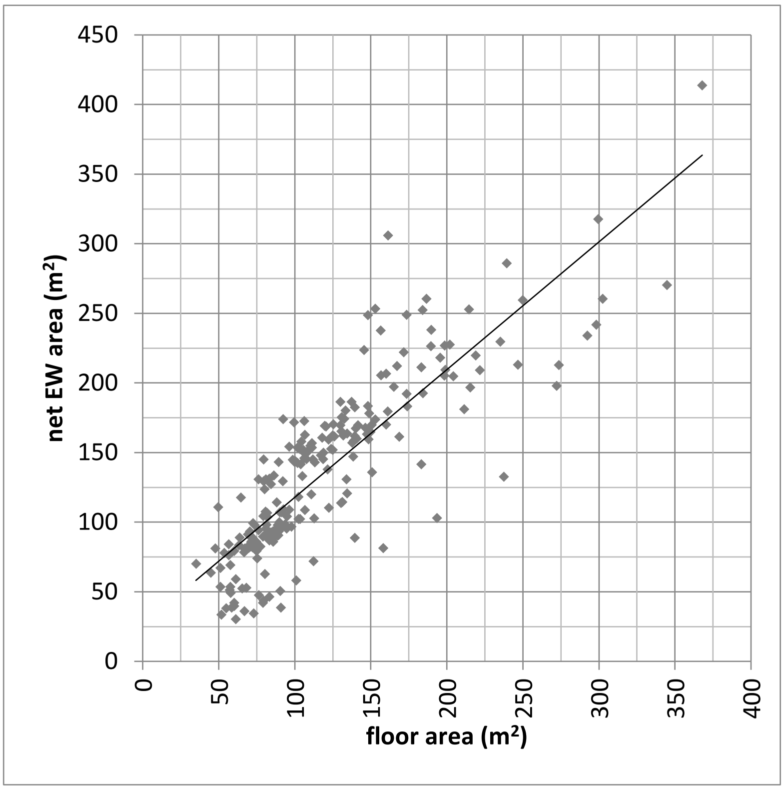


Figure 4. 6 - Scatter graph plotting floor area against net EW area of 'houses'

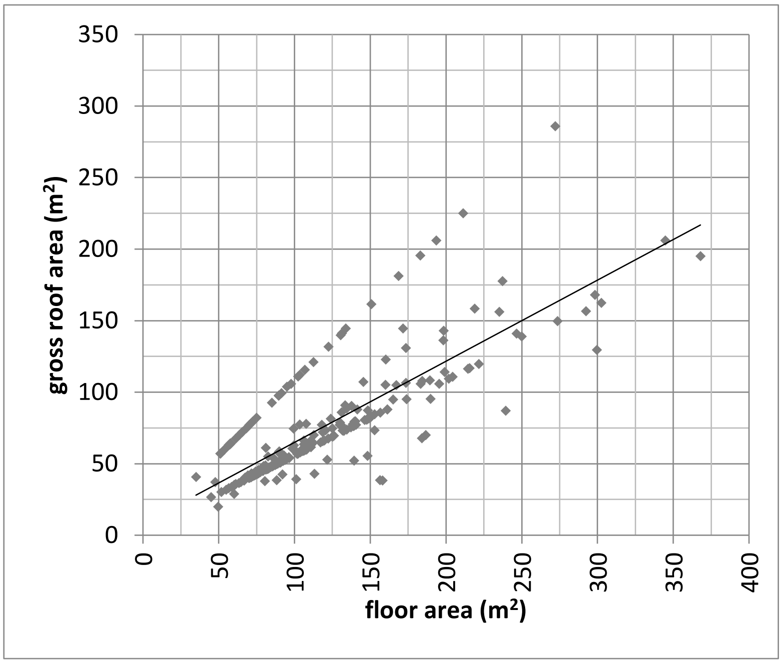


Figure 4. 7 - Scatter graph plotting floor area against gross roof area of 'houses'

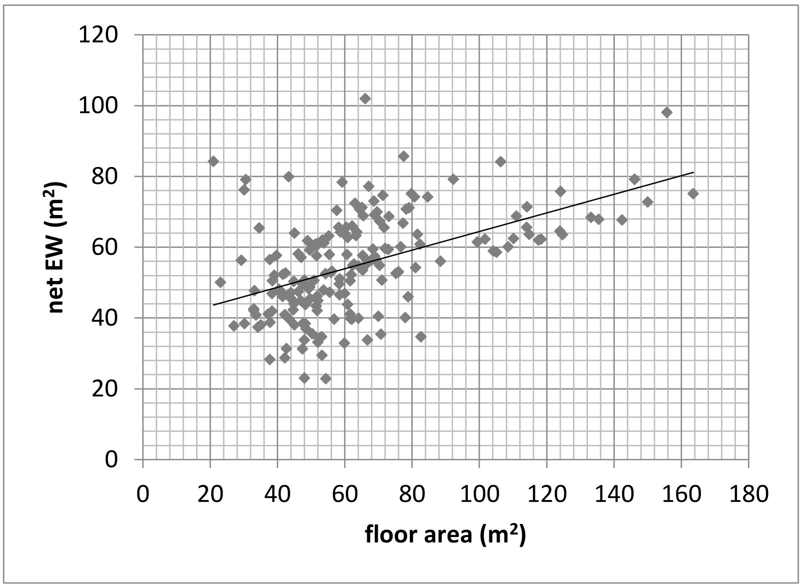


Figure 4. 8 - Scatter graph plotting floor area against net EW area of 'flats'

Table 4. 13 shows the calculations resulting in envelope-to-floor ratios represented by the straight lines in the previous scatter graphs. To estimate average EW and roof areas of future dwellings, the average ratios of EW/floor (for houses and flats) and roof/floor (only for houses) of Table 4. 13 are multiplied by the respective average total floor area as calculated in Table 4. 12 from EPC records (DCLG 2014).

Table 4. 13 – Envelope-to-floor ratios obtained from the analysis of LWHS dataset

Dwelling type	Statistical indicators		units
Houses	Average floor area	118.93	m^2
	Average net EW area	134.08	m^2
	Average ratio net EW area/ floor area	**1.16**	
	Standard deviation of the ratio EW area / floor area	0.29	
	Average loft area	75.52	m^2
	Average ratio loft area / floor area	**0.65**	
	Standard deviation of the ratio loft area / floor area	0.20	
Flats	Average floor area	64.90	m^2
	Average net EW area	55.20	m^2
	Average ratio EW area/ floor area	**0.95**	
	Standard deviation of the ratio EW area / floor area	0.41	

Roof area of flats is assumed to be equal to floor area. However, not all flats are top-floor units, therefore it is acknowledged that a portion of future flats will not need roof insulation. The NEED indicates that only 42% of the flats built in Wales after 1996 have a loft, suggesting that these are top-floor units. This proportion implies that the majority of recent Welsh blocks of flats have two or three residential storeys. It is assumed that future blocks will have on average three residential storeys following the current trend towards urban densification, and therefore 33%

of future flats will be top-floor units. For the same reason, 33% of future flats will be bottom-floor units, thus suitable for ground floor insulation. Therefore a coefficient of 0.33 is applied to the floor area of flats in order to estimate the corresponding roof and ground floor areas to be insulated. The final figures for EW, roof and ground floor areas used to estimate the total areas to be insulated in new dwellings are shown in Table 4. 14.

Table 4. 14 - Calculation of the average envelope area of houses and flats.

Dwelling type	Houses	Flats	units	Source
Average floor area	111.1	58	m^2	DCLG 201
Average ratio net EW area/ floor area	1.16	0.95	/	LWHS (WG 2013a)
Average ratio loft area / floor area	0.65	/	/	LWHS (WG 2013a)
Percentage of top-floor flats	/	33	%	author assumption
Net EW area	128.9	55.1	m^2	(results)
Gross roof area	72.22	/	m^2	(results)
Net roof area	65	19.1	m^2	(results)
Ground floor area	65	19.1	m^2	(results)

The procedures used to calculate the geometry of future dwellings are simplifications producing an average value for dwelling types and ages. Although the results are consistent for houses, there is less confidence in the results for flats. This is due to the smaller number of flats recorded in the LWHS and also to the format of the data, which does not allow correlating the flat floor area with its own EW and roof.

The geometric profile of lofts and roofs is not considered in the calculations, as the data in the NEED does not distinguish between horizontal and sloped roofs. Insulation can be installed between the rafters of the sloped roof plane, or on the horizontal surface of a loft (or roof). While installing insulation on a sloped surface, additional insulation material is required due to the larger area to be covered n comparison to the horizontal surface. Coefficients can be applied to the figures for LI and roof areas in order to take into account the larger area of sloped surfaces. These coefficients would have value set between one (all insulation is horizontal) and the square root of two (all insulation is sloped at 45°).

Calculating thermal resistance (variable B)

The Building Regulations of Wales 2010 set maximum thermal transmittance (i.e. U-value) to be ensured in the envelopes of new dwellings (Welsh Government, 2014a). An envelope component (wall, roof, floor) consist of several layers of materials, and the layer(s) of insulation provides the majority but not all of the thermal resistance (i.e. R-value, inverse of U-value). Equation 4. 2 is used to formalise this concept, in a similar way to (Kunic (2017).

Equation 4. 2 - R-value of the additional insulation for new dwellings

$$U = 1 / (R_{SO} + R_{SI} + R_I + R_{ST})$$

U = thermal transmittance (U-value)\ (W/m^{2}K)

R_{SO} = thermal resistance of the outside surface (m^{2}K/W)

R_{SI} = thermal resistance of the inside surface (m^{2}K/W)

R_I = 'insulation R-value', thermal resistance of the insulation layer(s) (m^{2}K/W)

R_{ST} = 'structure R-value', thermal resistance of the structure and the other layers of the envelope (m^{2}K/W)

To identify the share of thermal resistance typically ensured by the insulation layer in contemporary dwellings, technical details provided in CSH case studies (DCLG, 2009; 2010a; 2010b; 2013) are reviewed. The details of the envelope construction used in the recorded dwellings (14 units) are analysed to identify average ranges for the ratio between the 'insulation R-value' and the total R-value of the envelope (details in Appendix II). Though single examples of building envelopes may vary considerably from these figures, for the purpose of this research it is assumed that the average shares of the "insulation R-value" (R_I) to the total R-value are as follows:

- Walls: 75%
- Roofs: 82%
- Ground floors: 55%

There is a possibility that future changes to Building Regulations will introduce further reductions in the U-values to push all new dwellings to achieve net-zero carbon emissions, thus increasing the demand for insulation. This possibility is taken into account by modelling two different conditions for the U-value set by regulations. These two conditions will be combined to generate different scenarios in the construction forecasts.

In the first condition, the U-value requirements remain as in the current Part L1 2014 for Wales. In the second condition, U-value requirements are set to the Passivhaus Standard of 0.15 W/m^{2}K for all building envelopes (Passivhaus Trust, 2017), and the percentage of the "insulation R-value" (R_I) to the total R-value is assumed to reach 80% for walls and 60% for ground floors, in order to account for a larger thermal resistance. The U-value requirements of the Passivhaus standard are chosen as representative of best practice for a highly energy-efficient dwelling in northern climates. Figures are given in Table 4. 15.

Table 4. 15 – Process of estimation of R-values (m2K/W) to be satisfied by the insulation layer(s) in new dwellings

Condition		Wall	Roof	Ground floor	Units
Current Regs **(Part L1a 2014 Wales)**	**Required U-value**	0.21	0.15	0.18	W/m^2K
	R-value	4.76	6.67	5.56	m^2K/W
	$R_I + R_{ST}$ (R-value excl. R_{SO} and R_{SI})	4.61	6.52	5.32	m^2K/W
	% of insulation	75	82	55	%
	R_I (insulation R-value)	3.46	5.34	2.92	m^2K/W
Passivhaus	**Required U-value**	0.15	0.15	0.15	W/m^2K
	R-value	6.67	6.67	6.67	m^2K/W
	$R_I + R_{ST}$ (R-value excl. R_{SO} and R_{SI})	6.52	6.52	6.43	m^2K/W
	% of insulation	80	83	60	%
	R_I (insulation R-value)	5.21	5.34	3.86	m^2K/W

Forecasting new domestic constructions (variable C)

Two methods for estimating the number of future dwellings built in Wales include:

a) projecting the construction rates recorded in recent years, or
b) considering related forecasts by the Welsh Government (2014c).

These two methods result in different trends, therefore two different conditions are hypothesised and modelled:

a) a condition of ‘growth’, where the construction of new dwellings is sustained at the rate recorded before the economic crisis of 2008 (StatsWales, 2017a);
b) a condition of ‘decline’, where the construction of new dwellings follows the rates determined by the forecast of household numbers in Wales (Welsh Government, 2014c).

The first condition models domestic construction as driven by a steady growth in economic activity, while the second condition models domestic construction following closely the trends of household numbers in Wales.

For both conditions, the ‘split’ between new houses and flats is chosen on the basis of recent constructions. Data in Figure 4. 9 shows that the construction of new dwellings in Wales is divided between houses and flats with an average split of 80%-20% over the 14 years period. In 2008 the construction of flats reached its maximum with 37%. For comparison, the NEED indicates that in the whole UK, flats constitute about one quarter of dwellings built after 1995. Considering the trend towards urbanisation and the likelihood that a higher share of flats will be built in the future, it is assumed that the share of new flats in Wales will be closer to the UK figure, and therefore the demand scenarios modelled a split of 75%-25% between new houses and flats.

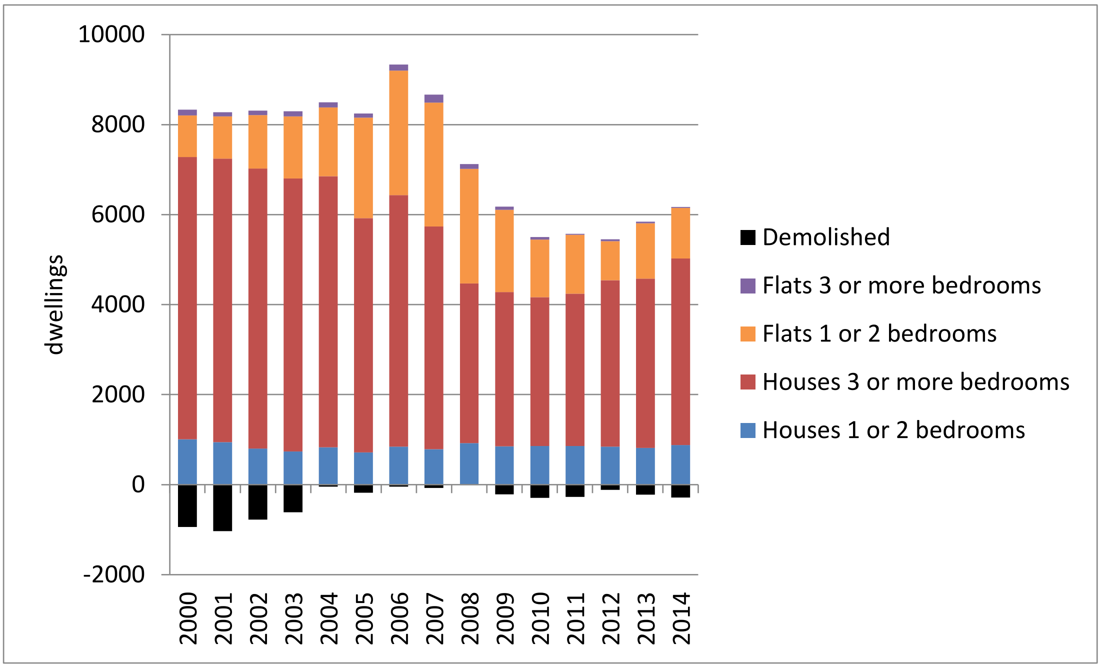


Figure 4. 9 – Dwellings built and demolished in Wales from 2000 to 2014 (source: StatsWales 2017a)

Condition of 'growth'

Data by StatsWales (2017a) illustrated in Figure 4. 9 shows that between 2000 and 2007 over 8,000 new dwellings were built in Wales each year, and this dropped just below 6,000 per year in between 2008 and 2010. Looking at construction rates together with annual Welsh Gross Value Added (GVA) in Figure 4. 10, it can be noticed that rates above 0.6% were sustained until 2008, when the economic crisis slowed GVA growth and the rates of construction fell below 0.5%. Demolition rates are much lower, have started declining even before the economic crisis, and have not risen to 0.05% since 2004. Therefore considering these figures it is assumed that in a condition of steady economic growth around the levels before 2008, the average rate of domestic construction will be 0.65% and the average demolition rate will be 0.05%. Figure 4. 11 shows the numbers of dwellings built and demolished each year to 2050 estimated on the basis of these rates.

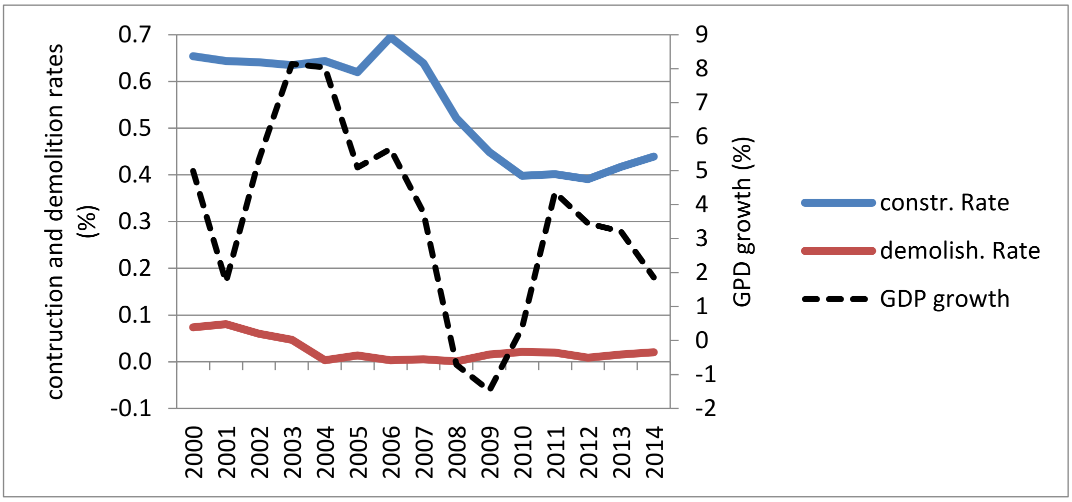


Figure 4. 10 – Construction and demolition rates compared to GDP growth in Wales from 2000 to 2014 (source: author's calculations based on data from StatsWales, 2017a; 2017b)

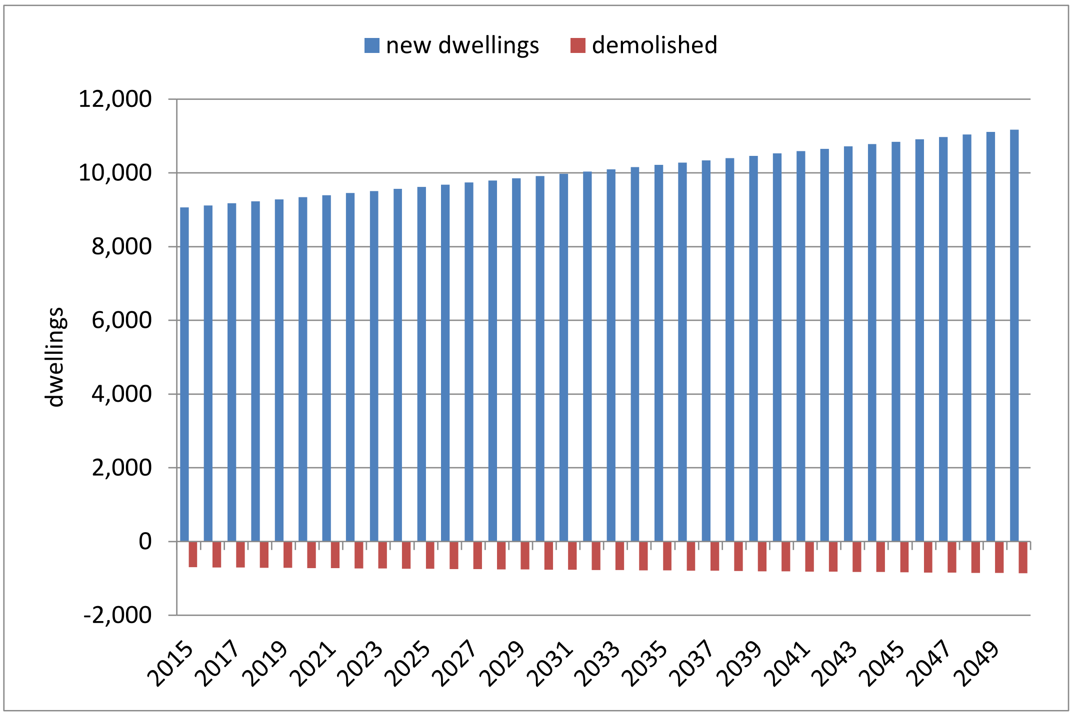


Figure 4. 11 – Forecast of dwellings built and demolished in Wales under the condition of "growth"

Condition of 'decline'

The Welsh Government (2014c) produced a projection of the number of households in Wales until 2036. This forecast of the number of families (not dwellings) indicates that the Welsh Government expects a progressive reduction in the number of *new* families each year, as illustrated in Figure 4. 12. These rates of reduction in households can be applied to the domestic Welsh stock and continued until 2050 to project a level of construction of housing units which follows the declining trend in household numbers, as shown in Figure 4. 13. Thus the condition of 'decline' in the level of construction is modelled assuming that construction rates will change following the household projection, while the average demolition rate remains at 0.05% (as in the 'growth' condition).

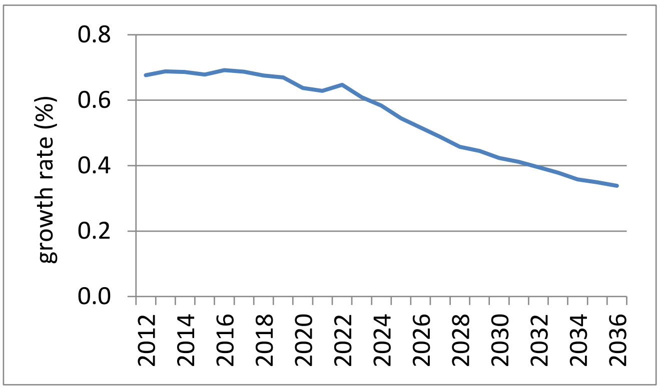


Figure 4. 12 – Annual growth rates associated with the household projection by the Welsh Government (2014c)

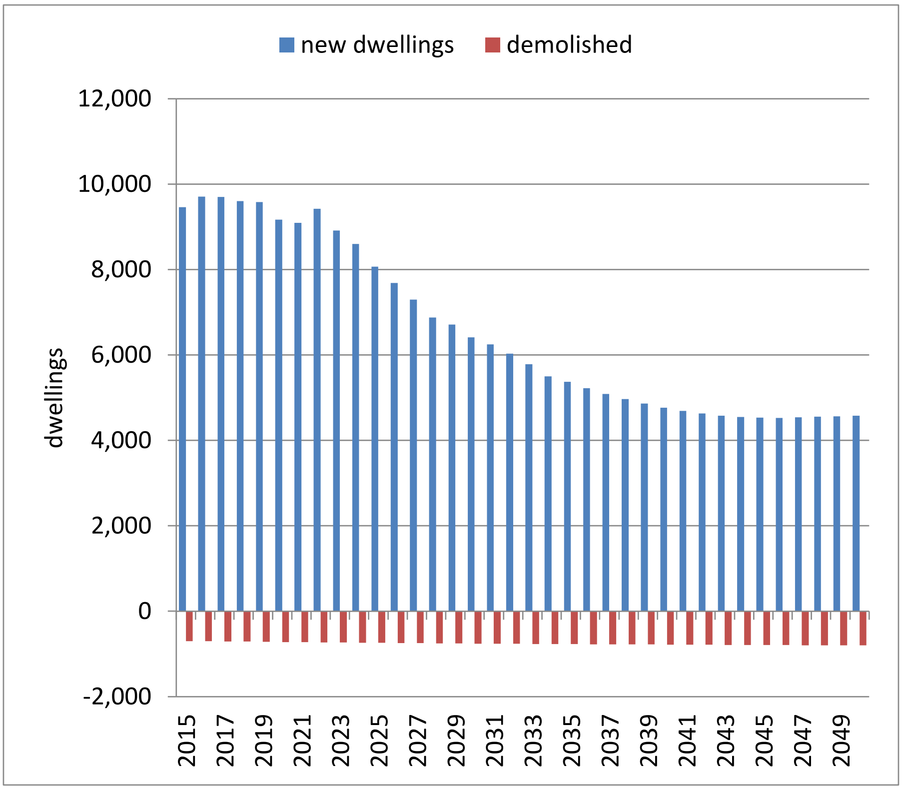


Figure 4. 13 – Forecast of new dwelling construction in Wales under the condition of 'decline'

Generating insulation demand scenarios for new domestic constructions

The two possible conditions given for U-value requirements from regulations ('current Regs' and 'Passivhaus') and the two possible conditions given for future domestic construction ('growth' and 'decline') are brought together to generate four demand scenarios (Table 4. 16). The domestic construction condition determines how many dwellings are built, while the U-value condition determines how much insulation is required on each dwelling. In the case of 'current Regs', the requirements for U-value remain as in the current PartL1 2014 for Wales. In the case of 'Passivhaus', the U-value requirements are brought to the level of the Passivhaus standard in gradual steps between 2021 and 2023.

Table 4. 16 – Generation of the four demand scenarios for new dwellings

New dwellings **Demand scenarios**		**Domestic construction**	
		Growth	**Decline**
U-value requirements	**Current Regs**	D1	D2
	Passivhaus	D3	D4

4.1.3 Results of insulation demand scenarios

This section presents the demand for insulation in Wales forecasted by the scenarios described above. Figure 4. 14 shows the total demand from retrofitted dwellings (in m^2K/W) in Wales from 2016 to 2050 divided by envelope type. The demand follows the rates of solid walls and loft insulation established in section 4.1.1. EWI applications have the largest contribution, with 48% of the cumulative demand. LI have 40% of the cumulative demand and IWI only 12%.

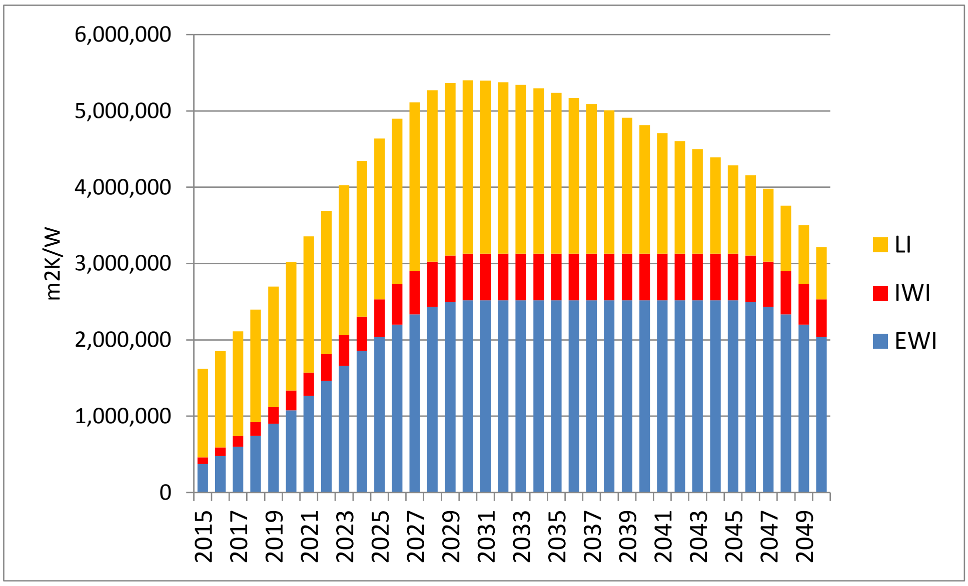


Figure 4. 14 – Total forecasted demand for insulation (m^2K/W) from retrofitted dwellings in Wales

Figure 4. 15 compares the total demand (in m^2K/W) forecasted by the four scenarios for insulation of new dwellings in Wales, divided by envelope type. The demand curves of each scenario are shown in Figure 4. 16, Figure 4. 17, Figure 4. 18 and Figure 4. 19. These curves are determined by the conditions of 'growth' and 'decline' for construction rates described in section 4.1.2. Scenarios D3 and D4 are also affected by the tightening in legal requirements introduced by the 'Passivhaus' condition after 2020. Clearly, the largest demand for insulation is determined in scenario D3 by the combination of growth in construction and tightening of legal requirements. The proportion between envelope types is not influenced by these conditions and therefore remains constant across the four demand scenarios. The insulation of walls has the largest contribution to total demand, followed by roof and then ground floors.

Comparing total demand from retrofits and new constructions, the latter appears as the largest sector. Assuming a steady growth in new constructions (as in demand scenarios D1), about 70% of the demand for domestic insulation from 2020 to 2050 is associated with new dwellings, and the rest with retrofits. If new constructions were to decline (as in demand scenarios D2) demand for insulation in retrofits would rise up to about 40% of the total.

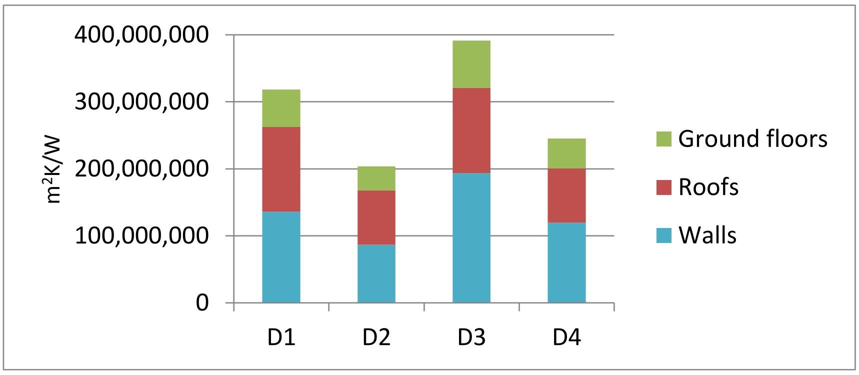


Figure 4. 15 – Total demand for insulation in the four demand scenarios for the new dwellings

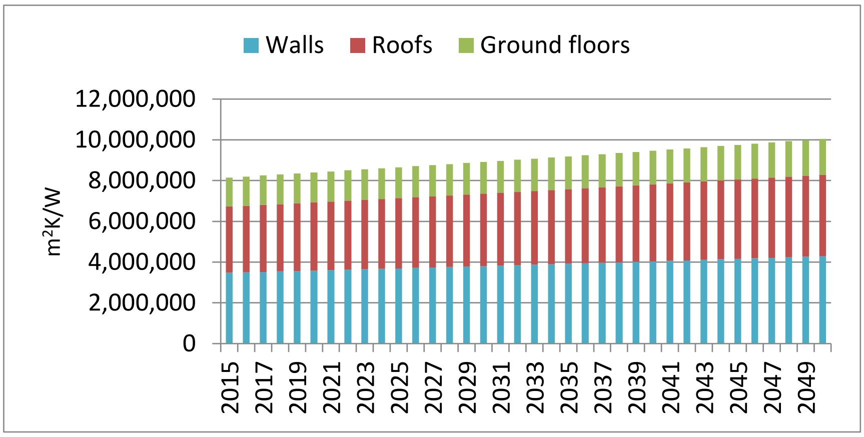


Figure 4. 16 – Demand for insulation from new dwellings in scenario D1: conditions 'current Regs' + 'growth'

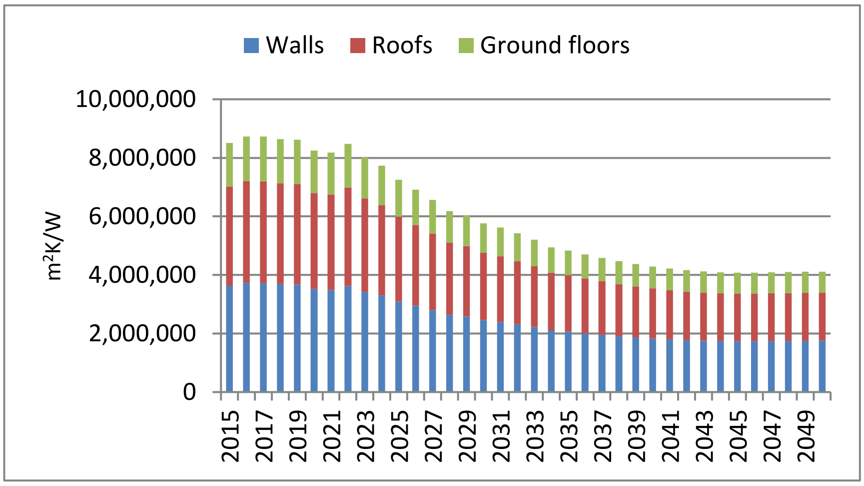


Figure 4. 17 – Demand for insulation from new dwellings in scenario D2: conditions 'current Regs' + 'decline'

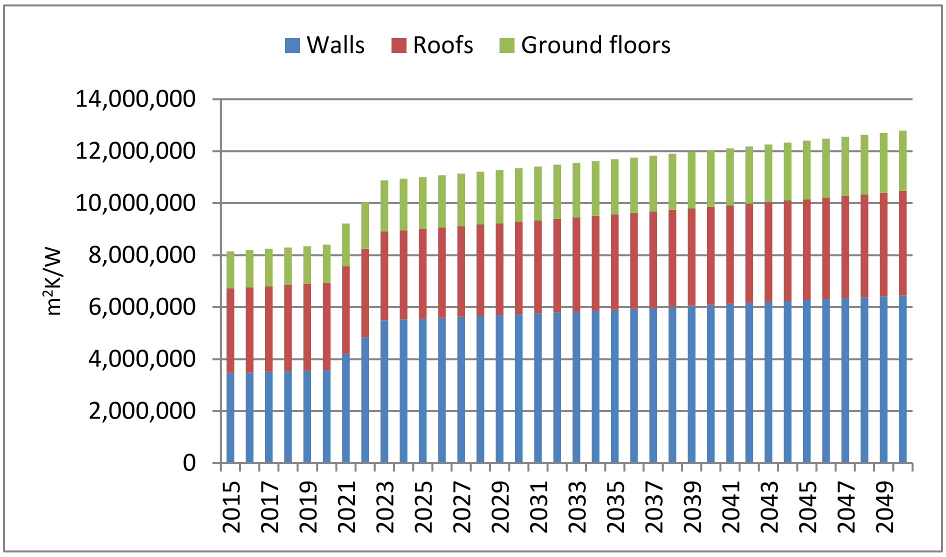


Figure 4. 18 – Demand for insulation from new dwellings in scenario D3: conditions 'Passivhaus' + 'growth'

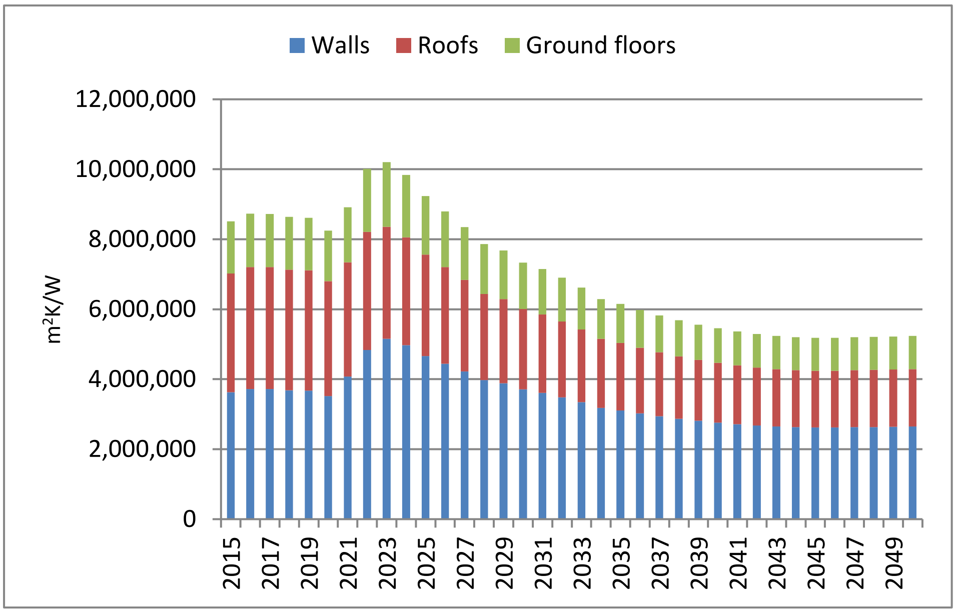


Figure 4. 19 – Demand for insulation from new dwellings in scenario D4: conditions 'Passivhaus' + 'decline'

4.2 Modelling future insulation supply scenarios

This section discusses the procedure used to establish the different combinations of products used to model the future supply of insulation in Wales. These combinations describe the share that each type of product occupies in the market, and therefore affect the quantities of products modelled by the supply scenarios. The shares associated with product types are referred to as *product mix*. For each envelope type modelled in the demand scenarios, a matching supply scenario is created with its associated product mixes:

- Retrofitted dwellings:
    - External Wall Insulation (EWI);
    - Internal Wall Insulation (IWI);
    - Loft Insulation (LI);
- New dwellings:
    - External Walls;
    - Roofs;
    - Ground Floors.

For each envelope type, baseline and alternative scenarios are built. The baseline scenarios model business-as-usual mixes of conventional products, based on the shares of the insulation market in recent years. A primary and a secondary baseline scenario are built for all envelope types, except loft insulation, to address the uncertainty which remains in determining reliable estimates of product mixes:

- the primary baseline ('Base.1') models the most reliable estimate of the product mix based on available data;
- the secondary baseline ('Base.2') models a variation on the primary baseline, taking into account the possibility of a different product mix.

For loft insulation in retrofits, only the primary baseline is modelled since there is sufficient confidence in the chosen product mix. The issues encountered when attempting to identify which products mixes are used for specific envelope types within the Welsh market are discussed in section 4.2.1.

The alternative scenarios are built onto baseline scenarios by modelling a progressive substitution of conventional products contained in the baseline with newly introduced products. Thus the alternative scenarios retain the share of conventional products which is left untouched by the substitution. The higher the substitution level (from 'Small' to 'Very large', see section 4.2.4), the fewer conventional products are retained in the alternative scenario.

Five alternative scenarios are modelled:

- Mineral (Min) – Low-impact versions of glass wool and HD stone wool are introduced into the market. This scenario is used as a "control group" to model the potential reduction in EEI achievable with the best options among conventional products.
- Hemp fibre (HeF) - hemp fibre insulation is introduced, together with HD wood fibre;
- Sheep wool (ShW) - sheep wool insulation is introduced, together with HD wood fibre;
- Wood fibre (WoF), LD wood fibre insulation is introduced, together with HD wood fibre;

All scenarios include a quantity of HD products (either stone wool or wood fibre) to provide the rigid layer of insulation required by most envelope types (see section 4.2.3).

4.2.1 Investigating product mixes in the current insulation market

The review of the available sources of information did not produce a detailed picture of product mixes in the UK insulation market, as discussed in section 2.3.2. Local industry representatives were contacted by the author in the attempt to estimate the current product mix for each envelope type and determine whether the Welsh market displays different product mixes in respect to the wider UK market. Companies associated with the insulation sector based in Wales were identified via a web search and the FAME Database (Bureau van Dijk, 2016). These were divided into the categories of:

- manufacturers;
- retailers;
- installers.

Interviews

A meeting with Mr Paul William, officer for Refurbishment and Regeneration at Rockwool, and a visit at the plant located in Bridgend was arranged. The encounter provided valuable information on stone wool manufacturing but no further data on market product mix was obtained. Major retailers located in Cardiff were contacted in the attempt to access information on products sold at local level. Unfortunately no data was obtained, due to the understandable reticence to release business-sensitive information.

Contacts with local installers of domestic insulation held better results. Informal interviews were conducted with Aled Thomas, sales manager at SPS Envirowall, and installers at SERS. These sources indicated that, differently from the UK figures by INCA (2015) (Figure 2.7), in Wales the market for the insulation of walls in both retrofitted and new dwellings is more equally shared between EPS and stone wool. The wider use of stone wool in Wales in comparison to the share that this product occupies at the UK level was attributed to the proximity of the Rockwool plant and the willingness of some companies to purchase products manufactured in Wales. Both local sources estimated that EPS and stone wool occupy about 80% of the market, with EPS still taking a larger share, and with the remaining market balanced between glass wool, PUR and phenolic foams.

Questionnaire

In the attempt to gather additional data, a small anonymous questionnaire was prepared and emailed to 85 recipients. These were business email addresses of active companies based in

Wales and related to the insulation sector, selected through a web search and access to the FAME Database (Bureau van Dijk, 2016).

Five questions were asked, one for each of the envelope type investigated. Loft insulation was not investigated due to the confidence in the product mix indicated by review of available data (see section 2.3.2). Participants were asked to attribute percentages to insulation products for on the basis of their professional experience, and to leave blank any product or envelope type on which they would not feel confident enough to express a figure. The following is an example of the question for EWI in retrofits:

> "On the basis of your experience, can you estimate percentages (%) for the following types of EXTERNAL SOLID WALL insulation installed on existing dwellings in Wales? Feel free to skip products which you do not feel confident enough to estimate."

Participants were also asked to indicate to which business categories their company would belong to. These are shown in Table 4. 17.

Table 4. 17 – Business categories declared by questionnaire participants

Participant	Business category
A	Manufacturing
B	Installation and maintenance
C	Manufacturing
D	Manufacturing, Installation and maintenance, Property management
E	Manufacturing
F	Installation and maintenance, Education and training

Six replies were received (response rate 7%) and their results are shown from Figure 4. 21 to Figure 4. 24. There is large disparity in some of the responses to the questionnaire, showing that even those working in the sector can have significantly different opinions. These differences might be attributed to the participants' individual experiences and to the habit of firms to rely on a limited range of products.

Figure 4. 20 shows the answers given by respondents on the EWI sub-sector in Wales. Despite the differences, EPS and stone wool appear to be the most popular products, which is consistent with the data in Figure 2.7 presented by INCA (2015) and the estimates given by representatives of SPS Envirowall and SERS during interviews.

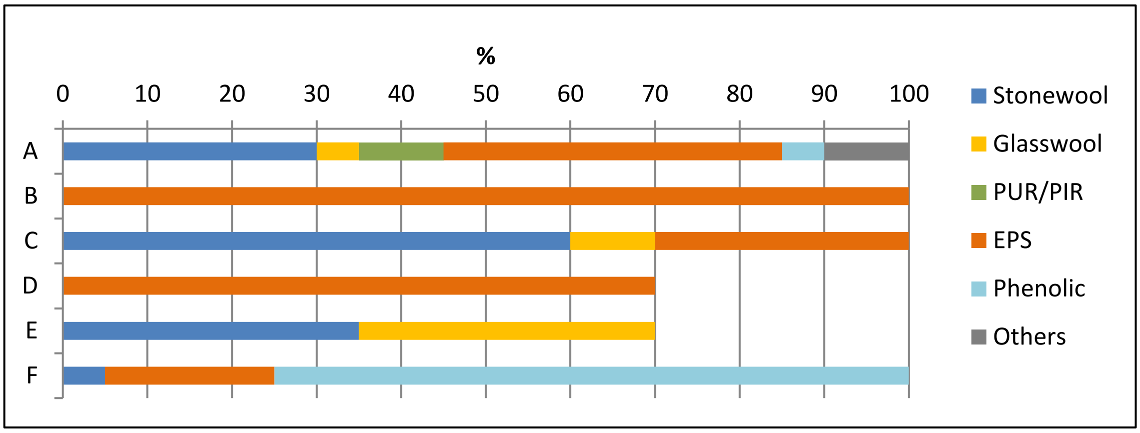


Figure 4. 20 – Questionnaire responses regarding the shares of the market held by products in the retrofit EWI sub-sector in Wales

Responses regarding the IWI sub-sector (Figure 4. 21) are even more conflicting. The only opportunity to compare with available market data (Figure 2.6, from Office for Fair Trading, 2012b) indicates that the market comprises of a large share of phenolic foams in solid wall insulation (although there is no distinction between external and internal applications). This information is consistent with the two responses from the questionnaire indicating a large prevalence of phenolic foams. The use of this product as internal insulation in retrofitted dwellings is a rational choice, since phenolic foams have lower thermal conductivity than EPS and mineral products, and thus can achieve the same performance with a thinner layer. The same is true of PUR and this product is estimated to have a large share by one of the respondents.

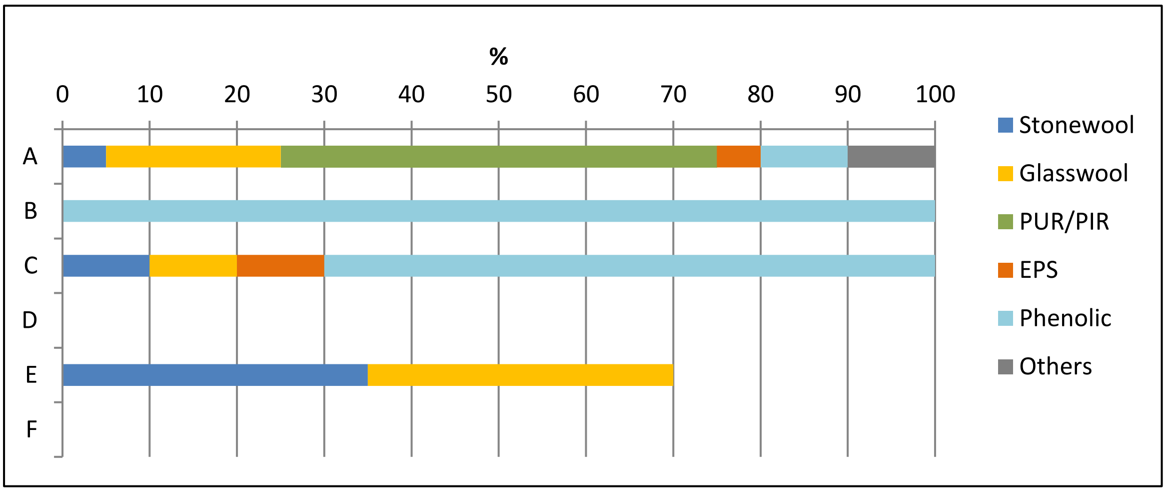


Figure 4. 21 – Questionnaire responses regarding the shares of the market held by products in the retrofit IWI sub-sector for in Wales

In the responses on the insulation of external walls in new dwellings (Figure 4. 22), three of four participants agree that stone wool occupies a large share of the market in Wales (which is consistent with estimates given by local installers), while opinions on the share of EPS are conflicting. The large share of PUR indicated by participant A is not supported by other sources.

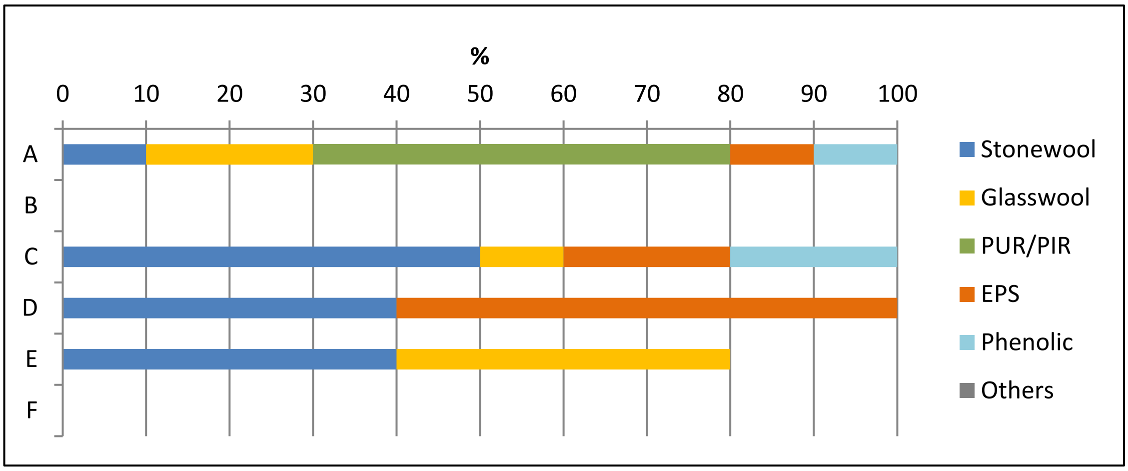


Figure 4. 22 – Questionnaire responses regarding the shares of the market held by products in the insulation of external walls in new dwellings in Wales

Figure 4. 23 shows responses on the insulation of roofs in new dwellings, which appear to agree on the large prevalence of glass wool, with two participants also giving significant market share to stone wool. This product mix does not appear consistent with the prevalence of PUR indicated by AMA Research (2015a) in roofs. However, the AMA estimate only considers flat roofs, while large part of new dwellings built in Wales are houses with pitched roof.

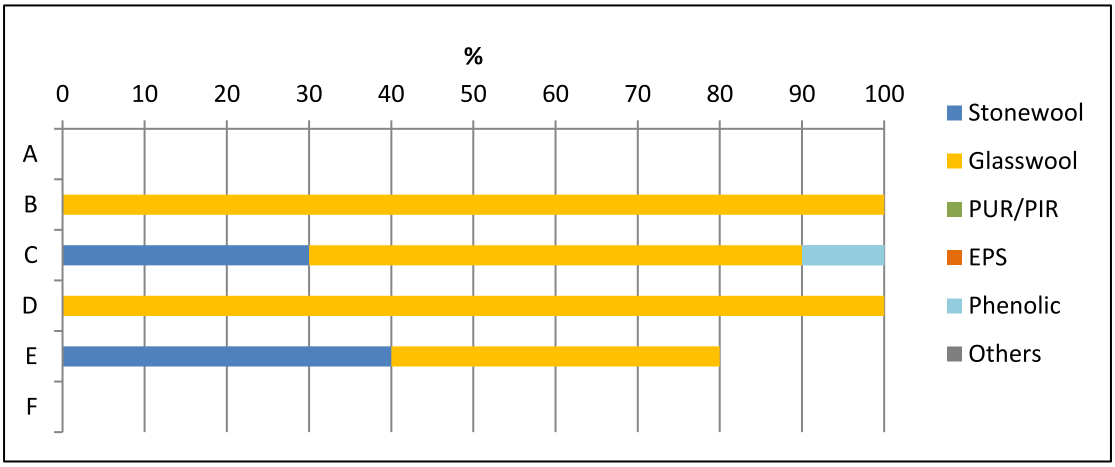


Figure 4. 23 – Questionnaire responses regarding the shares of the market held by products in the insulation of roofs in new dwellings in Wales

Three participants provided estimates for the product mix used to insulate the ground floors of new dwellings (Figure 4. 24). Two indicated a market dominance of PUR, while one indicated EPS as the only product used. The prevalence of PUR is consistent with the information in Figure 2.6 provided by the Office for Fair Trading (2012b).

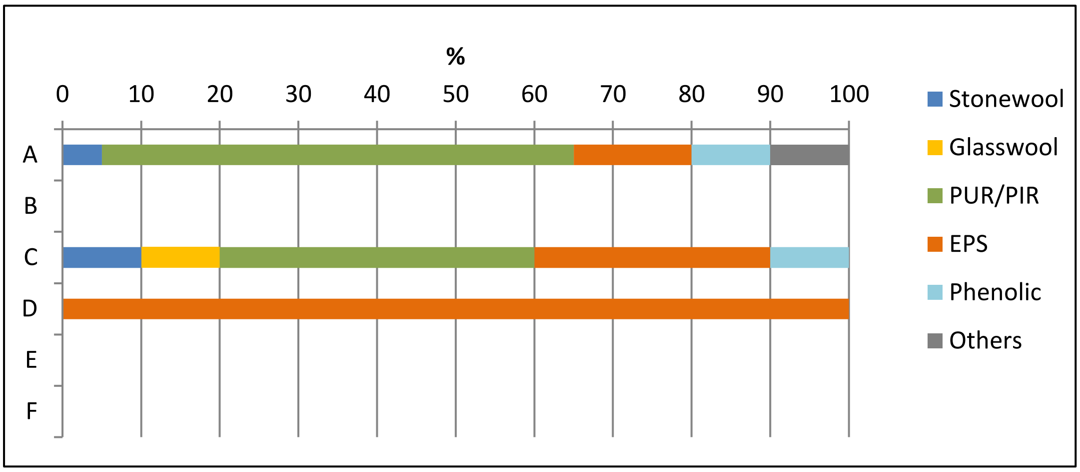


Figure 4. 24 – Questionnaire responses regarding the shares of the market held by products in the insulation of ground floors in new dwellings in Wales

In the next section, the information obtained through this questionnaire and the contacts with local installers is combined with the outcomes of the review of available sources (section Figures 2.4 to 2.7) to establish the product mixes modelled in the baseline scenarios.

4.2.2 Establishing product mixes for the baseline supply scenarios

This section presents the product mixes chosen for the primary and secondary baseline scenarios for each envelope type. As discussed above, it is difficult to determine with high confidence the share that each product occupies in Wales in each sub-sector of the insulation market. The choice of the product mix for the primary baseline scenarios are estimates based on the most reliable evidence collected and on the following assumptions:

- all five conventional products are included in the product mix of each envelope type, as little evidence points towards a subsector being completely occupied by one or two products;
- after identifying the most common conventional products in a subsector, the remaining share of the market is distributed equally between the less common ones, unless the available evidence suggests otherwise;
- ‘other products’ are given 5% the market as the evidence shows this to be within the range occupied by these products. The effect of this “cut-off” on the results is limited, as it simply means that 5% of the insulation demand is attributed to other products, the EEI is not calculated and these products are not substituted in the alternative scenarios;

secondary baselines (‘Base.2’) are modelled as variations from the product mix of the primary baseline (‘Base.1’), to investigate changes in EEI determined by different mix of conventional products.

Product mix in the baseline scenarios for domestic retrofits

Figure 4. 25 shows the product mixes used for the baseline scenarios of retrofitted dwellings. Each envelope type (except LI) is given a primary and a secondary baseline scenario, each with a product mix selected using the following rationales.

In the primary baseline (Base.1) for EWI, EPS and stone wool occupy the largest shares of the market with 45% and 35% respectively. Glass wool, PUR and phenolic foams are given each 5%. This product mix is based on the estimates given by local installers in interviews, which indicated the majority of EPS followed closely by stone wool, with the remaining product types in smaller quantities. The product mix of the secondary baseline for EWI (Base.2) is instead based on the figures given in the INCA (2015) report (Figure 2.7) and collected at the UK level.

The product mix of the primary baseline for IWI attributes 45% of the market to phenolic foams, 20% to PUR and the rest equally divided among the remaining product types. This mix is based on the estimates given in Figure 2.6 by the Office for Fair Trading (2012b), the questionnaire responses (Figure 4. 21), and on the general assumption that when insulating existing solid walls internally, PUR and phenolic foam are likely to be preferred among conventional products due to their lower thermal conductivity, which means thinner layers and thus a reduction in the loss of internal floor area. The product mix of the secondary baseline is based on the same assumption but explores the possibility that PUR will be preferred over phenolic foams.

The primary baseline scenario for LI is based on AMA Research (2015a) which indicates glass wool as the dominant product in the insulation of lofts in retrofitted dwellings. This is a rational choice, as glass wool is among the cheapest options and can be installed easily on the flat floor of lofts as well as under tilted roofs between rafters. Thus no secondary baseline is given for LI since no evidence was found contradicting the prevalence of glass wool.

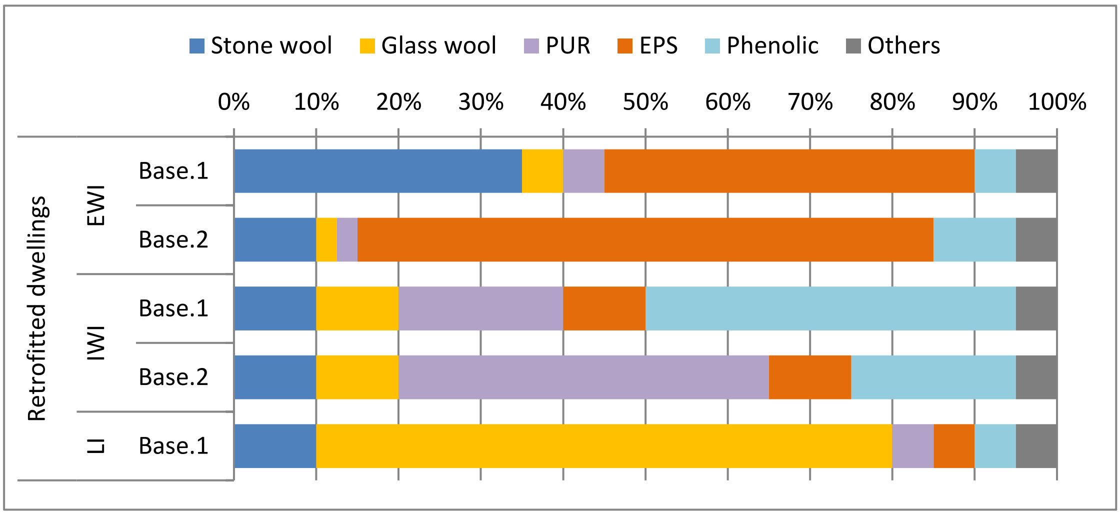


Figure 4. 25 – Product mix (%) used in the baseline supply scenarios for the insulation of retrofitted dwellings

Product mix in the baseline scenarios for new constructions

Figure 4. 26 shows the product mixes chosen for the primary and secondary baseline scenarios of new dwellings, which have been selected using the following rationales.

As for the EWI of retrofitted dwellings, the product mix of the primary and secondary baselines for the insulation of external walls are based on the estimates given by local installers and the figures given in the INCA (2015) report (Figure 2.7).

The product mix chosen for the primary baseline of roof insulation in new dwellings is based on the data of Figure 2.6 by the Office for Fair Trading (2012b), questionnaire responses (Figure 4. 23), and the following assumption: when forecasting the number and type of dwellings which will be built in Wales (see 0), it was assumed that one third of the dwelling forecasted to be built in Wales will be flats, and that one third of those flats will be top-floor units. Even if all those units were to have flat roofs insulated with phenolic foams, this product would only be installed in one ninth (11.1%) of dwellings. However, some houses might be built with flat roofs as well, and phenolic foams can be used to insulate pitched roofs. Thus the chosen product mix gives majority of the market to glass wool (55%) and smaller share to phenolic foam (20%) and stone wool (10%). In the secondary baseline, the proportion between glass and stone wool is more balanced, which takes into account some of the questionnaire responses.

The product mix chosen for the primary baseline of ground floor insulation in new dwellings is based on the data of Figure 2.6 by the Office for Fair Trading (2012b), and one of the survey responses (Figure 4. 24), indicating a large majority of PUR in the market. The other two responses indicated a larger share for EPS, therefore this condition is modelled in the product mix of the secondary baseline.

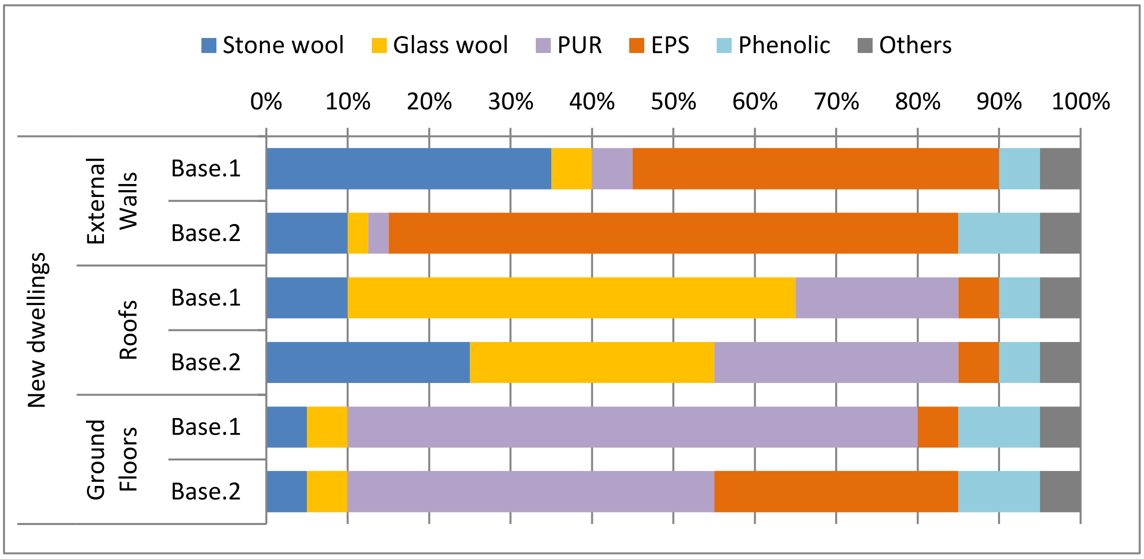


Figure 4. 26 - Product mix (%) used in the baseline supply scenarios for the insulation of new dwellings

4.2.3 Establishing product mixes for the alternative supply scenarios

This section shows the combination of ‘newly introduced’ products modelled in the alternative supply scenarios for the insulation of retrofitted and new dwellings. As introduced earlier, four alternative scenarios are modelled:

- Mineral – introducing glass wool and High-Density (HD) stone wool;
- Sheep wool – introducing sheep wool and HD wood fibre;
- Hemp fibre – introducing hemp fibre and HD wood fibre;
- Wood fibre – introducing LD wood fibre and HD wood fibre.

For each of these alternative scenarios, slightly different product mixes are introduced depending on the envelope type. For all envelope types except loft in retrofitted dwellings, a rigid HD product is included together with the soft product to take into account technical aspects. As discussed in section 2.3.1, soft fibrous materials are typically produced in rolls or batts which do not resist compression or traction, and can bend or sag if not adequately installed. This requires fixing the insulation to the envelope and/or encasing it in a stud frame in case of vertical applications, and between joists or rafters in case of roof and floor insulation. Studs, joists and rafters cause thermal bridges across the insulated surface, which can be reduced by covering it with an additional layer of rigid insulation. Rigid panels of HD fibrous insulation can be used for this purpose in different application, and both stone wool and wood fibre are available in HD format.

Manufacturers produce rigid panels – usually with thickness from 20 mm to 200 mm - specifically designed for achieving a more homogenous insulation of walls, roofs and floors. In the alternative scenarios, the thickness chosen for the layer of HD stone wool and wood fibre is 35 m. This choice is based on the assumption that in most applications the amount of HD product will be limited to minimise its cost, since rigid fibrous products have a higher price than soft ones (as will be shown in section 5.1.2). Table 4. 18 shows shares of the R-value required for the insulation layer which is satisfied by the 35mm rigid panel with thermal conductivity 0.035 W/mK. These percentages determine the mix of products introduced by the alternative scenarios. The higher proportion in retrofitted envelopes (EWI and IWI) in comparison to the envelopes of new dwellings is due to the lower R-value required in retrofits by Building Regulations (see section 2.3.2).

Table 4. 18 - Shares (%) of the R-value of the required insulation which is satisfied by rigid HD panels

Demand sector	Envelope type	**Proportion (%) of the R-value of the insulation taken by layer of HD insulation**
Retrofitted dwellings	EWI	32.8
	IWI	32.8
New dwellings	External walls	16.8
	Roofs	16.4
	Ground floors	22.7

The use of a timber frame to encase soft insulation slightly reduces the overall thermal resistance of the insulation layer across the surface, due to the lower R-value of timber. Thus in order to achieve the required thermal resistance, a slightly thicker layer of soft insulation is required. Assuming typical frame dimensions such as studs (and joists) 4 cm wide and paced every 60 cm, the thickness of the soft insulation layer requires to be increased by a factor of 1.05 for glass wool, sheep wool and hemp fibre, and a factor of 1.08 for LD wood fibre. These factors are taken into account in the calculations of the quantities of products required by the supply scenarios.

Figure 4. 27 and Figure 4. 28 show the product mixes determining the shares of newly-introduced products in each of the alternative scenarios for retrofitted and new dwellings. As described above, the shares of HD stone wool and HD wood fibre are determined by the use of 35 mm rigid panels to encase soft insulation products.

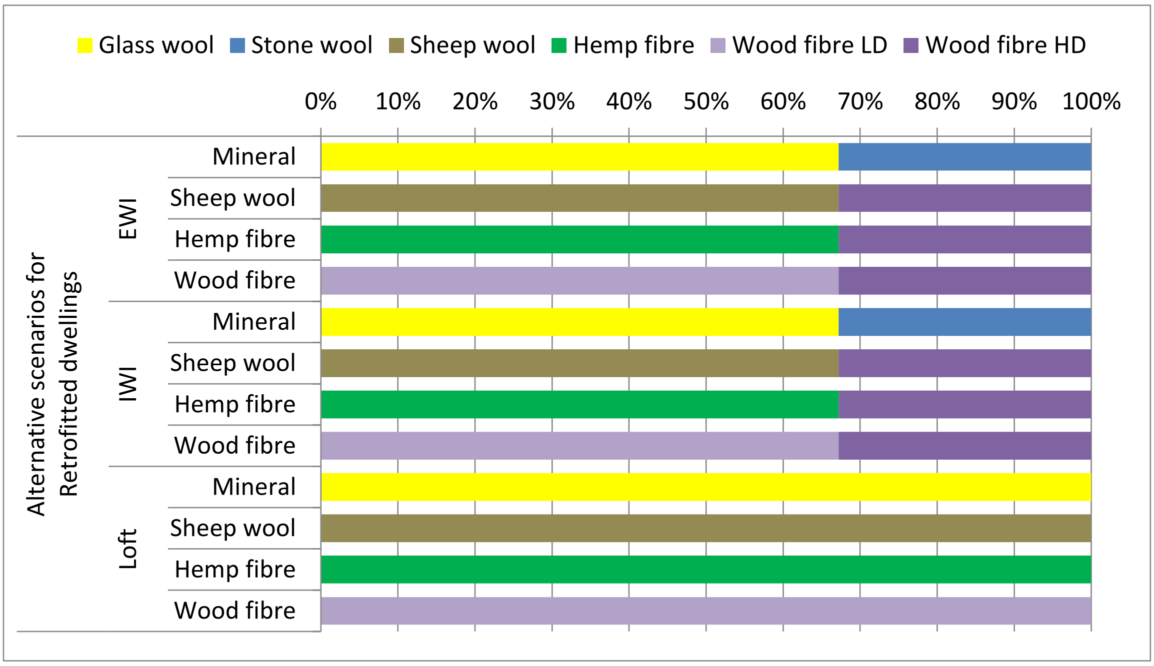


Figure 4. 27 - Mix of newly introduced products (%) in the alternative supply scenarios for the insulation of retrofitted dwellings

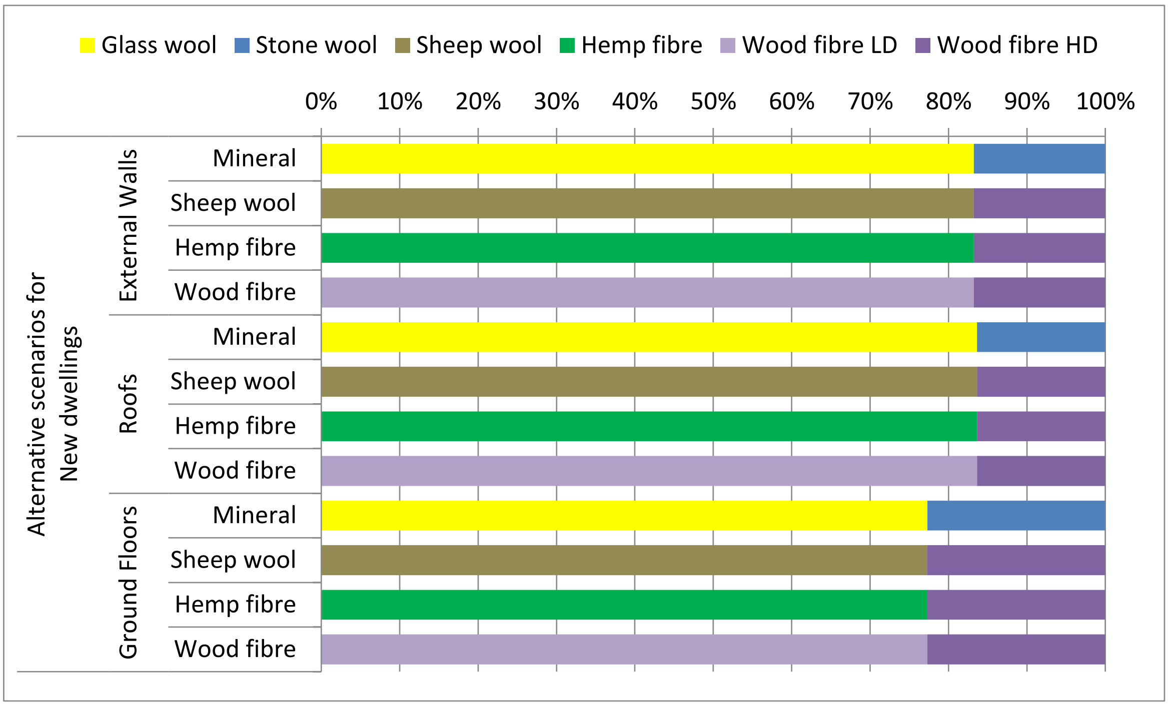


Figure 4. 28 - Mix of newly introduced products (%) in the alternative supply scenarios for the insulation of new dwellings

4.2.4 Modelling product substitution in the alternative scenarios

A *substitution curve* is used to model the progressive uptake of newly introduced products in the alternative scenarios, as introduced in section 3.2.2. The equation used in this research to model all substitution curves is adapted from the Gaussian function:

Equation 4. 3 – Substitution curve

For $2020 \leq x \leq p$

$$y = f(x) = m * e^{-\frac{(x-p)^2}{2*(s^2)}}$$

For $x > p$

$$y = f(p)$$

With:

y = share of newly introduced products in year ‘x’ (as %)

x = year (from 2020 to 2050)

m = maximum share reached by newly introduced products in year ‘p’ (as %)

p = year when maximum share ‘m’ is reached

s = standard deviation parameter

e = mathematical constant *e* (base of the natural logarithm)

This equation describes the percentage that newly introduced products occupy on the market each year. Its value rises following the typical 'S' shape used by Rogers (2003) to describe the diffusion of innovations within a market. After the peak year the share of newly introduced products remains constant at the peak value.

Since the conventional products modelled in the baseline scenarios are substituted gradually, the total supply modelled in the alternative scenarios retains considerable quantities of conventional products. The cumulative share of conventional products (S_R) retained for each envelope type is determined by the interaction between two curves: the substitution curve and the *demand curve*, namely the curve describing the annual demand for insulation for each envelope type (shown in section 4.1.3). Equation 4. 4 is used to calculate the cumulative share of conventional products not replaced by the newly introduced products over the 2020-2050 period:

Equation 4. 4 – Total share of remaining conventional products after the substitution (as %)

$$S_R = \frac{\sum_{x=2020}^{2050} \frac{t*(100-y)}{100}}{D} * 100$$

x = year (from 2020 to 2050)

y = share of newly introduced products in year 'x' (as %), see Equation 4. 3

t = demand in year 'x' (expressed in m^2k/W)

D = total demand (expressed in m^2k/W)

Four levels of substitution are modelled in the alternative supply scenarios, reflecting different levels of maximum share of market reached by newly introduced products:

- 'Small' - the annual share of newly introduced products reaches 25% of the market;
- 'Medium' - the annual share of newly introduced products reaches 50%;
- 'Large' - the annual share of newly introduced products reaches 75% of the market;
- 'Very Large' - the annual share of newly introduced products reaches 100% of the market

The maximum share of market reached by newly introduced products is the peak of the substitution curve. Therefore increasing the peak value decreases the total quantity of conventional products which are not replaced. The peak year is set for 2040 for all envelope types, except for LI, whose substitution peaks in 2030. The four levels of substitution are illustrated in the graphs from Figure 4. 29 to Figure 4. 32.

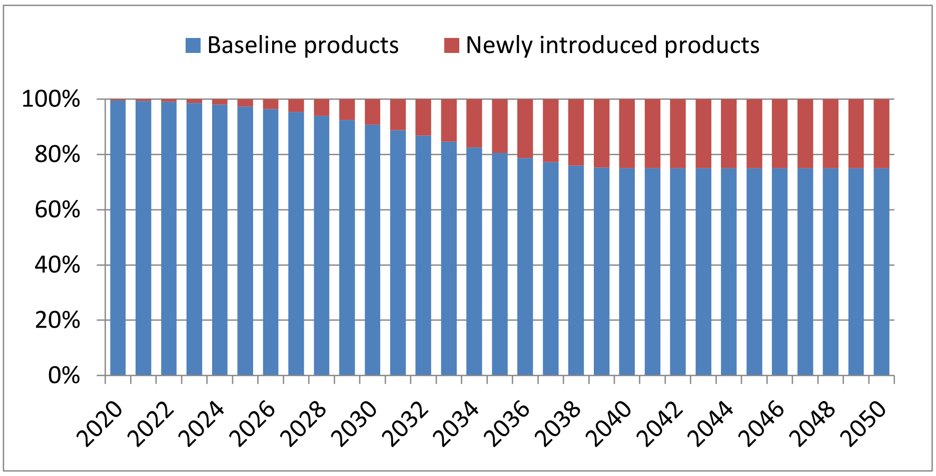


Figure 4. 29 – Annual shares of conventional and newly introduced products determined by the Small level of substitution

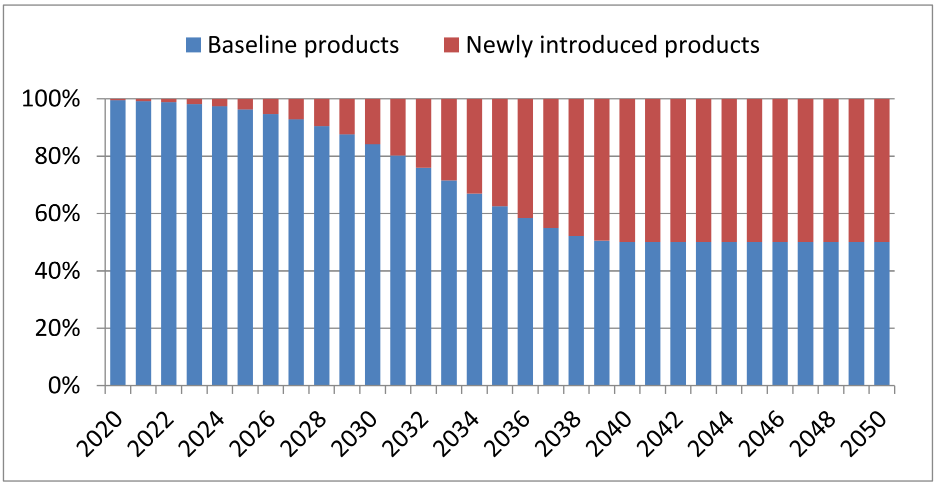


Figure 4. 30 – Annual shares of conventional and newly introduced products determined by the Medium level of substitution

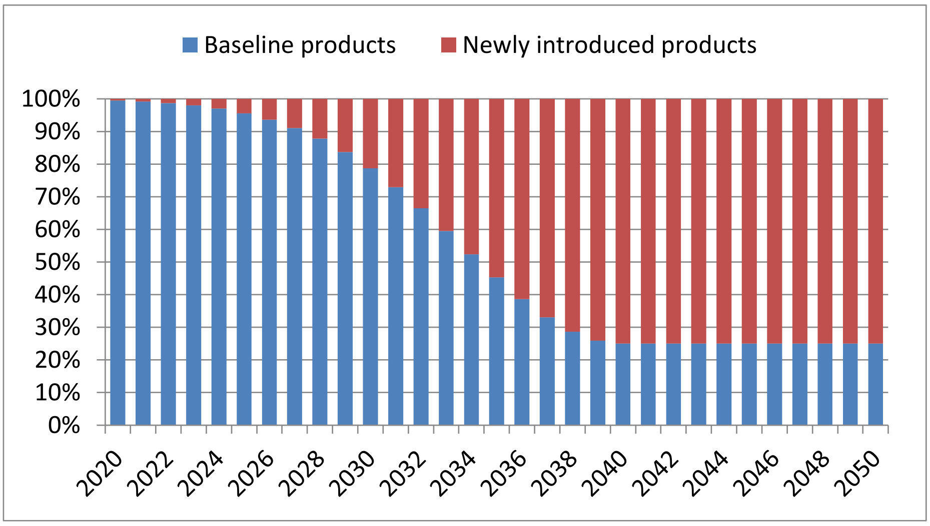


Figure 4. 31 – Annual shares of conventional and newly introduced products determined by the Large level of substitution

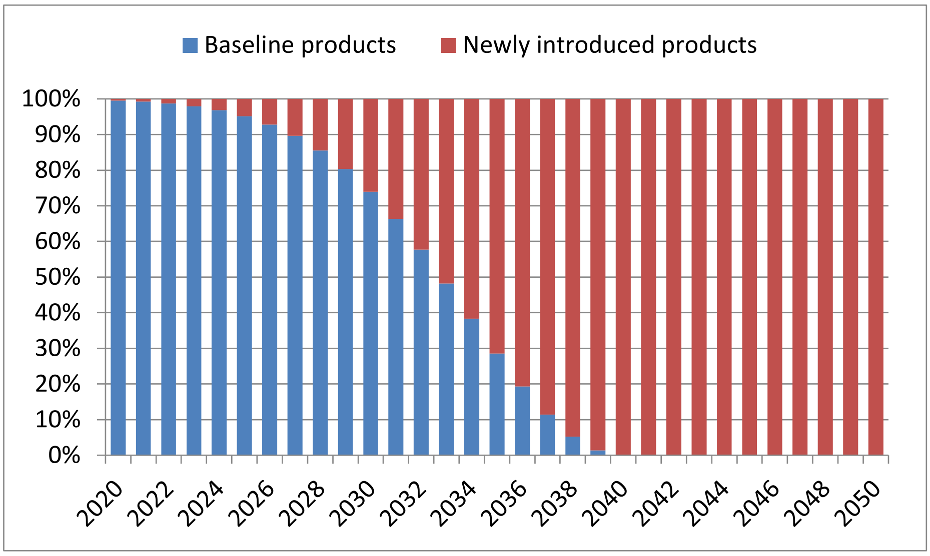


Figure 4. 32 – Annual shares of conventional and newly introduced products determined by the Very Large level of substitution

To provide an example of the interaction between the demand curve and the substitution curve, Figure 4. 33 and Figure 4. 34 show the Medium level of substitution applied to the demand curves of scenarios D1 and D2 for the insulation of walls in new dwellings. In comparison to D2, the rising demand in D1 determines a larger total quantity of newly introduced product.

The cumulative share of remaining conventional products in each scenario is influenced by the interaction of demand scenarios and levels of substitution. In cases where the annual demand diminishes over time, the cumulative share of remaining conventional products is larger than in cases where the annual demand increases over time. Table 4. 19 illustrates these differences. For example, there are about 14 percentage points of difference between the amounts of conventional products remaining after a Very Large substitution in the D2 and D3 demand scenarios for the external walls of new dwellings, but only about 3 points if the substitution level is Small. The effect that these differences have on the EEI of the supply scenarios will allow evaluating whether deviations in demand significantly affect the performances of the alternative scenarios.

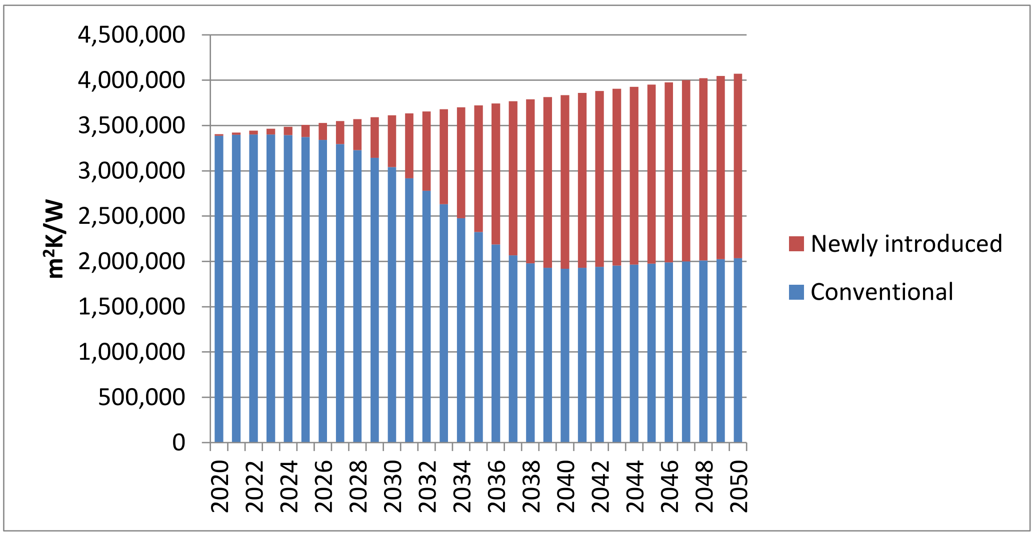


Figure 4. 33 – Medium level of substitution for demand scenario D1 for walls in new dwellings

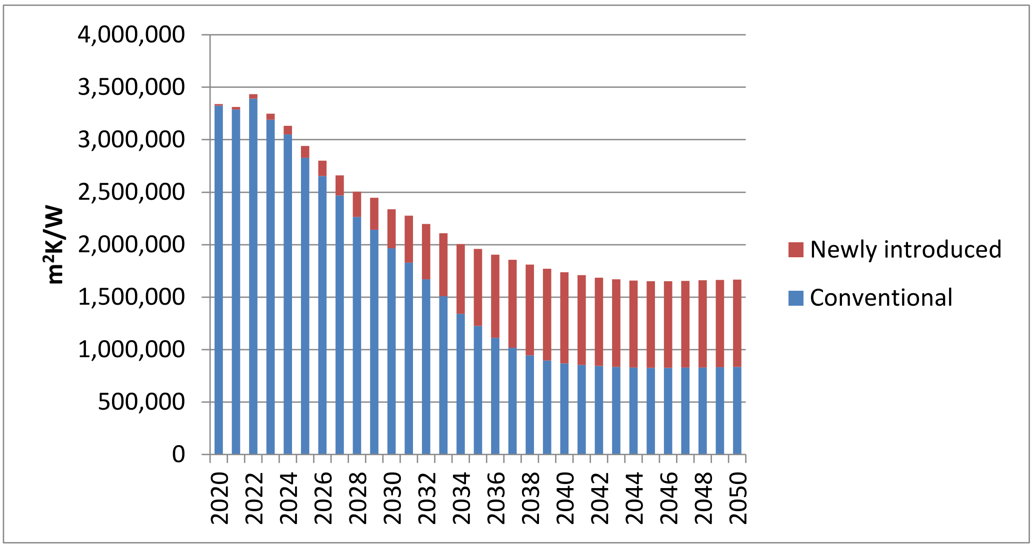


Figure 4. 34 - Medium level of substitution for demand scenario D2 for walls in new dwellings

Table 4. 19 - Total shares (%) of conventional products remaining at the end of the substitution in the alternative supply scenarios

Extent of substitution			**Small**	**Medium**	**Large**	**Very large**
Maximum substitution reached			25%	50%	75%	100%
Dwelling type	Envelope type	Demand scenario				
Retrofitted dwellings	EWI		83.2	67.5	52.2	37.1
	IWI		83.2	67.5	52.2	37.1
	LI		80.4	61.4	42.5	23.8
New dwellings	External walls	D1	83.9	68.7	54.0	39.4
		D2	86.9	75.0	63.4	52.1
		D3	83.6	68.1	53.0	38.2
		D4	86.5	74.1	62.2	50.5
	Roofs	D1 and D3	83.9	68.7	54.0	39.4
		D2 and D4	86.9	75.0	63.4	52.1
	Ground floors	D1	83.9	68.7	54.0	39.4
		D2	86.9	75.0	63.4	52.1
		D3	83.7	68.3	53.3	38.6
		D4	86.6	74.4	62.6	51.0

To simplify the analysis of results, demand scenario D1 is used as main reference to calculate and compare the EEI of the baseline and alternative supply scenarios, while the changes in EEI generated by the other demand scenarios (D2, D3 and D4) are assessed only as variations from the reference EEI of scenario D1. Similarly, in the assessment of the demand for natural resources for insulation products, D1 is used as the main scenario and the other three are only used to determine lowest and highest requirements for natural resources.

Finally, it must be noted that in the Mineral scenario (introducing glass wool and HD stone wool), part of the glass wool contained in the baseline is ‘replaced’ by the glass wool newly introduced by the substitution, and therefore no actual change takes place. This is necessary due to the method used to model product substitution in the market. In the discussion of results, this is interpreted as the Mineral scenario being more easily implemented than scenarios introducing biomass products, as it involves a smaller quantity of conventional products to be substituted. It should be also noted that the maximum market share reached by the totality of mineral products in the Mineral scenario is higher than the maximum share ‘declared’ by the level of substitution. For example, in the Small level of substitution newly introduced products reach 25% of the market. If mineral products are introduced by the substitution, these products reach a share of the market which is equal to 25% plus their original share, and minus the part that was substituted. Once calculations are made, it results that applying the Small level of substitution in the Mineral scenario equals to increasing the share of mineral products up to 25% of the market *originally occupied by non-mineral products* (PUR, EPS and phenolics).

4.3 Process-based LCA of insulation products

This section discusses the methods and data used to conduct the LCA of single insulation products, as introduced in section 3.2.3. Data sources and their limitations are introduced here as a whole, and successively presented individually for each product type (sections 4.3.1 to 4.3.8). The assessment of gate-to-site transportation is described in section 4.3.9. The procedures used for benchmarking, EEI variation and normalisation are discussed respectively in sections 4.3.11, 4.3.12 and 4.3.13. The resulting EEI figures for single insulation products are presented in section 4.3.14.

Data sources

This research does not contain original Life-Cycle Inventories (LCIs), but uses existing sources and introduces ad-hoc modifications for some products. Compiling original LCIs for all products studied would require surveying several manufacturers and accessing business-sensitive information. This was not considered feasible within the time and resource limits of this research. Since the aim of the research is not assessing the EEI of specific products but investigating large-scale potential for EEI reductions, existing LCA sources (reviewed in section

2.3.5) are considered of sufficient quality to provide representative EEI figures for product types. The main sources of LCA data are:

- GaBi Professional LCA database - used to:
    - generate LCA results for stone wool, glass wool, and EPS products from aggregated LCI datasets;
    - generate LCA results for transportation by truck and ship from aggregated LCI datasets;
    - generate LCA results for sheep wool and hemp fibre products on the basis of the disaggregated LCI provided by Norton (2008);
- PhD research by Norton (2008) - containing disaggregated LCI of sheep wool and hemp fibre;
- Agri-LCA model from Cranfield University (Williams et al., 2006) - providing values for the environmental impact caused by sheep raising, which is partially allocated to the sheep wool (modifying the LCI by Norton 2008);
- Data on industrial hemp farming inputs by van der Werf (2004) and Barth and Carus (2015) - used to modify the farming stage in the LCI by Norton 2008;
- Environmental Product Declarations (EPDs) - providing LCA results for PUR, phenolic foams and wood fibre products (in CML format) since no reliable aggregated or disaggregated LCI was found in the GaBi database and existing literature.

Impact of supply scenarios

The LCA sources listed above are used to calculate the average EEI of each product type for a Functional Unit (FU) of 1 m^2 with a thermal resistance of 1 m^2K/W. The EEI values are successively multiplied, product by product, by the number of FUs contained in the supply scenarios to generate the overall EEI of the supply of products. The assumption underlying this method is that the average impact of the FU can be scaled up to estimate the total impact of the supply scenarios. This is a standard practice in LCA studies: for example, the impact of a single brick might be scaled up to calculate the total impact of a brick wall. In this research it is applied at a large scale for the total supply of insulation product in Wales and over a time period of 30 years (2020 to 2050). However, this method has its limitations it does not take into account variations in impact associated with economies of scale and future changes in technology.

Using PEU as example, Equation 4. 5 and Equation 4. 6 describe how the total PEU impact of the baseline and alternative scenarios are calculated by summing the PEU of each product type modelled in the scenarios. In Equation 4. 5, the PEU per FU of each product ‘n’ is multiplied by the cumulative share that product ‘n’ occupies in the baseline scenario ‘B’. The results are summed and multiplied by the total demand, expressed in FUs (this process is equivalent to multiplying the PEU of product 'n' to the number of FUs of 'n' determined by baseline scenario 'B', and then adding the results for each product). Equation 4. 6 calculates the PEU of the newly introduced products in the same way, then adds it to the PEU of the remaining baseline products.

Equation 4. 5 – PEU of a generic baseline scenario 'B'

$$PEU_B = \frac{D}{100} * \left(\sum_{n=I}^{IX} PEU_n * MB_n \right)$$

With:

PEU_B = PEU of the baseline scenario 'B' (expressed in MJ)

D = total demand (expressed in m^2k/W)

PEU_n = PEU of product 'n' (expressed in $MJ/m^2k/W$)

MB_n = share of product 'n' in the scenario B

With condition: $0 \leq MB_n \leq 100$

With condition: $MB_I + MB_{II} + MB_{III} + MB_{IV} + MB_V = 100$

And 'n' as the index for the insulation products:

	Stone wool	Glass wool	PUR	EPS	Phenolic	Hemp fibre	Sheep wool	LD wood fibre	HD wood fibre
n	I	II	III	IV	V	VI	VII	VIII	IX

Equation 4. 6 - PEU of a generic alternative scenario 'A' substituted to the generic baseline scenario 'B'

$$PEU_{A,B} = S_R * PEU_B + (100 - S_R) * \frac{D}{100} * \left(\sum_{n=I}^{IX} PEU_n * MA_n \right)$$

$PEU_{A,B}$ = PEU of the alternative scenario 'A' substituted to the baseline 'B' (expressed in MJ)

S_R = total share of the remaining baseline after the substitution

MA_n = share of product 'n' in the alternative scenario A

With condition: $0 \leq MA_n \leq 100$

With condition: $MA_I + MA_{VI} + MA_{VII} + MA_{VIII} + MA_{IX} = 100$

And 'n' as the index for the insulation products (as above).

To calculate the other four impact categories, in Equation 4. 5 and Equation 4. 6 the terms PEU_B , $PEU_{A,B}$ and PEU_n are replaced with:

- GWP_B, $GWP_{A,B}$ and GWP_n for Global Warming Potential;
- AP_B, $AP_{A,B}$ and AP_n for Acidification Potential;

- EP_B, $EP_{A,B}$ and EP_n for Eutrophication Potential;
- $POCP_B$, $POCP_{A,B}$ and $POCP_n$ for Photochemical Ozone Creation Potential.

Using these equations, the baseline and alternative scenarios are associated with total EEI figures in each impact category, calculated by scaling up (i.e. summing) typical EEI figures for single products. Two significant assumptions are implied to do this:

- the potential diversity in the manufacturing processes of different companies which is likely to cause variations in EEI values is 'absorbed' by using data which is representative of the product type and is consistent with other LCA results for the same product type;
- the EEI of the products will not change significantly over the next 35 years due to changes in manufacturing process or energy mix for electricity production.

Both assumptions are simplifications of reality, but are necessary to keep the number of variables determining the EEI of the baseline and alternative scenarios within manageable limits for this research. The limitations of these assumptions are partially addressed using benchmarks and impact variations ~~(see sections 4.3.11 and 4.3.12).~~

With regards to manufacturing processes, it should be noted that conventional products are well established and in recent years manufacturers have been improving their processes to reduce EEI, thus it might be argued that major improvements are less likely to take place in the future. The same might be said for wood fibre, which has been produced in Germany for several decades, although not at the scale of mineral and plastic products. Some significant improvements in the manufacturing processes of sheep wool and hemp fibre could be expected, as these products are of more recent development and have not yet been produced at a scale comparable to that of conventional ones. In this research two improvements on sheep wool and hemp fibre are modelled by modifying the LCIs given in Norton (2008). ~~Details are given in sections 4.3.6 and 4.3.7.~~

In real conditions, differences in EEI as measured on the basis of the FU can also be caused by variations in thermal conductivity and density among different products of the same type, such as for example different brands of EPS. For most products thermal conductivity does not decrease linearly with increases in density (see section 2.3.5). Therefore thermal conductivity and density are key variables to calculate and compare LCA results. The values for thermal conductivity and density used in this research to calculate LCA results are considered to be adequate representative of product types, as they are taken from the LCA source and benchmarked against typical values obtained from the literature review and the survey of product prices.

LCA results obtained via aggregated LCI and EPD sources are affected by the energy mix of the geographic region modelled in the source. There is a limitation in the inability to change the energy mix for electricity chosen to model the manufacturing stages. Different energy mixes generate different EEI depending on the share of nuclear, thermal, renewable, etc. sources used in the production of electricity at the national level. In this research, sheep wool and hemp fibre manufacturing stages are modelled using UK energy mix to represent processes located in the UK. The aggregated LCIs for mineral products use an EU-27 average energy mix, while the EPD of PUR, phenolic foam and wood fibre products use German, French, Swiss and Dutch energy mixes (depending on the location of the manufacturing plant). Ideally, the UK energy mix should be used to represent manufacturing plants located in the UK for all products, since imports are a small fraction of domestic consumption (section 2.3.2). This was not possible due to limits in data sources and therefore in the EEI of conventional and wood fibre products there remains a component that is less accurate than for sheep wool and hemp fibre LCA. An analysis of the potential reductions of embodied GWP due to the future decarbonisation of the electricity supply is performed on the LCI for sheep wool and hemp fibre insulation in order to understand the potential effects on the results of the LCA.

Besides variety in manufacturing process and energy mix, comparing LCA results from different sources is problematic also due to possible differences in methods. Considering these limitations, evaluating the LCA results used in this research within the context of existing LCA sources serves two functions:

- it allows benchmarking and validating against existing examples the EEI figures used to assess the EEI of supply scenarios, reducing the degree of uncertainty associated with different manufacturers and different energy mixes;
- it provides figures of minimum and maximum EEI for those products whose LCA variations cannot be generated through sensitivity analysis, due to the format of the aggregated LCIs and EPDs. For sheep wool and hemp fibre it was possible to generate minimum and maximum EEI figures by modifying the LCIs. Details are given in sections 4.3.6 and 4.3.7.

Essentially, benchmarking and modelling EEI variations enable a partial evaluation of the uncertainties associated with using different LCA sources to represent average products in a series of large-scale scenarios.

The following sections (4.3.1 to 4.3.8) present the LCA sources for each insulation product type.

4.3.1 Stone wool insulation

LCA values for stone wool insulation are produced using the GaBi Professional aggregated LCI "EU-27 Rockwool PE", released by Thinkstep (2016a) and declared valid from 2013 to 2016. ~~Cut-off rules for each unit process are set to cover "at least 95% of mass and energy of the input and output flows, and 98% of their environmental relevance".~~ The LCI documentation specifies that it is valid for products with a density between 30 to 180 kg/m^3, but does not declare a thermal conductivity value. Literature (Table 2.2) and the survey of product prices (Appendix III) indicate a lambda of 0.035 W/mK and a density of 45 kg/m^3 to be representative values for most stone wool products. The resulting weight of the FU is 1.43 kg.

The same aggregated LCI from the GaBi database is used to obtain EEI figures for the HD version of stone wool introduced by the mineral scenario in combination with glass wool. Since all available evidence from existing studies and LCA sources indicates that environmental impact is directly proportional to the mass of material included in the product, it is sufficient to scale up (or down) the initial EEI figures obtained in proportion to the change in density. HD stone wool products are available in a range of densities (see section 2.3.3), however 90 kg/m^3 can be considered a representative value for the HD stone wool products in the lower density spectrum. The EEI figures used in this research to model HD stone wool (density 90 kg/m^3) are calculated by doubling the figures obtained for 1 FU of generic stone wool (density 45 kg/m^3) through the GaBi aggregated LCI.

4.3.2 Glass wool insulation

LCA values for glass wool insulation are taken from the EPD "Glass Mineral Wool Insulation with ECOSE® Technology" (Knauf, 2015) published by BRE for Knauf products (valid from 2015 to 2020) instead of the GaBi Professional aggregated LCI "EU-27 Glass wool PE" released by Thinkstep (2016a) (valid from 2013 to 2016). The Knauf EPD is preferred because it is made for products manufactured in the plants of St Helens, England, and Cwmbran, Wales, using the ECOSE binder (Knauf, 2015), which reduces the EEI (section 2.3.2 and 2.3.5). Therefore the Knauf EPD is considered a better option for the purpose of this research because it represents state-of-the-art technology for glass wool manufacture and refers to a plants using UK energy mix. Declared values of 0.039 W/mK and 15 kg/m^3 give a resulting weight of the FU of 0.59 kg.

4.3.3 Expanded Polystyrene (EPS) insulation

LCA values for EPS insulation are produced using the GaBi Professional aggregated LCI "EU-27 Expanded Polystyrene (PS30)" released by Thinkstep (2016a), and declared valid from 2015 to 2018. ~~Cut-off rules for each unit process are set to cover "at least 95% of mass and energy of the~~

~~input and output flows, and 98% of their environmental relevance".~~ The LCI documentation declares a density of 30kg/m^3 and thermal conductivity is not declared. However, the survey of product prices (Appendix III) actually indicates a density of 15 kg/m^3 and a lambda of 0.037 W/mK to be the representative values for most EPS products. Thus the lower density value of 15 kg/m^3 is chosen, and the LCI is scaled proportionally. The resulting weight of the FU is 0.55 kg.

4.3.4 Polyurethane rigid foam (PUR) insulation

LCA values for PUR insulation are taken from the EPD "(PU) board with aluminium facing" published by PU Europe (2014), declared valid from 2014 to 2019. This source is considered to be a better choice than the aggregated LCI available in GaBi Professional (Thinkstep, 2016a) for "Polyurethane Rigid Foam" (released by Plastics Europe and valid from 2005 to 2011) because the latter is older and does not include the aluminium facing, which is found in a large share of PUR products. The EPD by PU Europe is also preferred to the more recent EPD by IVPU from 2015 (which however displays very similar results) since the latter uses a German energy mix while the former refers to a European average. The declared values for thermal conductivity and density in the EPD are 0.023 W/mK and 34 kg/m^3. Literature and the survey of product prices (Appendix III) indicate these values to be representative for most PUR products. The resulting weight of the FU is 0.768 kg.

4.3.5 Phenolic foam insulation

The literature review shows that there is much less data available regarding the EEI of phenolic foam in comparison to most insulation products. The two significant sources for this product are:

- The LCA study by Densley Tingley et al. (2014), which uses the ILCD method, separating eutrophication into terrestrial, freshwater and marine, and thus cannot be fully compared to all the CML environmental impact categories.
- the EPD by Kingspan (2014) for the board "Kooltherm K5" (produced in Netherlands, valid from 2014 to 2019), which is compatible with the CML categories and thus suitable to be used in this research. The declared values for thermal conductivity and density in the EPD are 0.021 W/mK and 35 kg/m^3. The survey of product prices (Appendix III) indicates these values to be representative for most phenolic products. The resulting weight of the FU is 0.735 kg.

These two sources present very different EEI figures for a FU of phenolic foam, as shown in section 2.3.5. Overall, the Kingspan (2014) EPD is considered to be more reliable than the study by Densley Tingley et al. (2014), as the latter acknowledges that the research did not have access to an actual manufacturing plant.

4.3.6 Hemp fibre insulation

The LCA for hemp fibre insulation is calculated through GaBi software with a modified version of the LCI given in Norton (2008) which improves on the farming data and adapts the LCI to a hypothetical manufacturing plant located in Wales. The LCA is carried out for a product with thermal conductivity of 0.035 W/mK and a density of 35 kg/m^3 (Norton 2008). The survey of product prices (Appendix III) indicates these values to be representative for most hemp fibre products. The resulting weight of the FU is 1.365 kg.

The difficulty of conducting LCA of agricultural processes due to variation in inputs, climate, soil, etc. was discussed in section 2.3.5. Some of the generic datasets used by Norton (2008) to model the farming stage could not be accessed or replicated, thus additional literature was researched was identified to quantify farming inputs and outputs such as fertilisers and the emissions to soil due their use. The studies by van der Werf (2004) and Barth and Carus (2015) contain detailed data on industrial hemp farming and can be considered reliable sources. Table 4. 20 illustrates the variations of inputs (such as fertilisers and pesticides) and outputs (yield and emissions to soil). It can be noticed that there are several differences, particularly for quantities of fertilisers and yield. Considering these differences, it was preferred to compromise between these sources by choosing the median between the three figures given for each agricultural input, as shown in Table 4. 21.

Glyphosate is the most commonly used herbicide in the EU (European Commission, 2017), although a controversy has risen on its use since the International Agency for Research on Cancer classified this substance as “probably carcinogenic to humans” (category 2A) in 2015 (Cressey, 2015). In December 2017, the European Commission renewed the authorisation to use glyphosate in EU member states for another five years, following assessments by the European Food Safety Authority and the European Chemical Agency which did not find sufficient evidence to link this substance to cancer in humans (European Commission, 2017).

In addition, emissions to soil due to nitrogen fertilisers application (not included in Norton, 2008) are calculated following the “Tier 1 method - Emission factors for inorganic n-fertilisers” given in the Emission Inventory Guidebook 2013 (Hutchings et al., 2013) as follows:

- NH_3 (ammonia) 0.081 kg NH_3 per kgN applied;
- NO (nitric oxide) 0.26 kg NO per kgN applied.

Table 4. 20 – Comparison of inputs and outputs for industrial hemp farming per one hectare of cultivated land for a period of one year

	Source	Norton, 2008		van der Werf, 2004		Barth and Carus, 2015	
	Location	England		France		Europe	
		quantity per year	unit	quantity per year	unit	quantity per year	unit
Input	Seeds	not given		55	kg/ha	33 (+/-2)	kg/ha
Fertilisers	Nitrogen	100	kg N/ha	75	kg N/ha	100 (+/-25)	kg N/ha
	Phosphorus	30	kg P/ha	16.6	kg P/ha	32.7 (+/-2)	kg P/ha
	Potassium	30	kg K/ha	93.8	kg K/ha	83 (+/-21)	kg K/ha
	Lime	0	kg/ha	333	kg CaO/ha	200	kg CaCO$_3$/ha (for 5-6 years)
	Pig slurry, as organic alternative	not given		not given		22.5 (+/-2.5)	m^3/ha
Pesticides	Glyphosate	3	l/ha	0	kg/ha	2.6 (+/-2.6)	kg/ha
Field operations	Fuel use	(not applicable, data given in units of operation by hectare)		65	liters of diesel /ha	75	liters of diesel /ha
Yield		6	tonne retted straw /ha	6.7	tonne retted straw /ha	8.5	tonne retted straw /ha
Physical allocation	mass	fibre 29%, shives 66.7%, dust 4.3%		not given		fibres 28%, shives 55%, others (mostly dust) 17%	
Emissions	N2O- (nitrous oxide)	not given		not given		1	% of applied N
	NH3 (ammonia)	not given		not given		0.02	kg NH$_3$-N per applied kg N
	NO3 (nitrate) to ground water	not given		40	NO$_3$-N /ha per year	not given	

Table 4. 21 – Explanation of agricultural input chosen for the LCI of hemp fibre

Agricultural inputs	Explanation
Nitrogen: 100 kgN/ha per year	Median between 75 kgN in van der Werf (2004), 100 kgN in Norton (2008), and 100 (+/-25) kgN in Barth and Carus (2015);
Phosphorus: 30 kgP/ha per year	Median between 16.6 kgP in van der Werf (2004), 30 kgP in Norton (2008), and 32.7 kgP in Barth and Carus (2015);
Potassium: 83 kgK/ha per year	Median between 30 kgK in Norton (2008), 93.8 kgK in van der Werf (2004) and 83 kgK in Barth and Carus (2015);
Lime: 200 kgCaO/ha per year	Median between 0 kgCaO/ha in Norton (2008), 200 kgCaO/ha in Barth and Carus (2015) and 333 kgCaO/ha in van der Werf (2004)
Glyphosate: 2.6 liter/ha per year	Median between 3 liters in Norton (2008), 0 liters in van der Werf (2004) and 2.6 (+/-2.6) liters by Barth and Carus (2015).
Field operations: 70 liters of diesel /ha per year	Median between 65 liters in van der Werf (2004) and 75 liters in Barth and Carus (2015);
Yield: 6.7 tonnes of retted straw /ha per year,	Median between 6 tonnes in Norton (2008), 6.7 tonnes in van der Werf (2004) and 8.5 tonnes in Barth and Carus (2015).

The impact attributed to hemp straw farming and its transportation is allocated economically between the two main co-products, i.e. fibre and shives. Accessible data on prices is scarce but Carus et al. (2013) indicate that the price per kg of fibre is about twice the price of shives. Combining this figure with the composition of hemp straw given by Norton (2008) as 29% fibre and 66.7% shives, the resulting economic allocation is 46.5% to fibre and 53.5 to shives (Table 4. 22).

Table 4. 22 – Economic allocation for hemp fibre and shives (based on data from Carus et al. 2013)

	Product	Mass (kg)	Ratio (cost/kg)	Percentage allocation (%)
Input	Hemp straw	1.45		
Outputs	Hemp fibre	1	2	46.5
	Hemp shives	2.3	1	53.5
	Dust	0.15		

Table 4. 23 shows the LCI used to conduct the LCA to produce one FU of hemp fibre insulation. Besides the farming stage, other modifications are made on the original LCI by Norton (2008):

- The original LCI is based on output from a French company. The product includes a large share of recycled cotton fibres due not to a technological requirement but to the proximity of the recycling plant and the low cost of this material. In the modified LCI the cotton fibres are replaced by the author with an equal amount of hemp fibres, since a hypothetical plant located in Wales would not need to include recycled cotton fibres.

- The original LCI contains a small share of plastic fibres which is necessary to ensure stiffness and cohesion in the product, although this material results in a significant environmental impact. Norton (2008) and Haufe and Carus (2011) identified a potential bio-plastic alternative in polylactid acid (PLA) fibres. This product is available on the market, and therefore is used by the author to replace the plastic fibre in the modified LCI.
- The length of transportation trips and the energy mix for electricity production are modified to model a hypothetical plant located in Wales, while the original processes are located in France and England.

Table 4. 23 - LCI used to calculate EEI of hemp fibre insulation, output = 1 FU

Stages		Flow	Quantity	Unit	Reference
Farming	Inputs	Ammonium nitrate (N fertiliser, 33.5% N)	0.0657	kg	van der Werf, 2004; Norton, 2008; Barth and Carus, 2015
		Transport (N fertiliser to farm)	50	km	author's assumption
		Triple superphosphate (P fertiliser, 46% P205)	0.0146	kg	van der Werf, 2004; Norton, 2008; Barth and Carus, 2015
		Transport (P fertiliser to farm)	50	km	author's assumption
		Potassium chloride (K fertiliser, 60% K20)	0.0292	kg	van der Werf, 2004; Norton, 2008; Barth and Carus, 2015
		Transport (K fertiliser to farm)	50	km	author's assumption
		Limestone flour (CaCO3)	0.0438	kg	van der Werf, 2004; Norton, 2008; Barth and Carus, 2015
		Transport (limestone to farm)	50	km	author's assumption
		Diesel use for agriculture	0.014	kg	Barth and Carus, 2015
		Carbon dioxide	-2.56	kg	Barth and Carus, 2015
	Outputs	Hemp straw (retted, yield 7 tonnes/ha per year)	1.53	kg	van der Werf, 2004; Norton, 2008; Barth and Carus, 2015
		Glyphosate	0.000547	kg	Barth and Carus, 2015
		Ammonia (from N fertiliser)	0.00177	kg	Emission Inventory Guidebook, 2013
		Nitric oxide (Nitrogen monoxide)	0.000569	kg	Emission Inventory Guidebook, 2013
Fibre manufacture	Inputs	Hemp straw	1.53	kg	van der Werf, 2004; Norton, 2008; Barth and Carus, 2015
		Transport (hemp straw to plant)	100	km	author's assumption
		Electricity	2.97	MJ	Norton, 2008

		Flow	Quantity	Unit	Reference
	Outputs	Hemp fibre	0.955	kg	Norton, 2008
		Hemp shives (by-product)	2.2	kg	Norton, 2008
		Dust (by-product)	0.14	kg	Norton, 2008
Insulation manufacture	Inputs	Hemp fibre	0.955	kg	Norton, 2008
		Transport (hemp fibre to plant)	100	km	author's assumption
		Electricity	0.737	MJ	Norton, 2008
		Thermal energy	11.4	MJ	Norton, 2008
		Flame retardant (ammonium phosphate based)	0.205	kg	Norton, 2008
		Transport (Pflame retardant to plant)	150	km	author's assumption
		Ingeo Polylactide (PLA) by NatureWorks	0.205	kg	Norton, 2008 +author's assumption
		Transport (PLA to plant)	200	km	author's assumption
	Outputs	Hemp fibre insulation	1.365	kg	Norton, 2008

4.3.7 Sheep wool insulation

The LCA for sheep wool insulation is calculated using GaBi software with a modified version of the LCI given in Norton (2008) to include the impact of the sheep raising stage and to adapt the LCI to a hypothetical manufacturing plant located in Wales. The LCA is carried out for a product with thermal conductivity of 0.035 W/mK and a density of 25 kg/m^3, as in Norton (2008). The price survey (Appendix III) indicates these values to be representative for most sheep wool products. The resulting weight of the FU is 0.975 kg.

In the LCA by Norton (2008) the impact of sheep raising for meat production is completely allocated to the meat product. As discussed in section 2.3.5, this can be justified because the low-quality wool used in insulation is produced by animals raised purely for meat production. Thus the wool is a by-product of the meat sector, and would not be produced without the latter. However, the wool does have a commercial value, albeit a low one, and the large number of sheep raised in Wales does have a significant environmental impact. Since this research is concerned with the impact of supply at the large scale, the allocation of the impact of the sheep raising stage is further investigated to be taken into account in the LCA of the insulation product.

The percentages of economic allocation between meat and wool are calculated at the regional scale for the years 2006 to 2015, as shown in Table 4. 24. Data from Welsh Agricultural Statistics (Welsh Government, 2016c) is used to obtain the prices paid to producers for the totality of sheep meat and wool produced in Wales each year. As can be seen, the economic value of the meat is significantly higher than wool, so the impact of sheep raising which can be allocated to the wool ranges between 0.9% and 3.1%, a small proportion of the overall impact. The average proportion of economic value over the 2006 to 2015 period is 2%, and this value is used in the LCI of the sheep wool product.

The calculations in Table 4. 24 are based on 20 kg of ‘deadweight’ per animal, which is the average for upland lambs given in the Agri-LCA model (Williams et al., 2006), developed at Cranfield University to investigate the impact of agricultural and horticultural production in the UK. *Deadweight* refers to the mass of the animal after the first stage of butchering. Figures for the environmental impact caused by sheep farming (per tonne of deadweight meat) taking into account the whole UK sector are provided by this model.

Table 4. 25 shows that these impact figures can be multiplied to the average 2006-2015 deadweight production in Wales (7,747 tonnes) and successively allocated to meat (98%) and wool (2%) based on the calculations in Table 4. 24.

The LCI used in this research to conduct the LCA for the production of one FU of sheep wool insulation is shown in Table 4. 26. Besides the addition of the sheep farming stage, other modifications are made on the original LCI by Norton (2008):

- As in the case of hemp fibre, the original LCI contains a small share of plastic fibres necessary to ensure stiffness and cohesion in the product. These are replaced in the modified LCI by polylactid acid (PLA) fibres as discussed previously for hemp fibre.
- The length of transportation trips are modified to model a hypothetical plant located in Wales, while the original LCI processes are based in England.

Table 4. 24 – Data and process used to determine the economic allocation of sheep farming between sheep wool and meat in Wales (*=meat produced in Wales but the animals might come from outside Wales). All original figures (a, b, d, e, g, m) taken from Welsh Agricultural Statistics (Welsh Government, 2016c)

		Units	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average
a	Total greasy wool production	tonnes	10,000	8,800	8,000	7,901	7,200	7,400	7,800	8,300	7,400	7,600	8,040
b	Wool valuation to producers	1000£	4,700	2,700	2,700	2,400	3,200	7,200	9,300	6,200	7,300	7,500	
c	Wool price to producers (c=b/a)	£/kg	0.47	0.31	0.34	0.30	0.44	0.97	1.19	0.75	0.99	0.99	0.67
d	Livestock meat production*	tonnes	82,613	79,952	81,153	70,975	65,514	69,016	61,512	62,142	64,196	64,672	
e	Marketing sheep and lamb value	1000£	196,064	177,457	193,980	232,845	244,460	295,588	257,991	254,278	254,278	254,278	

			Units	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
f	Deadweight meat value (f=e/d)	£/kg	2.37	2.22	2.39	3.28	3.73	4.28	4.19	4.09	3.96	3.93	
g	Livestock slaughter	1000 animals	4,556	4,280	4,576	3,929	3,621	3,816	3,462	3,356	3,395	3,377	
h	Corresponding deadweight meat (h=g*20kg)	tonnes	91,136	85,616	91,526	78,584	72,436	76,338	69,256	67,128	67,904	67,546	76,747
i	Total deadweight meat value (i=h/f)	1000£	216,291	190,029	218,775	257,809	270,288	326,947	290,472	274,681	268,965	265,577	
l	Ratio kg greasy wool/kg deadweight (l=a/h)		0.11	0.10	0.09	0.10	0.10	0.10	0.11	0.12	0.11	0.11	
m	Marketing sheep and lamb	1000 animals	4,554	4,434	4,579	4,429	4,515	4,707	4,352	4,438	4,376	4,321	
n	Wool valuation (n=b*100/(b+i))	%	2.1	1.4	1.2	0.9	1.2	2.2	3.1	2.2	2.6	2.7	2.0
o	Meat valuation (o=i*100/(b+i))	%	97.9	98.6	98.8	99.1	98.8	97.8	96.9	97.8	97.4	97.3	98.0

Table 4. 25 – Environmental impact of the sheep raising stage allocated to meat and sheep wool

Impact categories	**Impact of sheep raising stage per 1 tonne deadweight (source: Agri-LCA model, Williams et al., 2006)**	**Total annual impact of sheep raising in Wales**	**Impact allocated 98% to meat, 2% to wool**		**Units**
			per kg of meat	**per kg of wool**	
PEU	25,188	1,933,111,156	24.692	**4.735**	MJ
GWP	16,823	1,291,082,063	16.491	**3.162**	kg CO2eq
AP	99	7,621,320	0.097	**0.019**	kg SO2eq
EP	116	8,914,176	0.114	**0.022**	kg PO4eq
POCP	-0.663	-50,879	-6.499E-04	**-1.246E-04**	kg ethene eq

Table 4. 26 - LCI used to calculate EEI of sheep wool insulation, output = 1 FU

Stages		**Flow**	**Quantity**	**Unit**	**Reference**
Sheep raising	Inputs	/	/	/	AgriLCA model (Williams et al 2006)
	Outputs	Impact per kg of greasy wool (from in Table 4. 25) scaled to 0.977 kg			
Wool scouring	Inputs	Greasy wool	0.977	kg	Norton 2008
		Transportation (greasy wool to plant)	150	km	author's assumption
		Electricity	0.881	MJ	Norton 2008
		Thermal energy	2.82	MJ	Norton 2008
		Fatty alcohol sulphate	0.0085	kg	Norton 2008
		Borax	0.0723	kg	Norton 2008
		Water	6.07	kg	Norton 2008
	Outputs	Clean wool	0.85	kg	Norton 2008
Sheep wool insulation manufacture	Inputs	Clean wool	0.85	kg	Norton 2008
		Transportation (clean wool to plant)	50	km	author's assumption
		Electricity	2.09	MJ	Norton 2008
		Thermal energy	0.94	MJ	Norton 2008
		Ingeo Polylactide (PLA) by NatureWorks	0.15	kg	Norton 2008 +author's assumption
		Transport (PLA to plant)	200	km	author's assumption
	Outputs	Sheep wool insulation	1	kg	Norton 2008
		Dust	0.1	kg	Norton 2008

4.3.8 Wood fibre insulation

In the review of LCA studies (section 2.3.5) no sources providing a disaggregated LCI for wood fibre insulation could be found. An aggregated LCI for “EU-27 Lightweight wood fiber panels”, released by Thinkstep (2016a) and valid from 2015 to 2018, is contained in the GaBi Professional database. The quality of this source is unclear, because the LCI documentation declares a density of 360 kg/m3, which is incompatible with a “lightweight” product, and the LCI itself does not seem to account for carbon sequestration in timber. It is also unclear if the figures of this LCI can be scaled down to model products with a lower density. Therefore wood fibre EPDs (see section 2.3.5) are considered better choices as a data source for this research. The EEI figures used in the model are obtained by averaging the EPDs results, for LD and HD products separately, on the basis of the FU. This procedure is similar to the one used by Hammond and Jones (2008) to provide reference values of embodied energy and carbon in construction products.

Low-Density (LD) wood fibre

Two EPD certificates are used to obtain EEI figures for LD wood fibre:

- The EPD for Pavaflex (dry process) is valid from 2014 to 2019 and refers to a product manufactured in Germany with a density of 55 kg/m3 and a thermal conductivity of 0.038 W/mK (Pavatex, 2014a). Wood content is minimum 80% of the product, with the rest being water (4-8%), plastic fibres (3-8%) and flame retardant (6-8%). In comparison to all other wood fibre EPDs, only this one shows a small but positive value in GWP. The EPD states that carbon sequestration in timber is taken into account, thus the difference with the GWP figures of all other wood fibre EPD might be related to the manufacturing process. However, the EPDs for HD products by the same manufacturer also show negative GWP values (i.e. beneficial), therefore the high embodied carbon of the Pavaflex EPD (Pavatex, 2014a) cannot be easily explained.
- The EPD for generic Steico products (wet and dry process) is valid from 2016 to 2021 and refers to a product manufactured in France with density between 50 and 256 kg/m^3 and a thermal conductivity of 0.038 W/mK (Steico, 2016). Wood content is at 82%, and together with water (6%), plastic fibres (1.3%) and flame retardant (2.4%), the Steico product also contains recycled paper (6.3%). The EPD states that its results are calculated for a density of 157.5 kg/m3, and that results for products with different densities can be extrapolated on a mass basis.

A comparison of the LCA results (on a FU basis) from the two available EPDs for LD wood fibre is shown in Figure 4. 35. The main differences between the two products can be found in the values for AP and especially GWP as discussed above. Averages between these figures are calculated for this research with a thermal conductivity of 0.038 W/mK and a density of 55 kg/m3. The survey of product prices (Appendix III) indicates these values to be representative for most LD wood fibre products. The resulting weight of the FU is 2.09 kg.

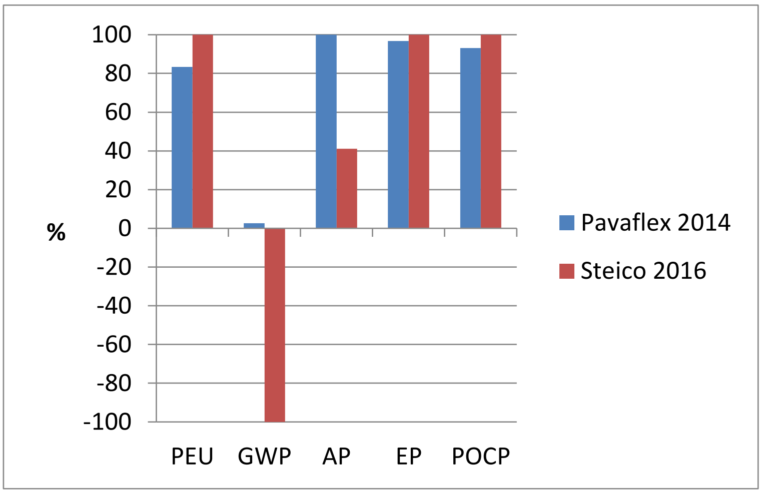


Figure 4. 35 – Comparison between EEI figures for LD wood fibre from EPDs based on 1 FU

High Density (HD) wood fibre

Three EPD certificates are used to obtain EEI figures for HD wood fibre:

- The EPD for Pavatex products (dry process) is valid from 2014 to 2019 and refers to products manufactured in France with density between 110 and 210 kg/m^3, with the results calculated for 210 kg/m^3 (Pavatex, 2014b). The EPD for Pavatex products (wet process) is valid from 2014 to 2019 and refers to products manufactured in Germany with density between 135 and 200 kg/m^3, with the results calculated for 140 kg/m^3 (Pavatex, 2014c). Both products have a thermal conductivity of 0.044 W/mK and a wood content between 89% and 98% of the product, with the rest being paraffin and other chemical compounds.
- The EPD for generic Gutex products (dry process) is valid from 2015 to 2020 and refers to products manufactured in Germany with density between 80 and 250 kg/m^3, with the results calculated for 173 kg/m^3, and thermal conductivity of 0.042 W/mK (Gutex, 2015). Wood content is between 93% and 98% with the rest being paraffin and other chemical compounds.
- The EPD for generic Steico (2016) products (wet and dry process) has been described previously for LD products.

A comparison of LCA results (on a FU basis) for the available EPDs for HD wood fibre is shown in Figure 4. 36. The Pavatex and Gutex products display similar results while the Steico product shows significant higher impact in all categories except GWP. Wood waste is incinerated and allocation is carried out on the basis of the energy value in all EPDs except for Gutex

where allocation is on a mass basis, which might explain the higher impact of this product Averages between these figures are calculated for this research with a thermal conductivity of 0.04 W/mK and a density of 160 kg/m^3. The survey of product prices (Appendix III) indicates these values to be representative for most HD wood fibre products. The resulting weight of the FU is 6.4 kg.

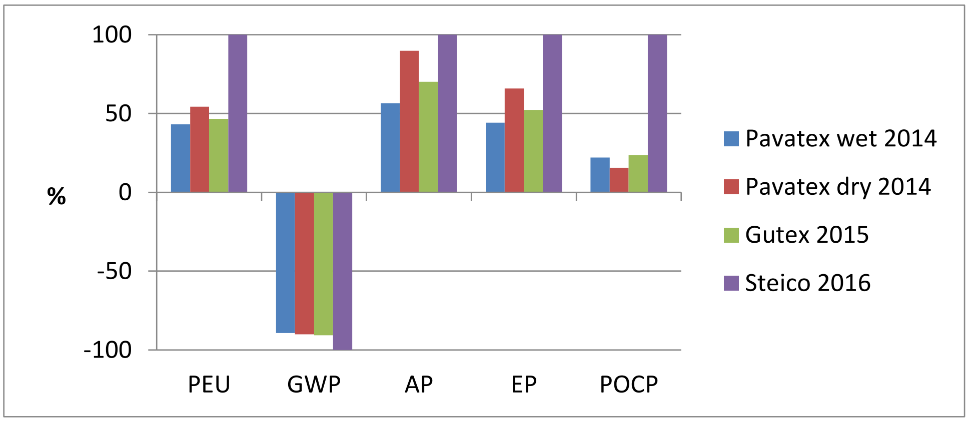


Figure 4. 36 - Comparison between EEI figures for HD wood fibre from EPDs based on 1 FU

4.3.9 Gate-to-site transportation

The environmental impact caused by the gate-to-site transportation is calculated separately to distinguish its contribution from the previous stage of life-cycle. Two aggregated LCI datasets from the GaBi Professional database are used to model transport by road and by sea.

Transport by road is modelled considering a typical medium sized truck with maximum payload of 24,700 kg and a maximum volume of 90 m^3 and using the relative GaBi LCI "GLO Truck" released by Thinkstep (2016a) and valid from 2015 to 2018. As insulation products are light but bulky materials, they can fill the cargo space well before reaching the maximum payload. The ratio between the actual weight of the cargo and the maximum payload is called *utilisation factor* and its value has an effect on the emissions from the truck. The utilisation factors calculated for each product are show in Table 4. 27. It can be noticed that the lowest utilisation factor (5.5%) corresponds to products with low density such as glass wool and EPS, while the highest (59.3%) corresponds to the product with the highest density, namely HD wood fibre.

Table 4. 27 – Calculation of utilisation factor for gate-to-site transportation of insulation products

	Number of FU in 1 m^3	Max number of FU in truck	Corresponding weight	Utilisation factor
	m^2K/W	m^2K/W	kg	%
Stone wool	28.6	2,571	4,050	16.4
Glass wool	25.6	2,305	1,350	5.5
PUR	43.5	3,913	3,005	12.2
EPS	27.0	2,432	1,350	5.5
Phenolic	47.6	4,286	3,150	12.8
Hemp fibre	28.6	2,571	3,510	14.2
Sheep wool	28.6	2,571	2,507	10.2
LD wood fibre	26.3	2,368	4,950	20.0
HD wood fibre	25.0	2,250	14,400	58.3

About 10% of the insulation products used in the UK are imported from abroad (OFT, 2012a). To take into account this factor, 10% of the gate-to-site transport of products is modelled assuming that it is imported from Europe by ship. Transport by ship is modelled considering a large carrier and using the GaBi LCI "E_27 Bulk carrier ocean going" released by Thinkstep (2016a) and valid from 2013 to 2016. This excludes stone wool and biomass products as:

- the location of the Rockwool plant in Wales means a lower likelihood of the product being imported from abroad;

- biomass products are modelled on the hypothesis that they can be entirely manufactured and sourced in Wales.

Since this research models a large-scale supply of products, it would be meaningless to calculate transportation distances for specific locations. Instead, rough figures for travel lengths are assumed to represent average distances for product transportation. Table 4. 28 shows the travel lengths for truck and ship transport used to calculate the EEI per FU unit of product. As a reference, Wales extends for about 200 km from North to South. Therefore a manufacturer located in central Wales would have most of the region within a linear radius of 100 km, which is the figure chosen for manufacture to retail distance.

Table 4. 29 shows the resulting EEI figures for the gate-to-site transportation of products on a FU basis. It can be noticed that the highest impact is associated to glass wool and HD wood fibre, which might be due to low utilisation factor (for glass wool) and high weight (for HD wood fibre). The lowest EEI figures, about 50% lower than the highest, are associated with PUR and phenolic products. Negative POCP figures are due to the controversial CML characterisation discussed earlier (see section 3.2.3).

Table 4. 28 – Calculation of travel lengths for truck and ship used to model gate-to-site transportation of insulation products

Share of product imported from outside UK (%)		**Domestic transport (km)**		**Import transport (km)**				**Total km per kg of product transport**	
		manufacture to retail	retail to site	manufacture to port	port to port (by ship)	port to retail	retail to site	total truck	total ship
Stone wool	0	100	50	/	/	/	/	150	0
Glass wool	10	100	50	150	500	150	50	170	50
PUR	10	100	50	150	500	150	50	170	50
EPS	10	100	50	150	500	150	50	170	50
Phenolic	10	100	50	150	500	150	50	170	50
Hemp fibre	0	100	50	/	/	/	/	150	0
Sheep wool	0	100	50	/	/	/	/	150	0
LD wood fibre	0	100	50	/	/	/	/	150	0
HD wood fibre	0	100	50	/	/	/	/	150	0

Table 4. 29 – EEI of gate-to-site transportation per 1 FU of insulation product

	PEU	GWP	AP	EP	POCP
	MJ	kg CO2eq	kg SO2eq	kg PO4eq	kg ethene eq
Stone wool	0.74718424	0.050357286	4.34411E-05	8.4435E-06	-3.4651E-07
Glasswool	1.01482904	0.068432316	5.98089E-05	1.1717E-05	-7.57E-07
PUR	0.50922909	0.034328418	2.979E-05	5.8111E-06	-3.013E-07
EPS	0.77023352	0.05195175	4.56805E-05	8.9811E-06	-6.7632E-07
Phenolic	0.45516041	0.030681242	2.65772E-05	5.1787E-06	-2.5165E-07
Hemp fibre	0.67709325	0.045635996	3.94223E-05	7.6688E-06	-3.3398E-07
Sheep wool	0.65972856	0.044480264	3.87323E-05	7.571E-06	-4.3932E-07
LD wood fibre	0.75758553	0.05103795	4.36E-05	8.4236E-06	-1.9313E-07
HD wood fibre	1.0478373	0.070447208	5.71315E-05	1.0673E-05	8.5885E-07

4.3.10 Assessment of end-of-life disposal options

The end-of-life stage of the insulation products is assessed by adopting the 'recycled content' approach and establishing typical shares of disposal options for each product, as described in section 3.2.3. The shares of each product are shown in Table 4. 30 together with references to the information used to identify those shares (when such data is available) and to the LCA sources used to produce LCA results for incineration with energy recovery and landfilling. In the case of PUR, EPS and wood fibre, specific LCA values for landfilling and /or incineration were not available, thus aggregated LCI in the GaBi database (Thinkstep, 2016a) for generic plastic and wood products were used as proxies. Since the 'recycled content' approach excludes the impact of recycling, LCA values for this option are not required.

Limited information was found about the typical shares of disposal options therefore some assumptions were necessary, considering also that the chosen shares should represent an 'average' condition for the period 2020-2050, and thus take into account that recycling rates will probably increase or at least remain at current levels due to legislative pressure. DEFRA estimated that in 2014 about 90% of non-hazardous construction and demolition waste in the UK was recovered (which includes recycling and reuse in various applications). (DEFRA, 2018). However, most of this waste is constituted by aggregates, whilst insulation generally makes up a very small percentage (about 1%) of all demolition waste (WRAP, 2009). WRAP (2008) acknowledged that estimating C%D waste streams in detail is difficult due to the lack of data, and estimated 12% as the 'standard' share of recycling insulation waste, and 50% for 'good practice'. Beside pressure from regulations, the disposal of insulation waste from retrofit/demolition is affected by cost of landfilling versus the cost of separating the waste for recycling or incineration (Hobbs and Ashford, 2013).

For both mineral products, all sources indicate landfilling as the main disposal option. While some degree of recycling is taking place, a specific share was not found. Considering that there are several options for recycling mineral wool products (Väntsi, O. & Kärki 2014) and that both Rockwool and Knauf accept waste material as input for new products (Hobbs and Ashford, 2013), the recycling share for both stone and glass wool for the period 2020 to 2050 is assumed as the ‘standard’ share estimated by WRAP (2008), i.e. 12%.

In the case of PUR insulation, data from 2008 indicates typical disposal practices in the UK for PUR waste arising *from manufacturing and installation*: landfilling (71%), incineration (20%), re-use (7%) and mechanical/chemical recycling (2%) (Consultic, 2008, in Hobbs an Ashford, 2013). Since separation of waste arising *from retrofit and demolition* is more generally difficult than in the case of waste arising from manufacturing and installation, and that recovering PUR waste from demolition is economically viable only in some areas of the UK (Hobbs an Ashford, 2013), it is possible that the shares of PUR waste from retrofit and demolition being re-used or recycle are lower than those indicated above. However, it is assumed that for the period 2020 to 2050 the recycling share of PUR insulation waste will reach to the ‘standard’ share estimated by WRAP (2008), i.e. 12%.

According to the project LIFE-PSLOOP (2017) at European level 52% of EPS insulation is incinerated with energy recovery, 40% is landfilled or incinerated without energy recovery, and only 7.5% is recycled. Considering that an increase in the rates of recycled EPS is likely to be encouraged by legislation, for the period 2020 to 2050 the recycling share of EPS insulation waste in the UK is assumed as the ‘standard’ share estimated by WRAP (2008), i.e. 12%. It is also assumed that all incineration of EPS will take advantage of energy recovery, reaching a share of 60%.

No specific information was found to identify the shares of disposal options for phenolic foam insulation waste, except for the EPD by BRE (2018) for 'Kingspan Kooltherm K5' boards, where the typical end-of-life phase of phenolic insulation is modelled as 89.5% as landfilling, 9.5% as incineration with energy recovery and only 1% as recycling. It is assumed that in the period 2020-2050 the share of recycled phenolic insulation in the UK will rise to at least ½ of the ‘standard’ share estimated by WRAP (2008), while the proportion between landfilling and incineration are maintained as in BRE (2018).

All three types of biomass products studied in this research can be recycled, landfilled incinerated (with heat recovery) or composted (see section 2.3.3), but no specific shares were identified. The recycling share for the period 2020-2050 is assumed at 12%, as the ‘standard’ share estimated by WRAP (2008). Norton (2008) identifies landfilling to be the most likely option for both hemp fibre and sheep wool insulation waste, considering it the typical practice for insulation waste in the UK. However, it is probable that legislative pressure (including possible rises of taxes on landfilled waste) will make incineration with heat recovery more popular. Thus the share of hemp fibre and sheep wool insulation waste which is not recycled is assumed to be divided equally between incineration with heat recovery and landfilling. In the case of wood fibre insulation, landfilling is not excluded but incineration with heat recovery appears to be the more likely option, as it is also modelled as the typical end-of-life scenario in all wood fibre EPDs. Thus two-thirds of the share of wood fibre insulation waste which is not recycled is assumed to be incinerated, and while the remaining one-third is landfilled. Although manufacturers claim that biomass insulation products are compostable due to their organic nature, the presence of plastic fibres and/or chemical additives in these products raises the question of its technical feasibility, as noted by Duijve (2012). In fact, no practical examples of composting biomass insulation products were found in the available sources, thus this option is not modelled in this research.

	Recycling	**Incineration with energy recovery**	**Landfilling**	**References for typical shares**	**References for incineration with energy recovery LCA values**	**References for landfilling LCA values**
Stone wool	12%	0%	88%	WRAP, 2008	/	IBU, 2016b
Glass wool	12%	0%	88%	WRAP, 2008	/	IBU, 2014e
PUR	12%	19%	69%	WRAP, 2008; Consultic, 2008, in Hobbs an Ashford, 2013	PU Europe, 2014	Aggregated LCI for landfilling of generic plastic product, in GaBi database (Thinkstep, 2018)
EPS	12%	60%	28%	WRAP, 2008; LIFE-PSLOOP, 2017	Aggregated LCI for incineration of generic plastic product, in GaBi database (Thinkstep, 2016a)	Aggregated LCI for landfilling of generic plastic product, in GaBi database (Thinkstep, 2016a)
Phenolic	6%	0%	94%	WRAP, 2008; BRE, 2018a	BRE, 2018a	BRE, 2018a
Hemp fibre	12%	44%	44%	WRAP, 2008; author's assumptions	Norton, 2008	Norton, 2008
Sheep wool	12%	44%	44%		Norton, 2008	Norton, 2008
Wood fibre (LD and HD)	12%	59%	29%		For wood fibre LD: Pavatex, 2014a; Steico, 2016 For wood fibre HD: Gutex, 2015; Steico, 2016	Aggregated LCI for landfilling of generic wood product, in GaBi database (Thinkstep, 2016a)

Table 4. 30 – Typical shares for end-of-life disposal options of insulation products

Table 4. 31 shows the LCA values resulting from the assessment of the end-of-life stage of the insulation products. These are compared and discussed together with the other results for the single product LCA (section 4.3.14).

	Unit	Stone wool	Glass wool	PUR	EPS	Phenolic	Hemp fibre	Sheep wool	Wood fibre LD	Wood fibre HD
PEU	MJ	7.999E+00	4.347E-01	1.681E-01	2.176E-05	1.560E-01	8.408E-05	6.006E-05	8.485E-05	2.598E-04
GWP	kg CO2eq	5.368E-01	3.234E-02	3.751E-01	2.429E-01	6.138E-03	4.950E-01	4.926E-01	4.701E+00	8.390E+00
AP	kg SO2eq	3.414E-03	2.457E-04	2.686E-04	3.428E-04	4.296E-05	6.285E-04	3.865E-04	2.972E-04	9.106E-04
EP	kg PO4eq	4.664E-04	5.280E-05	2.784E-04	8.222E-05	1.410E-05	1.996E-03	1.496E-03	1.177E-03	3.605E-03
POCP	kg ethene eq	2.138E-04	3.142E-05	1.979E-05	1.780E-05	6.204E-06	1.759E-04	1.109E-04	2.001E-04	6.129E-04

Table 4. 31 – LCA results for the end-of-life stage of 1 FU of insulation products (1 m^2K/W)

4.3.11 Benchmarking EEI against LCA sources

In this section the EEI figures chosen to be used in the model are compared on a FU basis to EEI figures found in LCA studies. This replicates in part the information shown in section 2.3.5, but here the focus is on evaluating the chosen LCA sources as adequate representatives of product types. As a general rule, for the purpose of this research an LCA source is considered an adequate representative if the resulting EEI figures:

- are within minimum and maximum values found in existing LCA sources for *all* of the five impact categories, and
- are within typical ranges, i.e. ranges established by recurring values in LCA sources, for *most* of the five impact categories.

Some exceptions are made for specific cases, as discussed in the next pages for each product type. In particular, EEI figures of conventional products falling in the lower spectrum of the range identified by existing sources are considered particularly adequate, as they can represent good state-of-the-art products. Given that the EEI figures used in this research are meant to model products supplied until 2050, for conventional products it is reasonable to select representatives with relatively low EEI, as these are more likely to constitute a large part of future supply.

Stone wool

Stone wool products are manufactured at different density, which directly affects the EEI per FU. HD stone wool provides rigidity and/or compressive strength, whereas LD stone wool is preferred for broader applications. In this research, a medium-low density product is used to represent conventional stone wool in the baseline scenarios, while a HD product is used in the

Mineral alternative scenario (in combination with glass wool). The same LCA source (GaBI aggregated LCI, by Thinkstep, 2016a) is used to model both products, but the impact is scaled in proportion to material density per FU.

The EEI figures used in this research to represent conventional stone wool insulation are compared (on a FU basis) to the results found in the available sources in Appendix V. In all impact categories the results of the GaBI aggregated LCI are within minimum and maximum values, and within the lower spectrum of figures resulting from other studies of Rockwool productions (EPDs and Schmidt et al., 2004). Therefore this LCA source can be considered a good representative for a state-of-the-art Rockwool product. Because of plant in Bridgend, this company is well positioned to supply the Welsh market, thus the GaBi aggregated LCI is particularly appropriate given the focus of this research on regional supply.

Glass wool

The product used in this research to represent conventional glass wool is an innovative type of glass wool manufactured by Knauf using an organic binder instead of formaldehyde. The EEI figures for glass wool insulation (Knauf, 2015) are compared (on a FU basis) to figures found in existing sources in Appendix V. In all categories except POCP the EPD by Knauf presents values of EEI within the lower spectrum of existing studies. This is consistent with the claim of Knauf that by using the ECOSE binder the EEI is lower than more traditional glass wool products. However even the high POCP value is lower than the maximum established by existing studies. Given the presence of Knauf in Wales and the fact that this EPD used UK energy mix, this LCA source can be considered a good representative for a state-of-the-art glass wool product.

EPS

The EEI figures used in this research for EPS products (Thinkstep, 2016a) are compared (on a FU basis) to the figures found in the existing studies in Appendix V. In PEU, AP and POCP categories the results from the GaBi LCI are within minimum and maximum found in existing sources. In GWP and EP categories, GaBi results are just below minimum values found in existing sources. However, since these minimum values are not single cases, the low figures given by the GaBi LCI can still be considered a reasonable representative of a state-of-the-art EPS product.

PUR and phenolic foam

The EEI figures used in this research for PUR and phenolic products are compared (on a FU basis) to figures found in existing studies in Appendix V. Since only two sources are available for phenolic products, these are presented together with PUR as the two product types share some similarities in performance, materials and manufacturing processes.

In the case of PUR products, the EPD by PU Europe (2014) is chosen for research as it is most recent one among those based on European energy mix. For all categories except POCP the EEI values by PU Europe are very close to or just below minimum values found in existing sources. Given that these minimum values do not appear to be extreme cases, the EPD figures by PU Europe can be considered good representatives for a state-of-the-art PUR product.

The two existing studies on phenolic products have very different results, as discussed in section 2.3.5. The LCA conducted by Densley Tingley et al. (2014) shows a much higher impact in all categories than the EPD by Kingspan (2014) and even in comparison to PUR products. Since Densley Tingley et al. (2014) did not have access to actual manufacturing data, the EPD by Kingspan is considered to be a better representative for phenolic products. In addition, PEU and EP are not available for Densley Tingley et al. (2014), and therefore the Kingspan (2014) EPD is the only viable choice for this research.

Hemp fibre and sheep wool

The EEI figures used in this research for hemp fibre and sheep wool products are compared (on a FU basis) of the FU to figures found in existing sources in Figure 4. 37 to Figure 4. 41. For both products the main reference is the LCA by Norton (2008), whose LCI were modified by the author to be used in this research (see sections 4.3.6 and 4.3.7). Given the limited number of existing studies on these two products, the presence of methodological differences (allocation, etc.) and the modifications introduced in the original LCI, benchmarking hemp fibre and sheep wool against other sources has many limitations. In addition, as described later in section 4.3.12, maximum and minimum EEI figures for hemp fibre and sheep wool are obtained by changing LCI parameters and not via existing studies. Nonetheless, comparison between sources can highlight important aspects.

Hemp fibre insulation

The LCI used in this research for hemp fibre insulation is based on Norton (2008), who modelled an existing product manufactured in France with British hemp fibre, recycled cotton fibres and polyester fibres as binder. Norton's LCI was modified to model a hypothetical product manufactured in Wales with local hemp fibre and polylactic acid as binder, as replacing the plastic binder significantly decreases the PEU and GWP of the final product. Manufacturers of hemp fibre insulation currently available on the UK market have not adopted this technology. Therefore these differences should be taken into account when considering the particularly good environmental performance of the hemp fibre product modelled in this research.

EEI figures obtained for the hemp fibre product are within the range of other sources in terms of PEU (not calculated in Norton, 2008) and AP. In GWP, EP and POCP categories the figures obtained via modified LCI are lower than those of existing studies, although with different magnitudes and for different reasons. In terms of GWP, the hemp fibre product modelled in this research has a negative value (due to carbon sequestration) which is slightly higher than that of Zampori et al. (2013), while Norton (2008) showed a small but positive value. The difference with GWP as calculated by Norton is caused by the replacement of the plastic fibres with a plant-based compound and by changes introduced in the farming stage. These are also the causes for the minor reductions in AP and EP from figures obtained by Norton (2008). As for sheep wool, the lower impact in POCP value in respect to Norton (2008) is caused by the replacement of the plastic fibres with a plant-based compound, and by the characterisation of the CML assessment method for this category.

Sheep wool insulation

The LCI used in this research for sheep wool insulation is based on Norton (2008), who modelled an existing product manufactured in England with British wool and polyester fibres as binder. This LCI was modified to model a hypothetical product manufactured in Wales with local wool and polylactic acid as binder, as done for hemp fibre. In addition, a fraction (2%) of the environmental impact of sheep farming was allocated to raw wool on an economic basis. EEI figures obtained for sheep wool insulation are within the range of other sources in terms of PEU (not calculated by Norton, 2008). In GWP, AP and EP categories the figures obtained via modified LCI are considerably higher than those found in other sources and in particular in Norton (2008). This increase is caused entirely by the allocation of the environmental impact of sheep farming (which was not included by Norton), therefore the inclusion of economic allocation significantly penalises the sheep wool product. The lower impact in POCP value in respect to Norton (2008) is caused by the replacement of the plastic fibres with a plant-based compound, and by the problematic characterisation of the CML assessment method for this category.

Arguments can be made in favour or against the choice of economic allocation in LCA of Welsh wool:

- On one hand, the large majority of Welsh raw wool is a by-product of the sheep meat sector (see section 2.3.4). The environmental impact of sheep farming occurs whether or not wool is used as insulation, and would take place even if the wool was not collected. Thus raw wool should not be attributed any part of the environmental impact of sheep farming, because that impact exists only as a consequence of choosing to raise sheep for meat production.
- On the other hand, a monetary transaction takes place when wool is purchased to make insulation (or for any other manufacture). Revenues from wool sales, however small, contribute to the economic balance of sheep farmers. Thus wool should be attributed

the share of environmental impact that its revenues contribute to 'sustain'. This is not applicable if revenues from wool sales are not sufficient to cover the expenses associated with selling the wool (e.g. transportation).

The allocated impact of sheep farming is included in the EEI of the sheep wool insulation product modelled in this research, but its "equivocal" nature is taken into account in the interpretation of results.

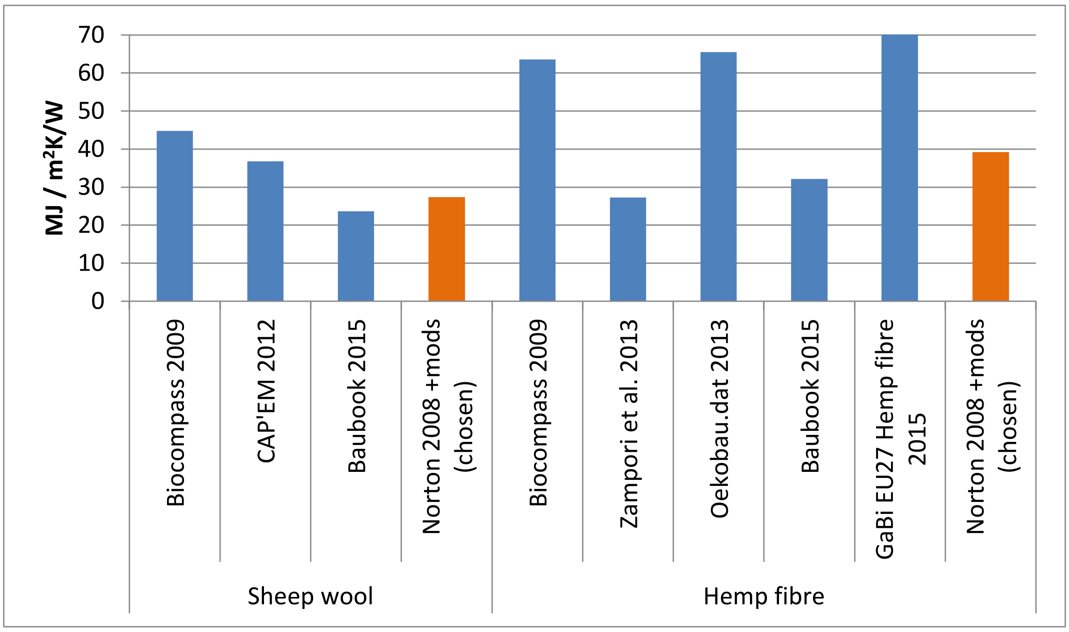


Figure 4. 37 – Comparison between the PEU used in this research for sheep wool and hemp fibre products and the results of other LCA studies

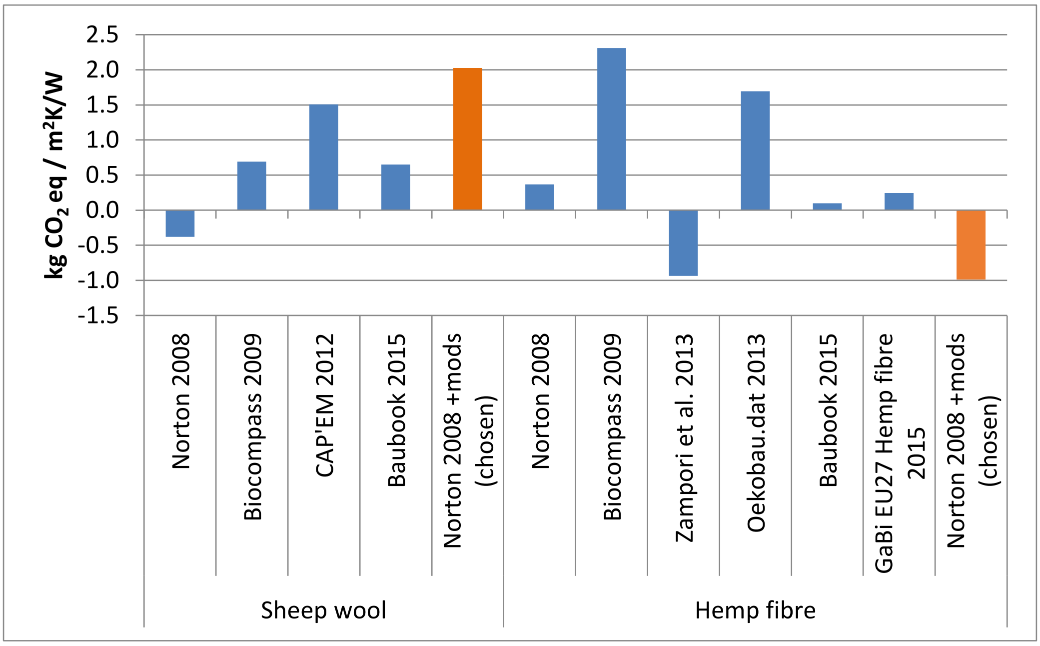


Figure 4. 38 – Comparison between the GWP used in this research for sheep wool and hemp fibre products and the results of other LCA studies

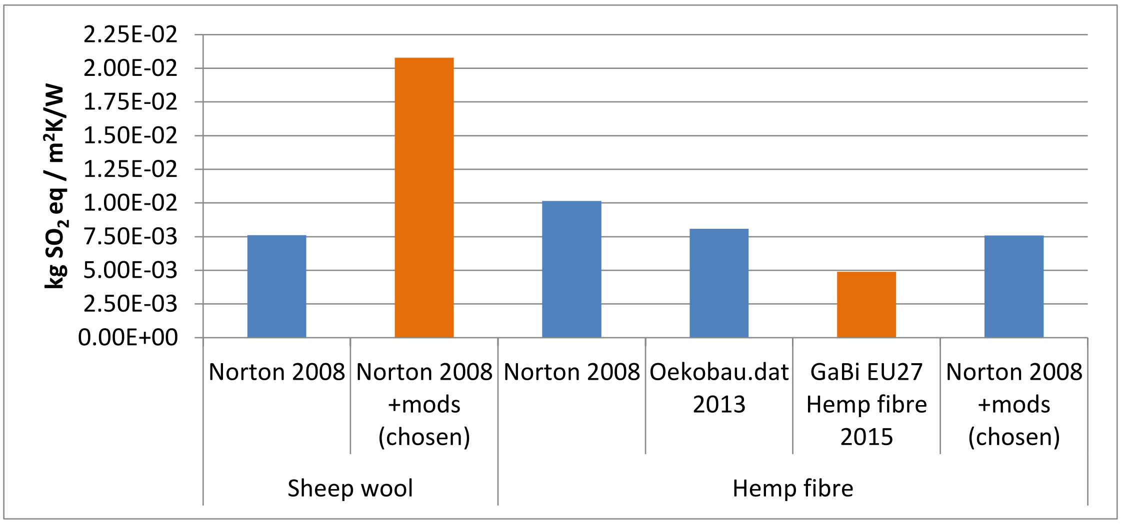


Figure 4. 39 – Comparison between the AP used in this research for sheep wool and hemp fibre products and the results of other LCA studies

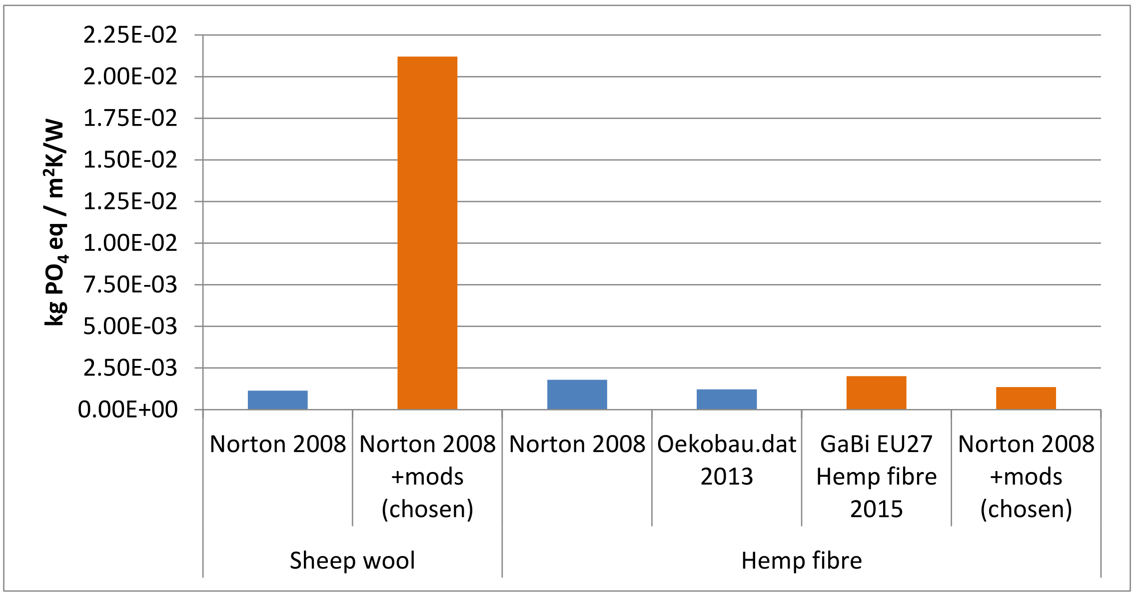


Figure 4. 40 – Comparison between the EP used in this research for sheep wool and hemp fibre products and the results of other LCA studies

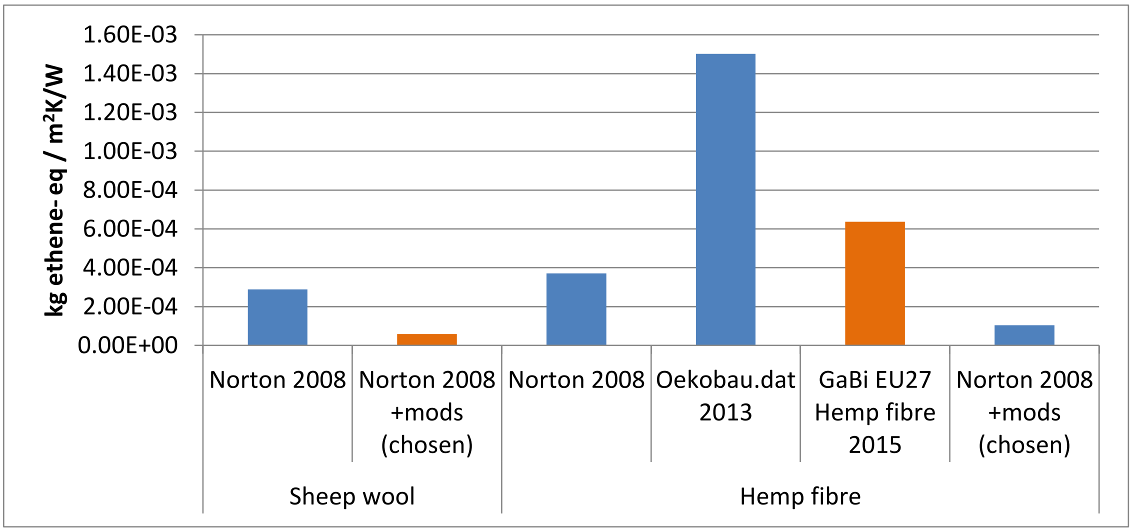


Figure 4. 41 – Comparison between the POCP used in this research for sheep wool and hemp fibre products and the results of other LCA studies

LD and HD wood fibre

The EEI figures used in this research to represent wood fibre products were obtained by averaging EEI figures from EPDs for products manufactured in Western Europe, due to the lack of disaggregated LCI (as described in 4.3.8). The resulting figures represent a typical European wood fibre, but it should be considered that some changes in EEI would take place if the product were to be manufactured in the UK, due to the different energy mix for electricity. Since the EEI figures used in this research are obtained by averaging these EPDs, it is not necessary to comment these LCA results further.

~~Comparison between the PEU used in this research for wood fibre products and the results of other LCA studies~~

~~Comparison between the GWP used in this research for wood fibre products and the results of other LCA studies~~

~~Comparison between the AP used in this research for wood fibre products and the results of other LCA studies~~

~~Comparison between the EP used in this research for wood fibre products and the results of other LCA studies~~

~~Comparison between the POCP used in this research for wood fibre products and the results of other LCA studies~~

4.3.12 Modelling EEI variations

In the attempt to take into account the uncertainties created by the assumptions underpinning the model discussed in section 4.3, maximum and minimum values of EEI are selected based on the ranges identified by the available literature. These maximum and minimum values affect only the cradle-to-gate stage and are selected in addition to the 'base' values used in the model, i.e. those discussed in previous sections. Maximum and minimum are used to calculate two variations of the supply scenarios to represent worst case and best case in terms of EEI.

- In the first variation, the conventional products in the baseline scenario are given maximum EEI, while biomass products in the alternative scenario are given minimum EEI values. This combination represents the best possible case for biomass products, since the latter have a lower (better) EEI than their 'base' values while the conventional products have a higher (worse) EEI than their 'base' values.
- In the second variation, the conventional products in the baseline scenario are given minimum EEI, while biomass products in the alternative scenario are given maximum EEI values. Thus the second variation represents the worst possible case for biomass products,

These best and worst cases are used in the analysis of results to associate a range of possible variation to the changes in EEI brought by the alternative scenarios. These ranges allow at least a partial evaluation of the magnitude of variations in total EEI that could be caused by changes in the impact of single products.

The maximum, minimum and base EEI values used in the model to represent the product types are shown in Table 4. 32 and Table 4. 32. The base values are the results of the selected LCI and EPD (as introduced in sections 4.3.1 to 4.3.8), while the maximum and minimum values have been selected from the values found in the available literature according to the following criteria.

For base EEI values obtained from EPDs or aggregated LCIs (stone wool, glass wool EPS, PUR, phenolic, wood fibre): for each impact category, maximum and minimum EEI values are taken respectively from the highest and lowest values found in the literature. Exceptions include:

- Since the only other source for phenolic products might be overestimating the impact, values for phenolic insulation are calculated by multiplying the base value to factors 1.2 and 0.8. These factors account for a +/-20% variation on the LCA results, which can be considered a large but reasonable margin of error for LCA studies.
- In the few cases where the highest and lowest values found in the literature belong to the chosen LCI (or EPD) or are very close to the 'base' value (within +/-5%), the higher and/or lower value is calculated by applying 1.2 and 0.8 factors.

Table 4. 32 – Minimum, base and maximum EEI for 1 FU (cradle-to-gate) for conventional products

		Stone wool	Glass wool	PUR	EPS	Phenolic
PEU (MJ/ m2K/W)	min	20.72	8.50	49.94	25.10	47.46
	base	23.51	15.05	62.42	53.05	59.33
	max	47.66	46.48	112.85	61.78	71.20
GWP (kgCO2eq/ m2K/W)	min	1.34	0.47	2.60	1.27	1.58
	base	1.71	0.73	2.78	1.58	1.97
	max	3.60	2.40	6.52	4.21	2.37
AP (kgSO2eq/ m2K/W)	min	9.51E-03	3.00E-03	6.06E-03	1.70E-03	3.84E-03
	base	1.19E-02	3.65E-03	8.08E-03	3.15E-03	4.80E-03
	max	3.80E-02	1.40E-02	2.16E-02	1.44E-02	5.76E-03
EP (kgPO4eq/ m2K/W)	min	1.18E-03	5.22E-04	7.20E-04	2.32E-04	4.31E-04
	base	1.34E-03	6.32E-04	9.00E-04	2.91E-04	5.38E-04
	max	1.46E-03	2.12E-03	2.59E-03	1.32E-03	6.46E-04
POCP (kg ethene-eq /m2K/W)	min	6.24E-04	1.05E-04	1.10E-03	4.66E-03	1.58E-03
	base	9.52E-04	1.36E-03	1.72E-03	9.05E-03	1.98E-03
	max	4.62E-03	2.83E-03	1.88E-03	1.89E-02	2.38E-03

Table 4. 33 – Minimum, base and maximum EEI for 1 FU (cradle-to-gate) for biomass products

		Hemp fibre	Sheep wool	LD wood fibre	HD wood fibre
PEU (MJ/ m2K/W)	min	38.53	22.79	61.18	97.28
	base	39.12	27.30	67.31	137.30
	max	41.01	29.66	73.44	224.90
GWP (kgCO2eq/ m2K/W)	min	-0.13	-0.99	-2.30	-7.81
	base	-0.99	2.02	-1.12	-6.51
	max	-3.78	3.60	0.06	-5.21
AP (kgSO2eq/ m2K/W)	min	6.33E-03	3.00E-03	4.06E-03	7.03E-03
	base	7.60E-03	2.08E-02	6.97E-03	9.83E-03
	max	1.17E-02	3.01E-02	9.88E-03	1.24E-02
EP (kgPO4eq/ m2K/W)	min	1.07E-03	3.96E-04	7.29E-04	1.25E-03
	base	1.36E-03	2.12E-02	9.12E-04	1.86E-03
	max	2.29E-03	3.21E-02	1.09E-03	2.84E-03
POCP (kg ethene-eq /m2K/W)	min	1.82E-04	1.77E-04	6.94E-04	4.28E-04
	base	1.04E-04	5.83E-05	8.67E-04	1.11E-03
	max	-1.49E-04	-3.83E-06	1.04E-03	2.75E-03

For base EEI values obtained from on disaggregated LCI: for the sheep wool and hemp fibre products the confidence in the results of the LCA is high since the availability of the disaggregated LCIs enabled introducing improvements and using the UK energy mix. The disaggregated LCIs also allow sensitivity analysis to be conducted to take into account cases where the EEI could be higher or lower, rather than relying on other studies which are limited in numbers. For sheep wool and hemp fibre, the parameter chosen to be investigated in the sensitivity analysis is the allocation of the impact of the "resource extraction" stage:

- The allocation of 2% of the sheep farming stage increases the EEI of the sheep wool product, and therefore it is worth investigating its variation. To calculate minimum impact values, the allocation to sheep wool is set at 0% (thus excluding it), while for maximum impact values the allocation to sheep wool is raised at 3%.
- The allocation of the farming stage to the hemp fibre product is also an important contributor to its overall EEI (albeit not as much as for sheep wool), and several modifications to this stage were introduced on the original LCI by Norton (2008). The percentage used to determine the economic allocation (46.5% to hemp fibre) is the result of a rough estimate (see section 4.3.6) and therefore its variation should be investigated. To calculate minimum EEI values, the allocation to hemp fibre is set at 30%

to represent a case where a higher economic value it attributed to hemp shives. For maximum EEI values, the allocation to hemp fibre is raised at 100 to represent a case where no economic value is attributed to shives, and therefore the EEI of the agricultural stage is entirely allocated to the insulation product. These maximum and minimum EEI values for the farming stage can also represent cases where the industrial hemp yield is respectively lower and higher than the figure (7 tonnes/ha) chosen for the LCI.

Two limitations arise from these choices:

- Due to the problematic CML characterisation for POCP, the EEI of both products in this category increases when the lower allocation is applied and decreases when the higher allocation is applied.
- The PEU of hemp fibre is not significantly affected by changes in the allocation percentage.

4.3.13 Normalising and aggregating impact categories

In the final results of the first research component the comparison between the EEI of the alternative scenarios is shown for each category separately as well as in form of an aggregated EEI score. The latter is calculated by normalising the LCA results and summing them without applying a weighting factor. The resulting figure is unit-less (as are normalised values) and can be read as an indicator combining the five impact categories. Not applying a weighting factor (which is equal to say that all categories are given a weighting factor of 1) means that no distinction is made among the categories on the assumption of their relative importance to each other. However, for each category the normalised values reflect the importance of the environmental impact in relation to a reference impact. Therefore a low impact in the EP category, for example, will produce a low EP contribution to the impact score in comparison to the other categories.

The factors used in this research to normalise the LCA results (with the exception of PEU) are the latest available for CML impact categories and are based on data from 2000 at the world level (Wegener Sleeswijk et al. 2008). The data contained in the Statistical Review of World Energy (British Petroleum, 2016) is used as alternative source for PEU as this category is not included in Wegener Sleeswijk et al. (2008). The normalisation factors for the all five impact categories at world level are divided by world population to obtain the average impact of one person, or ‘world citizen’. Final figures are shown in Table 4. 34.

Table 4. 34 – Normalisation factors for World 2000 corresponding to one ‘world citizen’

Impact category		Unit	Source
PEU	3.931E+14	MJ	Statistical Review of World Energy (British Petroleum, 2016)
GWP	4.184E+13	kg CO2eq	(Wegener Sleeswijk et al., 2008)
AP	2.388E+11	kg SO2eq	
EP	1.583E+11	kg PO4eq	
POCP	3.683E+10	kg ethene eq	

4.3.14 Comparison of single product EEI

This section concludes the discussion of methods used to quantify the EEI of insulation products by presenting the results of the assessment for single product types. These figures are successively applied to the supply scenario to produce to the total EEI values, presented in section 4.4.

From Figure 4. 42 to Figure 4. 46 the nine product types studied in this research are compared across the five EEI categories on a FU basis. The total impact is broken down into ‘manufacture’ (cradle-to-gate) and ‘transport’ (gate-to-site) stages. The ranges shown in the Figures are maximum and minimum EEI values obtained from existing studies and LCI changes (see section 4.3.12).

Firstly, it can be noticed that in all EEI categories the contribution of the gate-to-site transportation is rather negligible. Among all products, glass wool and HD wood fibre are the ones with the highest impact per FU in this stage. Their values in all categories except POCP are about two times the values of the products with the lowest impact in this stage, namely PUR and phenolic. ~~However, all EEI figures for transportation are dwarfed by the EEI impact of the manufacturing stage of all products.~~ Looking back at the rough estimate of travel lengths used to model transportation (section 4.3.9), it is clear that those parameters have very little effect on the overall EEI of products, and therefore are not worth a more accurate estimate.

Considering cradle-to-gate EEI figures, it can be noted that products may perform well in some impact categories and worse in others. For PEU, stone wool and sheep wool are the products with the least embodied energy while HD wood fibre towers over all products. In terms of GWP the situation is almost reversed, with HD wood fibre having the best performance (thanks to the carbon sequestered in the biomass) while stone wool and sheep wool are among the products with the highest embodied carbon. In AP and EP categories, EPS is the product with the least impact while sheep wool has the highest impact. Conversely, in the POCP category sheep wool performs very well (together with hemp fibre) while EPS is the most impacting product.

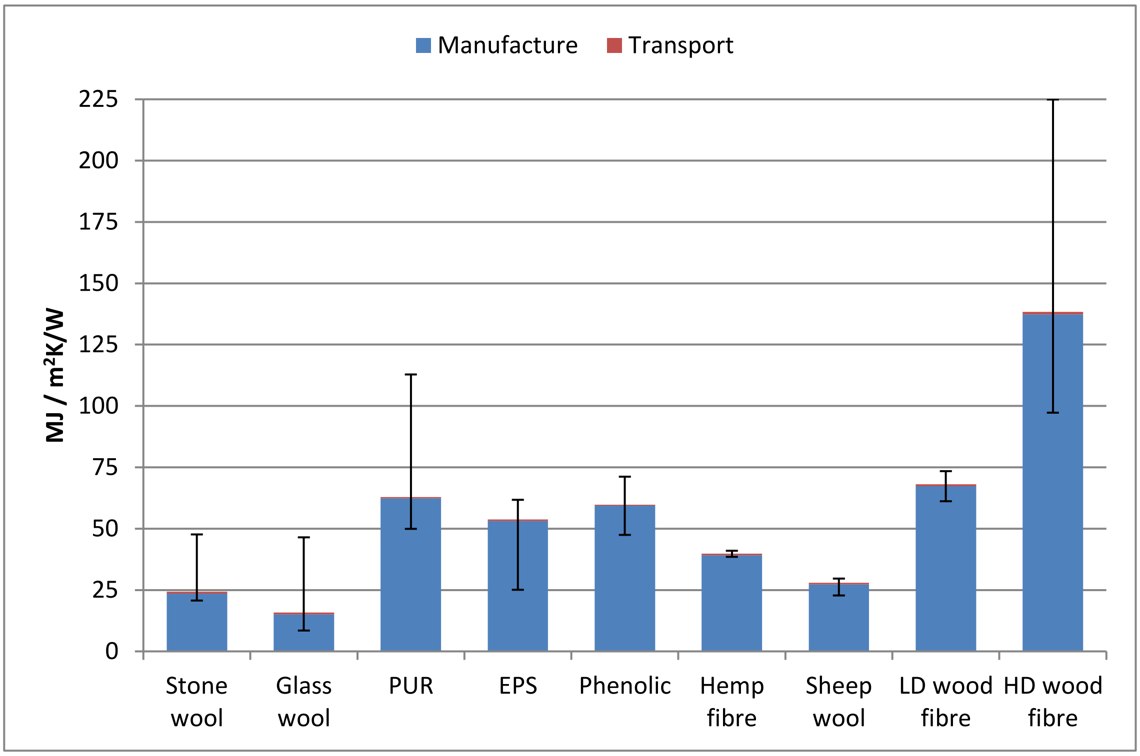


Figure 4. 42 – Comparison between PEU of insulation products used in this research

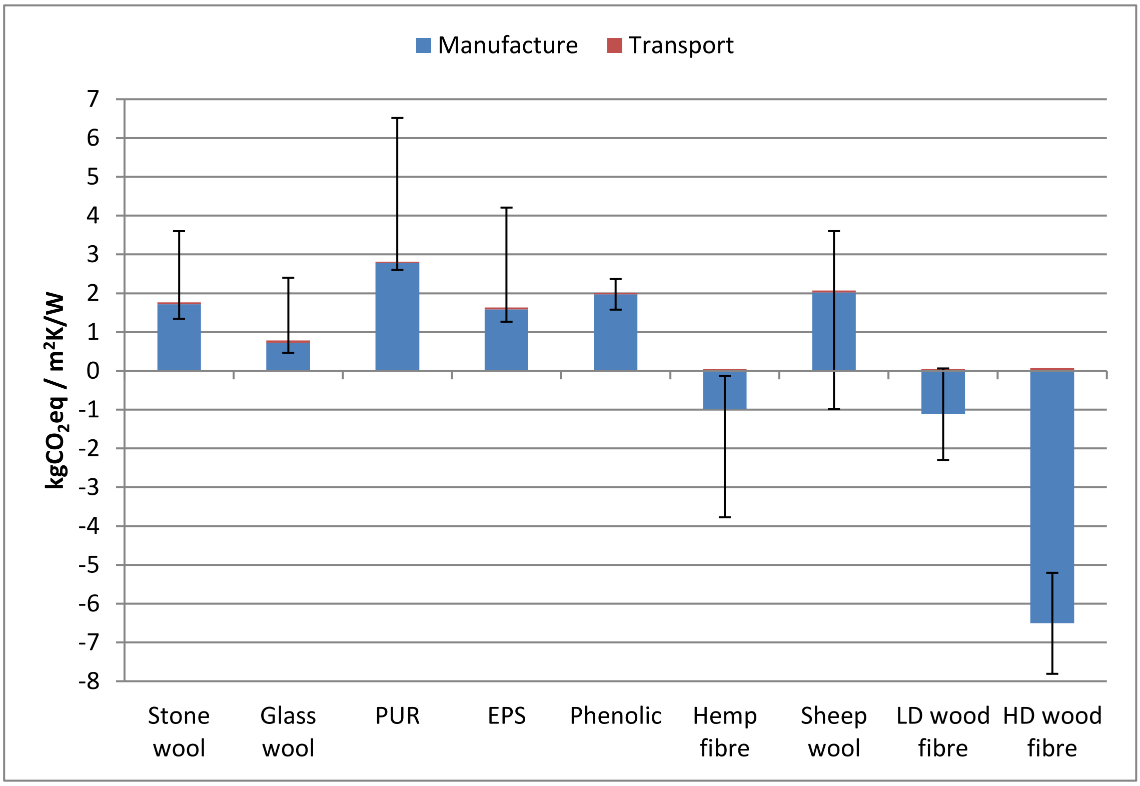


Figure 4. 43 – Comparison between GWP of insulation products used in this research

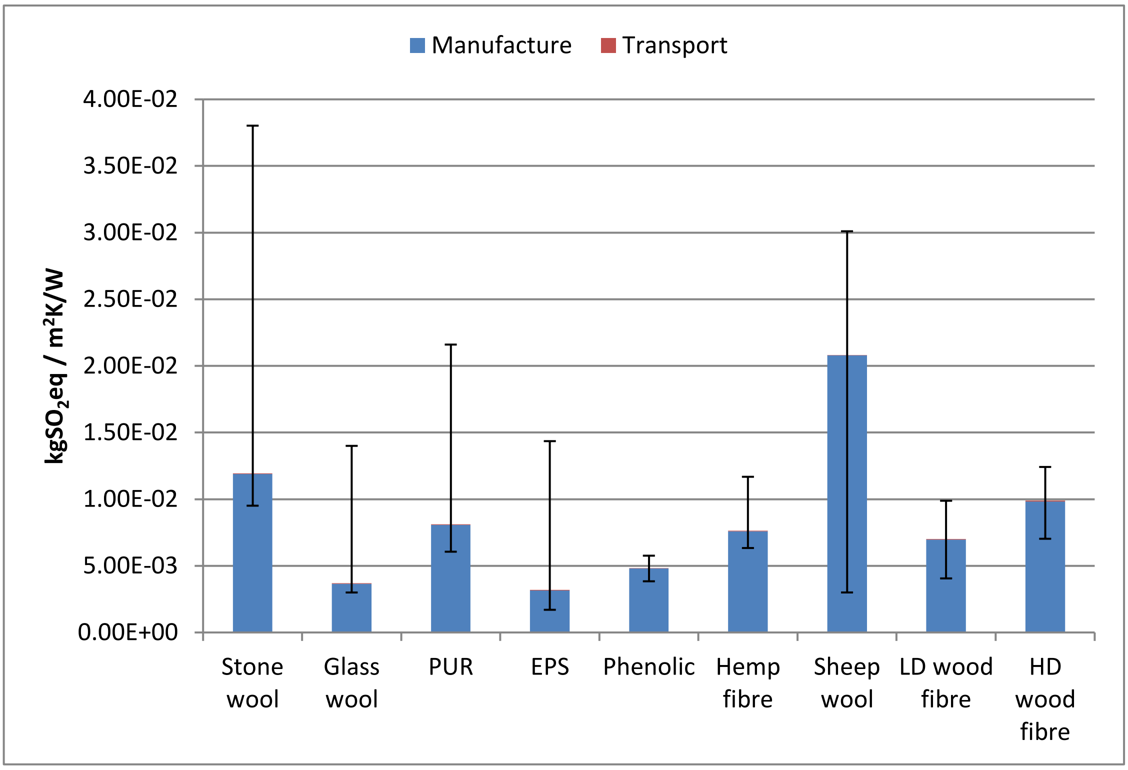


Figure 4. 44 – Comparison between AP of insulation products used in this research

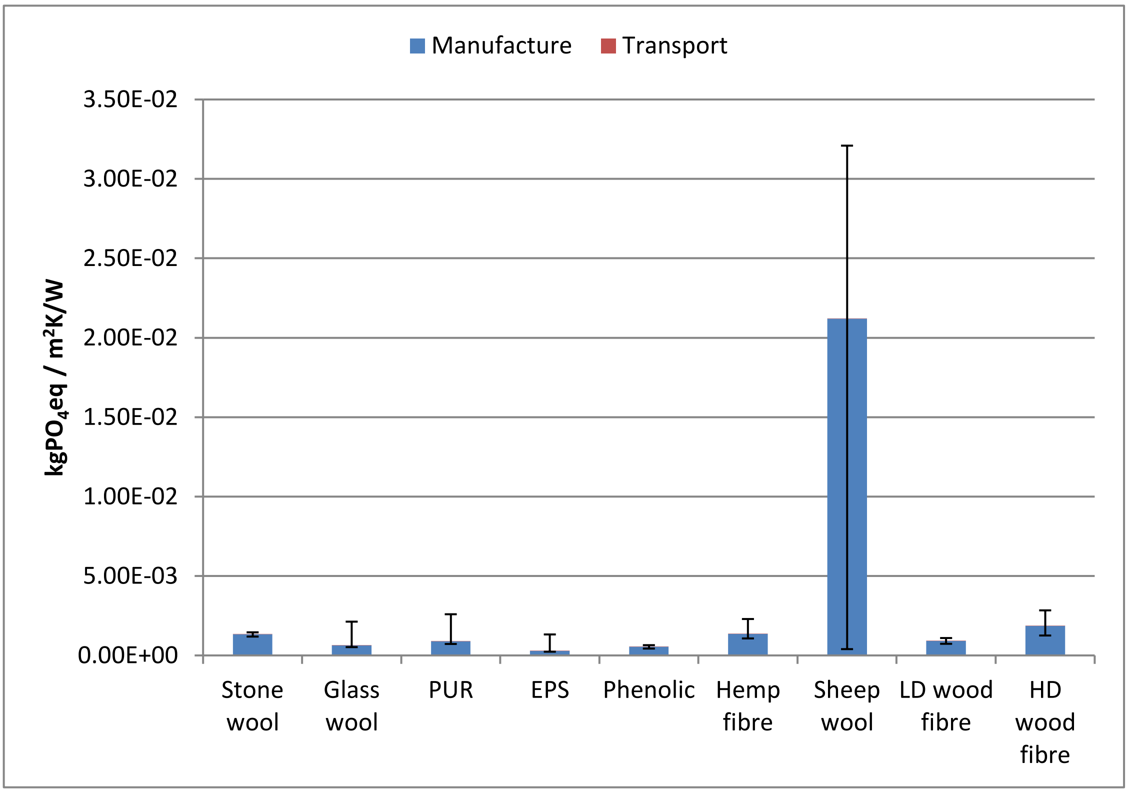


Figure 4. 45 – Comparison between EP of insulation products used in this research

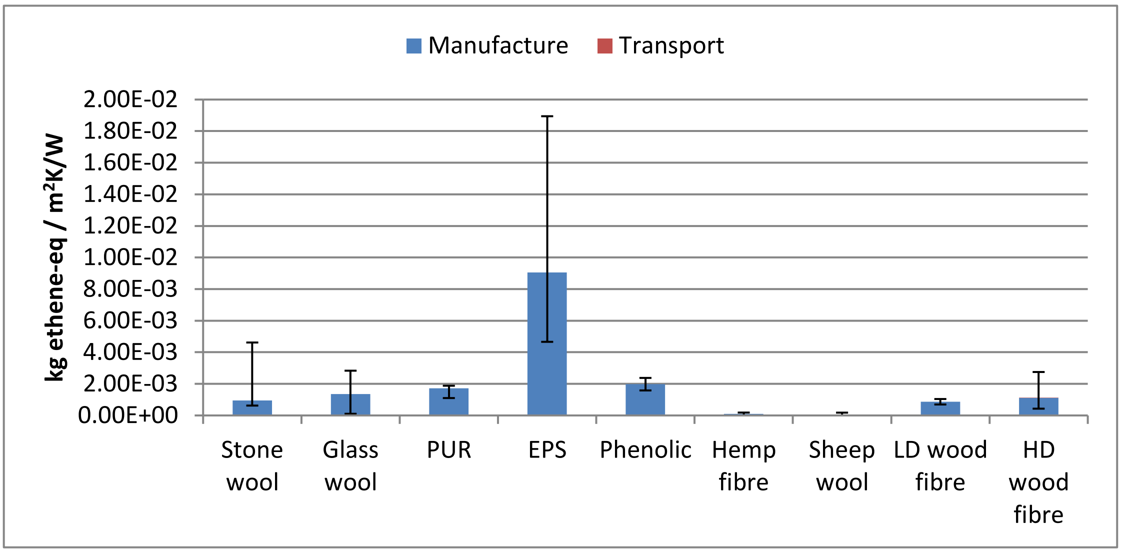


Figure 4. 46 – Comparison between POCP of insulation products used in this research

To facilitate an overall evaluation of the best performing products on the FU basis, the impact of the products is also presented by aggregating the five categories into one EEI score. The scoring system, which as discussed in section 4.3.13, is obtained through normalisation and equal weighting. In Figure 4. 47 the EEI scores of products are divided by life-cycle stage and the ranges of maximum and minimum are also shown. In Figure 4. 48 the same EEI scores are broken down by impact categories, to allow identifying which categories contribute more significantly to the overall score.

According to the EEI score system, glass wool and EPS are respectively the best and worst performing among conventional products, while hemp fibre has the best performance among both biomass ones and is very close to glass wool. Looking at the contribution of each category, it can be noticed that PEU has by far the largest contribution to the scores of PUR, phenolic, hemp fibre and wood fibre products. Mineral products present more balanced scores, with significant contributions from GWP, AP and POCP categories. The contribution of GWP is significant for hemp fibre, LD and especially HD wood fibre products, as its negative value helps lowering the scores of these products. The contribution of AP is generally rather limited, with the exceptions of stone wool and especially sheep wool. The latter is also the only product whose score is severely penalised by a large EP contribution, while for all other products this category has negligible effect. The contribution from POCP is secondary for most products and minimal in the case of hemp fibre and sheep wool, but it is clearly a very significant one in the case of EPS.

Although hemp fibre is the biomass product with the lowest impact per FU, the minimum value for sheep wool in Figure 4. 47 is lower than the minimum for hemp fibre. The minimum for sheep wool indicates the EEI achieved if allocation is excluded, i.e. if raw wool is considered entirely as a by-product of the meat sector. In the following pages the contribution of the farming stage to the EEI of hemp fibre and sheep wool is analysed further.

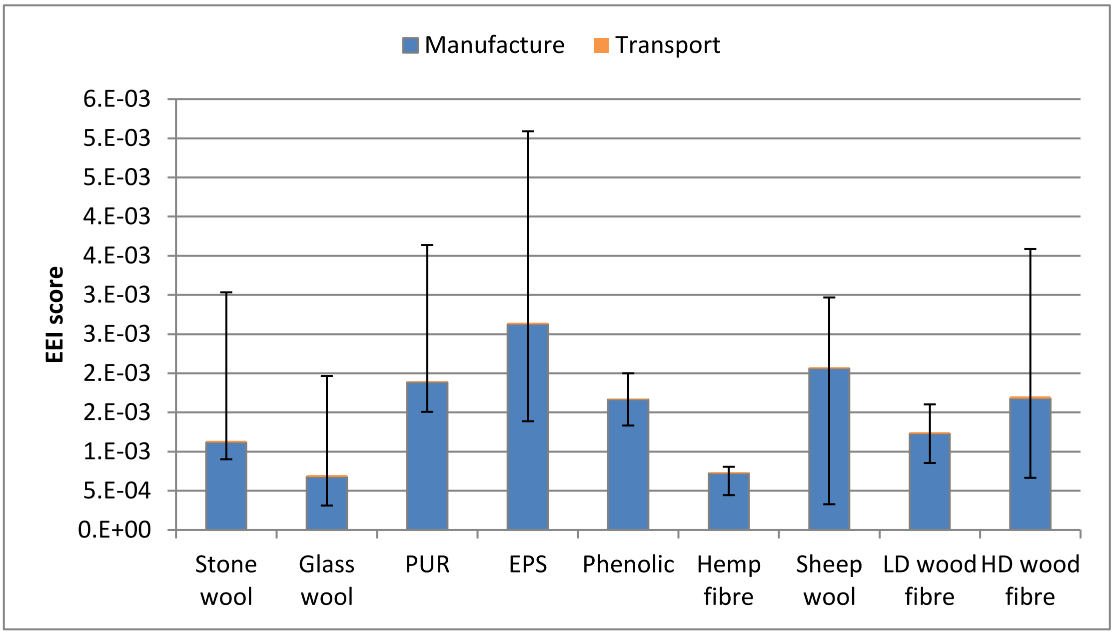


Figure 4. 47 – Comparison between the EEI scores of insulation products used in this research, broken down by life-cycle stage

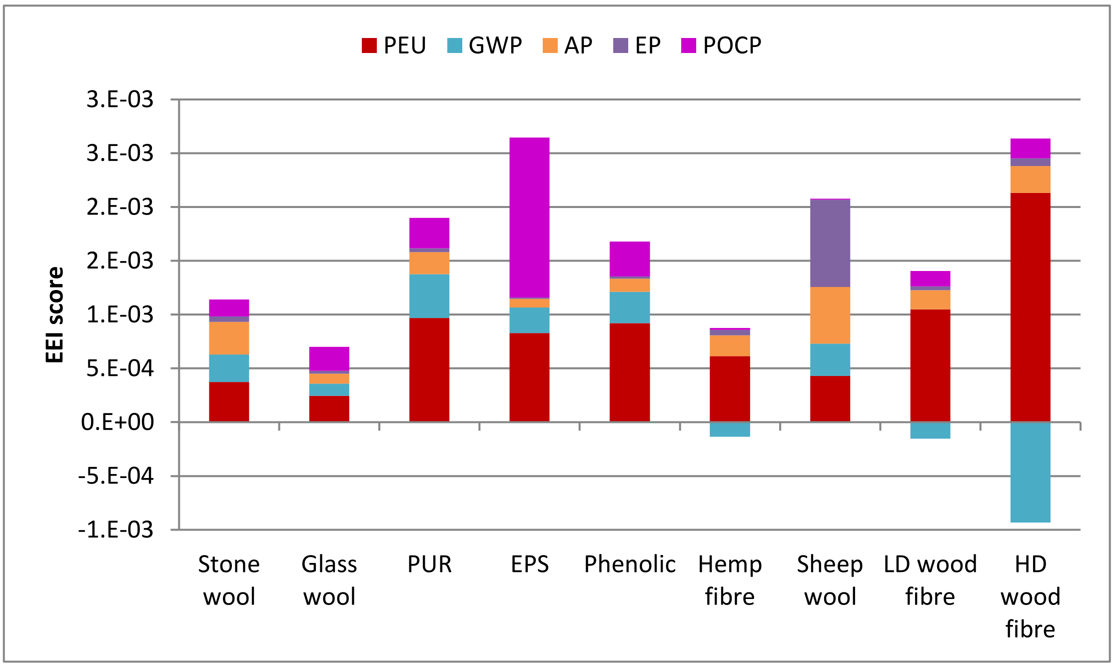


Figure 4. 48 – Comparison between the EEI scores of insulation products used in this research, broken down impact category

Farming stage contribution to hemp fibre and sheep wool EEI

Thanks to the detailed LCIs used for the LCA of the hemp fibre and sheep wool products, it is possible to breakdown the cradle-to-gate EEI into 'farming' and 'manufacture' stages, and evaluate their relative contribution. With 'farming' stage it is intended the processes leading to the generation of primary biomass materials, namely retted hemp straw in the case of hemp fibre insulation and raw wool in the case of sheep wool insulation. As described in sections 4.3.6 and 4.3.7, the EEI of this stage is partially allocated to the insulation products on an economic basis.

In Figure 4. 49. the contribution of farming and manufacture stages to each of the EEI categories for hemp fibre and sheep wool products are compared in percentage terms, together with the contribution to GWP by the carbon sequestered in the biomass during the farming stage. For hemp fibre, the contribution of the farming stage is negligible in terms of PEU, close to that of the manufacturing stage in terms of AP and EP, and actually beneficial for GWP and POCP. For sheep wool, the contribution of the farming stage becomes dominant in the AP and EP categories, which eventually leads to a high impact in these categories (as shown in Figure 4. 44 and Figure 4. 45). The contribution of the farming stage to the GWP category is also very significant, though it is reduced by the carbon sequestered in the animal fleece.

The negative POCP figures associated with the farming stage of both products contribute significantly to reduce the total POCP for both hemp fibre and sheep wool. These negative figures result from the problematic CML characterisation of the POCP in truck transportation (see section 3.2.3), and thus should be considered with care.

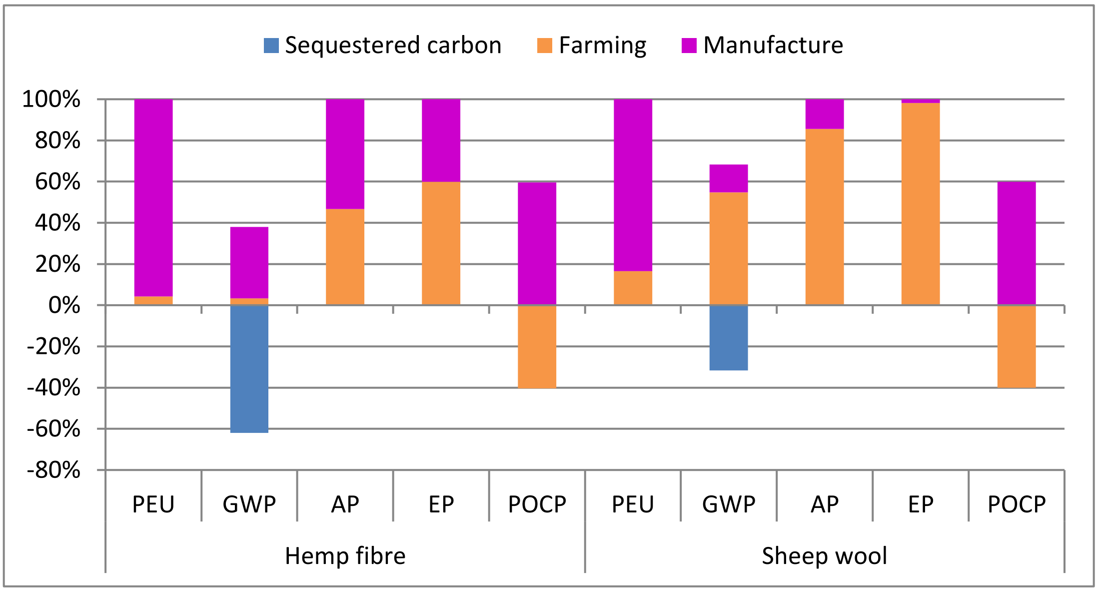


Figure 4. 49 – Comparison between the contributions of carbon sequestration and life-cycle stages to the EEI of hemp fibre and sheep wool products used in this research

Evaluating the effects of decarbonising the electricity supply

The LCA values used in this research to quantify the environmental impact of insulation products are based on carbon emission factors for typical electricity generation mix in the period 2013-2016. it is very likely that in the future these emission factor will decrease, in the UK as well as in mainland Europe, as electricity generation will progressively move from fossil fuel plants to less carbon-intensive energy sources. This decarbonisation will affect the GWP embodied in insulation products, in proportion to the electric energy used in the extraction and manufacturing stages. Since disaggregated LCIs are not available for most of the insulation products studied in this research, it is not possible to model this effect. Figures for Primary Energy Use (PEU) in aggregated LCI and EPD sources do not show specify values for electric energy and other sources of energy, and cannot be separated into the stages of extraction and manufacture. However, disaggregated LCIs are available for hemp fibre and sheep wool insulation, thus it is possible to investigate this effect on these products to gain an understanding of its extent.

The emission factors used to investigate the effect of decarbonising the electricity supply are taken from the Future Energy Scenarios (FES) 2018 by the UK National Grid (2018a). These scenarios are produced by National Grid to show a range of potential pathways until the year 2050. Four pathways are modelled to represent different speeds of decarbonisation and levels of decentralisation, as shown in Figure 4. 50. The assumptions underlying these pathways are described in UK National Grid (2018a). It must be noted that although all four pathways significantly reduce the carbon intensity of the UK electricity supply, only the '2 degrees' and 'community renewables' pathways are able to meet the GHG reductions required by the Climate Change Act 2008.

High decentralisation	*Consumer evolution*	*Community renewables*
Low decentralisation	*Steady progression*	*2 degrees*
	Slow decarbonisation	Fast decarbonisation

Figure 4. 50 – Matrix generating the four pathways modelled in UK National Grid (2018)

Figure 4. 51 compares the GWP of one FU unit of hemp fibre insulation (within the cradle-to-gate boundary) as calculated in section 4.3.6 for the year 2014 (i.e. the 'base value') with the GWP values resulting from the application of the FES emission factors of the four pathways for the years 2020, 2035 and 2050. Since the GWP of the base value is negative due to the carbon sequestered in the hemp fibre, decarbonising the energy supply increases the 'net' carbon sequestration (up to about 145% of the base value). While there is a stark difference between the base value and the GWP values resulting from the four pathways, the differences between the latter can be considered of negligible consequence for the purpose of this analysis.

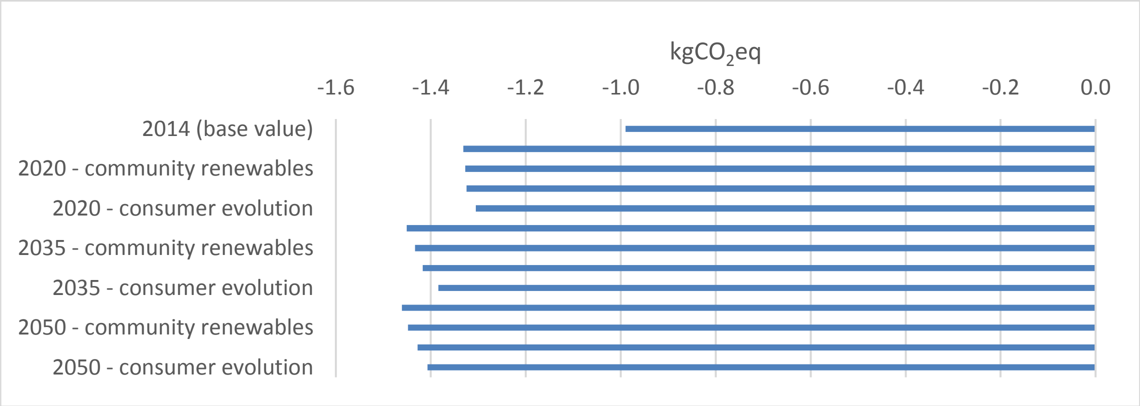


Figure 4. 51 – Potential changes in GWP per FU of Hemp fibre insulation due to future decarbonisation of the electricity supply

In Figure 4. 52, the same results of the previous Figure are shown with the exclusion the GWP associated with the farming stage, which allows evaluating the contribution of electricity use to the total GWP associated with the manufacturing stage. Decarbonising the electricity supply has the potential to significantly reduce GWP due to electricity use in manufacturing, which would result in an overall reduction of GWP of from manufacturing of about 60% of the base value by 2050.

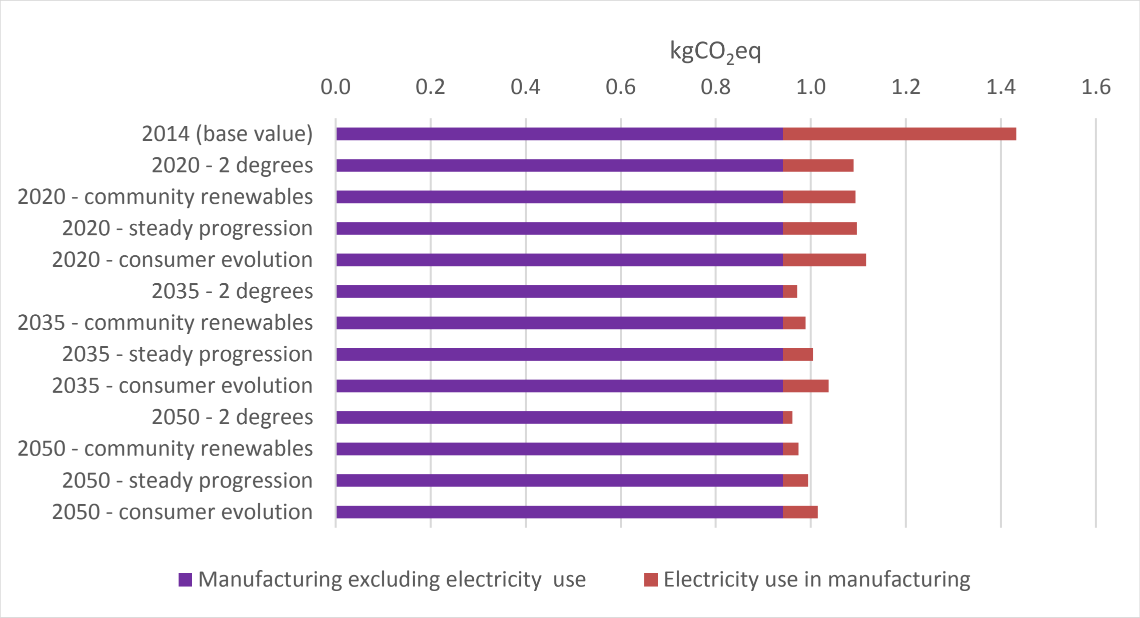


Figure 4. 52 - Potential changes in GWP per FU of Hemp fibre insulation due to future decarbonisation of the electricity supply – Breakdown of manufacturing stage

Figure 4. 53 compares the GWP of one FU unit of sheep wool insulation (within the cradle-to-gate boundary) as calculated in section 4.3.7 for the year 2014 (i.e. the ‘base value’) with the GWP values resulting from the application of the FES emission factors of the four pathways for the years 2020, 2035 and 2050. Figure 4. 54 shows the same results but excludes the GWP associated with the sheep raising stage. In terms of total GWP (Figure 4. 53), decarbonising the electricity supply has the potential to reduce the impact up to about 82% of the base value. Considering only the manufacturing stage, the GWP of sheep wool insulation has the potential to be reduced up to 50% of the base value.

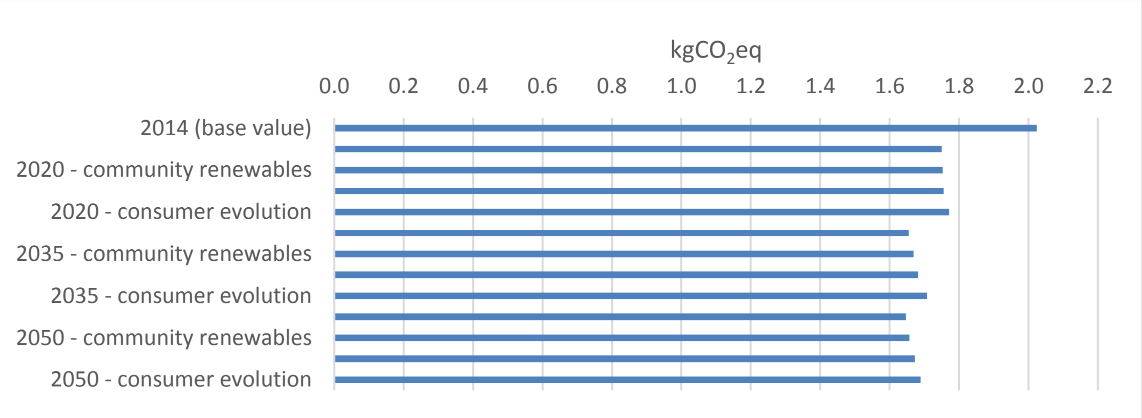


Figure 4. 53 - Potential changes in GWP per FU of Sheep wool insulation due to future decarbonisation of the electricity supply

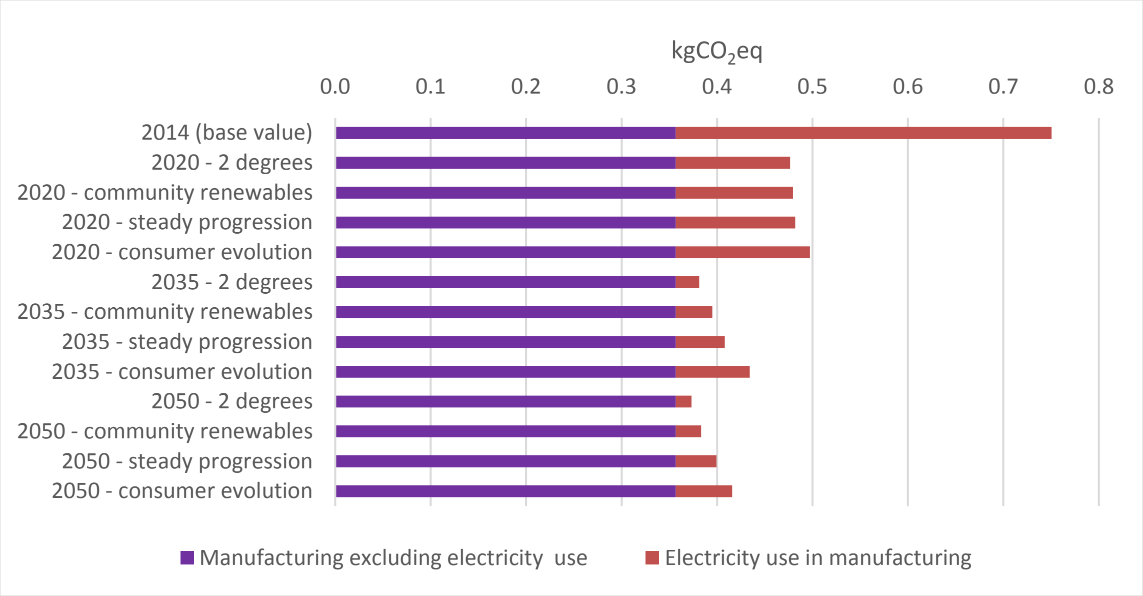


Figure 4. 54 - Potential changes in GWP per FU of Sheep wool insulation due to future decarbonisation of the electricity supply – Breakdown of manufacturing stage

Overall, the analysis of the potential effect of decarbonising the electricity supply shows that a significant reduction in carbon intensity is expected in all pathways already by the year 2020. This will affect the total GWP of all the products used in this research to model future supply of domestic insulation in Wales in the period 2020-2050. However, products with a higher share of GWP contribution from electricity use in the manufacturing stage (as in the case of sheep wool in comparison to hemp fibre, see Figure 4. 52 and Figure 4. 54) will benefit more markedly from the decarbonisation of the electricity supply. These potential changes in GWP cannot be assessed for most of the products studied in this research, but the analysis for hemp fibre and sheep wool insulation shows that reductions of in the order of 20% to 50% are possible.

Inclusion of the end-of-life stage

The following Figures compare the results of the LCA of the insulation products as assessed with the cradle-to-grave boundary, i.e. including the impact of the End-of-Life (EoL) stage. For glass wool and plastic products, the additional impact of the end-of-life stage results to be negligible in comparison to the impact of the cradle-to-site (CtS) stage. This can be explained in part by considering that these products are those with the lowest densities per FU.

Stone wool shows a higher impact than glass wool in the end-of-life stage, while biomass products are significantly penalised in the GWP, EP and POCP categories (Figure 4. 56, Figure 4. 58 and Figure 4. 59). The GWP of wood fibre products increases very significantly since two-thirds of non-recycled waste is incinerated, thus releasing the carbon stored in the biomass. Sequestered carbon is released in the case of hemp fibre and sheep wool insulation as well, but to a lesser extent since 'only' 50% of the non-recycled waste is incinerated. Only in the case of hemp fibre the balance still results in a (small) net intake of carbon throughout the life-cycle of the product.

Overall, the results clearly show that biomass products, and especially wood fibre, have a higher impact in the end-of-life stage in comparison to conventional products (Figure 4. 60). However, it should be noted that the LCA results of the end-of-life stage are associated with a higher degree of uncertainty than the results of the cradle-to-site stage, since there is less specific LCA data available and benchmarking was not possible. The end-of-life results are also strongly affected by the adoption of the 'recycled content' approach, which excludes from the assessment any benefit gained via recycling or energy recovery. It is reasonable to expect that accounting for the materials and energy use offset by recycling and incineration (with energy recovery) would produce a lower impact for the end-of-life stage of biomass products than the figure shown here. However, this is also true for conventional products and especially plastic ones, since considerable quantities of plastic products are incinerated with energy recovery (while mineral products are only recycled or landfilled).

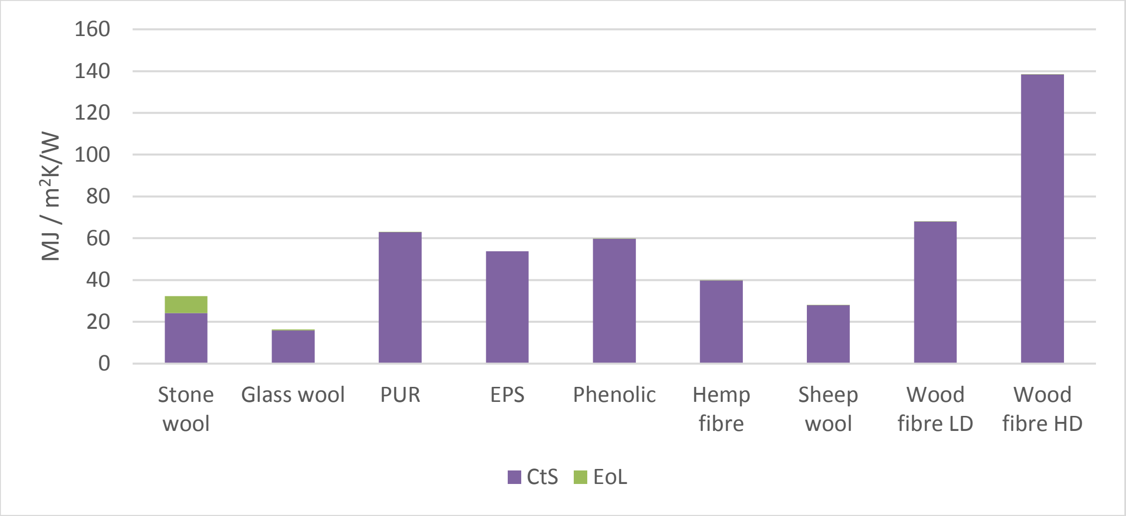


Figure 4. 55 – Comparison between the PEU of insulation products used in this research – Cradle-toSite (CtS) and End-of-Life (EoL) stages

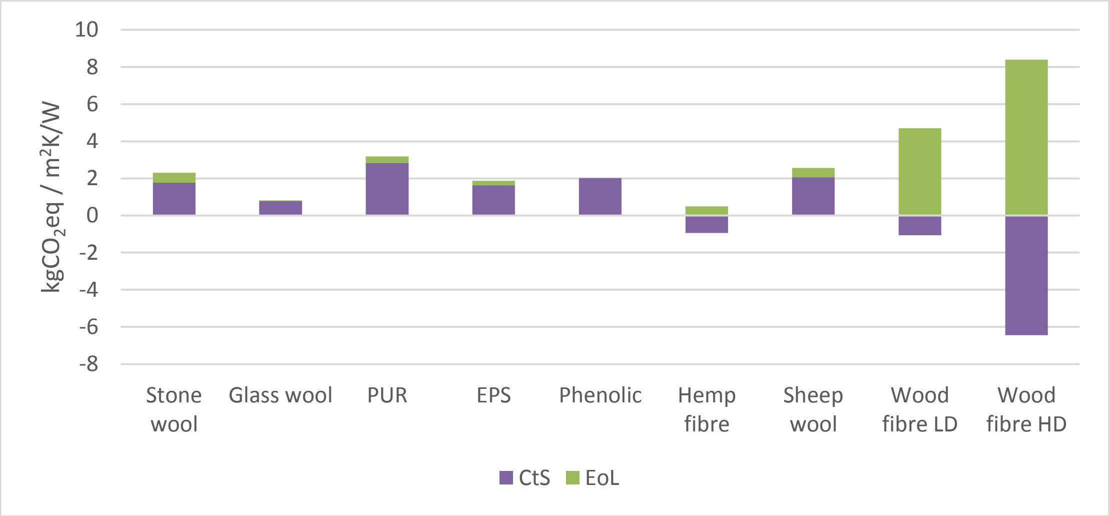


Figure 4. 56 - Comparison between the GWP of insulation products used in this research – Cradle-to-Site (CtS) and End-of-Life (EoL) stages

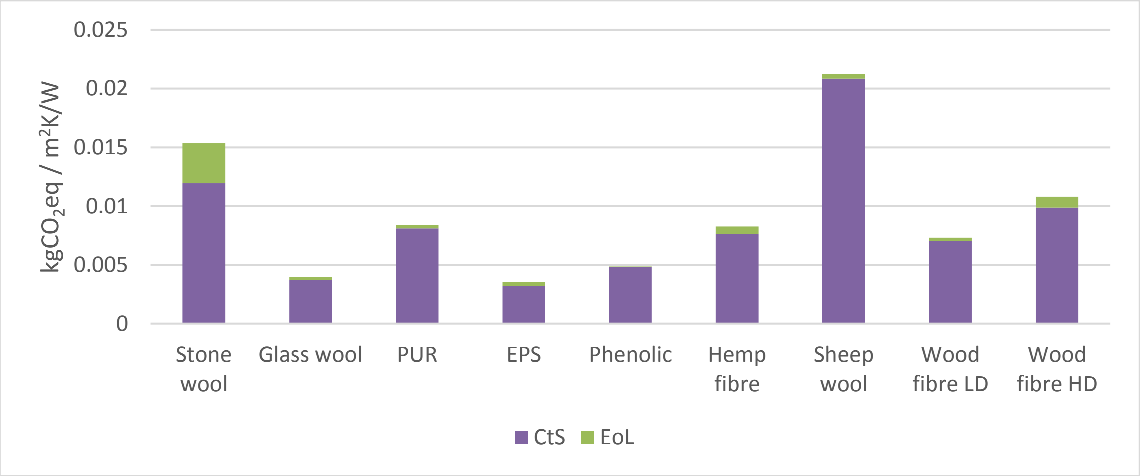


Figure 4. 57 - Comparison between the AP of insulation products used in this research – Cradle-to-Site (CtS) and End-of-Life (EoL) stages

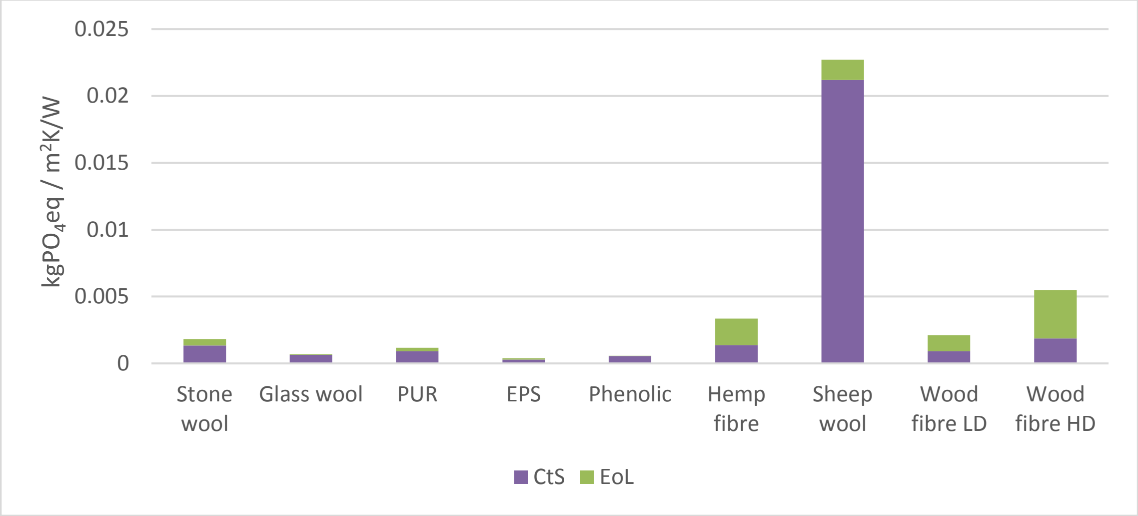


Figure 4. 58 - Comparison between the EP of insulation products used in this research – Cradle-to-Site (CtS) and End-of-Life (EoL) stages

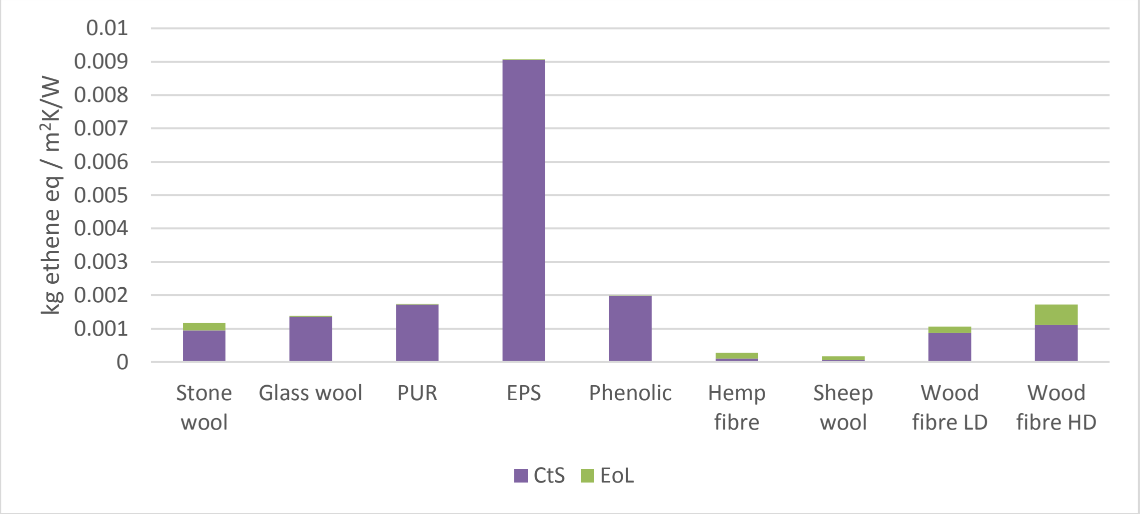


Figure 4. 59 - Comparison between the POCP of insulation products used in this research – Cradle-to-Site (CtS) and End-of-Life (EoL) stages

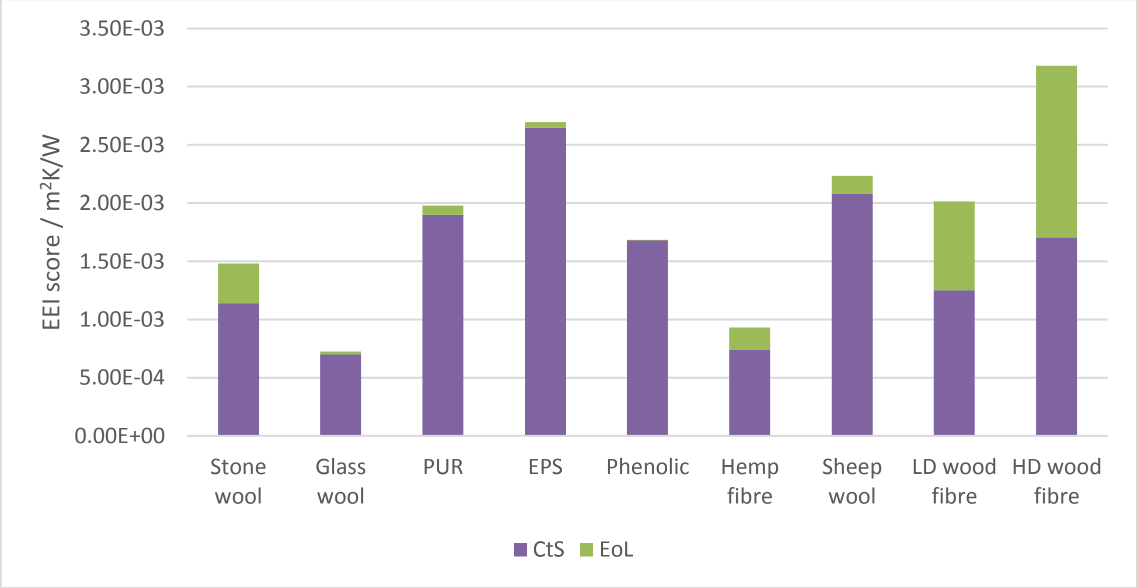


Figure 4. 60 – Comparison between the EEI score of insulation products used in this research – Cradle-to-Site (CtS) and End-of-Life (EoL) stages

4.4 Results of the environmental impact assessment

This section presents the final outcomes the first research component, namely the assessment of EEI of products for the insulation of Welsh dwellings from 2020 to 2050. The EEI is assessed through process-based LCA for FUs of 1 m^2K/W within cradle-to-site boundary, as described in previous sections. Firstly, the EEI of the baseline supply scenarios is presented (section 4.4.1). Successively, the performance of alternative supply scenario is compared in terms of changes from baseline EEI values (section 4.4.2).

4.4.1 EEI of baseline supply scenarios

EEI of baseline supply scenarios - Normalised impact

The normalised cradle-to-site EEI of the primary and secondary baseline scenarios for retrofitted and new dwellings are shown in Figure 4. 61 and Figure 4. 62, respectively. Normalisation compares the EEI of baseline scenarios to reference factors of environmental impact. The factors used in this research quantify the environmental impact of human activities at world level in 2000 and divide it by world population (see section 4.3.13). They represent the average environmental impact associated with a person in 2000.

Results for new and retrofitted dwellings are qualitatively similar in terms of relative importance of categories, but a higher impact is associated with insulation new dwellings, since figures for new dwellings are about two times larger than figures for retrofitted dwellings. Both Figure 4. 61 and Figure 4. 62 identify PEU and POCP as the impact categories with the highest EEI in comparison to the reference factors. GWP, AP and EP have gradually smaller EEI. This implies that the PEU of the baseline scenarios is much bigger than the average PEU of a person *in comparison* to the EP of the baseline scenarios and its relation to the average EP of a person. Thus more importance can be attributed to the EEI of the baseline scenarios in the PEU and POCP categories (and progressively less importance to GWP, AP and EP) on the basis of the normalised EEI values, although it must be noted that normalisation factors do not represent ‘safe’ levels of environmental pressure, but only current levels.

Considering the maximum EEI ranges in Figure 4. 61 and Figure 4. 62 (representing worst cases of EEI), all impact categories have the potential to be associated with much higher impact. This potential is larger for retrofitted dwellings and smaller for new dwellings. Considering the minimum EEI ranges (representing best cases of EEI), both Figure 4. 61 and Figure 4. 62 show that PEU and POCP have a larger potential than GWP, AP and EP to be associated with lower impact. Overall, the degree of uncertainty represented by the EEI ranges is not sufficient to alter the outcome of normalisation, as even in worst and best cases PEU and POCP remain the most important categories, followed progressively by GWP, AP and EP.

Both Figure 4. 61 and Figure 4. 62 show differences between the normalised EEI of the primary and secondary baselines (Base.1 and Base.2). These differences are quite small for GWP, AP and EP, but more marked for PEU and POCP, where the EEI of the secondary baseline can be up to 20% larger than the primary baseline. These differences are caused by the diverse product mix modelled in the secondary baseline, however they are not large enough to alter the qualitative outcome of normalisation, as PEU and POCP are the most important categories (followed by GWP, AP and EP) in both primary and secondary baselines.

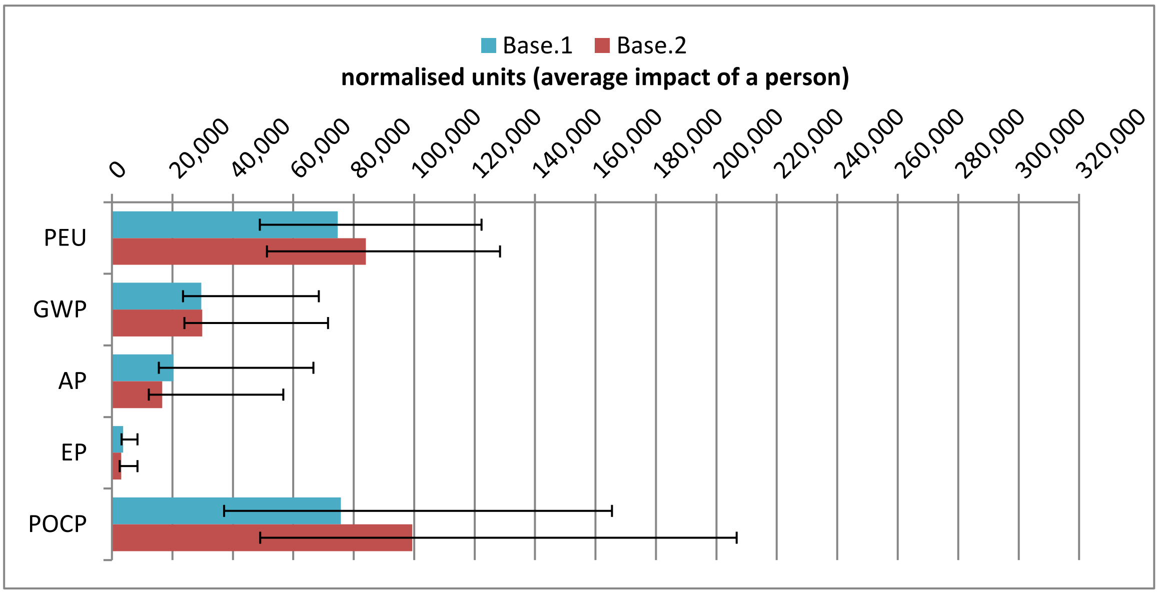


Figure 4. 61 – Normalised cradle-to-site impact of primary and secondary baseline scenarios for retrofitted dwellings

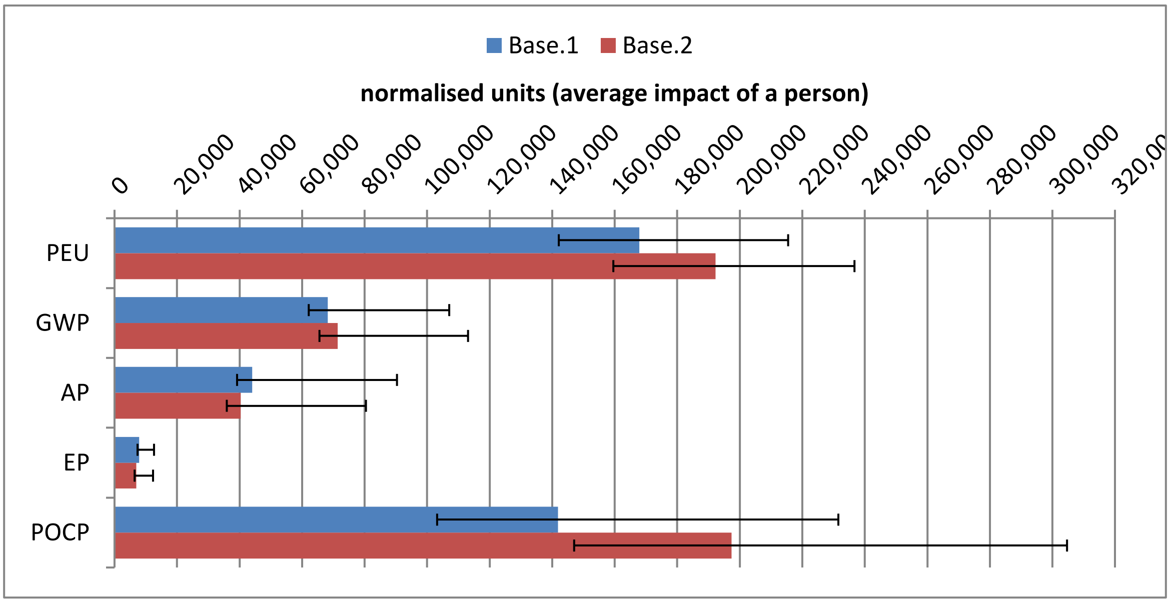


Figure 4. 62 – Normalised cradle-to-site impact of primary and secondary baseline scenarios for new dwellings (demand scenario D1)

EEI of primary baseline supply scenarios - Breakdown by envelope type

In Figure 4. 63 the total cradle-to-site EEI of the primary baseline supply scenario for both retrofitted and new dwellings is broken down by envelope type. The contributions (i.e. shares) of each envelope type are quite similar across categories except for POCP, where a larger share is associated to the insulation of walls. In all impact categories, over 60% of the EEI is caused by the insulation of new dwellings. The smallest contributions to EEI are caused by the insulation of internal walls (IWI) and lofts in retrofits. In both retrofitted and new dwellings, the insulation of walls is associated with the largest EEI. This is due to the products used in the market mix as well as to the large demand. As shown in section 4.1.3, the demand for wall insulation (measured in m^{2}K/W) is roughly equivalent to the sum of the demand for insulation of the other envelope types.

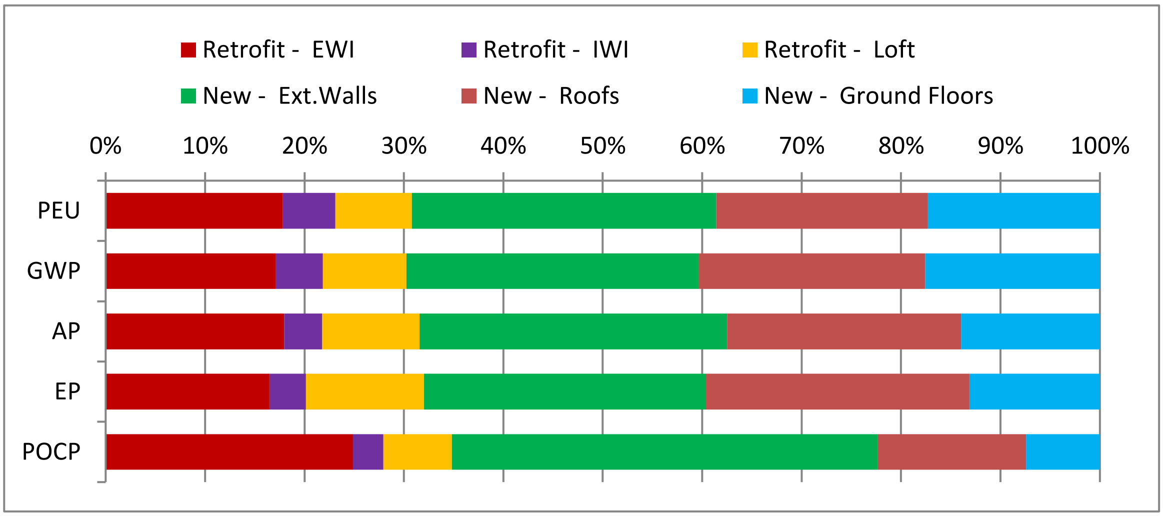


Figure 4. 63 – EEI of primary baseline scenario broken down by envelope type

EEI of primary baseline supply scenarios - Breakdown by product type

In Figure 4. 64 the EEI of the primary baseline for retrofitted dwellings is broken down by product type. Stone wool is associated with the largest impact in AP and EP, while EPS has small impact in AP and EP but the largest share in PEU and POCP. Glass wool, PUR and phenolics have medium to small contribution in all categories.

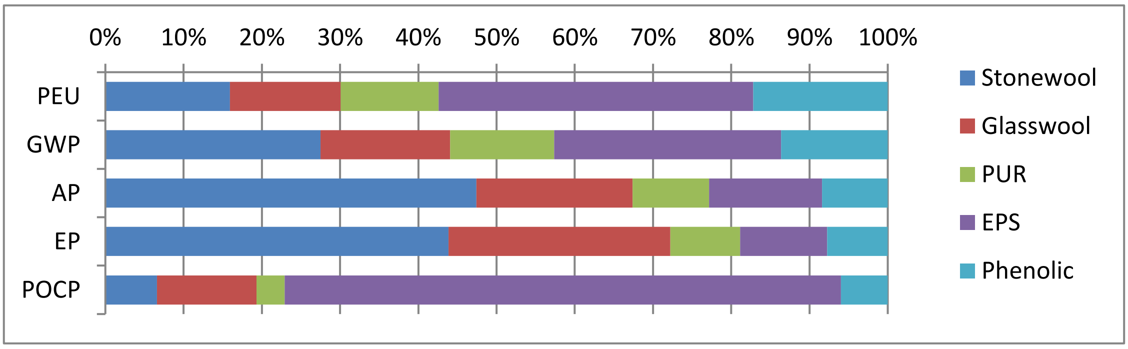


Figure 4. 64 - Breakdown of EEI of primary baseline scenario by product type for retrofitted dwellings

In Figure 4. 65 the EEI of the primary baseline for new dwellings is broken down by product type. In comparison to the breakdown for retrofitted dwellings shown above (Figure 4. 64), PUR is associated with a larger share of impact in all categories except POCP, and the shares of impact associated with stone wool and EPS are smaller. These differences are due to the diverse mixes of conventional products modelled in the baseline scenarios for new and retrofitted dwellings.

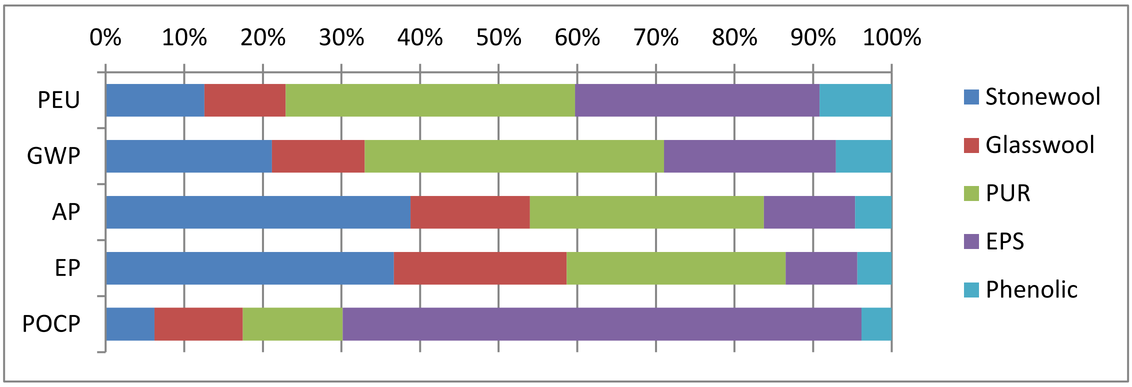


Figure 4. 65 - Breakdown of EEI of primary baseline scenario by product type for new dwellings

EEI of primary baseline supply scenarios - Breakdown by product and envelope type

In the following five graphs (Figure 4. 66 to Figure 4. 70), the EEI in each impact category is broken down by both product and envelope type to allow identifying the most impacting product applications. Products are shown in order of impact (from largest to smallest) in both legends and bar graphs. Envelope types are identified in the legends by the following codes:

R.EWI = Retrofitted dwellings - external (solid) wall insulation

R.IWI = Retrofitted dwellings - internal (solid) wall insulation

R.Loft = Retrofitted dwellings - loft insulation

N.EW = New dwellings - insulation of external walls

N.RO = New dwellings - insulation of roofs

N.GF = New dwellings - insulation of ground floors

In terms of PEU and GWP, (Figure 4. 66 and Figure 4. 67), the most impacting products are:

- EPS used to insulate walls of new and retrofitted dwellings;
- PUR used to insulate roofs and ground floors of new dwellings;
- Stone wool used to insulate walls of new dwellings.

Together, these three products make up over 50% of the PEU and GWP embodied in the baseline supply of insulation products.

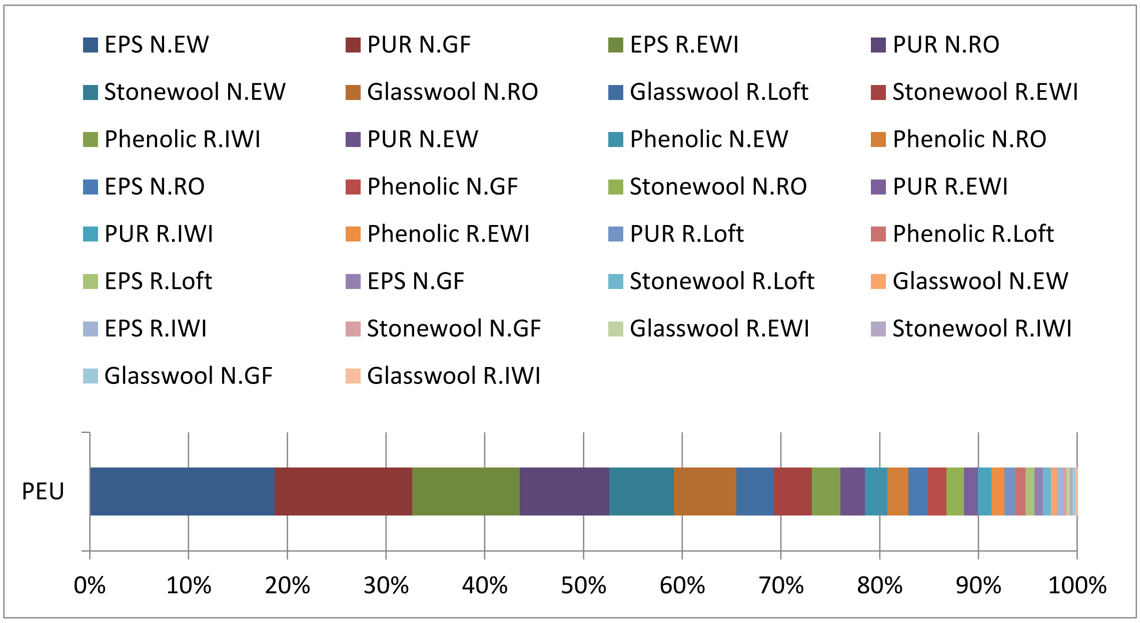


Figure 4. 66 – Breakdown of the PEU of the primary baseline by product and envelope type

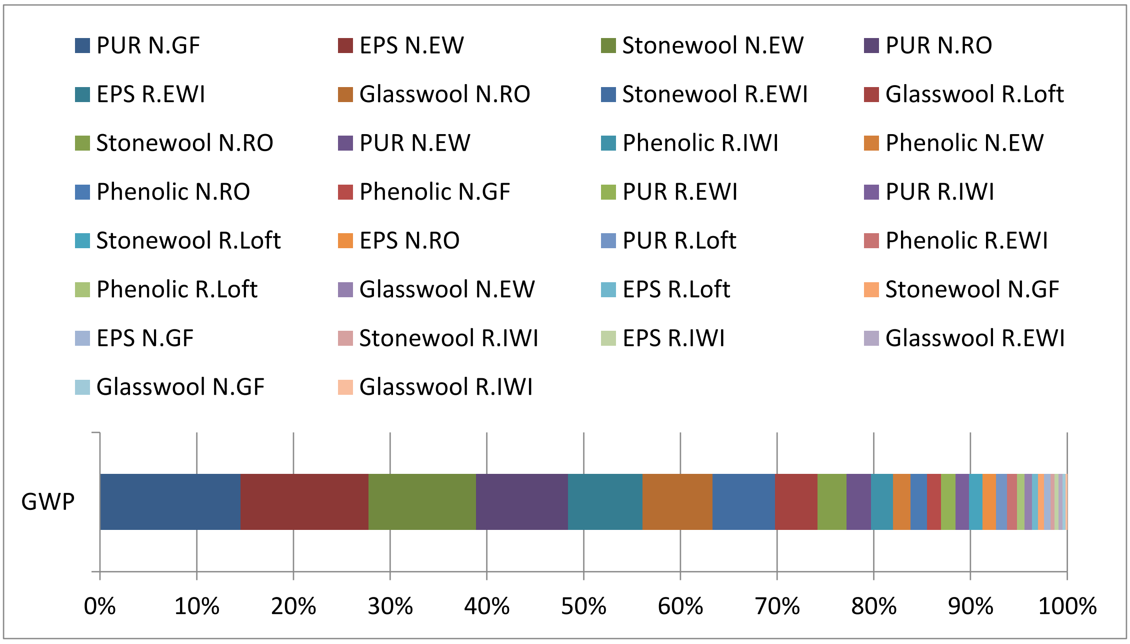


Figure 4. 67 – Breakdown of the GWP of the primary baseline by product and envelope type

In terms of AP and EP (Figure 4. 68 and Figure 4. 69), the most impacting products are:

- Stone wool used to insulate walls of new and retrofitted dwellings;
- PUR used to insulate ground floors of new dwellings;
- Glass wool used to insulate roofs of new dwellings.

Together, these three products make up over 50% of the AP and EP embodied in the baseline supply of insulation products.

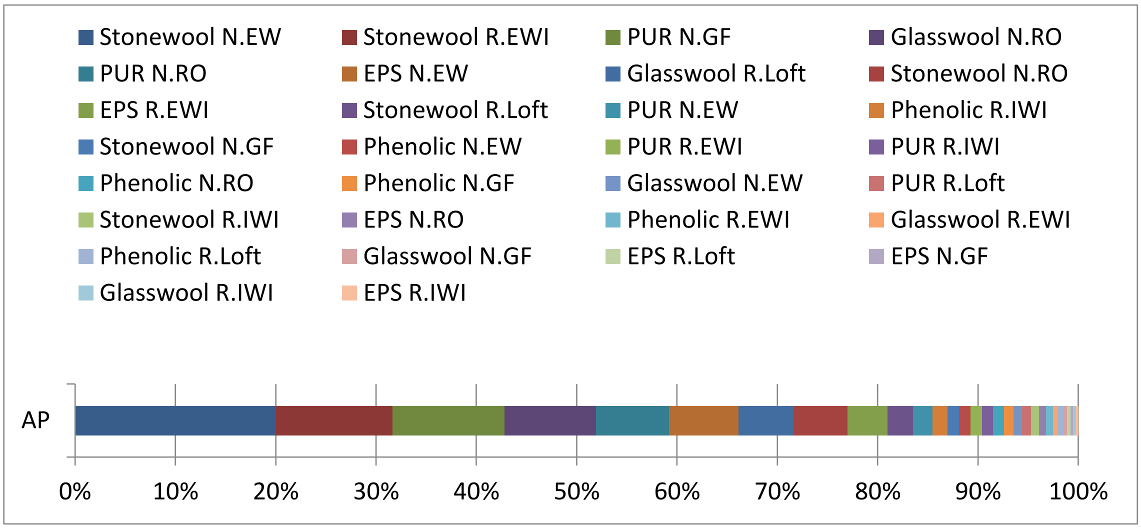


Figure 4. 68 - Breakdown of the AP of the primary baseline by product and envelope type

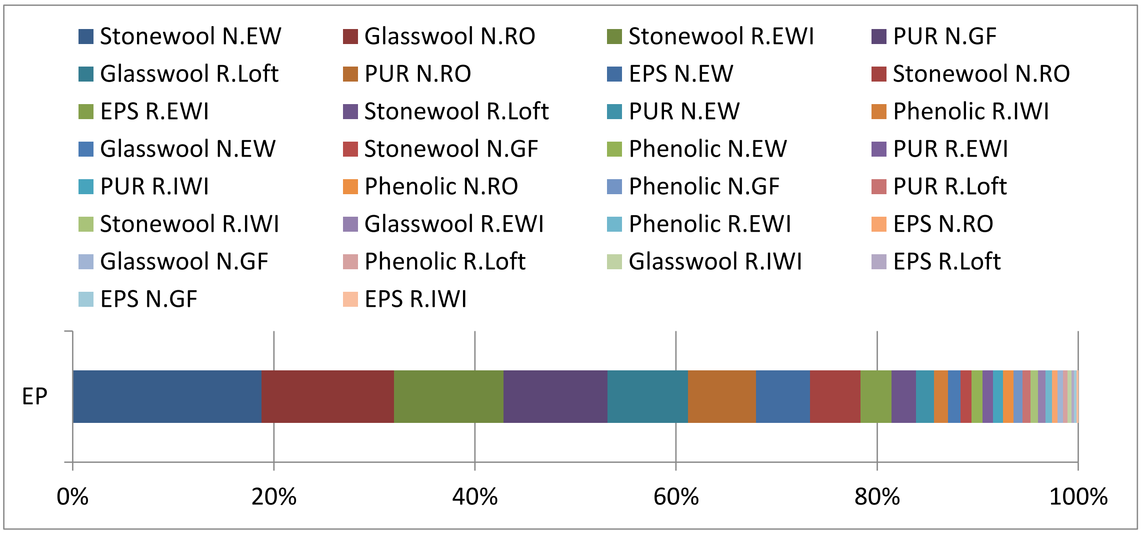


Figure 4. 69 - Breakdown of the EP of the primary baseline by product and envelope type

In terms of POCP (Figure 4. 70), the most impacting product is EPS used to insulate walls of new and retrofitted dwellings, making up almost 60% of the POCP embodied in the baseline supply of insulation products.

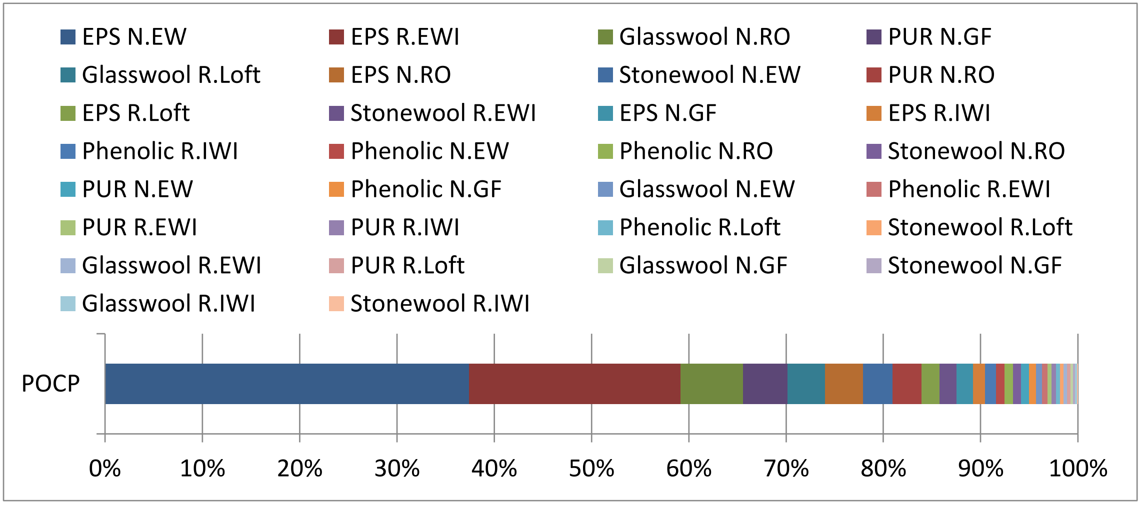


Figure 4. 70 - Breakdown of the POCP of the primary baseline by product and envelope type

Considering this breakdown of the primary baseline together with the normalised impact (Figure 4. 61 and Figure 4. 62), it can be noted that EPS, PUR and stone wool have the largest impact in the most important categories (PEU and POCP, but also GWP) and thus can be identified as the most impacting products in the baseline supply scenarios.

4.4.2 EEI of alternative supply scenarios - Cradle-to-site

The cradle-to-site environmental performances of the alternative supply scenarios are presented here. By comparing the changes in EEI caused by product substitution on the baseline scenarios, the performances of the alternative scenarios can be evaluated against each other. Results are presented separately for the insulation of retrofitted and new dwellings. The alternative scenarios for new dwellings are assessed based on demand scenario D1 (see section 4.1.2), while variations brought about by different demand scenarios (D2, D3 and D4) are evaluated later, using D1 as reference.

Results are presented for each impact category as well as in form of the aggregated EEI score. A few points need to be mentioned to help the interpretation of the following graphs:

- The EEI of the alternative scenarios is evaluated as percentage in reference to the EEI of the respective baseline, taken as '100%' and indicated by a black dotted line in the graphs. This method enables highlighting the relative changes in EEI caused by alternative scenarios (i.e. their 'performance') while avoiding comparison between absolute figures, as discussed in section 3.2.3.
- Changes in EEI caused by the four levels of substitution are shown next to each other, from Small to Very Large. This enables the reader to follow the potential change in EEI cause by larger levels of substitution within an alternative scenario (up to its potential maximum), and to compare them to the respective changes caused by the other alternative scenarios.
- The minimum and maximum EEI figures which accompany the columns in the following graphs represent 'extreme' variations, as explained in section 4.3.12. To avoid confusion, these are referred to as *best case* and *worst case* (omitting the word 'scenario'), and the figures represented by the columns in the following graphs (i.e. the main figures quantifying the EEI of the alternative supply scenarios) are referred to as the 'standard case'. For alternative scenarios introducing biomass products, minimum EEI figures (i.e. the best case) are obtained decreasing the EEI of biomass products and increasing the EEI of conventional ones. Maximum EEI figures (i.e. the worst case) are obtained in the opposite manner. This operation results in a very large difference between minimum and maximum EEI figures. In comparison, the difference between maximum and minimum EEI figures for the alternative scenario introducing mineral

products is generally smaller. This happens because there is no ‘opposition’ between products in the baseline and those newly introduced by the Mineral scenario. For example, minimum EEI figures (i.e. the best case) are obtained decreasing the EEI of all conventional products, those contained in the baseline as well as those newly introduced by the substitution.

- The substitution modelled for biomass products cannot be equally replicated for mineral ones, because the use of glass wool is not reduced but increased (as described in section 4.2.4). Thus the Mineral scenario is not fully comparable to the alternative scenarios introducing biomass products. For example, the use of biomass products in the Small level of substitution is increased until 25% of the market is reached, while the use of glass wool and HD stone wool is increased until 25% *of the remaining market* (i.e. the market occupied by conventional stone wool, EPS, PUR and phenolics) is reached. In comparison to alternative scenarios introducing biomass products, the Mineral scenario reaches a higher share of the market but achieves this by replacing a smaller quantity of conventional products (since glass wool is already used in the baseline product mix).

Alternative scenarios – Changes in PEU

Figure 4. 71 and Figure 4. 72 show changes in PEU caused by alternative scenarios for retrofitted and new dwellings, respectively. While biomass scenarios increase PEU, the Mineral scenario can achieve reductions. The largest increase is caused by the Wood fibre scenario. The Sheep wool scenario does not substantially change the PEU of new dwellings, as changes reach up to about 105% against the primary baseline but decrease down to about 95% against the secondary baseline.

Maximum and minimum PEU ranges indicate that the best case for the Mineral scenario achieves only small additional reductions, while the worst case causes minimal increases from baseline values. A large variation is associated with scenarios introducing biomass products, as all worst cases reach much higher PEU values. While best cases for Sheep wool and Hemp fibre scenarios can achieve some reductions in PEU, even the best case for the Wood fibre scenario increases PEU.

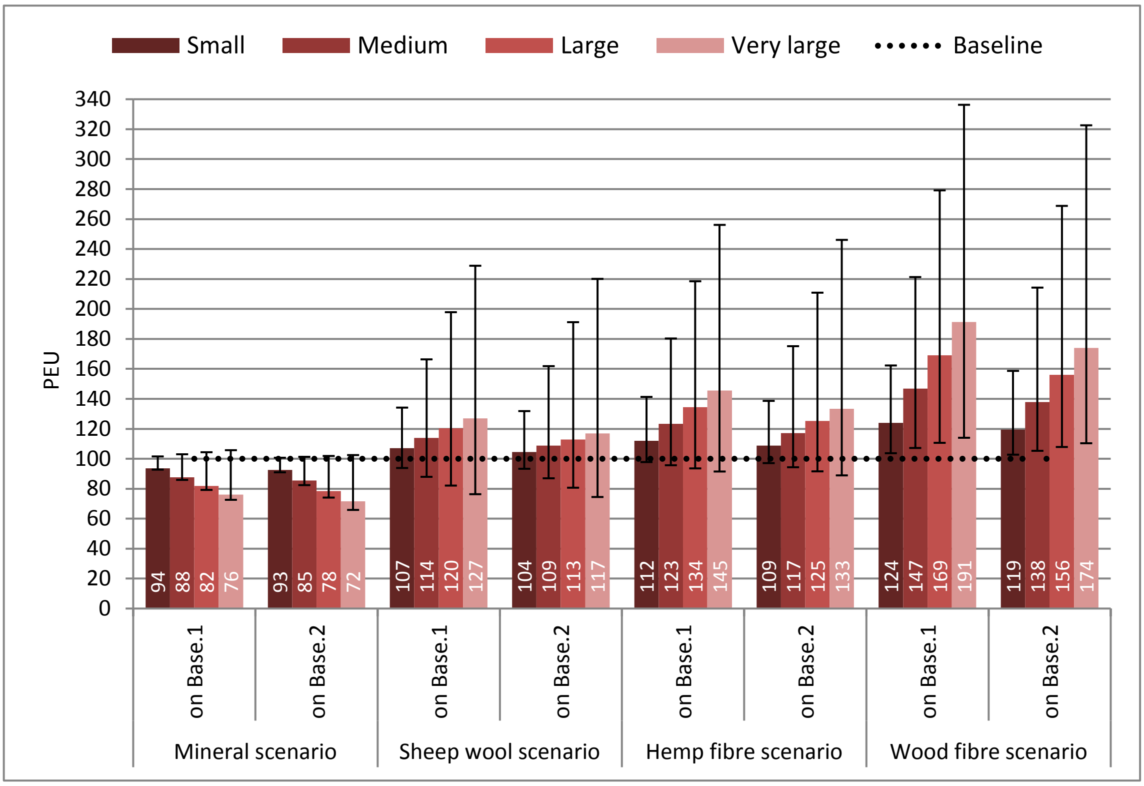


Figure 4. 71 – Changes in PEU from baseline values (=100) caused by alternative scenarios for retrofitted dwellings

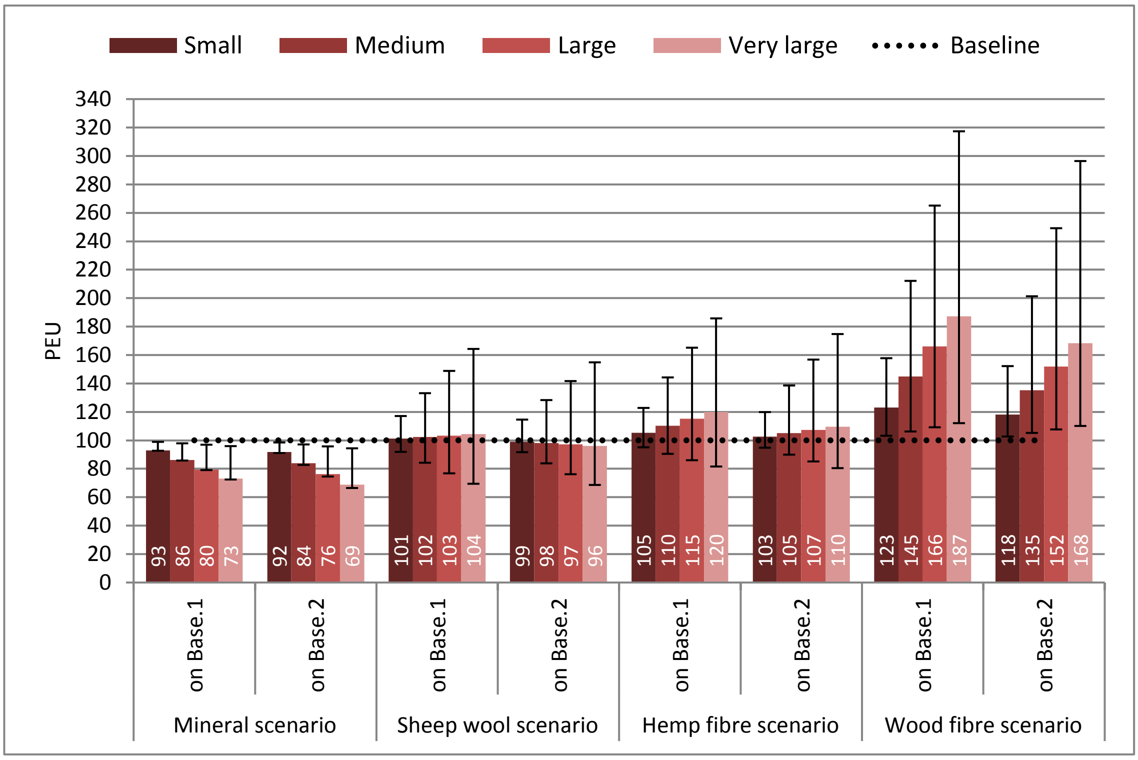


Figure 4. 72 - Changes in PEU from baseline values (=100) caused by alternative scenarios for new dwellings

Alternative scenarios – Changes in GWP

Figure 4. 73 and Figure 4. 74 show changes in GWP caused by alternative scenarios for retrofitted and new dwellings, respectively.

Reductions are achieved by all scenarios, though these are rather small for the Mineral scenario and more significant for scenarios introducing biomass products. The largest reductions are achieved by the Hemp fibre and Wood fibre scenarios. For Large and Very Large levels of substitution, these two scenarios achieve negative GWP values, meaning that there is a beneficial net intake of carbon in the supply of insulation products. The Sheep wool scenario achieve smaller reductions in comparison to the Hemp fibre and Wood fibre scenarios, and the maximum GWP ranges show that in the worst case the Sheep wool scenario would increase GWP. Conversely, maximum GWP ranges of the Hemp fibre and Wood fibre scenarios indicate that reductions are achieved even in the worst case. In comparison to scenarios introducing biomass products, maximum and minimum GWP ranges in the Mineral scenario indicate a smaller degree of variation.

GWP reductions achieved by alternative scenarios introducing biomass products in new dwellings are smaller in comparison to GWP reductions achieved for retrofitted dwellings. Conversely, the Mineral scenario achieves larger GWP reductions in new dwellings than in retrofitted dwellings.

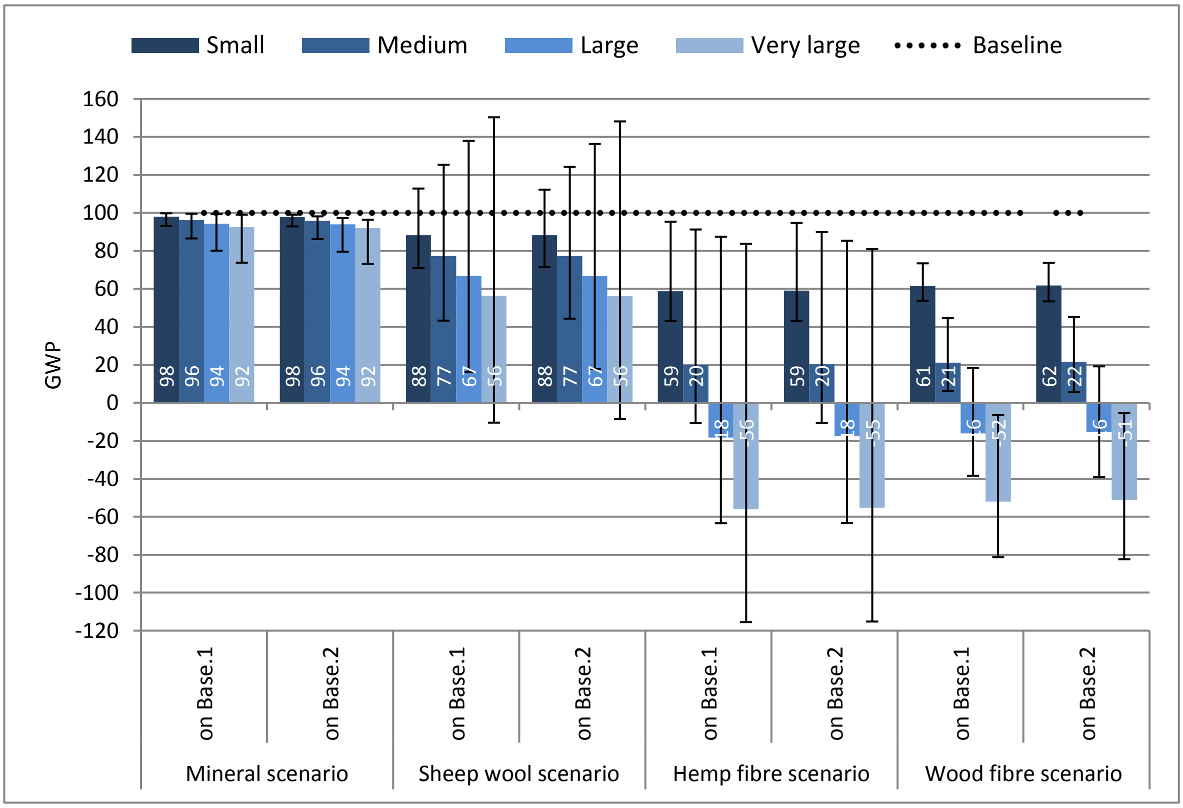


Figure 4. 73 – Changes in GWP from baseline values (=100) caused by alternative scenarios for retrofitted dwellings

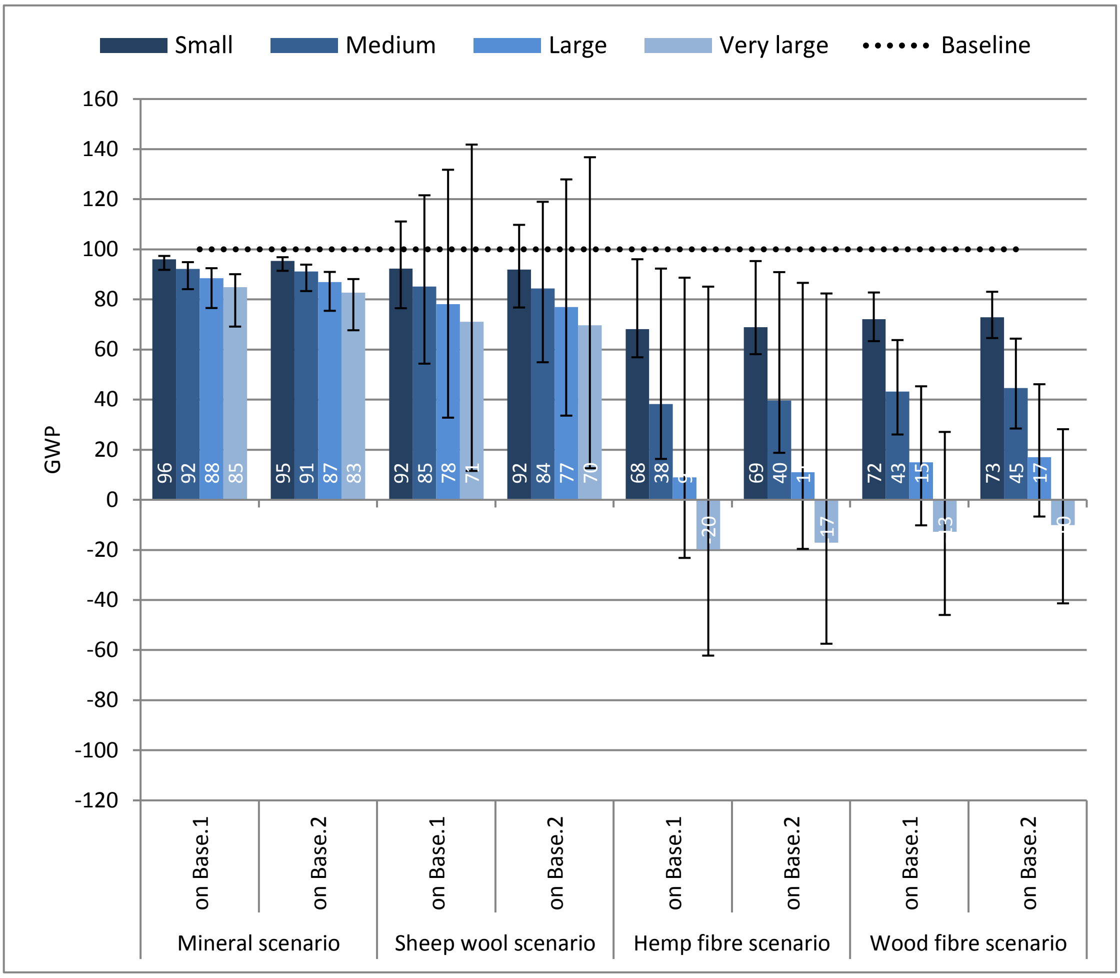


Figure 4. 74 – Changes in GWP from baseline values (=100) caused by alternative scenarios for new dwellings

Alternative scenarios – Changes in AP

Figure 4. 75 and Figure 4. 76 show changes in AP caused by alternative scenarios for retrofitted and new dwellings, respectively.

All alternative scenarios increase AP, but the Sheep wool scenarios significantly more than the others (up to 300%). Changes in AP caused by the Mineral, Hemp fibre and Wood fibre scenarios are similar in magnitude (up to about 140%) and quite significant in comparison to the baseline impact, although they can be considered rather small in comparison to the poor performance of the Sheep wool scenario. The performances of the alternative scenarios in new and retrofitted dwellings are not qualitatively different, however AP changes in new dwellings are smaller (in percentage terms) to those in retrofitted dwellings.

Maximum and minimum AP ranges show very small variation in the Mineral scenario. Conversely, maximum ranges of scenarios introducing biomass products indicate that in worst cases AP could be increased very significantly (especially by the Sheep wool scenario), but also that reductions could be achieved in best cases.

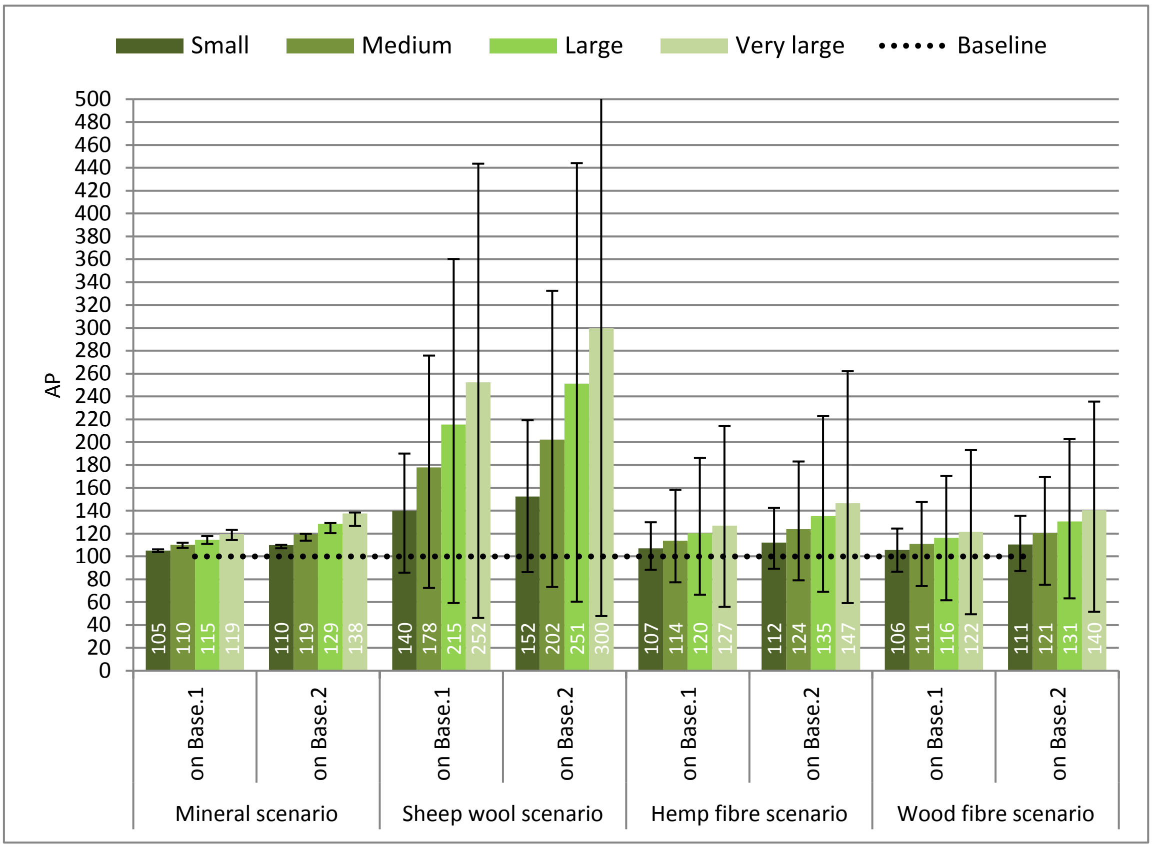


Figure 4. 75 - Changes in AP from baseline values (=100) caused by alternative scenarios for retrofitted dwellings

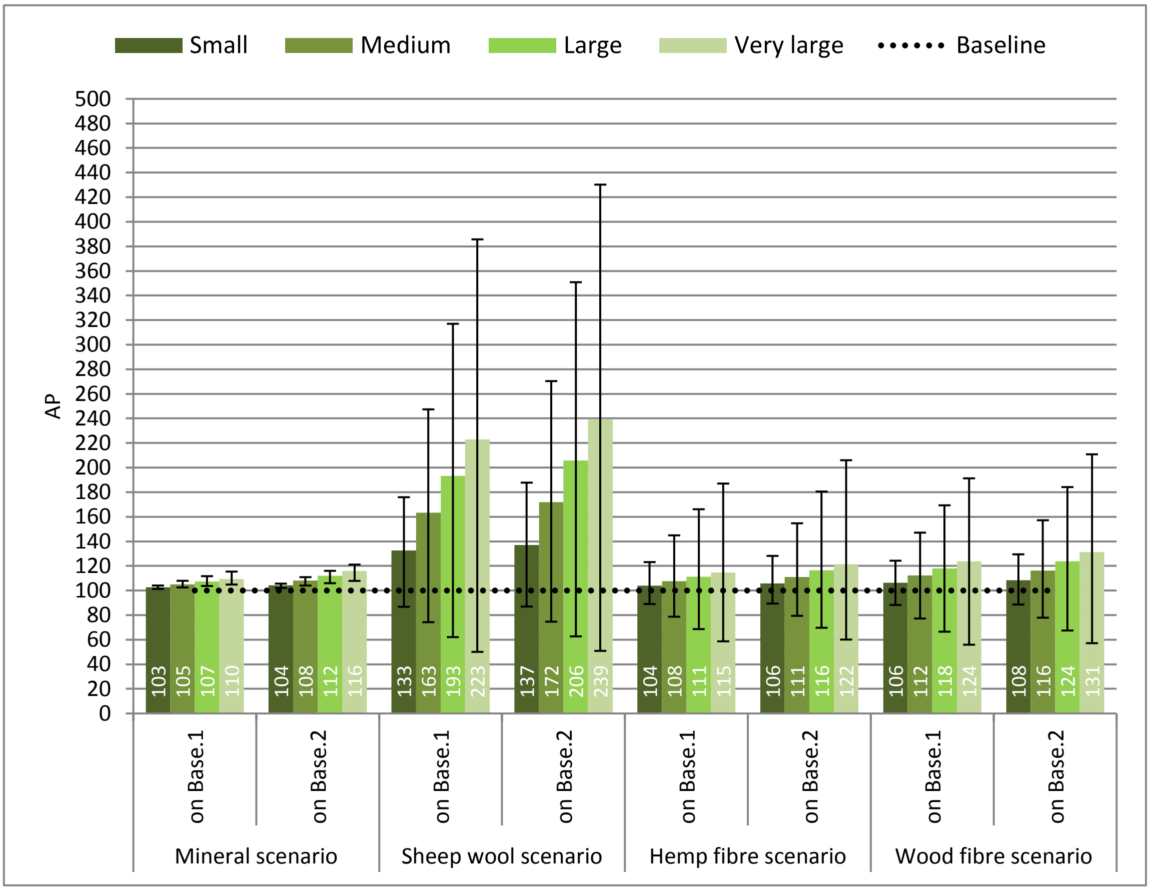


Figure 4. 76 – Changes in AP from baseline values (=100) caused by alternative scenarios for new dwellings

Alternative scenarios – Changes in EP

Figure 4. 77 and Figure 4. 78 show changes in EP caused by alternative scenarios for retrofitted and new dwellings, respectively. Changes from the baseline EP values are qualitatively similar to those for the AP category (i.e. all alternative scenarios increase EP), but more marked. The Sheep wool scenario achieves the poorest performance, causing increases up to 20 times the baseline EP value. However, the increases caused by the other scenarios are also significant. EP changes in new dwellings are smaller (in percentage terms) to those in retrofitted dwellings.

As for the AP category, maximum and minimum EP ranges show small variations for the Mineral scenario and large ones for the others. Reductions in EP could be achieved in best cases by the alternative scenarios introducing biomass products.

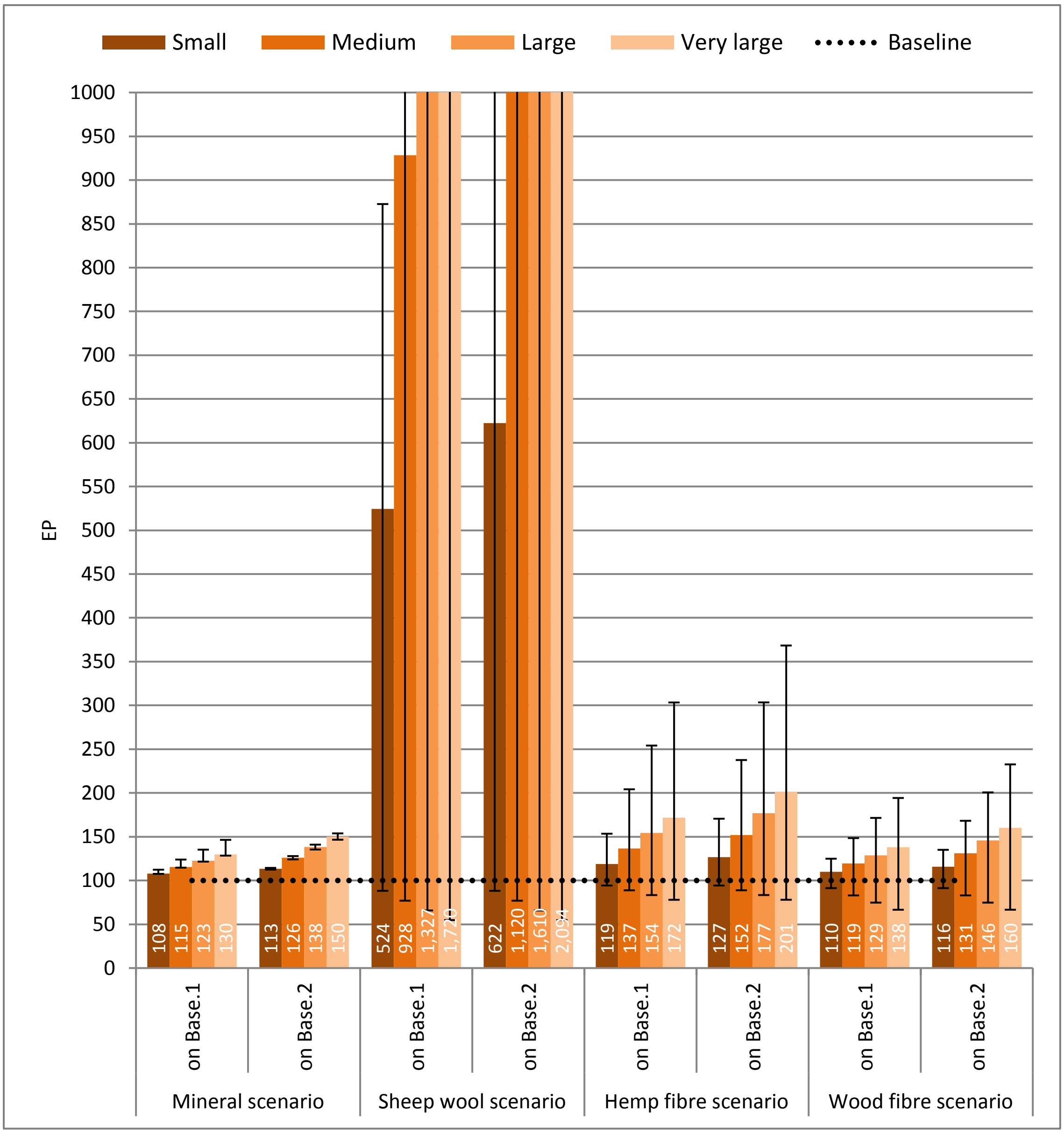


Figure 4. 77 – Changes in EP from baseline values (=100) caused by alternative scenarios for retrofitted dwellings

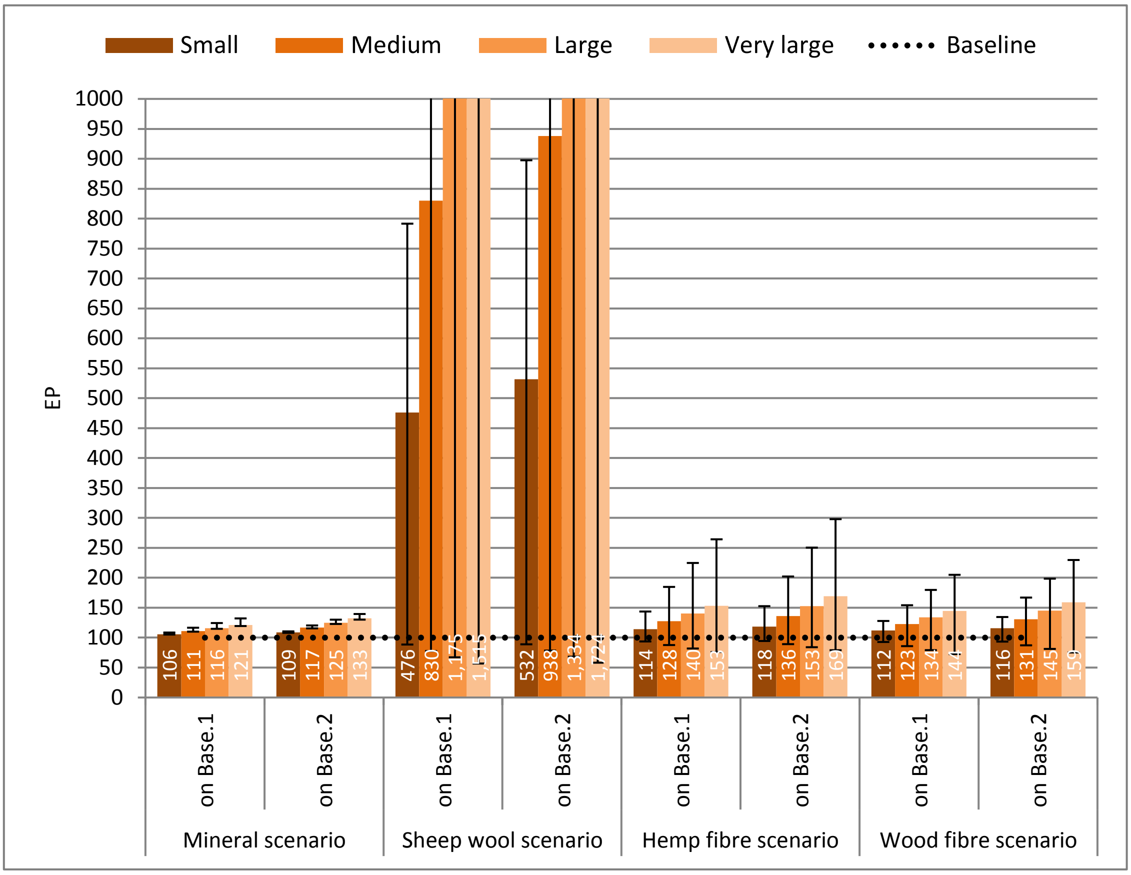


Figure 4. 78 - Changes in EP from baseline values (=100) caused by alternative scenarios for new dwellings

Alternative scenarios – Changes in POCP

Figure 4. 79 and Figure 4. 80 show changes in EP caused by alternative scenarios for retrofitted and new dwellings, respectively. All alternative scenarios achieve reductions, though the largest ones are caused by the Sheep wool and Hemp fibre scenarios.

In comparison to retrofitted dwellings, slightly smaller reductions are achieved by alternative scenarios for new dwellings. A difference can be noted for the Wood fibre scenario: against the primary baseline of new dwellings, the maximum POCP values (i.e. the worst case) are higher than the baseline impact, while against the primary baseline of retrofitted dwellings, POCP reductions are achieved even in the worst case.

Maximum and minimum POCP ranges show that even in worst cases all scenarios still achieve reductions, though rather limited ones for the Wood fibre one. In best cases, the additional reductions achieved by the Mineral scenario are still smaller than those achieved by the Sheep wool and Hemp fibre scenarios in standard cases. It must be noted that the good performance of hemp fibre and sheep wool products in this impact category is affected by the issue with the POCP characterisation of the CML assessment method (see section 3.2.3). However, it can be also noted that the levels of POCP reductions achieved by the Sheep wool and Hemp fibre scenarios are relatively close to those achieved by Mineral and Wood fibre scenarios, which are based on LCA figures less affected by the problematic CML characterisation, and therefore more reliable. Considering this context, it can be argued that the performances of the alternative scenarios are essentially equivalent in terms of POCP reductions.

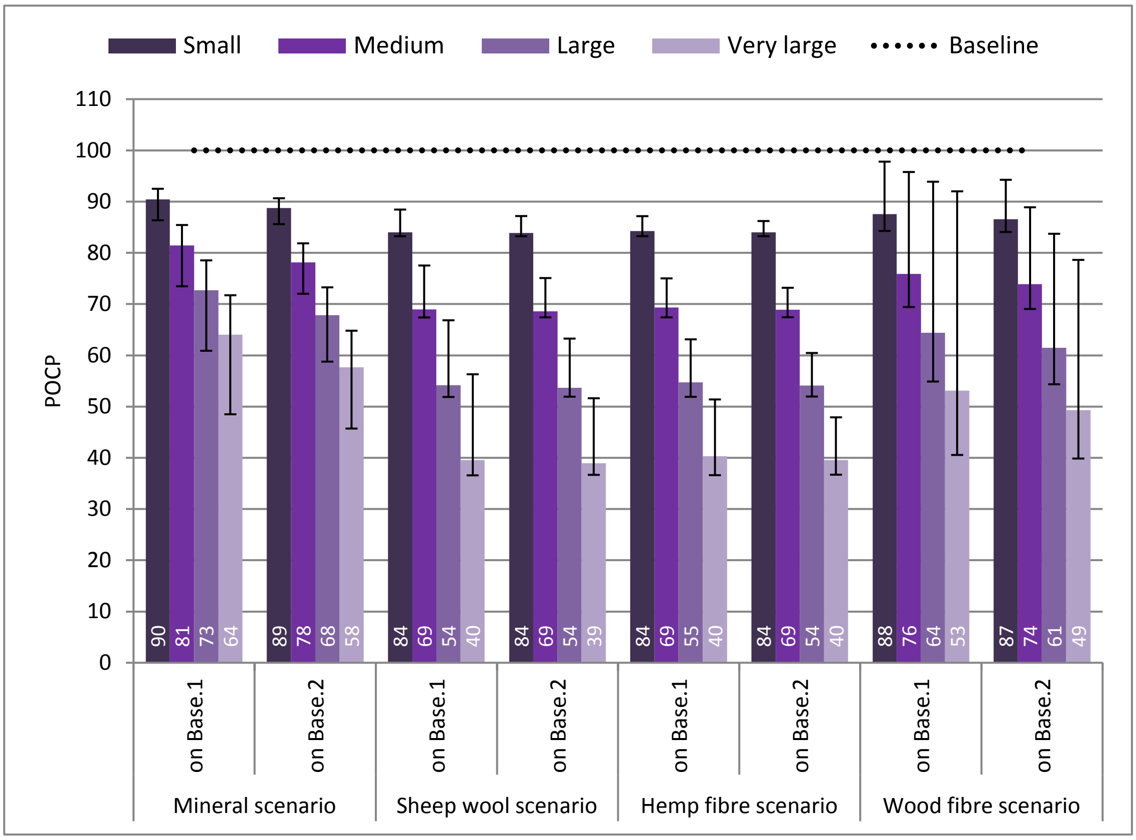


Figure 4. 79 - Changes in POCP from baseline values (=100) caused by alternative scenarios for retrofitted dwellings

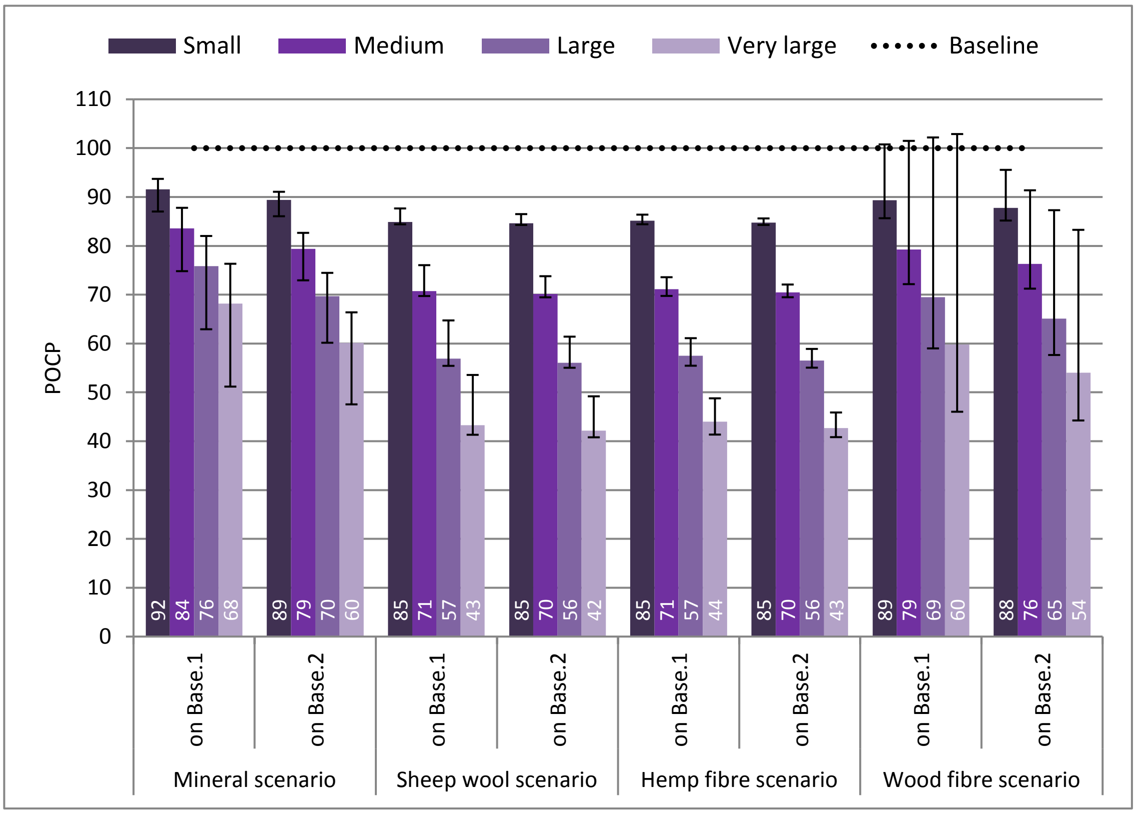


Figure 4. 80 - Changes in POCP from baseline values (=100) caused by alternative scenarios for new dwellings

Alternative scenarios – Changes in EEI score

Changes in EEI caused by alternative scenarios for retrofitted and new dwellings are presented in Figure 4. 81 and Figure 4. 82, respectively, as a score aggregating the five impact categories. The score is calculated by summing together the normalised EEI figures without applying a weighting factor, as described in section 4.3.13. This EEI score helps evaluating the environmental performance of alternative scenarios as a whole, but does not have more importance than the analysis of individual impact categories.

The Sheep wool scenario is the only one increasing the EEI score, up to about 120%. The Wood fibre scenario achieves minor reductions of the score, while the Mineral and Hemp fibre scenarios achieve the largest ones.

Some differences between then performances achieved in retrofitted and new dwellings are present:

- Slightly smaller increases than in retrofitted dwellings are achieved by the Sheep wool scenario for new dwellings.
- The Wood fibre scenario against the primary baseline for new dwellings does not effectively change EEI score.
- The Hemp fibre scenario for new dwellings reduces the EEI score even in the worst case, while for retrofitted dwellings the EEI score is increased in the worst case.

Minimum EEI score ranges show that no additional reductions could be achieved by Mineral scenario in the best case, while further reductions (down to about 50%) could be achieved by scenarios introducing biomass products scenarios in best cases. On the other hand, maximum EEI score ranges show that even in worst cases the Mineral scenario still achieves some reductions, while the score is increased by all other scenarios, although to a lesser extent by the Hemp fibre scenario.

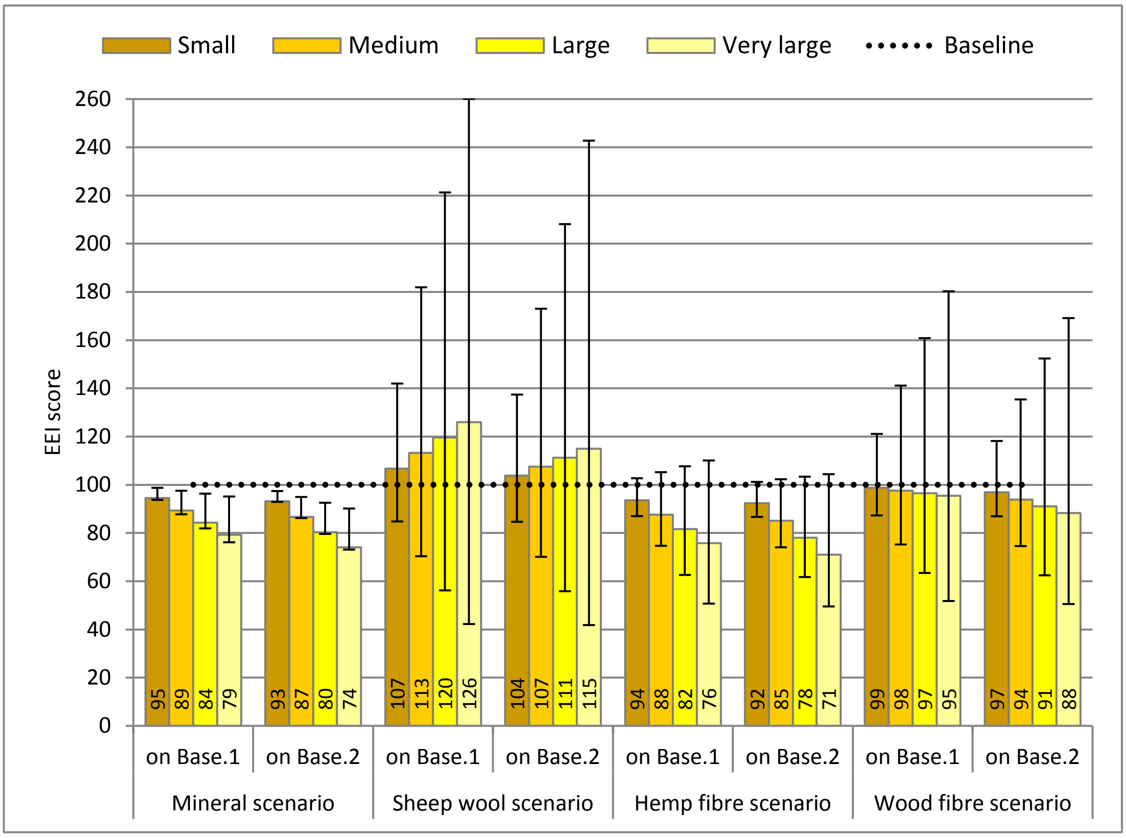


Figure 4. 81 – Changes in EEI score from baseline values (=100) caused by alternative scenarios for retrofitted dwellings

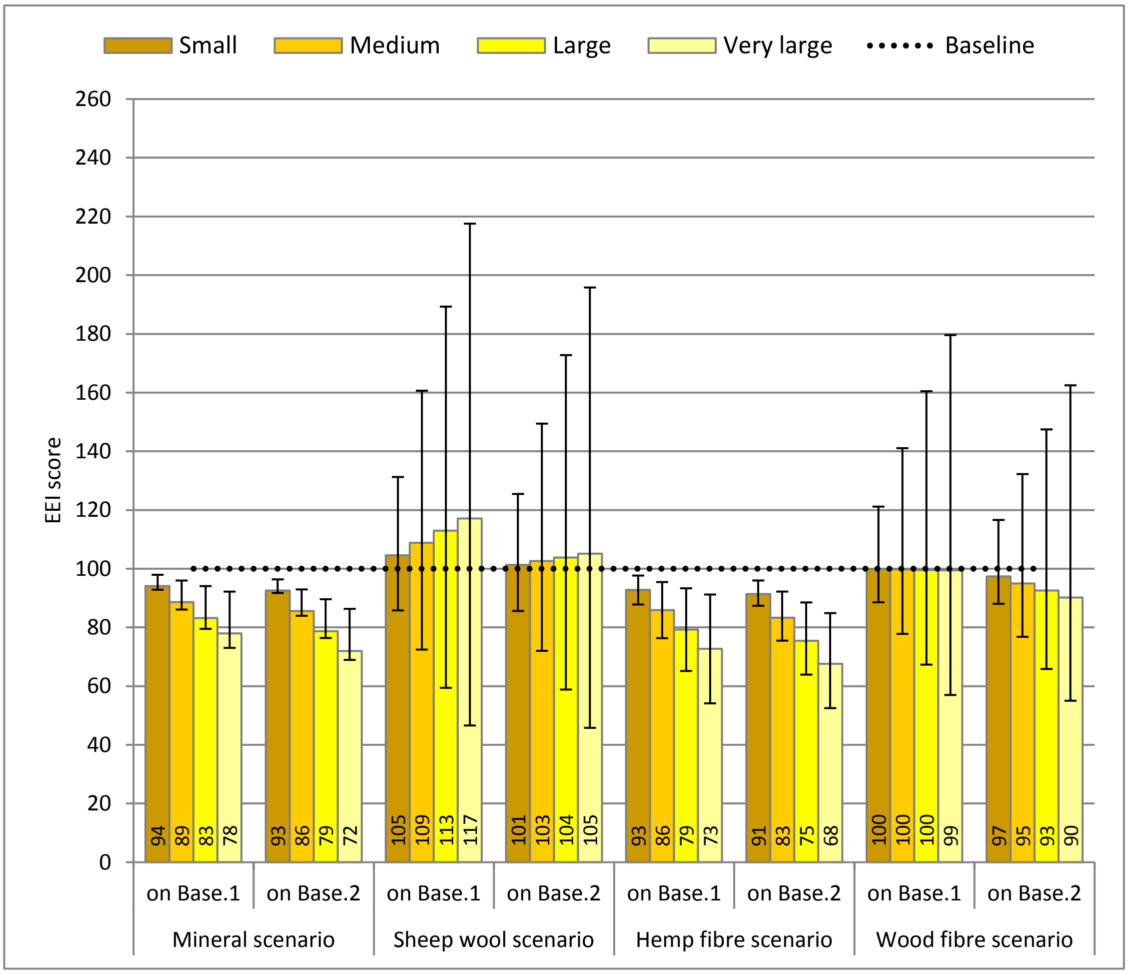


Figure 4. 82 – Changes in EEI score from baseline values (=100) caused by alternative scenarios for new dwellings

Differences between primary and secondary baselines

The previous graphs (Figure 4. 71 to Figure 4. 82) show some differences in EEI changes caused by alternative scenarios on the primary baseline in comparison to EEI changes on the secondary baseline. However, these differences are not qualitatively significant, as there is never a case where the 'trend' of EEI changes caused by an alternative scenario on the primary baseline is reversed when the same alternative scenario is applied to the secondary baseline. This implies that variations in the product mix used to model primary and secondary baselines do not affect significantly the performance of one alternative scenario in comparison to the others.

Differences between new and retrofitted dwellings

In terms of percentage, the outcomes of the assessment of EEI changes for new dwellings are close to those for retrofitted dwellings. However, there are some differences between the outcomes of the two sectors. Due to the structure used to model insulation demand, supply and product mix, three factors are affecting these differences between the outcomes for retrofitted and new dwellings:

- The two sectors have different demand curves, which affects the quantity of conventional product being substituted, which in turn affects the extent of changes caused by alternative scenarios (see sections 4.1.3 and 4.2.4);
- The two sectors model different product mixes in the respective baseline supply scenarios, which affects the total EEI of the baselines (see section 4.2.2);
- The split between the soft LD product and the rigid HD product newly introduced by the alternative scenarios for retrofitted dwellings is different from the split for new dwellings (see section 4.2.3).

Comparing the total EEI of the baseline scenarios for new and retrofitted dwellings (see Figure 4. 63), in all impact categories the EEI of the baseline scenario for new dwellings is larger than the EEI of the baseline scenario for retrofitted dwellings. Therefore EEI changes caused by alternative scenarios for new dwellings are larger, in absolute figures, than those for retrofitted dwellings, despite being similar in percentage terms.

Impact variation under different demand scenarios for new dwellings

The previous graphs have shown the performance of the alternative supply scenarios under demand scenario D1 for new dwellings. To simplify the interpretation of results, the environmental performance of the alternative supply scenarios under different demand scenarios for new dwellings is presented here using the performance of D1 and the Small level of substitution as reference. Changes in EEI score are shown in Figure 4. 83 connected by coloured lines, while the black dotted line represents the baseline EEI (=100%). The continuous blue line indicates the EEI changes by the alternative supply scenarios under demand scenario D1. The dotted lines indicate the EEI changes of alternative supply scenarios under the other three demand scenarios.

The fact that the coloured lines in Figure 4. 83 do not perfectly overlap means that there are variations in the performance of alternative supply scenarios if the demand scenario is changed. In particular, under demand scenarios D2 and D4, the alternative scenarios have a smaller effect on the EEI score of the baseline. This is the consequence of the declining demand curves modelled in D2 and D4 (Figure 4. 17 and Figure 4. 19), which result in smaller quantities of conventional products being substituted. However, these differences are not qualitatively significant, as the ‘shapes’ of the coloured lines in Figure 4. 83 are similar, and differences between EEI score changes are below 5 percentage points. If the level of substitution is increased, these differences between EEI score changes become larger. However even at the Very Large level of substitution (i.e. reaching 100% of product substitution), differences between EEI score changes remain below 10 percentage points. It can be concluded that different demand scenarios do not substantially affect the performance of one alternative supply scenario in comparison to the other alternative scenarios.

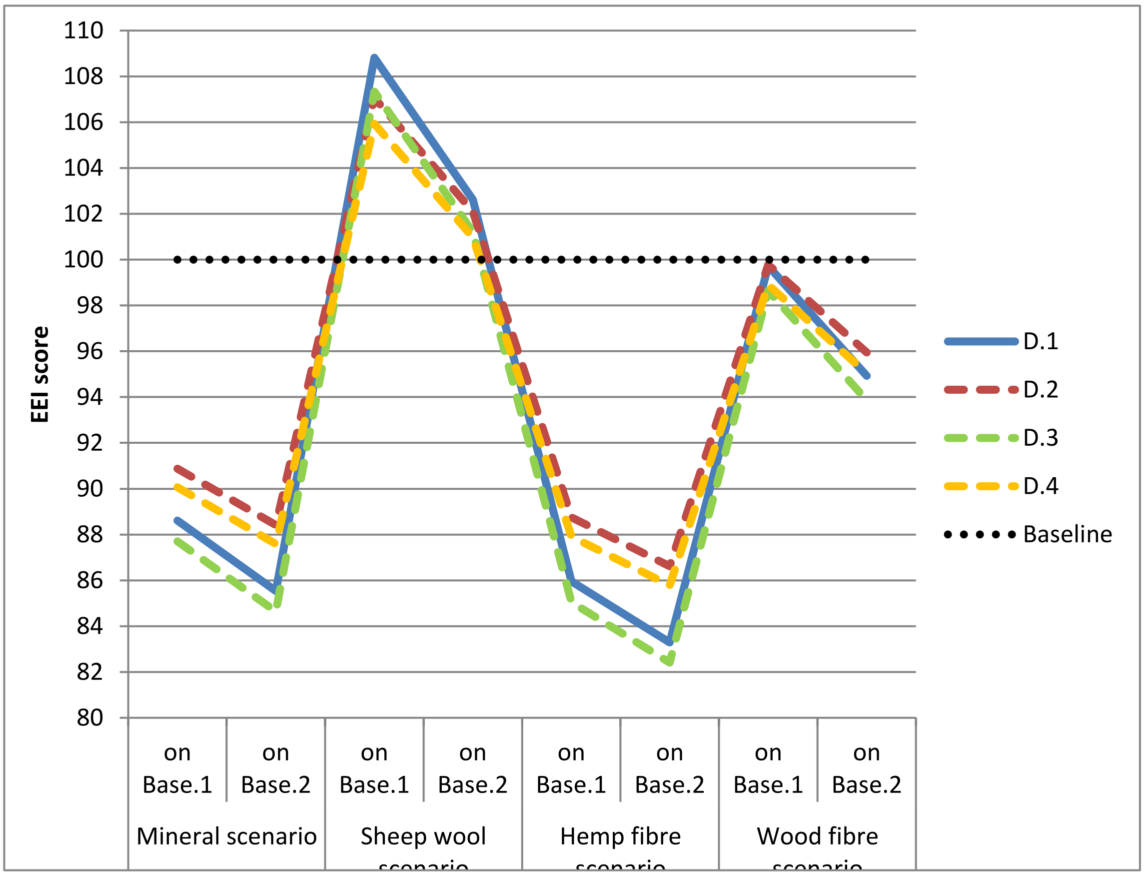


Figure 4. 83 – Comparison between the effects of different demand scenarios for new dwellings on changes in EEI score caused by alternative scenarios

4.4.3 EEI of alternative supply scenarios – Cradle-to-grave

Figure 4. 84 to Figure 4. 95 compare the performance of the alternative supply scenarios assessed with a cradle-to-site boundary (presented in the previous sections) and same scenarios assessed with the cradle-to-grave boundary, i.e. including the impact of the end-of-life stage. As described in sections 3.2.3 and 4.3.10, this stage was assessed by identifying typical shares for recycling, incineration (with energy recovery) and landfill options, and adopting the 'recycled content' modelling approach, which excludes the benefits of recycling and energy recovery.

For simplicity, the performance of the alternative scenarios in the following graphs are compared only against the primary baseline. It must be remembered that the graphs show the EEI of the alternative scenarios as percentage of the EEI of the baseline scenario (which is equal to 100%), and that the EEI of the cradle-to-site baseline scenario can be smaller or larger, *in absolute figures*, than the EEI of the cradle-to-grave baseline scenario. This also true for the alternative scenarios.

Alternative scenarios – Changes in PEU

Figure 4. 104 and Figure 4. 105 show changes in PEU caused by alternative scenarios for retrofitted and new dwellings, respectively. For both sectors, the inclusion of the end-of-life stage increases the PEU embodied in the Sheep wool and Hemp fibre scenarios, while the Mineral and Wood fibre scenarios are much less affected.

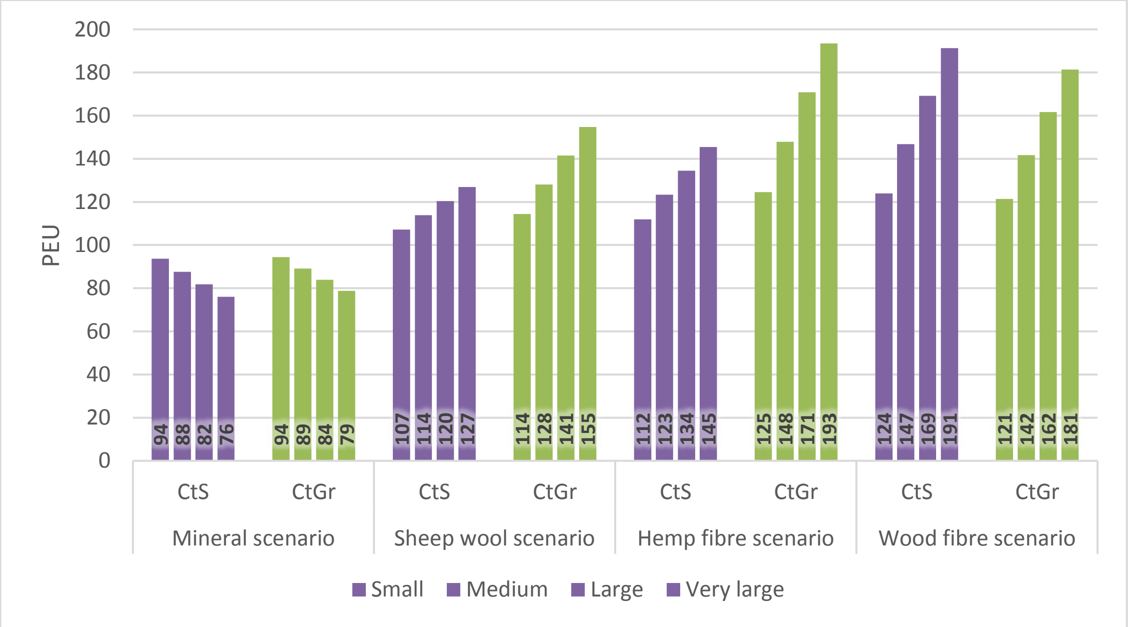


Figure 4. 84 –Changes in PEU caused by alternative scenarios for retrofitted dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

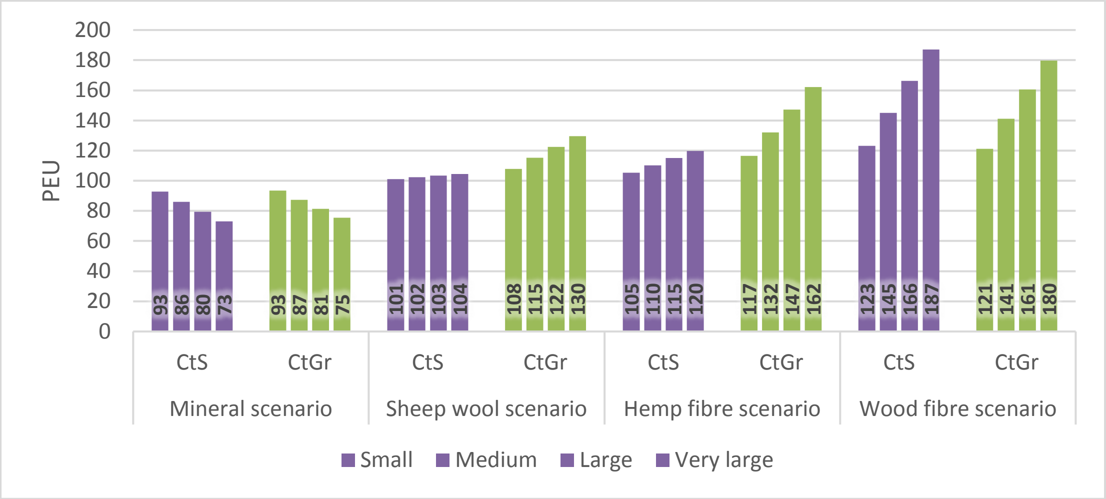


Figure 4. 85 - Changes in PEU caused by alternative scenarios for new dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

Alternative scenarios – Changes in GWP

Figure 4. 106 and Figure 4. 107 show changes in GWP caused by alternative scenarios for retrofitted and new dwellings, respectively. For both sectors, the inclusion of the end-of-life stage has negligible effect on the Mineral scenario, but changes substantially the performance of the alternative scenarios introducing biomass products. This is due in large part to the release of the carbon stored in the biomass in the incineration and landfilling processes. However, the Hemp fibre scenario reduces the total GWP in comparison to the baseline even with the inclusion of the end-of-life stage, while the Sheep wool and Wood fibre scenario increase the total GWP. Moreover, the potential for GWP reduction of the Hemp fibre scenario (up to 20% for retrofits and 25 for new dwellings) is still larger than in the case of the Mineral scenario (up to -8% for retrofits and -15% for new dwellings).

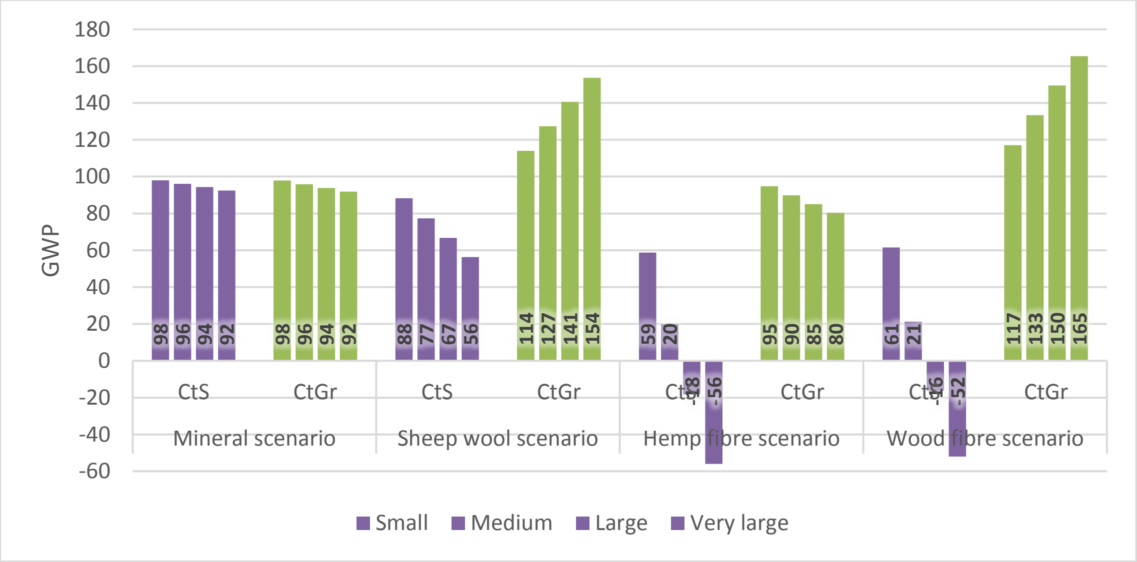


Figure 4. 86 – Changes in GWP caused by alternative scenarios for retrofitted dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

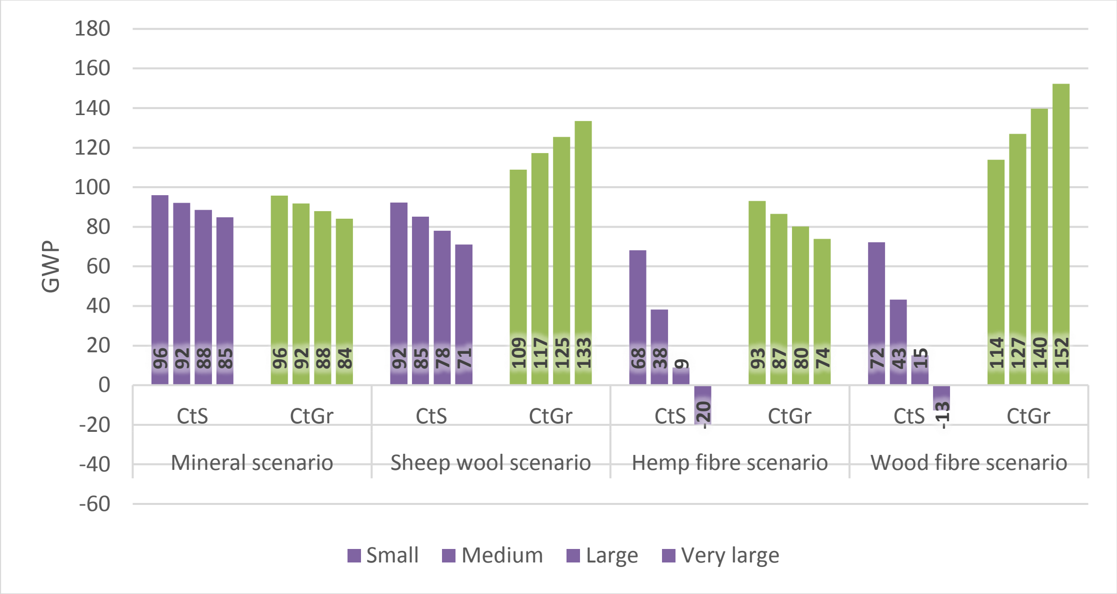


Figure 4. 87 - Changes in GWP caused by alternative scenarios for new dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

Alternative scenarios – Changes in AP

Figure 4. 88 and Figure 4. 89 show changes in AP caused by alternative scenarios for retrofitted and new dwellings, respectively. Noticeable differences can be seen only for the Hemp fibre and Wood fibre scenarios. However, these differences do not significantly alter the performances of the alternative scenarios in comparison to each other.

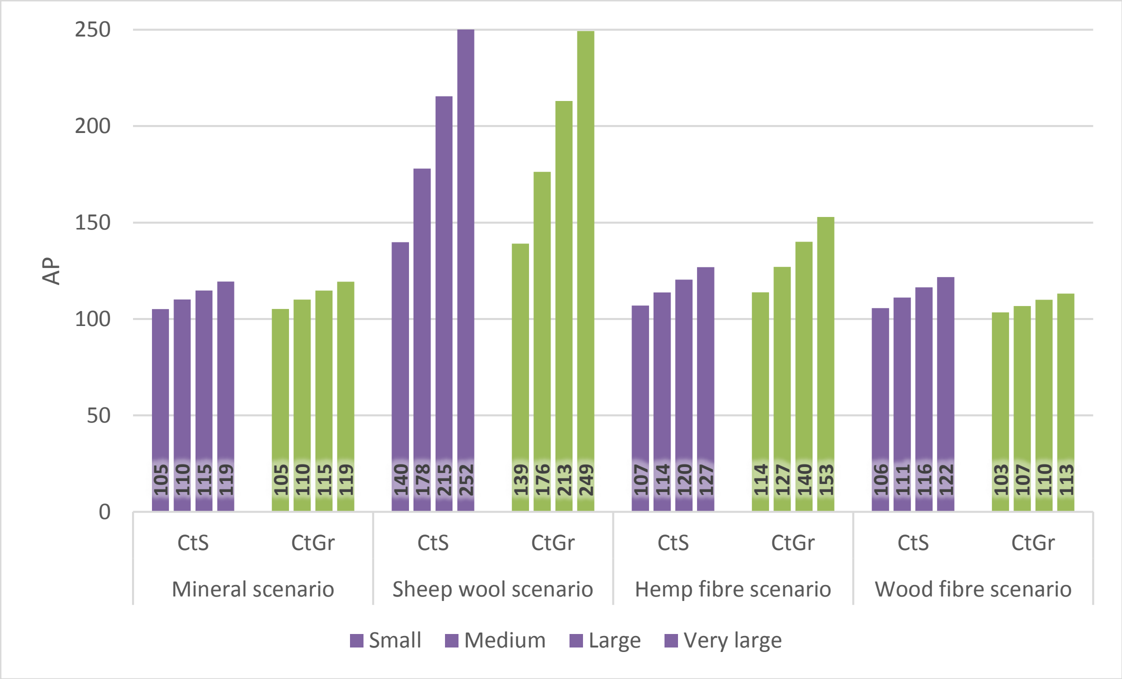


Figure 4. 88 –Changes in AP caused by alternative scenarios for retrofitted dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

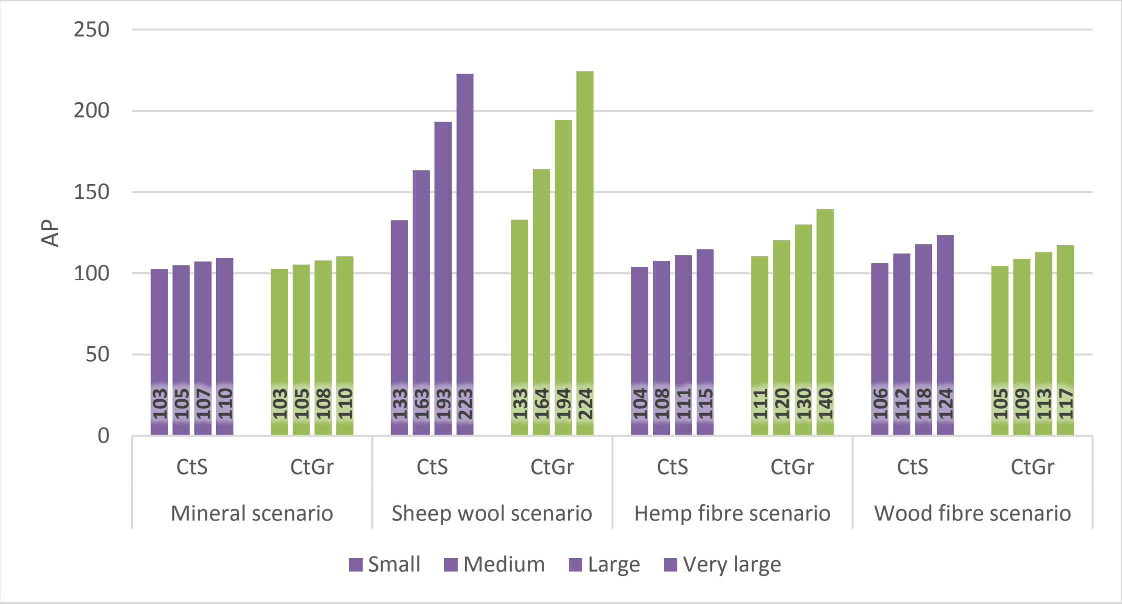


Figure 4. 89 - Changes in AP caused by alternative scenarios for new dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

Alternative scenarios – Changes in EP

Figure 4. 90 and Figure 4. 91 show changes in EP caused by alternative scenarios for retrofitted and new dwellings, respectively. For the Sheep wool scenario, the inclusion of the end-of-life stage reduces the overall increase in EP in comparison to the baseline, but it is not sufficient to effectively improve the performance of this scenario. Conversely, the end-of-life stage increases the total EP embodied in the Hemp fibre and Wood fibre scenarios, increasing the difference with the baseline and the almost 'neutral' performance of the Mineral scenario.

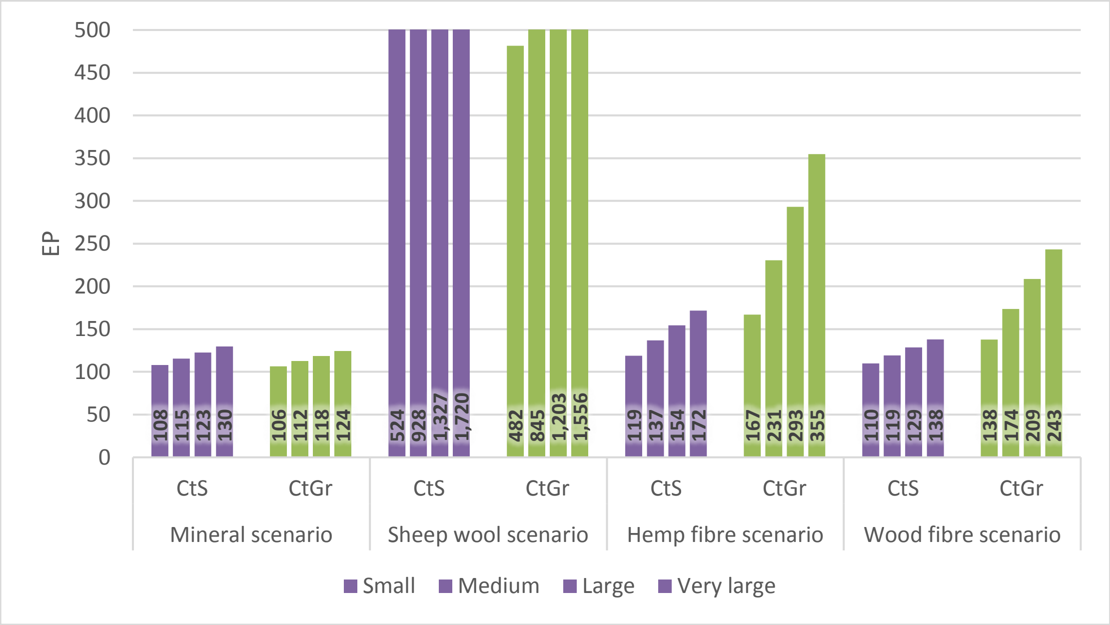


Figure 4. 90 –Changes in EP caused by alternative scenarios for retrofitted dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

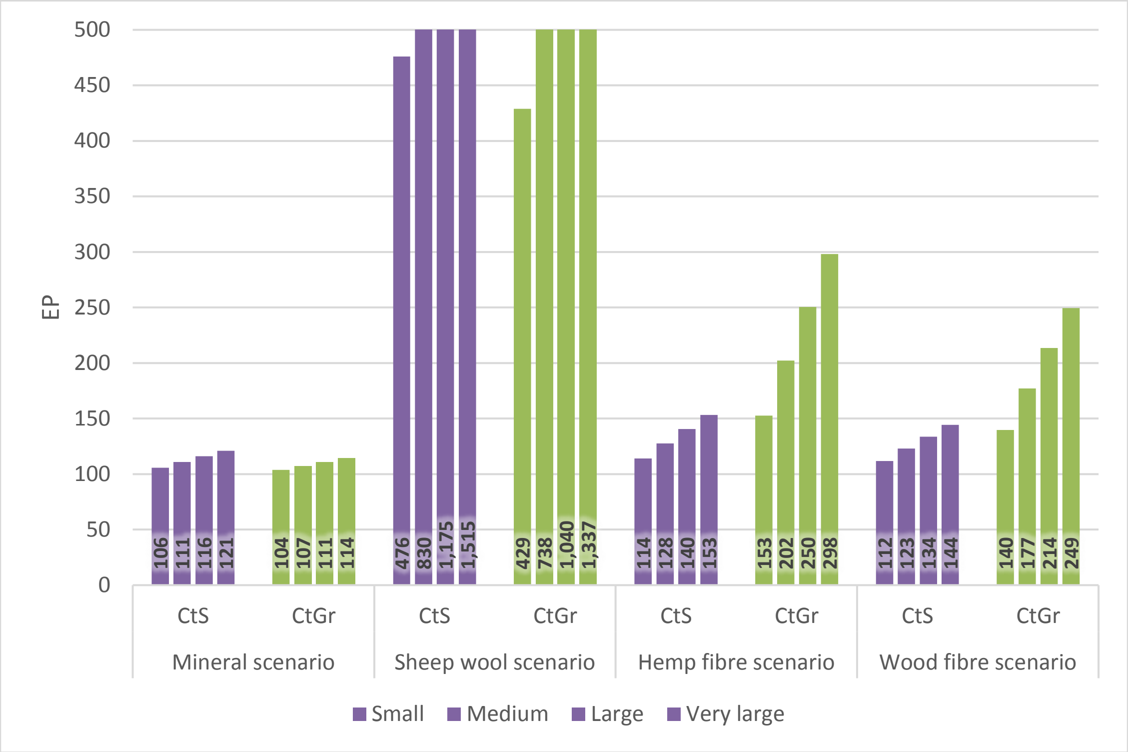
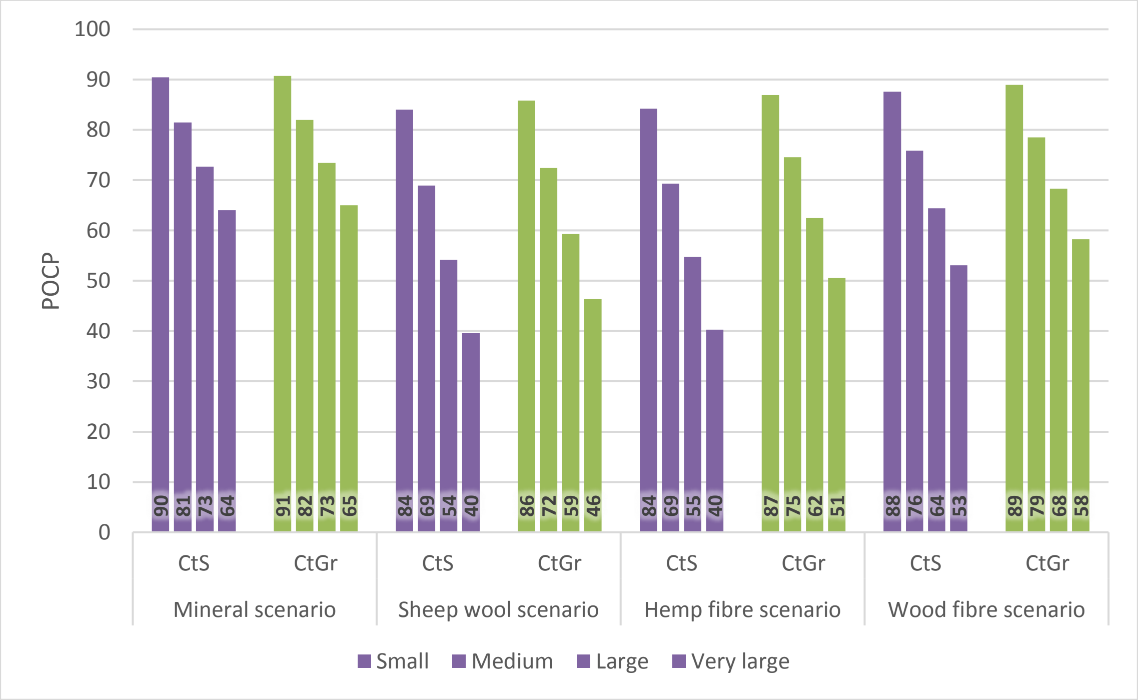


Figure 4. 91 - Changes in EP caused by alternative scenarios for new dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

Alternative scenarios – Changes in POCP

Figure 4. 92 and Figure 4. 93 show changes in POCP caused by alternative scenarios for retrofitted and new dwellings, respectively. In both sectors, the inclusion of the end-of-life stage penalises the performance of the alternative scenarios only minorly.

Figure 4. 92 –Changes in POCP caused by alternative scenarios for retrofitted dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA



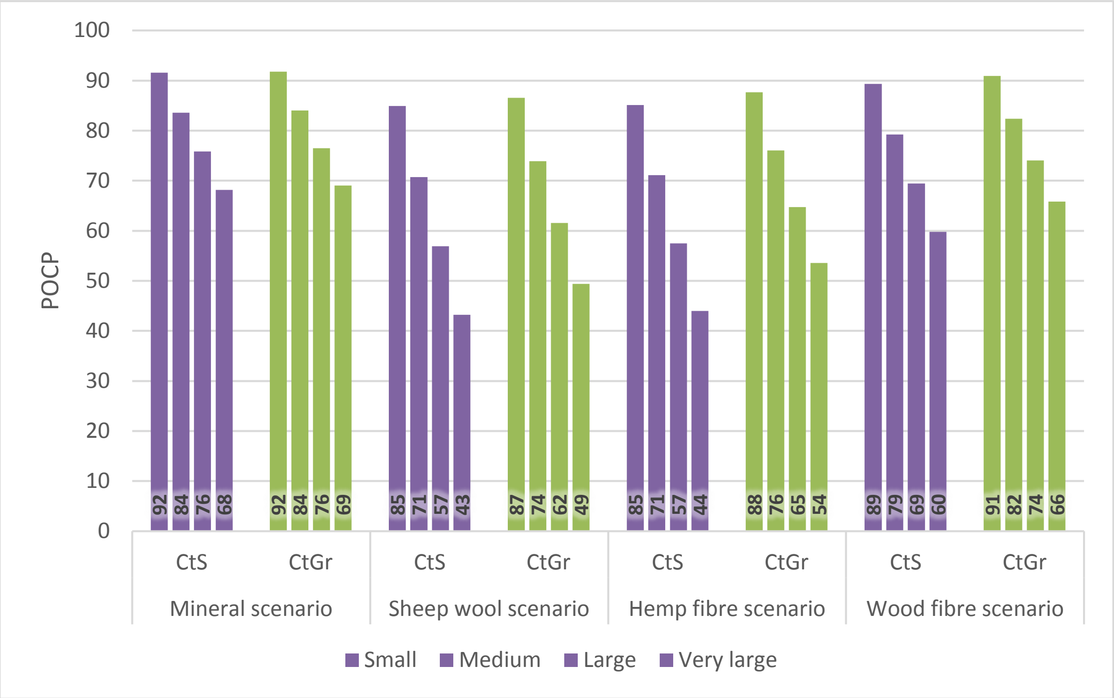


Figure 4. 93 - Changes in POCP caused by alternative scenarios for new dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

Alternative scenarios – Changes in EEI score

Figure 4. 94 and Figure 4. 95 show changes in EEI score caused by alternative scenarios for retrofitted and new dwellings, respectively. These reflect well the overall outcome of the comparison between the cradle-to-site and cradle-to-grave boundaries of LCA presented in the previous Figures. The inclusion of the end-of-life stage has negligible effects on the Mineral scenario, but penalises the performance of the alternative scenarios introducing biomass products. This particularly affects the Hemp fibre scenario, which has a comparable EEI score to the Mineral scenario of only the cradle-to-site boundary is considered.

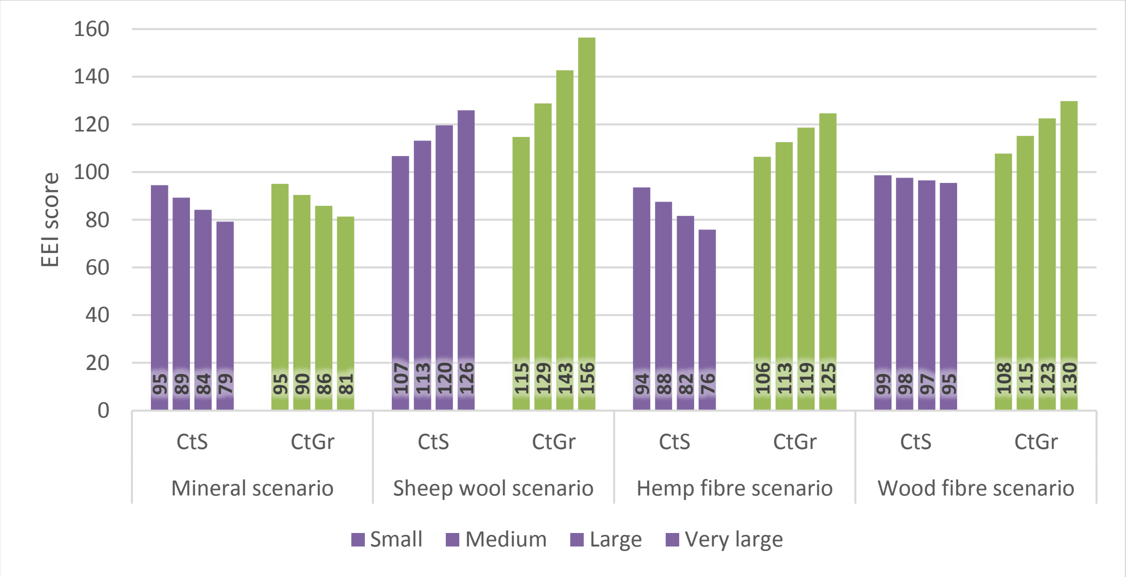


Figure 4. 94 –Changes in EEI score caused by alternative scenarios for retrofitted dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

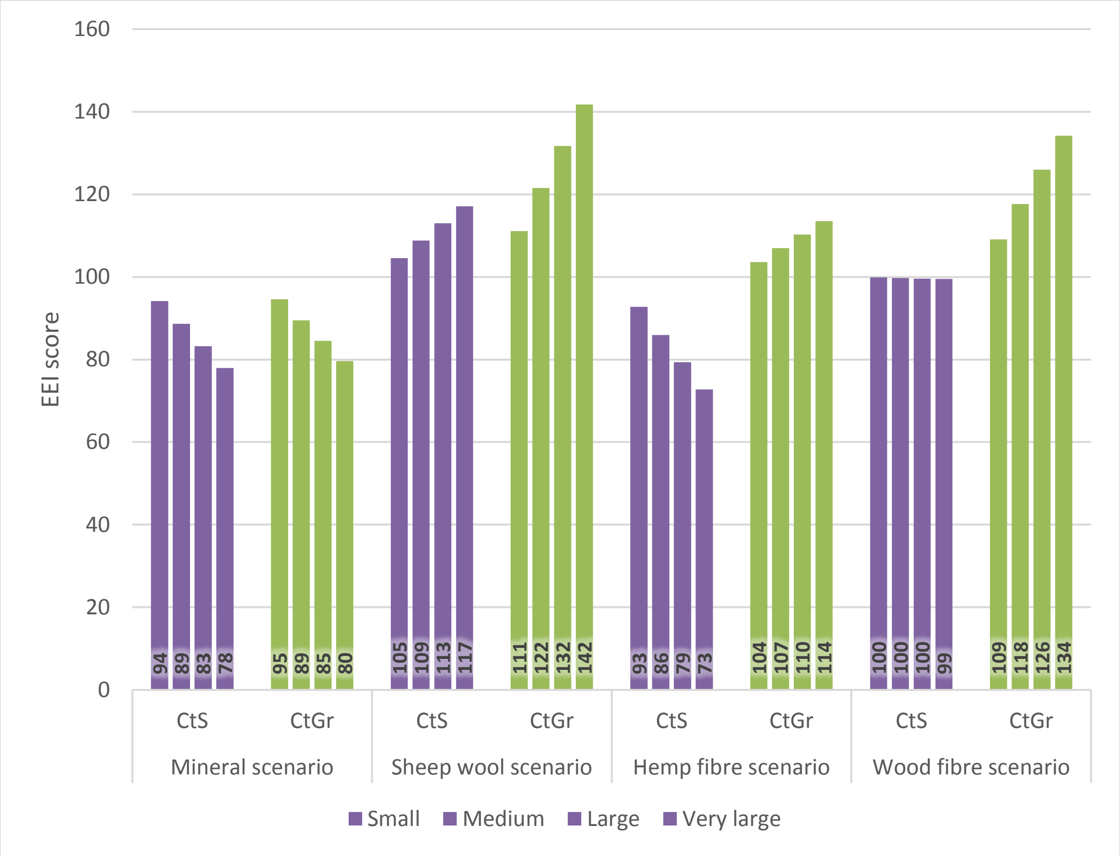


Figure 4. 95 - Changes in EEI score caused by alternative scenarios for new dwellings – Comparison between Cradle-to-Site (CtS) and Cradle-to-Grave (CtGr) boundaries for LCA

4.5 Summary of results of the first component

This chapter presented the methods and results of the first component of the research, which focuses on the assessment of the EEI of the supply of products for the insulation of Welsh dwellings from 2020 to 2050. The research process comprised three parts:

- modelling demand scenario;
- modelling baseline and alternative supply scenarios;
- assessing environmental impact.

Scenarios were built to model the demand and supply for insulation products in Welsh dwellings from 2020 to 2050. The EEI of baseline and alternative supply scenarios was assessed through process-based LCA and compared to identify potential improvement via product substitution.

Considering the results of the demand forecast and of the assessment of the EEI of baseline scenarios, it can be observed that:

- Demand for insulation generated by new domestic construction is larger than the demand generated by retrofits (Figure 4. 14 and Figure 4. 16). This is due to the number of new constructions as well as to the amount of insulation required per property.

- The larger demand for insulation of new dwellings results in a larger EEI (Figure 4. 63). For both new and retrofitted dwellings, the largest demand and EEI are associated with the insulation of walls.
- The analysis of the effect that different demand scenarios for new dwellings have on the EEI of the alternative scenarios (Figure 4. 83) shows that deviations in demand do not substantially affect the EEI changes achieved by the alternative scenarios and neither the 'performances' of the alternative scenarios in comparison to each other.
- The most impacting conventional products in terms of total cradle-to-site EEI are EPS, PUR and stone wool (Figure 4. 66 to Figure 4. 70). This is a consequence of the high demand for these products (as modelled in the baseline product mix, see Figure 4. 25 and Figure 4. 26) but also of high EEI per FU of these products in specific impact categories (Figure 4. 48).

Comparing the EEI changes caused by the alternative scenarios, it can be concluded that:

- It is possible to achieve reductions in the overall cradle-to-site EEI of insulation by progressively substituting conventional products with less impacting products based on mineral or biomass resources. The largest potential for reduction in the cradle-to-site stages is with GWP, due to the carbon sequestered in biomass products (Figure 4. 73 and Figure 4. 74). If sufficient quantities of conventional products are replaced with hemp fibre and wood fibre, the GWP of the insulation supply becomes negative, i.e. a carbon storage. However, this happens only at the Very Large level of substitution. The Small level of substitution (reaching 25% of the market) can be considered the most realistic of the four levels modelled, since it replaces fewer conventional products. If this level was achieved, the GWP of the supply of insulation products would be reduced to 70-60% of the baseline due to the increase in biomass products.
- There are trade-offs in the EEI changes caused by the alternative scenarios across the five impact categories. Substituting conventional products reduces EEI in some categories while increasing it in others, and no alternative scenario has an entirely negative or positive performance.
- In both new and retrofitted dwellings, in the cradle-to-site stages the Hemp fibre alternative scenario (introducing hemp fibre and HD wood fibre) achieves the largest reductions in GWP and POCP, while causing limited increases in PEU, AP and EP. At the Small level of substitution, the Hemp fibre alternative scenario could reduce GWP to about 65% of baseline and POCP to about 85% of baseline. At the same time, PEU would be increased to about 105 % of baseline, AP to about 105% and EP to about 117%.

- The Wood fibre alternative scenario (introducing LD and HD wood fibre) has a similar performance to the Hemp fibre scenario in the cradle-to-site stages, but with smaller reductions in POCP and higher increases in PEU.
- In the cradle-to-site stages the Sheep wool alternative scenario (introducing sheep wool and HD wood fibre) achieves reductions in GWP and POCP but increases PEU and especially AP and EP. This is due to the high EEI of sheep wool insulation in latter two categories, caused by the economic allocation of a small fraction (2%) of the environmental impact of sheep farming (see section 4.3.7). Normalised results show that AP and EP are the least relevant categories in comparison to the current levels of environmental impact, however the increases in AP and EP caused by the Sheep wool alternative scenario are sufficiently large to conclude that its performance is poorer in comparison to the other alternative scenarios. The minimum EEI ranges associated with the Sheep wool alternative scenario indicate that the EEI values resulting from the assessment are significantly improved if the impact of sheep farming is not allocated to the insulation product.
- The Mineral alternative scenario (introducing glass fibre and HD stone wool) has comparable performance to the Hemp fibre scenario in terms of overall EEI improvement in the cradle-to-site stages, as indicated by the EEI score (Figure 4. 81). Both alternative scenarios cause limited increases in AP and EP, but while the Mineral scenario decreases PEU, its reductions in GWP are smaller in comparison to the Hemp fibre scenario.
- Once the end-of-life stage is included in the assessment the EEI, the performance of the Mineral scenario is not affected significantly, while the reductions achieved by the alternative scenario in GWP are severely decreased. This is a consequence of the disposal processes of the biomass products (landfilling and incineration with energy recovery), which release large part of the carbon stored in the materials. While this is sufficient to increase the total GWP of the Sheep wool and Wood fibre scenarios in comparison to the baseline, there remains a potential for GWP reductions with the Hemp fibre scenario even if the end-of-life stage is taken into account. These reductions are larger than those achieved by the Mineral scenario, although to a lesser extent. Furthermore, the cradle-to-grave results offer only a partial perspective on the impact at the end-of-life of insulation products, as the ‘recycled content’ approach excludes benefits from the energy use offset by incineration with energy recovery.

In summary, replacing conventional products with a combination of hemp fibre and wood fibre could bring overall benefits in terms of EEI reductions in the cradle-to-site stages, particularly

GWP and POCP. On the other hand, increasing the use of mineral products could also reduce EEI, particularly PEU and POCP. Considering POCP reductions can be considered as equal, then if GWP reductions are preferred over PEU savings, then biomass products can be considered a better option than mineral ones, and vice-versa. If the impact of the end-of-life stage is included in the assessment, the performance of biomass products is affected significantly, and only the Hemp fibre scenario offers GWP reductions form the baseline in comparison the Mineral scenario. These results are discussed further in chapter 7, together with the outcomes of the other two research components.

5 Second component: Socio-economic impact

This chapter presents the methods and results of the second component of the research, namely the socio-economic assessment of insulation products. Section 5.1 describes the survey of product prices while section 5.2 focuses on the economic I-O analysis. Section 5.3 describes the LCWE assessment. Section 5.4 presents the results of the I-O LCA. ~~Limitations of the second component are discussed in section,~~ while section 5.5 provides a summary of the research outcomes.

5.1 Insulation product prices

5.1.1 Surveying product prices

Product price, as a measure of affordability, is one of the indicators chosen in this research to assess the economic impact of products (see section 3.3). A desk-based collection of market prices was conducted to investigate price ranges of conventional and biomass insulation. Data was collected between August 2015 and March 2016 (155 prices recorded) and again in February 2017 (168 prices recorded). Data from two different periods allows for price variation over time. Prices were found on large retailer websites and on manufacturer's catalogues. For each entry, the product brand, name and thickness were recorded together with price per volumetric unit, its density, thermal conductivity and compressive strength (where available). VAT and delivery costs were excluded, and prices were taken for the largest quantities when bulk discounts were available. The price per FU (£ per 1 m^2K/W) was calculated to allow comparison between products on the basis of equal thermal performance. The complete dataset of collected prices is shown in Appendix III.

In the presentation of results, values of minimum, average and maximum prices per FU for each product type are shown separately for the two periods. These values should be taken as indicative figures, because the collected prices cannot be considered to be an adequate population for a rigorous statistical analysis. Since it was not always possible to collect prices for exactly the same products after 2 years, changes between 2015 and 2017 values may be caused not only by price variations but also by using a slightly different sample. The ideal population for analysis would contain prices of all the products sold in the UK together with their quantities, or at least provide a representative random sample. Instead, prices have been collected for each product focusing on the thinnest and thickest formats available. Products are manufactured in rolls, slabs and panels of different thicknesses, and it was noticed that in some cases price per FU changes with the increase in thickness, with some products being more expensive in thick formats and others in thin formats. Thus prices were collected to enable recognising such condition, which in turn allows determining with more confidence price ranges of products in relation to layer thicknesses assumed in the supply scenarios.

Prices collected in 2017 are also necessary to use multiplier effects obtained through I-O analysis (section 5.2), as prices enable translating the FU of products from a unit based on physical measurement of performance (m^2K/W) to a unit based on price value (£). Since the market prices collected through the survey are *retailer's prices* (i.e. contain the retailer's profit margin and costs), the corresponding *producer prices* need to be estimated to be used in the I-O LCA. The producer price is the value paid to the manufacturer by the retailer, who then distributes and sells the product. Average producer prices for the insulation products studied in this research are estimated by taking 73.6% of the averages values resulting from the price survey. This 73.6% corresponds to the share that the purchase of goods (to be sold) occupies in the estimate of cost structure for UK retailers of construction products in 2017 by IBISWord (Clutterbuck, 2017, p.20).

5.1.2 Results of the survey of product prices

A summary of the results of the price survey is presented in Figure 5. 1. Prices are expressed in British pounds per FU (£/m^2K/W) to enable a comparison on the basis of equal thermal resistance. For each product type, average values are presented (as bars) together with minimum and maximum values recorded (as ranges) to show the magnitude of price variation. The minimum, average and maximum prices per FU found in 2017 are the figures used in the I-O analysis to calculate embodied work and GVA generation through multiplier effects.

The average prices in Figure 5. 1 indicate glass wool as the least expensive product and HD wood fibre the most expensive one. Among conventional products, stone wool and EPS occupy a middle range, while PUR and especially phenolic foams are more expensive. All three soft biomass products (hemp fibre, sheep wool and LD wood fibre) have prices around 4 £/m^2K/W, slightly higher than PUR but lower than phenolics. Considering minimum and maximum prices expressed by the ranges in Figure 5. 1, the smallest variations are found in glass wool, EPS and hemp fibre, while PUR and HD wood fibre show the largest variations.

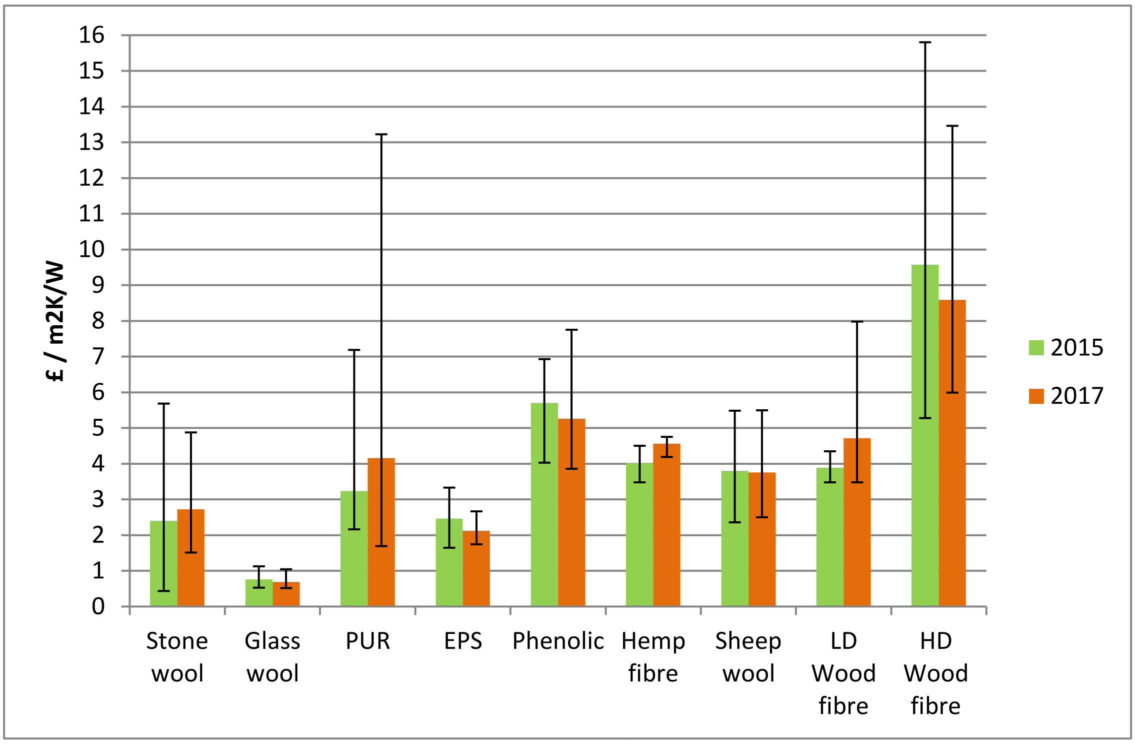


Figure 5. 1 – Market prices of insulation products (£ / m^{2}K/W) in 2015 and 2017. Average values (green and orange bars) and minimum and maximum values (ranges)

Taking average prices in 2017, Table 5. 1 can be produced to show the percentage reductions (in red) or increases (in green) that prices of biomass products need to achieve to reach the prices of conventional products. In present conditions, soft biomass products are competitive only against phenolic products, and to a lesser extent PUR. However, phenolic and PUR products have higher thermal resistance, and therefore have the advantage of requiring less space than biomass products. In the following pages, price differences are discussed in detail by looking at single results of the price survey for mineral, plastic and biomass products separately.

Table 5. 1 – Percentage reduction (or increase) of average prices per FU of biomass products necessary to equal average prices of conventional products (prices for 2017)

	Stone wool	Glass wool	PUR	EPS	Phenolic
Hemp fibre	-40 %	-85 %	-16 %	-54 %	(+15 %)
Sheep wool	-27 %	-82 %	(+2 %)	-44 %	(+40 %)
LD wood fibre	-42 %	-85 %	-19 %	-55 %	(+12 %)
HD wood fibre	-68 %	-92 %	-55 %	-75 %	-39 %

Figure 5. 2 shows all the prices recorded for mineral products in 2017, from lowest to highest for each product type (stone wool and glass wool). There is a much wider variation among stone wool products than glass wool ones. Different formats (e.g. 100mm or 200mm thickness)

do not appear to affect price per FU of glass wool, which is priced between 0.5 and 1 £/m^{2}K/W. The highest prices are associated with products (called "Earthwool") manufactured by Knauf with the organic binder ECOSE. However, at 1 £/m^{2}K/W this type of glass wool is still less expensive than most of the other products.

Stone wool prices range from 1.5 £/m^{2}K/W to almost 7 £/m^{2}K/W, though only two products are over 5 £/m^{2}K/W. The high price of these products can be explained by their high density (140 kg/m^3) which requires a much larger quantity of material in comparison to a typical low-density stone wool product (between 30 and 60 kg/m^3). As for glass wool, differences in product thickness do not appear to affect prices per FU of stone wool.

Figure 5. 3 shows all the prices recorded for plastic products in 2017, from lowest to highest for each product type (PUR, EPS and phenolics). All EPS prices are within 1.5 and 3 £/m^{2}K/W, while PUR and phenolics display much wider variations. PUR ranges from just below 2 £/m^{2}K/W up to 6 £/m^{2}K/W, while prices for phenolic foams range from just below 4 £/m^{2}K/W to over 13 £/m^{2}K/W. Thin panels are more expensive than thick ones for both product types, though more markedly in the case of phenolics. Density and compressive strength are rather homogenous within product types (about 32 kg/m^3 and 120-150 kPa for PUR, and about 35 kg/m^3 and 120-125 kPa for phenolics) and therefore do not significantly affect prices per FU.

Figure 5. 4 shows all the prices recorded for biomass products in 2017, from lowest to highest for each product type (hemp fibre, sheep wool, and LD and HD wood fibre). Prices for hemp fibre are between 4 and 5 £/m^{2}K/W, while prices for sheep wool display a wider range, from about 2.5 to about 5.5 £/m^{2}K/W, with no significant difference between thicknesses for both product types. All sheep wool priced above 5 £/m^{2}K/W is "Thermafleece Ultrawool", which has a lower U-value (0.035 W/m^{2}K) than the typical sheep wool product (about 0.038 W/m^{2}K). It must be noted that if hemp fibre and sheep wool products were manufactured with organic binder (as modelled in the first research component), prices would probably be higher due to higher cost of this material. ~~Knauf products containing the organic ECOSE binder have prices which are about £0.4 higher than the average price per FU of glass wool (Figure 5. 2), thus it possible that adopting this innovation in hemp fibre and sheep wool manufacturing would increase their price per FU in a similar way.~~

Prices for most LD wood fibre are between 3.5 and 4.5 £/m^{2}K/W, with only some products above 5 £/m^{2}K/W. HD wood fibre is significantly more expensive, with prices starting from 6 £/m^{2}K/W up to over 15 £/m^{2}K/W. Since wood fibre products are not manufactured in the UK, the high price of HD wood fibre might be in part caused by transportation costs from continental Europe. For both LD and HD wood fibre products, price differences are caused by density rather than thickness. Denser products have higher price per FU, because a larger quantity of material is included in comparison to lighter products. Since the thermal resistance of HD wood fibre products does not appear to increase proportionally with density, denser products have a higher price per FU.

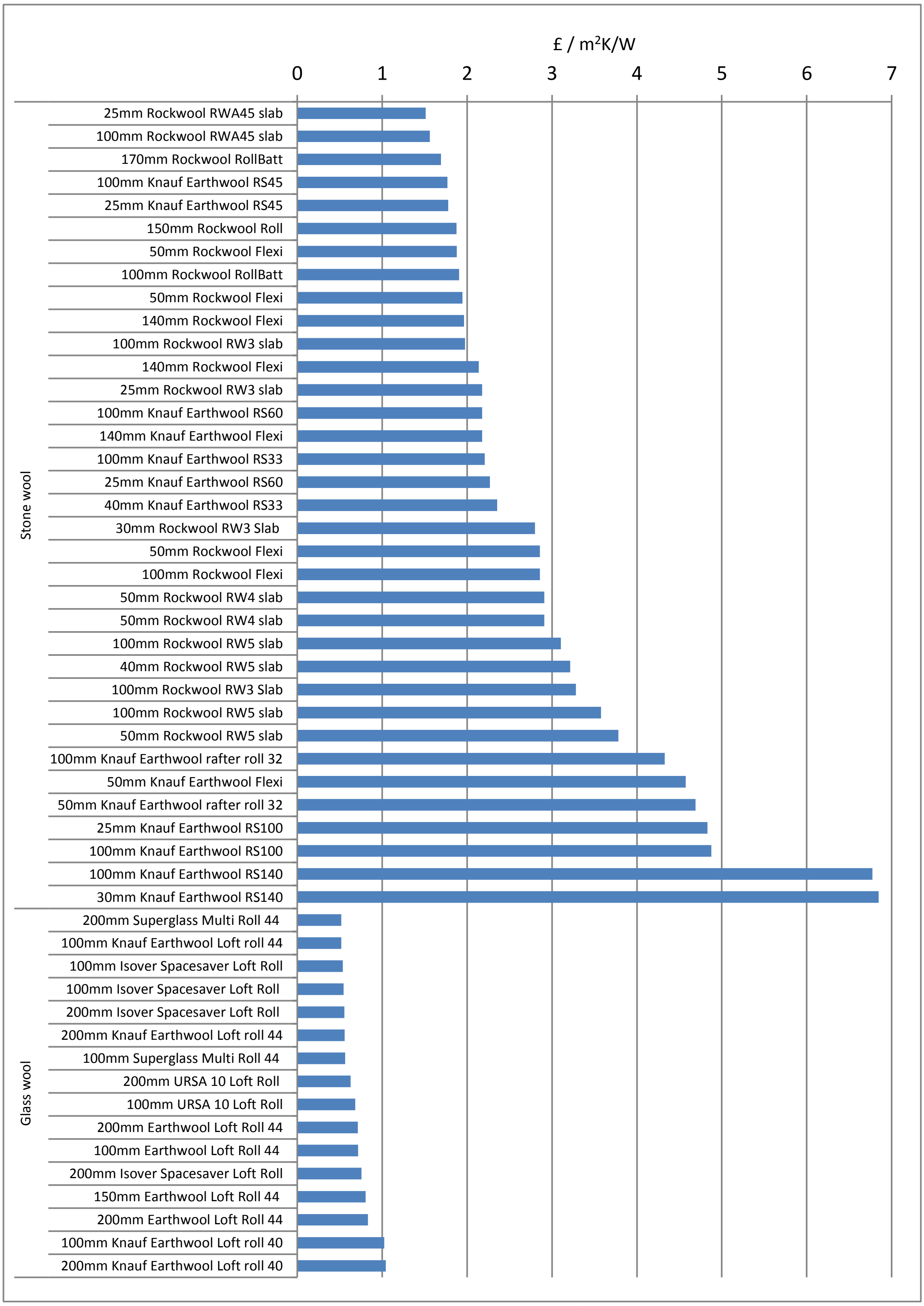


Figure 5. 2 – Market prices of mineral insulation products (£ / m²K/W) in 2017 (source: see Appendix II)

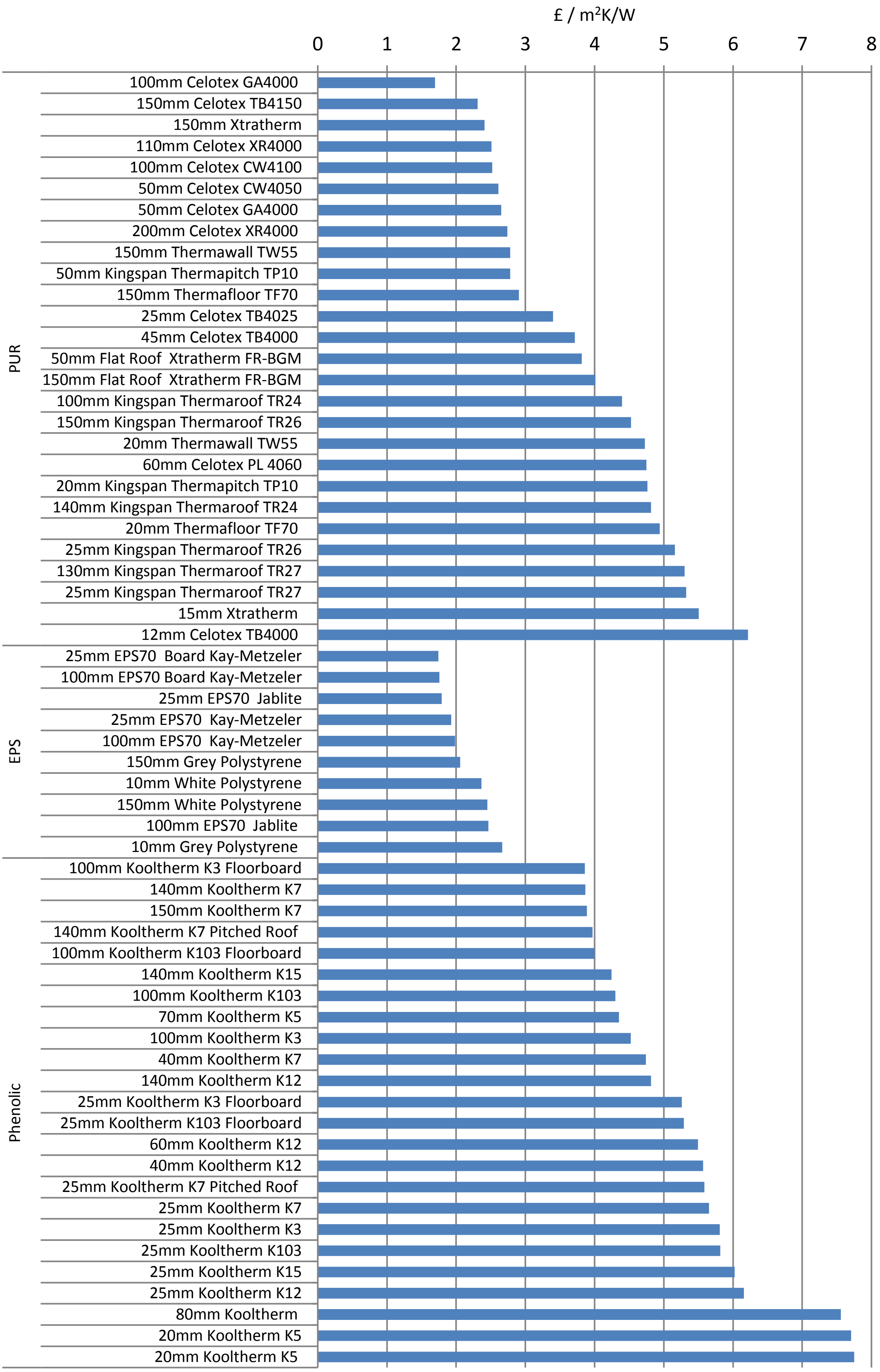


Figure 5. 3 – Market prices of plastic insulation products (£ / m^{2}K/W) in 2017 (source: see Appendix II)

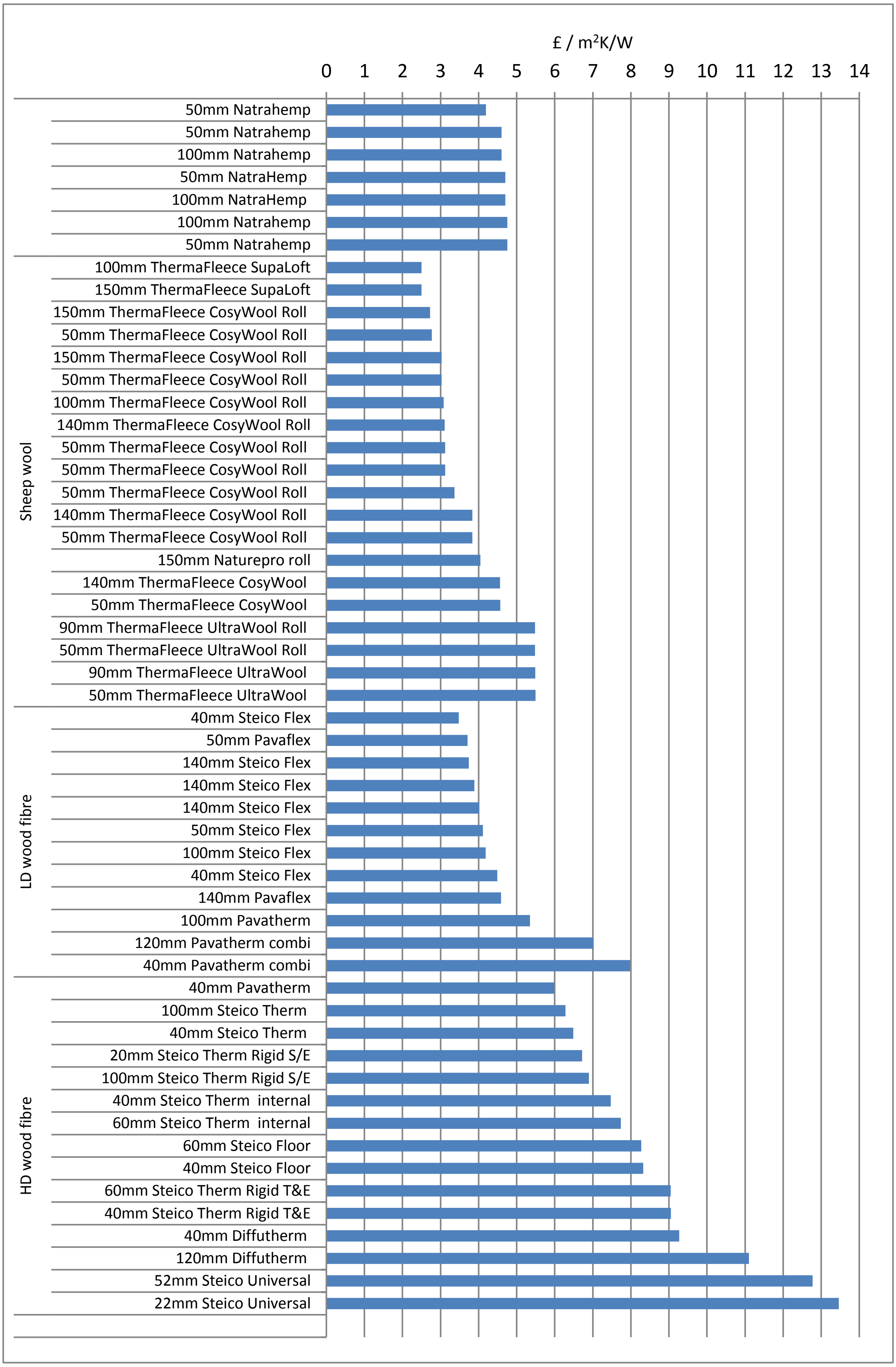


Figure 5. 4 – Market prices of biomass insulation products (£ / m^{2}K/W) in 2017 (source: see Appendix II)

5.2 Economic input-output analysis

The procedure of the assessment of embodied work and GVA generation through I-O LCA are described in this section. Multiplier effects resulting from economic I-O analysis allow quantifying direct and indirect effects caused by purchasing goods from specific industry sectors, as introduced in section 2.2.2. The insulation products studied in this research are associated to industry sectors based on their manufacturing process. For each product, embodied work and GVA generation are calculated by multiplying price per FU to the multiplier effects of the relative industry sector. Producers' prices are estimated by taking 73.6% of the values resulting from the survey of market prices (see section 5.1). Calculations were performed using the Excel software.

The data used to conduct I-O analysis is contained in the Eora dataset (Lenzen et al., 2012; 2013). supply-and-use tables for the UK economy are available for each year from 1970 to 2013 together with satellite accounts. As discussed in section 3.3, Eora is preferred over other I-O datasets because it features the highest level of industry disaggregation, which enables obtaining more accurate results.

There are two fundamental methodological choices made in this research to conduct I-O analysis. The first one concerns the procedure used to obtain I-O tables from national supply-and-use tables. This can be done using several methods, based on different assumptions and leading to different results. Miller and Blair (2009) acknowledge that there is no large consensus in the scientific community on which method should be preferred, but also note that Eurostat I-O manual (2008) supports the choice of industry-by-industry format together with the "fixed product sales structure" assumption. This method produces I-O tables describing the interactions between industry sectors (hence 'industry-by-industry') and assumes that each product has its own sales structure irrespectively of the industry producing it (hence 'fixed product sales structure'). This method is popular among I-O practitioners (Thage, 2007) and it is preferred among other methods by the Eurostat manual (2008) because it does "not involve any technology assumptions" and does "not require the application of sometimes arbitrary methods to adjust for negatives." (p. 310). For these reasons, this method is used in research to produce I-O tables from the supply-and-use tables provided in Eora.

The second fundamental methodological choice refers to the boundary of the I-O analysis. Household consumption and exports are treated as 'final demand' and imports as 'primary input', as this enables excluding the effects on household consumption and international trade from the analysis. This choice is determined by the intention to assess the socio-economic impact which occurs locally (i.e. within the UK border) and to exclude the *induced* effects (i.e. effects from "household income generation through payments for labor services and the associated consumer expenditures on goods produced by the various sectors", Miller and Blair, 2009, p.247) which derive from having household consumption inside the boundary of the I-O analysis.

5.2.1 Procedure of the I-O analysis

The following pages present the procedure used to calculate I-O tables and multiplier effects from the original supply-and-use tables provided in the Eora dataset. The methodology follows guidance given in Miller and Blair (2009), the I-O analysis for Scotland (Scottish Government 2015) and the Eurostat manual (2008). Table 5. 2 represents the structure of the annual supply-and-use tables for the UK economy provided in the Eora dataset. supply (i.e. production) is accounted in industry-by-product format while use (i.e. consumption) is accounted in product-by-industry format. To produce industry-by-industry I-O tables, a 'transformation' matrix is calculated as shown in Equation 5. 1.

Equation 5. 1 – Transformation matrix "T"

$$T = \frac{V}{\hat{q}}$$

q = vector of total output by product (sums of U and Y rows)

= diagonalisation of vector q

Consumption and final demand by industry are obtained via the transformation matrix (Equation 5. 2 and Equation 5. 3) and the IO table can be assembled as shown in Table 5. 3. The figures contained in the IO tables are finally transformed from US dollars to UK pounds via the exchange rate for the relative year. Exchange rates are taken from the WIOD dataset (Timmer et al., 2015).

Table 5. 2 – Structure of the extended supply-and-use tables used provided in the Eora dataset

	Industries	Products	Final demand (incl. exports)
Industries		V	
Products	U		Y
Primary inputs (incl. imports)	P		
Satellite accounts	SA_1		SA_2

V = matrix of domestic production ('supply') industry by product

U = matrix of domestic consumption ('use') product by industry

Y = matrix of final demand by product

P = matrix of primary inputs by industry

SA_1 and SA_2 = satellite accounts by industry and final demand

Equation 5. 2 - Domestic consumption industry by industry "B"

$$B = T \times U$$

Equation 5. 3 - Final demand by industry "F"

$$F = T \times Y$$

Table 5. 3 - Structure of I-O table

	Industries	Final demand (incl. exports)
Industries	B	F
Primary inputs (incl. imports)	P	
Satellite accounts	S_1	

The structure of the IO table represented inTable 5. 3 is shown with more detail in Table 5. 4. Industries are grouped in 'n' sectors (512 in the case of UK tables in Eora) and their inputs and outputs are organised in a matrix *n* x *n* which describes the *intermediate consumption*. This is the consumption of goods and services taking place in between domestic industries to enable them to produce goods and services meeting final demand (i.e. the demand from households, governments, non-profit organisations and gross fixed capital formation) and exports. Below the matrix of intermediate consumption, primary inputs are accounted by industry sector. The sum of intermediate consumption and primary inputs for industry 'j' is the total output of industry 'j'. At the bottom of the table, the satellite account consists of row of FTE jobs associated to each industry sector. These FTE figures are used later to calculate employment multiplier effects by industry sector.

Table 5. 4 – Detailed structure of I-O table

		Buying industries					Final demand and exports
		1	…	j	…	n	
Selling industries	1						
	…						
	i			z_{ij}			
	…						
	n						
Primary inputs	Imports						
	GVA						
	Salaries						
	Others						
Total output				x_j			
FTE							

The technical coefficient a_{ij} describes the proportion between the input from industry *i* to industry *j* and the total output of industry *j* (Equation 5. 4).

Equation 5. 4 – Technical coefficient

$$a_{ij} = \frac{z_{ij}}{x_j}$$

a = technical coefficient between the output of industry j and its input from industry i

i = selling industry

j = buying industry

z_{ij} = input from industry *i* to industry *j*

x_j = total output of industry j (sum of column j)

The *matrix of technical coefficients* is calculated as shown by Equation 5. 5.

Equation 5. 5 – Matrix of technical coefficients

$$A = Z\hat{x}^{-1}$$

A = matrix of technical coefficients

Z = matrix of production industry-by-industry (i.e. intermediate consumption)

x = vector of total outputs (sums of industry columns)

matrix with values of vector x on its diagonal

In the next step, the matrix of technical coefficients is subtracted to the identity matrix *n* x *n*. The inverse of the resulting matrix is called the *Leontief inverse matrix* (Equation 5. 6). While the technical coefficient matrix describes how much each industry sector buys directly from other sectors in order to generate its output, the Leontief inverse matrix describes how much each sector buys directly *and indirectly* from other sectors. The sum of values in each column of the Leontief inverse matrix is called the *output multiplier* (or Leontief total). This figure quantifies direct and indirect effects caused by one unit (pound) of final demand for industry j, and therefore it is always larger than one.

Equation 5. 6 – Leontief inverse matrix

$$L = (I - A)^{-1}$$

L = Leontief inverse matrix

I = identity matrix *n* x *n*

In the last step of the I-O analysis, multiplier effects are calculated using the Leontief inverse and the rows of FTE and GVA by industry contained in the I-O table. Equation 5. 7 shows the formula for a multiplier effect of a generic variable 'W', which stands for any row of values that can be associated to industry sectors. The multiplier effect can be described as the overall increase in 'W' as a consequence of an increase of 1£ in final demand. It is defined as a type I multiplier (Miller and Blair, 2009), which means that direct and indirect effects are modelled. Conversely, "induced" effects, associated to final demand and included in multipliers type II, are not modelled.

Equation 5. 7 – Multiplier effect for generic variable "W"

$$(M_{EFF})_j = \sum_i W_i \, L_{ij}$$

$(M_{EFF})_j$ = multiplier effect of industry j

W = vector of impact associated to industry sectors

L = Leontief inverse matrix

Once multiplier effects are calculated for every industry sector of the I-O tables, these are associated to insulation products on the basis of the SIC code of manufacturers. For each insulation product studied in this research, Table 5. 4 shows the SIC2007 code of the product manufacturer and the corresponding Eora industry sector. SIC2007 codes (declared by manufacturing firm) were accessed via FAME database and companies' websites. The sector aggregation of SIC2007 allows associating specific sectors to stone wool, glass wool and wood fibre products. The three plastic products cannot be distinguished, as their manufacturers are all registered under code 20.16 “Manufacture of plastics in primary forms”. Similarly, hemp fibre and sheep wool products cannot be distinguished because both manufacturers are registered under code 13.95 “Manufacture of non-wovens”. In any case, a distinction between these manufacturers would not be useful, as the sector aggregation in the Eora dataset derives from the UK supply-and-use tables, which follow the SIC2007 system. This enables directly associating Eora industry sectors to corresponding SIC2007 codes on the basis of their description (as in Table 5. 4).

It must be stressed that although manufacturers of insulation products are *part* of the industry sectors shown in Table 5. 4, they do not constitute the *entirety* of those sectors. For example, manufacturers of stone wool constitute only about one quarter of sector 23.99 “Manufacture of other non-metallic products” (Mak, 2017). While some products can be associated with very specific sectors (such as glass wool), others can be associated with more generic sectors (such as plastic products). Therefore although insulation products are the object of the assessment, this is carried out by using industry sectors as proxies for their products. A high level of industry disaggregation (as provided by the UK tables in the Eora dataset) allows producing more accurate approximations.

The employment multiplier effect of a generic industry sector *j* quantifies the overall FTE jobs from all industry sectors that are generated through direct and indirect effects by investing 1£ in sector *j*. It is expressed in FTE per British pound, and is translated into FTE per FU of insulation product using the estimated producers’ prices. The resulting quantity of labour can be seen as the work embodied in a FU of product. The same procedure is carried out for GVA multiplier effects, and thus figures for GVA (£) generated per FU of insulation products are obtained. This last step of the procedure, i.e. the quantification of the “effect” via price values per FU, does not belong to I-O analysis as usually conducted for economic purposes, but it is the fundamental feature of conducting LCA through economic I-O data. The necessity to use price figures to translate physical FU into monetary ones adds an element of uncertainty, because there can be variations within the same product type as well as price variability over time. To allow a correct interpretation of the results of the I-O LCA, both multiplier effects and the resulting impacts per FU are shown. This enables comparing products on a monetary basis (impact per Pound) as well as on a functional basis (impact per FU).

Table 5. 5 – SIC codes and corresponding Eora industry sectors for insulation products studied in this research

Product	SIC2007 code of product manufacturer	Corresponding Eora industry sector
Stone wool	23.99 Manufacture of other non-metallic mineral products n.e.c; manufacture of mineral insulating materials.	Manufacture of other non-metallic mineral products n.e.c.
Glass wool	23.14 Manufacture of glass fibres; manufacture of glass fibres, including glass wool and non-woven products thereof.	Manufacture of glass fibres
PUR	20.16 Manufacture of plastics in primary forms. This class includes the manufacture of resins, plastics materials, and non-vulcanisable thermoplastic elastomers, the mixing and blending of resins on a custom basis, as well as the manufacture of non-customised synthetic resins. This class includes: manufacture of plastics in primary forms: polymers, including those of ethylene, propylene, styrene, vinyl chloride, vinyl acetate and acrylics; polyamides; phenolic and epoxide resins and polyurethanes; alkyd and polyester resins and polyethers; silicones; ion-exchangers based on polymers.	Manufacture of plastics in primary forms
EPS		
Phenolic foams		
Hemp fibre	13.95 Manufacture of non-wovens and articles made from non-wovens, except apparel;	Manufacture of non-wovens and articles made from non-wovens, except apparel
Sheep wool		
Wood fibre	16.21 Manufacture of veneer sheets and wood-based panels; - manufacture of oriented strand board (OSB) and other particle board - manufacture of medium density fibreboard (MDF) and other fibreboard.	Manufacture of veneer sheets; manufacture of plywood, laminboard, particle board, fibre board and other panels and boards

The socio-economic indicators obtained though I-O analysis could be used to assess future scenarios of product supply as done for EEI in the first component of the research. However, possible future changes in prices as well as multiplier effects would severely limit the validity of such assessment (as discussed in section 3.3.2). Therefore, it was preferred to further investigate the outcomes of the IO analysis, as described in the following section.

5.2.2 Time-series of multiplier effects

The multiplier effects used to assess the impact of insulation products are those for the year 2013, being the most recent available in the Eora dataset. It is possible to look at time-series of multiplier effects in order to understand if these values might be subject to significant changes over time. The following three graphs show multiplier effects for industry sectors relevant to insulation manufacturers calculated for 1993, 1998, 2003, 2008 and 2013.

Changes over time for output multipliers are shown in Figure 5. 5. Although output multipliers are not directly used in this research to assess insulation products, they are important outcomes of the I-O analysis. All the output multipliers show in Figure 5. 5 have declined from 1993 values, however industry sectors have mostly maintained the same positions in relation to each other. In every year, the highest output multipliers are for the manufacture of stone wool insulation ('other non-metallic mineral products'), while the lowest ones are for the manufacture of hemp fibre and sheep wool insulation ('non-wovens').

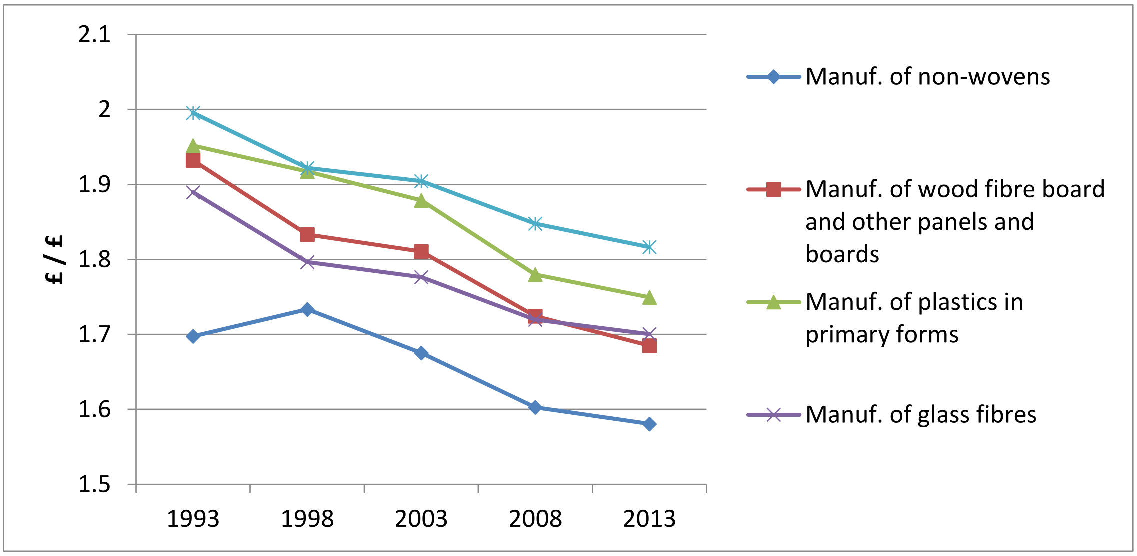


Figure 5. 5 – Time-series of output multipliers for industry sectors of insulation manufacturers

Figure 5. 6 shows changes in employment multiplier effects over time. These figures have declined from 1993 levels but this trend was reversed after 2008. Differently from the previous graph, the positions held by industry sectors in relation to each other have changed quite significantly. Most notably the manufacture of plastics held the highest value in 1993 and the lowest in 2013. In comparison to 1993 levels, the values assumed by all the employment multiplier effects in 2013 are much closer to each other.

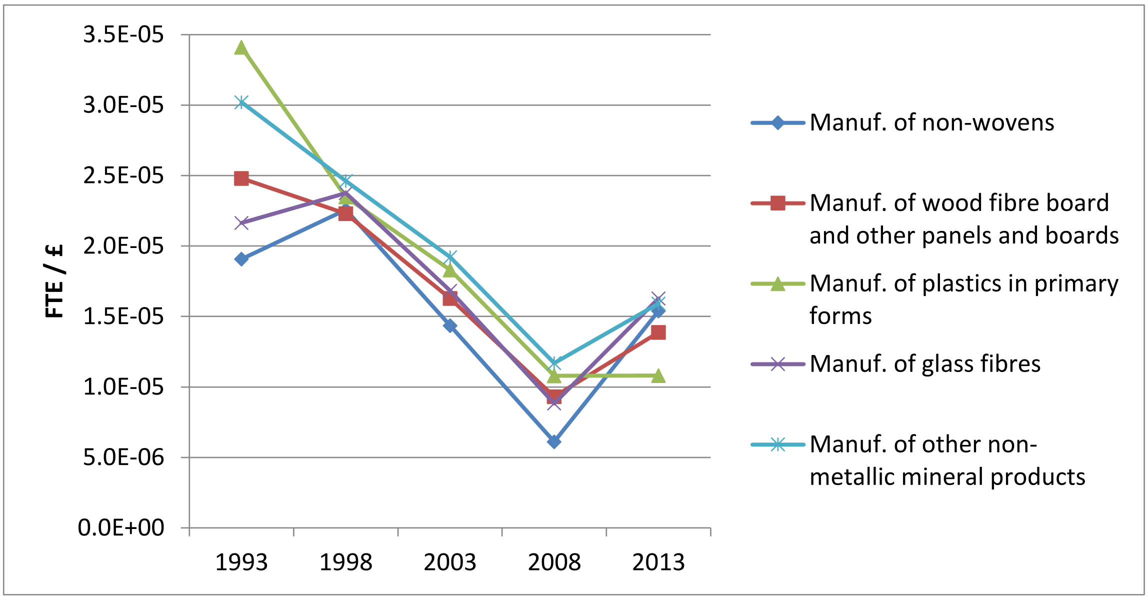


Figure 5. 6 – Time-series of employment multiplier effects for industry sectors of insulation manufacturers

Figure 5. 7 shows changes in GVA multiplier effects. As in previous graphs, values have declined from 1993 levels. However the positions held by industry sectors in relation to each other have remained unchanged. In every year the highest value belongs to the manufacture of glass fibre and the lowest one to the manufacture of plastics.

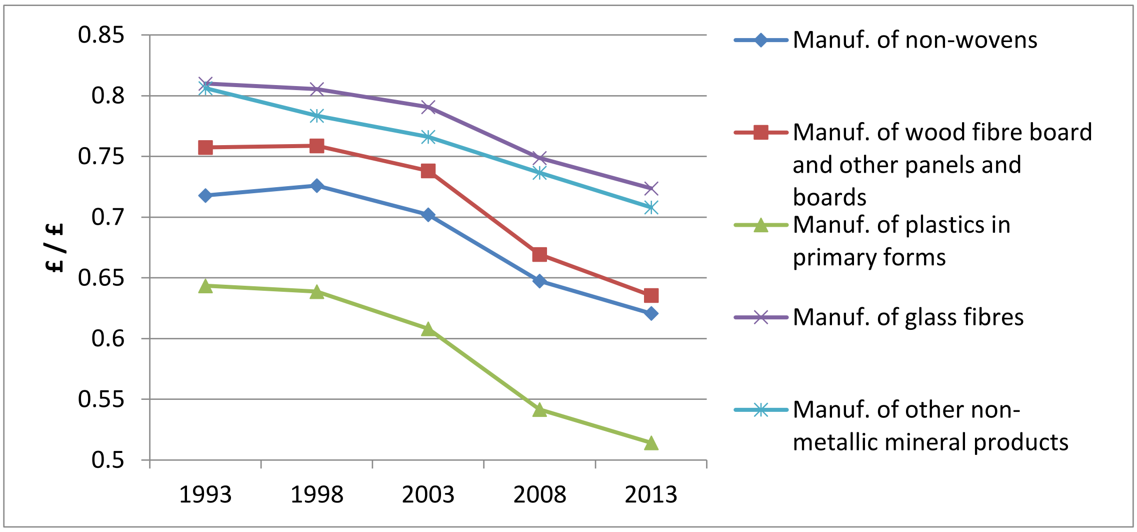


Figure 5. 7 – Time-series of GVA multiplier effects for industry sectors of insulation manufacturers

The time-series of employment and GVA multiplier effects indicate that these values have changed in the past, suggesting that they might also change in the future. A large degree of variation over time would decrease the validity of multiplier effects beyond their specific year. However, multiplier effects are used in this research to compare between products, and therefore stability in terms of relative position to each other is more significant than reliability of absolute figures. From this perspective, GVA multiplier effects in Figure 5. 7 appear to be quite stable in terms of relative positions to each other (although absolute figures are declining) and therefore using 1993 or 2013 values would not qualitatively change a comparative analysis. The same cannot be said for employment multiplier effects in Figure 5. 6. Nonetheless, although relative positions are not always maintained, it should be noted that after 1998 there are no abrupt changes and figures are rather close to each other (in each year). Therefore employment multiplier effects for 2013 can be considered to be adequate representative of the respective industry sectors for the purpose of this research, since they are used in a comparative analysis.

5.3 Life-Cycle Working Environment methodology

This short section describes the source of Life-Cycle Working Environment (LCWE) data. The LCWE is a method that applies life-cycle thinking to quantitatively assess the social impact of a product in terms of working environment, as introduced in section 2.2.3. The LCWE methodology follows the attributional process-based method of LCA, and therefore is subject to its assumptions and limitations. In this research the LCWE is used to provide an alternative assessment for the labour embodied in some of the insulation products. Due to its relatively recent development, there is very limited data available for LCWE studies. In fact the only source of LCWE data that was found to be accessible is the GaBi Professional database, but not all LCIs are given LCWE outputs, and therefore only some of the products considered in this research could be assessed with this method. Since there are no benchmarks to validate the LCWE data, the results are taken with caution.

The LCWE quantifies embodied work in terms of time (seconds), which is indirectly comparable to the FTE used in the I-O analysis. More important, the LCWE provides a breakdown of embodied work by level of skill required, which adds a qualitative aspect to the assessment and enables investigating whether some products require a higher amount of skilled labour.

The aggregated datasets contained in the GaBi database provide LCWE data for:

- Glass wool, in the aggregated LCI “EU-27 Glass wool PE” by Thinkstep (2016).
- EPS, in the aggregated LCI “EU-27 Expanded Polystyrene (PS30)” by Thinkstep (2016), the same used for the environmental LCA.
- Hemp fibre, in the aggregated LCI “EU-27 Hemp fibre fleece” by Thinkstep (2016), valid from 2015 to 2018.

The aggregated LCI “EU-27 Rockwool PE” by Thinkstep (2016), used for environmental LCA (see section metres2), contains LCWE data, but its resulting embodied work is significantly out of scale (over 20 times larger) in comparison to LCWE results for the other products. Therefore its validity is rather questionable.

The aggregated LCI “EU-27 Lightweight wood fiber panels” by Thinkstep (2016) contains LCWE data, but the lack of clarity about product density (as discussed in section 4.3.8) does not allow producing reliable results for wodd fibre products.

PUR, phenolic foams and sheep wool insulation could not be assessed with the LCWE method due to lack of relevant data in the GaBi Professional database.

5.4 Results of the I-O LCA and LCWE

The results of the socio-economic assessment of insulation products conducted through I-O analysis and LCA are presented in this section.

5.4.1 Embodied work

The work embodied in FUs of insulation products was calculated by multiplying product prices (minimum, average and maximum) to the relative employment multiplier effect. Results are shown in Figure 5. 8, where the blue bars represent embodied work per FU of insulation (units on the left axis) and the black dots represent the relative employment multiplier effect (units on the right axis). The highest employment multiplier effects are associated with mineral products, while the lowest one with plastic products. Non-woven products (hemp fibre and sheep wool) have rather high employment multiplier effect, while wood fibre products are in the middle of the range identified by the highest and lowest values. Once these multiplier effects are multiplied to product prices, the resulting figures for embodied work are a combination of both factors. Glass wool has the lowest embodied work, followed by EPS, while the highest embodied work is associated with HD wood fibre. The other products are close to the middle of this spectrum, though phenolic and soft biomass products have clearly more embodied work than stone wool and PUR products.

Figure 5. 9 shows the alternative assessment of embodied work, conducted using the LCWE method and data contained in the GaBi LCA database (see section 5.3). Only glass wool, EPs and hemp fibre products could be assessed with this process-based method. The results are rather consistent with those obtained via I-O analysis, confirming that the work embodied in hemp fibre insulation is higher than the work embodied in EPS and much higher than the work embodied in glass wool. The LCWE results also divide the embodied work by General Qualification Level (GQL), from “A” (most skilled) to “E” (least skilled). Hemp fibre insulation requires more skilled work than EPS and much more than glass wool, however this is the consequence of the larger requirement for total work and not of a higher share of skilled work

for sheep wool. In percentage terms, the three products have very similar proportions of skilled work requirements.

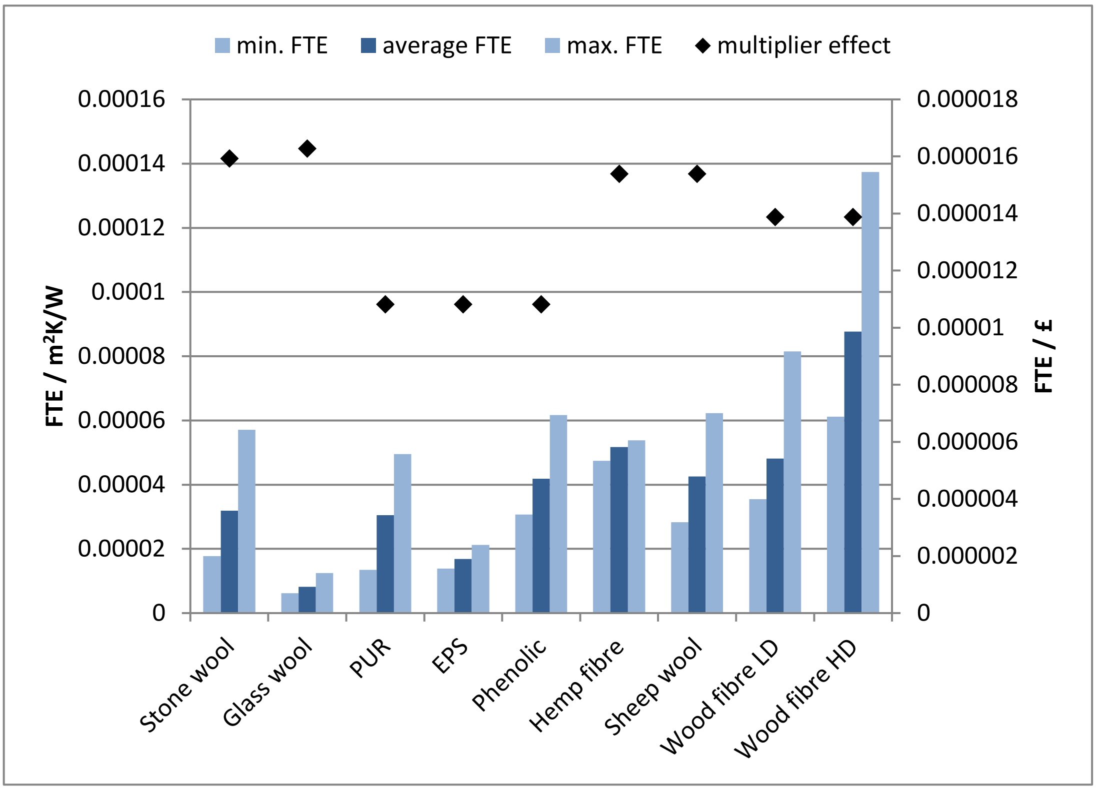


Figure 5. 8 – Embodied work per FU of insulation product and employment multiplier effect of the relative industry sector

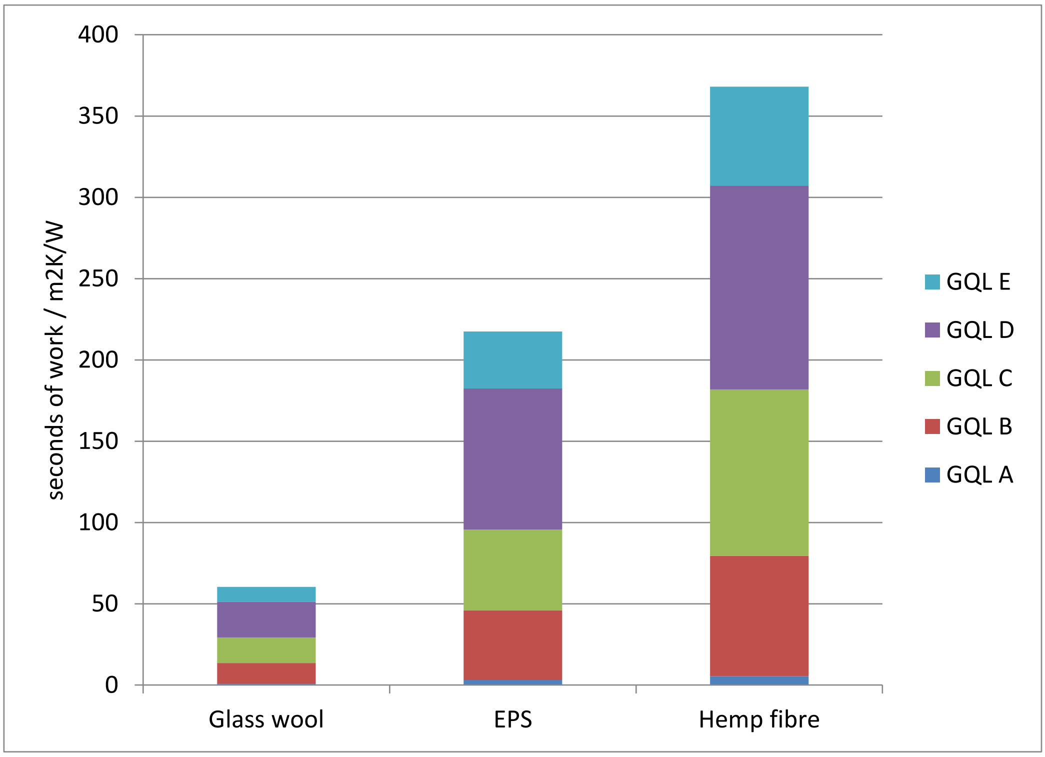


Figure 5. 9 – Embodied work per FU of insulation product obtained through LCWE methodology

5.4.2 GVA generation

The GVA generated within the UK by FUs of insulation products is calculated by multiplying product prices (minimum, average and maximum) to the relative GVA multiplier effect. Results are shown in Figure 5. 10, where the blue bars represent GVA generation per FU of insulation (units on the left axis) and the black dots represent the relative GVA multiplier effect (units on the right axis).

The highest GVA multiplier effects are associated with mineral products, while lowest ones with plastics products. Biomass products are the middle of this spectrum, with a slightly higher GVA multiplier effect for wood fibre products. These 'positions' are rather similar to those of employment multiplier effects (Figure 5. 8), therefore once GVA multiplier effects are multiplied to products prices, GVA generation results are qualitatively similar to embodied work results. Glass wool has the lowest GVA generation, followed by EPS, while the highest GVA generation is associated with HD wood fibre. The other products are in the middle of this spectrum, though phenolic and soft biomass products have slightly higher GVA generation than stone wool and PUR products.

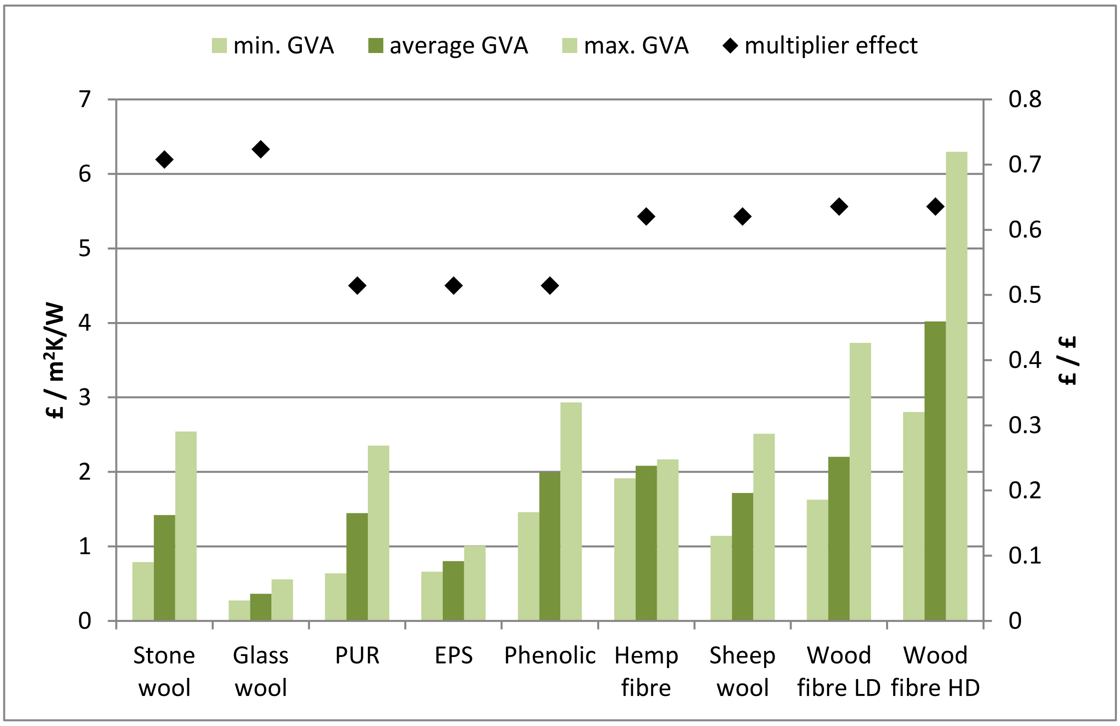


Figure 5. 10 – GVA generation per FU of insulation product and GVA multiplier effect of the relative industry sector

5.5 Summary of results of the second component

This chapter has presented the methods and results of the second component of the research, which focuses on assessing specific aspects of the socio-economic impact of insulation products such as affordability, labour intensity and wealth. A survey of insulation retailers was conducted to collect prices per FU of products. Figures for embodied work and GVA generation per FU of products were calculated by applying product prices to employment and GVA multiplier effects, obtained through I-O analysis of the UK economy.

With regards to the results of the price survey, it can be observed that:

- In the UK insulation market, glass wool products have the lowest price range (Figure 5. 1), which can explain their significant presence on the market. Stone wool and EPS have medium price ranges, higher than glass wool but lower than most PUR, phenolic and biomass products. Stone wool products are manufactured in different densities, which are reflected by the larger magnitude of price variation (in comparison to EPS price variations). Generally the price of stone wool increases with density, due to larger quantities of material per FU. PUR and especially phenolic products have a high price range, which can be justified by their robustness and high thermal resistance.
- Soft biomass products (hemp fibre, sheep wool and LD wood fibre) have high price ranges, in between those of PUR and phenolic. HD wood fibre has the highest price range of all products. In terms of price per FU, biomass products are not competitive with the most popular conventional products, namely stone wool, glass wool and EPS.

Considering the results of the I-O analysis an LCA, it can be concluded that:

- The manufacturing sectors associated with mineral products display the highest values of employment and GVA multiplier effects, while manufacturers of plastic products display the lowest values. The latter are about two thirds of the former (Figure 5. 8; Figure 5. 10). The multiplier effects associated with manufacturers of biomass products occupy the middle of this spectrum of values, except for the employment multiplier effect of non-woven products (hemp fibre and sheep wool), which is almost as high as mineral products. Thus on a monetary basis (i.e. impact per pound) mineral products have the highest socio-economic impact, and plastic products the lowest one.
- Glass wool shows the lowest values associated with embodied work and GVA generation per FU, followed by EPS. The highest embodied work and GVA generation is associated with HD wood fibre. The embodied work and GVA generation of the other products are relatively close to the centre of the spectrum of values. Phenolic and soft biomass products have moderately higher values than stone wool and PUR. Thus on a

functional basis (i.e. impact per FU) biomass products have higher socio-economic impact than most conventional products, especially with regards to glass wool and EPS.

- Considering both monetary and functional basis of assessment, in most cases the socio-economic impact of biomass products is equal or higher than that of conventional products.

The results indicate a trade-off between low prices and wider socio-economic impact. Less expensive products such as glass wool and EPS have a positive economic impact because they are more competitive (advantage for manufacturers) and more affordable (advantage for end-user). This is counter-balanced by a lower impact in terms of generating wealth and employment opportunities in comparison to more expensive products.

It must be noted that figures for embodied work and GVA generation per FU of insulation are significantly affected by product price, because differences between multiplier effects are less marked than differences between prices. Thus products with a high price per FU, such as HD wood fibre, are associated to high embodied work and GVA generation, and vice versa. It is reasonable to assume that products with high labour-intensity per FU would have a higher production cost and therefore a higher market price than less labour-intensive products, since more hours of work are paid per FU. However, this dependence on prices to translate monetary to physical units needs to be acknowledged as a methodological limitation of performing LCA at the product level via economic I-O analysis.

These results are discussed further in chapter 7, together with those of the other two research components. The next chapter describes the procedure used to compare demand and supply of natural resources in the third research component.

6 Third component: Demand and supply of regional resources

This chapter presents the method and results of the third research component, namely the assessment of the capacity of the Welsh territory and economy to supply biomass for insulation products. Section 6.1 describes the method ad data used to estimate the potential supply of natural resources for biomass insulation products. Demand and potential supply are compared in section 6.2.

6.1 Estimating potential supply of regional resources

This section presents the indicators chosen to assess the capacity of the Welsh territory and economy to supply biomass for insulation products. These indicators represent, to different extents, constraints on the regional capacity to supply biomass, and can be compared to the demand for biomass forecasted by the alternative scenarios (as modelled in section 4.2.3).

Welsh natural resources

An overview of land use in Wales is given here to provide a context for the specific indicators used to represent supply capacity. Figure 6. 1 shows the breakdown of land use in Wales in 2015. Over three quarters of the land is dedicated to grazing and common rough grazing. Public and private woodland occupy about 15% of total land, and arable crops only about 4%. Each of these three categories of land use (grazing, woodland and arable land) can be related to a biomass resource and its related insulation product: sheep wool, wood fibre and hemp fibre.

Land use is not constant but changes over time, as shown in Figure 6. 2. In comparison to 1998 levels, the total area of land used for agricultural purposes in Wales has increased by about 10%. In particular, grazing land has increased by 9% and land for arable crops by 22%. Therefore current land use can be considered as a relatively variable set of conditions.

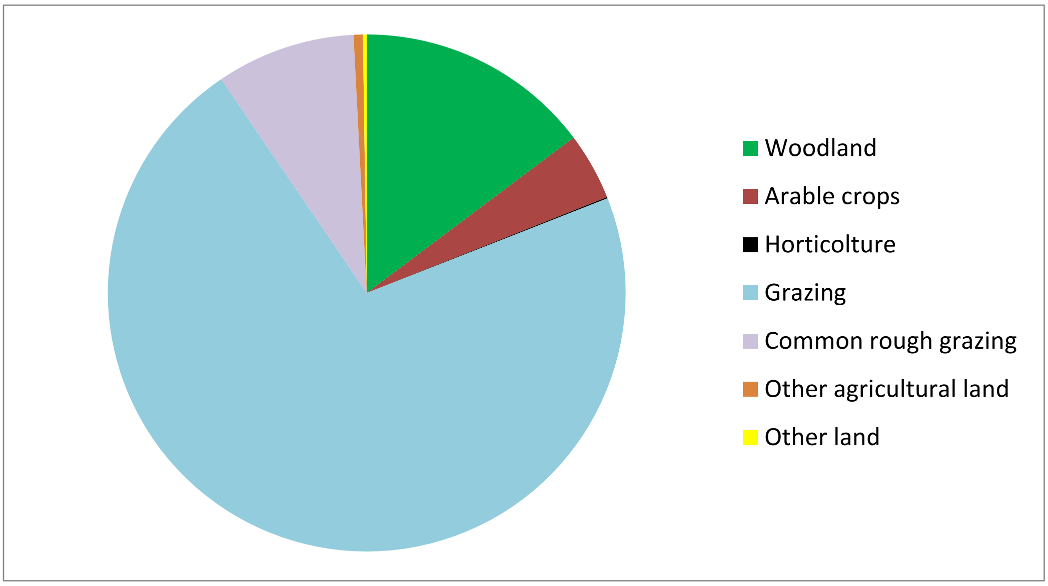


Figure 6. 1 –Land use in Wales in 2015 (source: WG, 2016c)

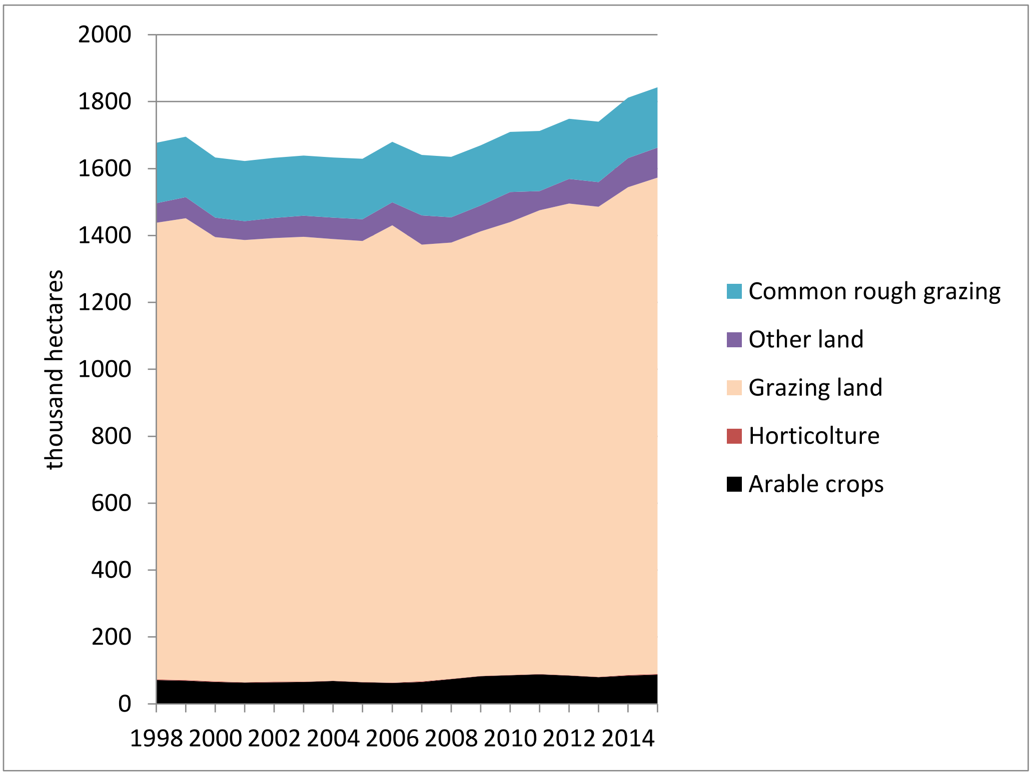


Figure 6. 2 – Agricultural land in Wales (source: WG, 2016c)

6.1.1 Potential supply of industrial hemp fibre

The main primary material used to manufacture hemp fibre insulation is industrial hemp fibre, which is produced from industrial hemp straw by separating fibres from shives (see section 2.3.4). Since industrial hemp is an agricultural crop, arable land is the main natural resource needed to produce hemp fibre insulation. Through the modified LCI for hemp fibre insulation (see section 4.3.6, Table 4.22), it is possible to quantify the area of land required to produce 1 FU of final product in 4.7 m^2. The key parameter for this figure is an annual harvest of 7 tonnes of retted hemp straw per hectare.

Currently, very little or no industrial hemp crop is grown in Wales (see section 2.3.4), and therefore current level of production cannot be considered an appropriate indicator for the *potential* production. Rather than the totality of land used to cultivate arable crops, the land used for "other crops" is a more appropriate indicator for the potential to cultivate industrial hemp. This category includes species, such as flax and linseed, which are similar to industrial hemp (section 2.3.4). Figure 6. 3 shows the breakdown of land used for arable crops in Wales from 1998 to 2015. In comparison to land used to cultivate wheat or barley, land use for "other crops" is small, with an average of about 2,700 hectares. However, there are large variations, as a peak of 4,625 ha was reached in 1999 and a minimum of 1,670 ha in 2006. Since land use changes over time, current land use can be seen as a flexible term of comparison for the area of land required to produce hemp fibre for insulation.

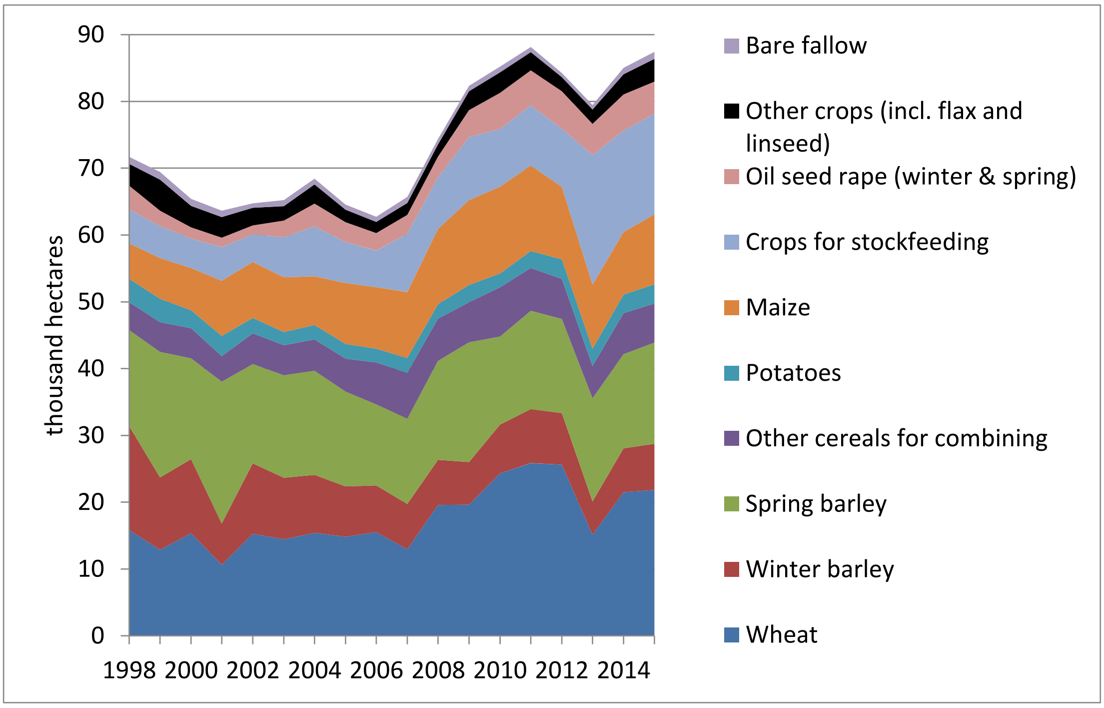


Figure 6. 3 – Arable crops in Wales (source: WG, 2016c)

6.1.2 Potential supply of raw sheep wool

The main primary material used to manufacture sheep wool insulation is raw sheep wool, i.e. 'greasy' wool. Through the modified LCI for sheep wool insulation (see section 4.3.7, Table 4.25), it is possible to quantify the amount of raw wool required to produce 1 FU of final product as 0.953 kg. As discussed in section 2.3.3, only low-quality raw wool is used to manufacture insulation, since high quality raw wool is more valuable and produced explicitly for garments and other textiles. Conversely, low quality raw wool is generated as a by-product of the sheep meat sector, as in the case of Wales. Figure 6. 4 shows the annual production of raw wool in Wales, whose maximum and minimum value are used as indicator of the Welsh capacity in this research, as there is no forecast for future production available. It can be noticed that in the last decade the production of raw wool has been generally declining in quantity, from over 9,000 tonnes in 2005 to less than 8,000 in 2014. In comparison to land use, the output of raw wool can be considered a fixed constraint to the potential production of sheep wool insulation.

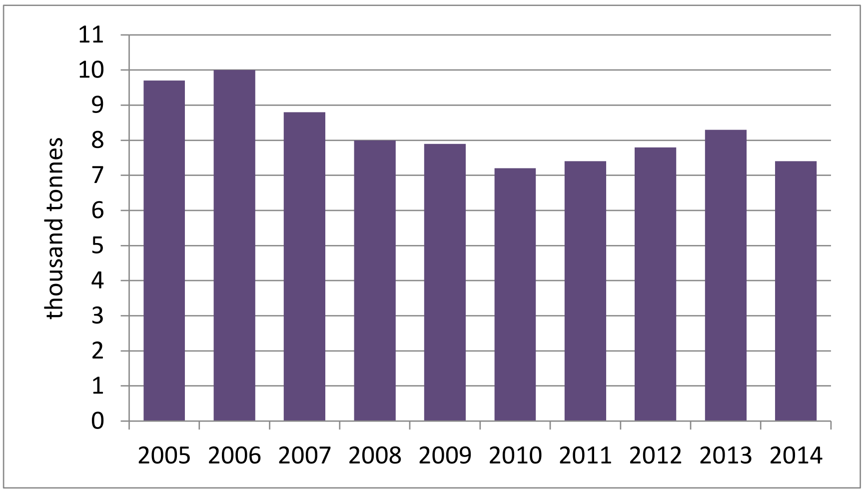


Figure 6. 4 – Raw wool production in Wales (source: WG, 2016c)

6.1.3 Potential supply of softwood chips

The main primary materials used to manufacture wood fibre insulation are softwood chips, as described in section 2.3.3. On the basis of the wood content of products declared in the EPDs used to produce LCA results, it is possible to quantify the amount of softwood chips required to produce 1 FU of final product in 1.985 kg for LD wood fibre and 6.08 kg for HD wood fibre.

Softwood chips are generally a secondary product of sawmills whose main output is 'solid' sawn softwood, such as timber joinery. It is also possible to use recycled woodchips, though the material needs to be clean and of homogenous quality. Softwood chips can also be produced specifically to manufacture wood fibre, though this implies renouncing to produce sawnwood. Considering these aspects and the fact that the value of virgin and recycled woodchips as energy sources is increasing (John Clegg Consulting Ltd, 2010), the output of softwood chips produced by Welsh mills and sold to wood-processing industries (thus excluding woodchips used for energy generation) is considered an appropriate indicator for the potential capacity of the Welsh territory and economy. On the basis of forestry data (Forestry Commission 2015a), it is possible to calculate the average ratio between output (the quantity of softwood chips sold to wood processing industries) and input (the quantity of 'green softwood' consumed by sawmills). Since a forecast of the availability of softwood in the UK until 2050 by region has been produced (Forestry Commission, 2014a), it is possible to take the forecasted availability of softwood in Wales (Figure 6. 5) and apply this ratio to estimate the amount of chips which will be sold to wood processing industries. The resulting figures are used as indicator of the potential capacity for the Welsh territory and economy to supply softwood chips for wood fibre insulation. The steps taken to obtain the ratio used to convert softwood availability to woodchips sold to wood-processing industries are described here.

Figures for the availability of softwood in the UK until 2050 (Figure 6. 5) are given in cubic meters of 'overbark standing' (Forestry Commission 2015a). These are converted into 'green tonnes' of timber by applying a factor of 0.818, given by Forestry Commission (2015b).

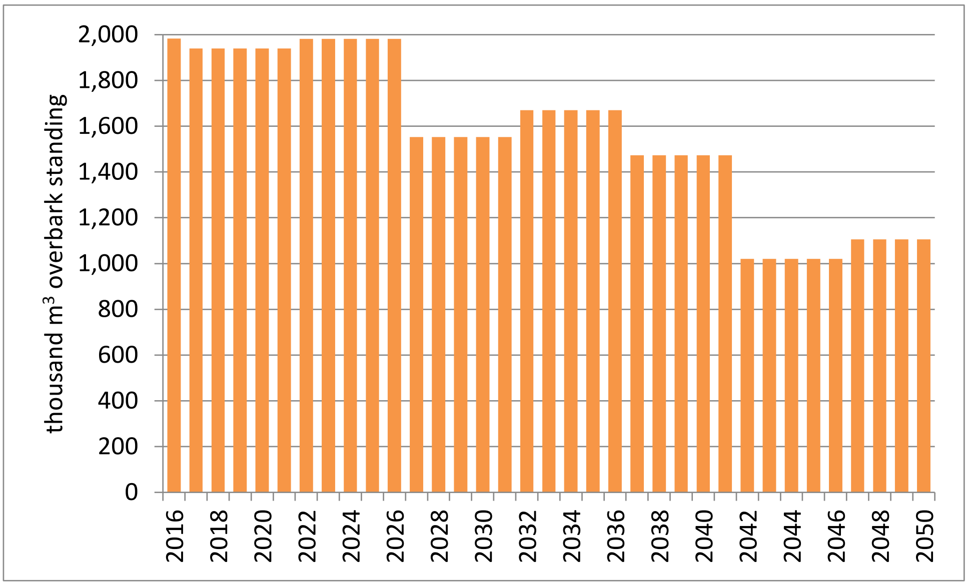


Figure 6. 5 – Forecast of softwood availability in Wales (Forestry Commission, 2014a)

Green tonnes of timber are consumed by sawmills to produce sawnwood and "other products", which include woodchips. Table 6. 1 shows the consumption of green tonnes and the output of "other products" from Welsh sawmills from 2011 to 2015. Since the proportion between input and output is rather constant, it can be used to estimate the quantity of "other products" that will be produced by Welsh sawmills given a certain input in green tonnes. The average factor of 0.566 is used to convert the available softwood (as forecasted in Forestry Commission, 2014a) to "other products".

Table 6. 1 – Softwood consumption and production of "other products" from Welsh sawmills (producing at least 10,000 m3 of sawnwood) from 2011 to 2015 (source: Forestry Commission, 2012; 2013; 2014b; 2015a; 2016)

	2011	2012	2013	2014	2015	Average
Consumption (thousand green tonnes)	612	610	661	667	616	
Other products (thousand tonnes)	339	351	376	374	352	
Factor from consumption to "other products" (unit-less)	0.554	0.575	0.569	0.561	0.571	0.566

The "other products" generated from softwood consumption are woodchips, bark and sawdust. These secondary products are sold to different industries, as shown in Table 6. 2. From 2011 to 2015, between 60% and 64% of these products consisted of "woodchips sold to wood-processing industries" (which include manufacturers of wood fibre products). Thus the factor of 0.618 (average 2011-2015) can be used to estimate the quantity of "woodchips sold to wood-processing industries" if the quantity of "other products" is known.

Table 6. 2 – Market destination of "other products" as percentage of the total output of "other products" from Welsh sawmills, from 2011 to 2015 (source: Forestry Commission, 2012; 2013; 2014b; 2015a; 2016)

		2011	2012	2013	2014	2015	Average
Sold to wood processing industries	Woodchips	64	61	62	62	60	61.8
	Bark	4	0	0	0	0	
	Sawdust & other	21	17	16	16	18	
Sold to bio-energy (including pellet manufacturers)	Woodchips	2	3	3	3	3	
	Bark	0	0	0	0	0	
	Sawdust & other	0	2	2	2	3	
Other sales	Woodchips	0	0	0	0	0	
	Bark	4	10	5	8	8	
	Sawdust & other	2	4	4	4	5	

Figure 6. 6 shows the estimate of the available woodchips sold to wood processing industries in Wales. These figures are obtained by converting cubic meters of overbark standing to green tonnes, to other products and finally to woodchips sold to wood-processing industries, as described above. It must be noted that the original forecast by the Forestry Commission (2014a) indicates the maximum amount of softwood that will be *available* to be harvested, and not the actual harvest. Therefore, the resulting estimate of woodchips sold to wood-processing industries should be taken as the maximum potential for woodchips to be produced.

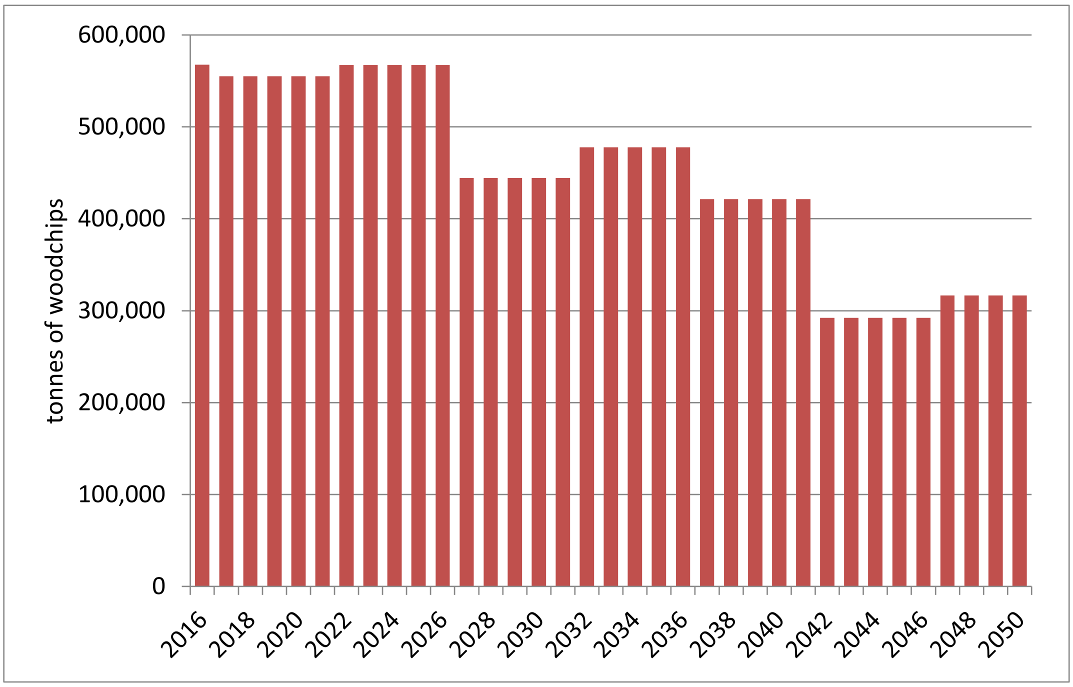


Figure 6. 6 – Estimate of available woodchips from Welsh sawmills sold to wood processing industries

6.2 Results on demand and supply of regional resources

This section presents the comparison between the demand for natural resources generated by the alternative scenarios introducing biomass products and the indicators of the potential capacity of the Welsh territory and economy to supply such resources.

6.2.1 Hemp fibre potential supply and demand

The comparison between demand and potential supply for hemp fibre insulation is shown in Figure 6. 7. The historical minimum and maximum area of land cultivated in Wales with crops comparable to industrial hemp are indicated in black lines. The coloured curves show the demand for hemp fibre insulation caused by the Hemp fibre alternative scenarios translated into the corresponding requirement for land cultivated with industrial hemp. On the right axis, hectares are expressed as a percentage of the average land cultivated in Wales with arable crops. To keep the graph readable, only the combinations between the requirement from retrofits and scenarios D1 for new dwellings are shown. To indicate the maximum and minimum possible requirements resulting from other scenarios for new dwellings (D2, D3, D4), Figure 6. 7 also shows highest (retrofit + D3 at Small level of substitution) and lowest (retrofit +D2 at Very Large level of substitution) combinations.

All curves in Figure 6. 7 reach their peak in 2040, when the combined requirements from retrofits and new dwellings are higher, and then slowly decline. Clearly, the total amount of land required for industrial hemp cultivation is dependent on the level of substitution. For the hemp fibre scenarios, only the Small level of substitution keeps the demand below the historical minimum for comparable crops, while the Very large substitution brings the demand above the historical maximum.

Increasing the uptake of hemp fibre insulation would require between 1,000 and 5,000 hectares of land per year, which correspond to 1.3 – 6.7% of the average land cultivated with arable crops in Wales, and is comparable to the amount of land cultivated with crops similar to industrial hemp (flax, linseed). The Small level of substitution would require up to 1,500 hectares. These conditions could be achieved within a long-term perspective, especially if industrial hemp were to be grown on marginal land to limit the displacement of existing crops. As noted in earlier, land use is not constant but can change over time, and indeed the total area used in Wales for arable crops oscillated between 60,000 and 90,000 hectares during the period from 1998 to 2015. In this context, increasing the area cultivated with industrial hemp up to 1,500 hectares over several years can be considered a feasible objective.

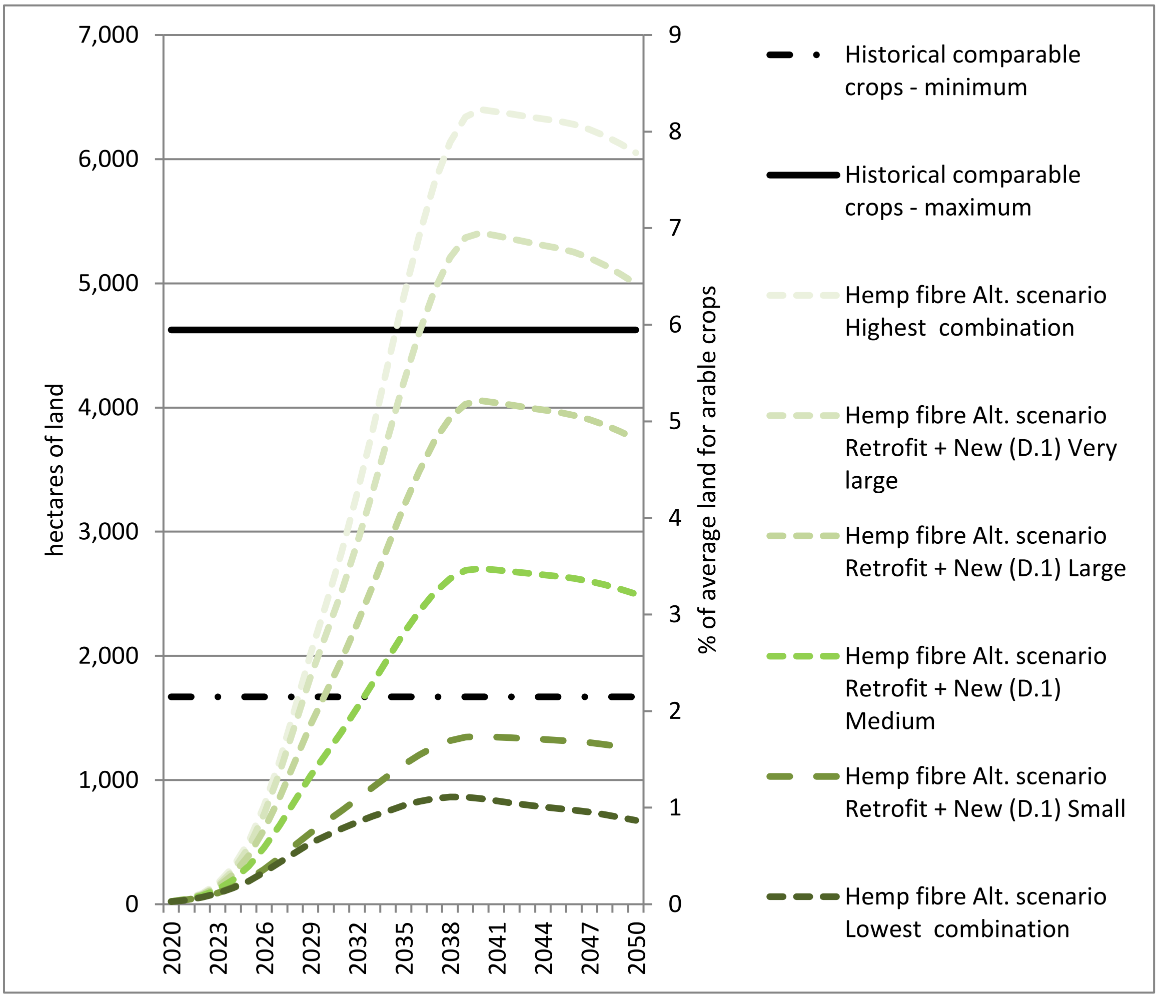


Figure 6. 7 – Comparison between demand and potential supply of land cultivated at industrial hemp

6.2.2 Sheep wool potential supply and demand

The comparison between demand and potential supply for sheep wool insulation is shown in Figure 6. 8. The historical minimum and maximum quantity of raw wool produced in Wales are indicated in black lines. The coloured curves show the demand for sheep wool insulation caused by the Sheep wool alternative scenarios translated into the corresponding requirement for raw wool. As in the case of hemp fibre, only some of the combinations between the requirement from retrofits and scenarios for new dwellings are shown, with all curves reaching reach their peak in 2040.

The historical minimum and maximum annual raw wool production can be considered a more stringent limits to the potential for local supply than in the case of land requirements for industrial hemp. In Figure 6. 8, most scenarios generate a demand for raw wool below the levels of historical production. Only Large and Very Large levels of substitution exceed historical production. Therefore it could be possible to meet a moderate amount of demand for sheep wool insulation with Welsh wool.

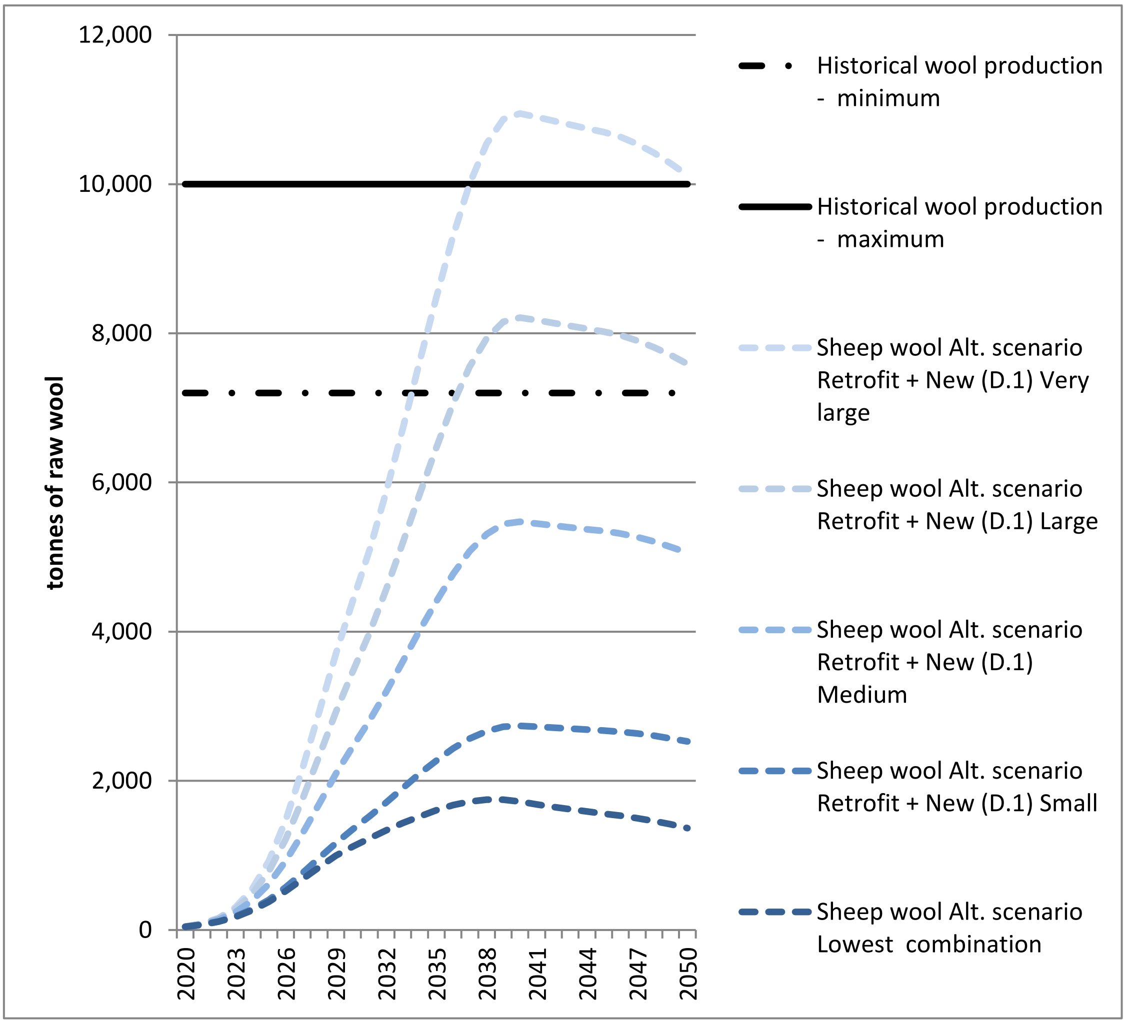


Figure 6. 8 - Comparison between demand and potential supply of raw wool

6.2.3 Wood fibre potential supply and demand

The comparison between demand and potential supply for wood fibre insulation is shown in Figure 6. 9. The annual available softwood chips sold to wood processing industries according to the forecast described in section 6.1.3 is shown in light blue bars and measured on the left axis. The coloured curves show the demand for wood fibre insulation caused by the alternative scenarios translated into the corresponding requirement for softwood chips, which are expressed as percentage (measured on the right axis) of the forecasted availability. Since HD wood fibre is introduced by both Hemp fibre and Sheep wool alternative scenarios, their demand for softwood chips is also shown here.

As in the case of hemp fibre and sheep wool, only some of the combinations between the requirement from retrofits and scenarios for new dwellings are shown, with all curves reaching their peak in 2040. In addition, the curves in Figure 6. 9 present a sharp increase in 2042, which is a consequence of the decrease in softwood chips availability. At its peak, the demand for softwood chips reaches over 2% of the forecasted availability for the lowest combination of the Wood fibre scenario and 18% for the highest combination. In the case of the Hemp fibre and Sheep wool scenarios, the demand for softwood chips for HD wood fibre peaks around 1% for the lowest combination and 5% or the highest one. Overall, these figures indicate that the demand for biomass for manufacturing wood fibre insulation would remain well within the forecasted potential availability of softwood chips from Welsh mills.

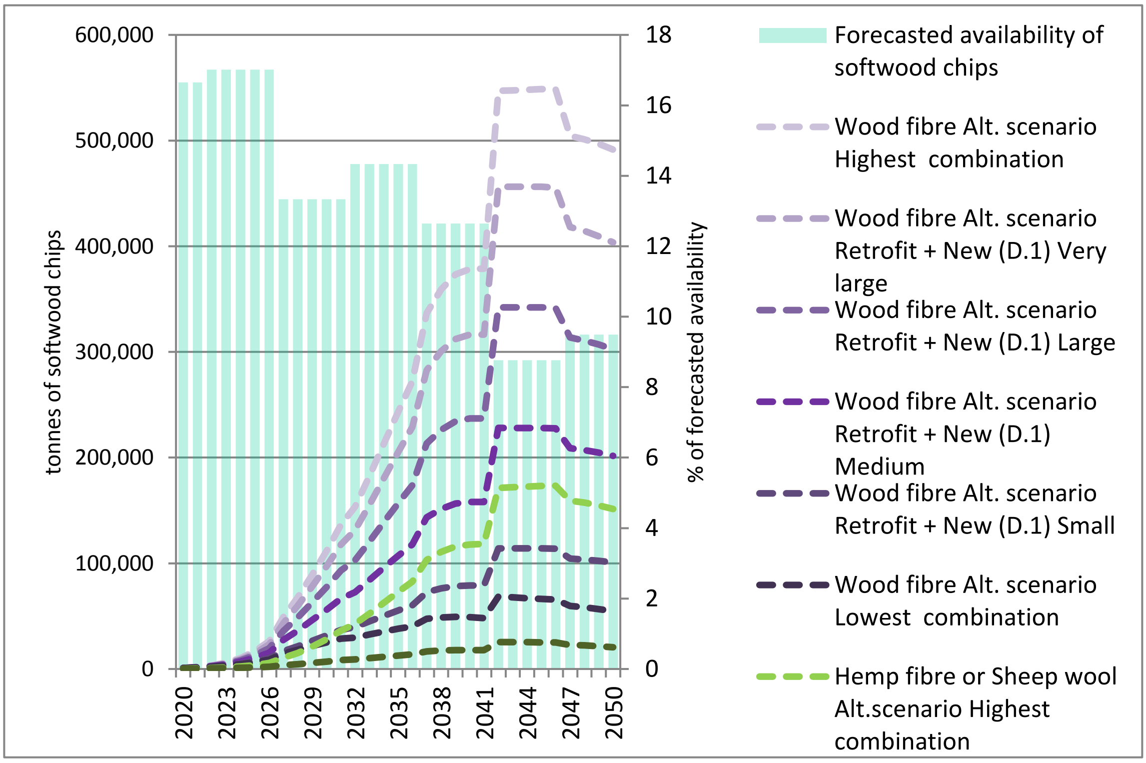


Figure 6. 9 - Comparison between demand and potential supply of softwood chips

6.3 Summary of results of the third component

This chapter has presented method and results of the third component of the research. The demand for regional resources generated by biomass insulation products (as modelled in the alternative supply scenarios) was compared to indicators of the potential capacity of the Welsh territory and economy to supply such resources. The outcomes of this assessment are:

- A moderate demand for biomass products reaching 25% of the market (corresponding to the Small level of substitution) could be sustained using Welsh resources. A larger demand for hemp fibre and sheep wool products would prove more difficult to be met locally due to resource constraints. Conversely, the demand for biomass used in wood fibre insulation would not surpass the potential supply even at the Very Large level of substitution.
- The historical minimum and maximum land area used for crops comparable to industrial hemp fibre are used to assess the potential supply of hemp fibre insulation in Wales. However, these 'boundaries' are used as reference and should not be taken as fixed constraints. To implement the Small level of substitution, the total demand for hemp fibre insulation would require a maximum of 1,500 hectares per year (Figure 6. 7), which is about 2% of the average area of land used for agriculture in Wales (1,500 hectares correspond to approximately 0.08% of Wales, and about one tenth of the area of Cardiff). The largest output of industrial hemp reached in the UK was around 2,000 hectares per year (see section 2.3.4). Although 1,500 hectares is a relatively large area of land, it is a feasible objective if strictly quantitative aspects are taken into consideration. A key factor is the ability of industrial hemp to grow on marginal land, which could reduce the necessity to displace other crops. There are additional factors which can affect the capacity of Wales to supply the required hemp fibre, such as land availability in relation to favourable weather conditions and the presence of processing facilities.
- The boundaries used to assess the potential supply of sheep wool insulation in Wales can be considered as rather rigid constraints, as they are based on historical minimum and maximum outputs of raw wool from Welsh farms (data from 2005 to 2014). Since production has been declining after 2005, it can be argued that is unlikely that future output will exceed recent levels. To implement the Small level of substitution, the total demand for sheep wool insulation would require a maximum of 2,400 tonnes of raw wool per year, corresponding respectively to 35% of the minimum and 24% and maximum outputs, which can be considered a feasible objective.

- The boundary used to assess the potential supply of wood fibre insulation in Wales is based on the forecast of softwood production and the estimate of the subsequent availability of softwood chips for wood-processing industries (such as manufacturers of wood fibre insulation). Taking this boundary as a fixed constraint and considering the Small level of substitution, the annual demand for LD and HD wood fibre insulation would require less than 4% of the available supply of softwood chips sold to wood-processing industries. At the Very Large level of substitution, the peak demand for insulation would require 14% of the annual available supply. Therefore, even the largest potential demand for wood fibre could be sustained locally, at least in strictly quantitative terms. However, an increase in demand for softwood chips from insulation manufacturers would increase competition with current purchasers, which has already increased due to the use of woodchips as fuel (see section 2.3.4), leading to a rise in price.

In summary, a moderate demand for biomass products (reaching up to 25% of the market) could be potentially supplied with Welsh natural resources. Higher levels of product uptake would become increasingly more difficult to supply in the case of hemp fibre and sheep wool.

Comparison between quantitative requirements should be done with care (as they express different physical quantities and are ‘fixed’ to different extents), however the demand for resources for wood fibre products appears as the least impacting on the potential supply. At the Small level of substitution, wood fibre demand affects up to 4% of its potential supply (Figure 6. 9), while the demand for sheep wool affects 30-40% of its potential supply (Figure 6. 8). The demand for hemp fibre affects 2% of its potential supply (Figure 6. 7), if the entirety of the agricultural land in Wales is considered as the ‘potential supply’. If the latter is restricted to the quantity of land cultivated in recent years with crops comparable to industrial hemp, the demand for hemp fibre affects 30-80% of its potential supply. Thus increasing the demand for wood fibre appears as the least impacting on its potential supply among the thee biomass products.

There are other factors affecting the supply of biomass such as market dynamics and the presence of supply chain infrastructure necessary for biomass production, harvesting and processing. The potential to supply the demand for biomass insulation in Wales is discussed in this wider context and in relation to the outcomes of the other research components in the next chapter.

7 Summary, discussion and conclusions

The results produced by the three research components are brought together and discussed in this chapter. In the first section (7.1) the research is summarised by connecting the outcomes to the questions introduced in chapter 1. Research limitations are discussed in section 7.2. In section 7.3 the research outcomes are examined in their entirety to determine whether the evidence supports a large uptake of biomass products in Wales. The last section (7.4) concludes this thesis by highlighting the main findings and discussing potential applications and future work.

7.1 Summary of research outcomes

The aim of this research was to provide evidence to support a significant substitution of currently used insulation products with biomass-based alternatives at a regional scale. The investigation focused on assessing the embodied impact of products in environmental and socio-economic terms and evaluating the potential to meet the demand for biomass products with regional resources. The research was divided into three components, each with its own question, objectives, method and outcomes.

First component: environmental impact.

Research question: what EEI savings are achievable in Wales through a large-scale substitution of conventional insulation products with biomass products?

Objective: to generate scenarios to assess the Embodied Environmental Impact (EEI) of the total domestic supply of insulation in Wales between 2020 and 2050 under different product combinations.

Method: the demand for domestic insulation in Wales was estimated by building scenarios based on the features of the Welsh dwelling stock, U-value requirements in Building Regulations and a forecast of construction and retrofit activity. Product supply was modelled using business-as-usual mix of conventional products to set up baseline scenarios. These provided the basis to create alternative scenarios modelled to progressively increase the share of specific mineral and biomass products, selected for their low EEI and regional relevance. The EEI of the supply scenarios was assessed by scaling up EEI figures for insulation products obtained through process-based LCA.

Outcome: in the baseline scenarios the most impacting conventional products are EPS, PUR and stone wool used to insulate walls in new and retrofitted dwellings (Figures 4.80 to 4.84). This is due to high demand for these products (determined by the baseline product mix) as well as to their high EEI in the most significant impact categories (PEU, POCP and GWP). Most alternative scenarios achieve overall reductions in comparison to the EEI of the baseline scenarios, but there are trade-offs since no alternative scenario reduces impact in all categories. Across biomass products, the combination of hemp fibre and HD wood fibre achieves the largest EEI reductions in the cradle-to-site stages (Figures 4.95 and 4.96), particularly in terms of GWP (Figures 4.87 and 4.88). However, increasing the use of glass wool and HD stone wool also achieves EEI reductions (Figures 4.95 and 4.96), particularly in terms of PEU (Figures 4.85 and 4.86). Thus, the decision to select biomass (hemp fibre and wood fibre) or mineral products is based on the desire to prioritise PEU or GWP. If GWP reductions are favoured over PEU savings, biomass products are considered a better option than mineral products, and vice-versa. If the impact of the end-of-life stage is taken into account, the environmental benefits of biomass products become are diminished: the Wood fibre scenario increases the total GWP, while the GWP reductions generated by the Hemp fibre scenario are reduced significantly, although they are still larger than those achievable with the Mineral scenario.

Second component: socio-economic impact.

Research question: ~~can the embodied socio-economic impact of insulation products be assessed?~~ Do biomass products have better embodied socio-economic impact than conventional products?

Objectives: to assess and compare the embodied socio-economic impact of insulation products.

Methods: the socio-economic impact embodied in insulation products was assessed in terms of price, embodied work and GVA generation. Prices for products sold in the UK in 2015 and 2017 were collected and compared on the basis of equal thermal resistance. Embodied work and GVA generation were estimated using I-O LCA. An economic I-O analysis was performed on supply-and-use tables of the UK in 2013 to produce multiplier effects for employment and GVA. Insulation products were associated with the respective manufacturing sectors and embodied work and GVA generation were calculated using multiplier effects and product prices.

Outcome: Assessing the socio-economic impact embodied in insulation products by collecting prices and performing I-O LCA proved to be a viable technique. The socio-economic assessment required less time and resources in comparison to environmental impact assessment conducted via process-based LCA. However, its results are considered less reliable, as they are based on monetary units and are affected by several limitations. The results are also more complex to interpret, since social and economic impact are not as clearly defined as environmental impact (see sections 2.1.2, 2.2.3 and 2.2.4). Overall, the outcomes of the socio-economic assessment for biomass products indicate a trade-off between price and wider impact (i.e. employment and GVA generation). In terms of affordability, biomass products would need to see a significant reduction in their price (from 30% to 85%, Table 5. 1) to become directly competitive with the most popular conventional products, namely glass wool, EPS and stone wool. While the price of soft biomass products (hemp fibre, sheep wool and LD wood fibre) is in the range of the more expensive conventional products (PUR and phenolics), HD wood fibre is the most expensive of all insulation products (Figure 5. 1). In terms of embodied work and GVA generation, biomass products have equal or higher impact than conventional products (Figure 5. 8 and Figure 5. 10), especially plastic ones. This is due to the high price of biomass products but also to medium-high multiplier effects, which imply a higher impact (i.e. a larger return on employment and GVA per pound invested) across their supply chain.

Third component: demand and supply of regional resources.

Research question: to what extent could regional resources meet the demand for biomass insulation products generated by the domestic sector in Wales?

Objective: evaluate the capacity of the Welsh territory and economy to meet the demand for biomass products with regional resources.

Method: the quantity of biomass products determined by the alternative supply scenarios (modelled in the first research component) was converted into the equivalent demand for biomass resources and compared on an annual basis to indicators of the capacity of the Welsh territory and economy to supply these resources. These indicators were based on agricultural land use (for hemp fibre), output of raw sheep wool (for sheep wool) and output of softwood chips (for LD and HD wood fibre).

Outcome: the comparison between demand and supply capacity showed that a moderate uptake of biomass products (i.e. up to 25% of the market) can be sustained entirely with Welsh resources (Figure 6. 7 to Figure 6. 9). At higher levels of product uptake, the local supply of biomass becomes more difficult for hemp fibre and sheep wool products, while the supply of softwood chips from Welsh mills is less significantly affected by the increased demand for wood fibre products.

7.2 Research limitations

The limitations of this research are discussed here according to the division into three components.

7.2.1 Limitations of the first component

The limitations of the first research component are associated with establishing demand and supply scenarios for insulation products and using process-based LCA to assess their EEI.

Limitations associated with demand scenarios

Future demand for insulation in Welsh dwellings will be determined by several interacting factors, which will be affected by many external forces. Some of these factors, for example U-value legal requirements, will be under the control of public bodies. Other factors, for example rate of intervention, will be affected to a certain extent by policy but will also depend on less 'controllable' conditions such as economic activity or availability of skills. Only some of these factors were considered when modelling the scenarios of future demand for insulation products in Wales (section 4.1). The curves describing the annual demand for insulation (in m2K/W) were determined by three main variables: (A) envelope dimensions, (B) insulation requirements and (C) future rates of new constructions and retrofits. Calculating these variables required making assumptions for several parameters, for example the share of R-value satisfied by the insulation layer. These assumptions are based on existing information, such as SAP tables and CSH case studies, however there remains a degree of subjectivity in some of the choices that have been made. For example, the rates of SWI retrofit interventions (Figure 4.3) are the results of a series of arbitrary choices based on reasonable assumptions. Parameters such as maximum rates of retrofits cannot be directly extrapolated from current conditions, but only estimated on the basis of existing information (such as the current rate) and realistic hypothesis (such as the maximum rate achievable). Thus the demand scenarios built for this research are intended as a 'model' of what future demand could be if the relative assumptions become true, rather than an accurate "prediction" of future demand based on current conditions.

Limitations associated with supply scenarios

The baseline supply scenarios used in this research are built to model a 'business-as-usual' condition of the insulation market (i.e. the 'product mix') where conventional products continue to occupy their current market shares. Since these shares have not remained constant in the past, it is reasonable to assume that they will not remain constant in the future. However, future product mixes cannot be assumed on the basis of previous and current conditions but only hypothesised. As in the case of the demand scenarios, the supply scenarios built for this research are intended as models of future supply rather than accurate predictions.

The ‘business-as-usual’ product mixes used to generate the baseline supply scenarios are based on several sources, with some assumptions required when the available information was not sufficient. Determining the exact product mix for every envelope type in terms of m^2K/W might be virtually impossible, as it would require knowledge of the exact quantity of every type of insulation installed in Wales, categorised by end use. This information is not recorded by installers, but could theoretically be approximated by accounting the insulation sold in Wales, although sales records are business-sensitive information and therefore are not available. Even if these records could be accessed, there is no guarantee that the recorded information would be sufficient to calculate m^2K/W and identify product end-use (i.e. envelope type). ~~Given this context, the product mixes used to model the Primary baseline supply scenarios are considered reasonable estimates for the purpose of this research~~. By comparing the performance of one alternative scenario against the primary and secondary baselines (as in Figure 4.95), it can be concluded that moderate deviations from the product mixes modelled in the primary baseline have a relatively small impact on the EEI changes caused by the alternative supply scenarios.

The value of product substitution introduced by alternative supply scenarios is based on numerical parameters, such as the year of maximum substitution. These parameters cannot be predicted but only hypothesised, and therefore the chosen parameters are reasonable assumptions (see section 4.2.4), and the alternative scenarios are intended as ‘models’ rather than predictions.

The model of product substitution used in this research replaces all conventional products *in equal proportions*. In real conditions, new products could be preferred as replacements for a specific group of conventional products, on the basis of format, cost, performance, etc. For example, soft biomass products could be favoured as replacement for soft mineral products rather than rigid plastic products, mainly due to similarity in format (see section 2.3.3). Modelling these dynamics in the alternative supply scenarios would introduce an additional element of realism, but it would also increase the number and complexity of these scenarios and of the resulting research outcomes. Furthermore, it might appear as an attempt to establish direct competition between products, which is not the purpose of this research. For these reasons, replacing conventional products in equal proportions was considered a more reasonable choice to be modelled.

Limitations associated with process-based LCA

The process-based LCA method presents a series of limitations, as introduced in section 2.2.2. The main criticism of this method is the necessity to exclude some processes from the assessment (the 'cut-off'), which leads to an underestimation of environmental impact (Lenzen, 2001b; Giesekam et al., 2014). This applies to the process-based LCA sources used in this research. For the LCA of hemp fibre and sheep wool products, the LCI by Norton (2008) was modified to include additional processes, thus reducing the cut-off boundary. LCA sources for the other products could not be modified due to their formats, namely aggregated LCIs and EPDs. These LCA were based on energy mix for electricity different from the UK energy mix, and could not be changed to model production using UK energy mix. Therefore the LCA results for hemp fibre and sheep wool products can be considered more accurate for the British context than those of the other products studied in this research.

By modifying the LCIs of hemp fibre and sheep wool products, the problem of allocating agricultural products was introduced (see section 2.3.5). For hemp fibre, economic allocation was estimated based on little available information, however the LCA results show that the EEI of the agricultural stage is relatively small in comparison to the manufacturing stage, thus changes in allocation do not significantly affect the overall EEI. For sheep wool, economic allocation was calculated in detail and the LCA results show that the EEI of the sheep farming stage is quite large in comparison to the manufacturing stage, thus changes in allocation significantly affect the overall EEI.

To include gate-to-site transportation of insulation products in the LCA, travel distances were roughly estimated. However, the results show that the EEI of this life-cycle phase is insignificant in comparison to the EEI of the cradle-to-gate phase, therefore using different travel distances would minimally affect the overall cradle-to-gate EEI figures.

EEI figures for single products obtained through LCA were multiplied by the quantities of products modelled in the supply scenarios to calculate the EEI of the supply of insulation for Welsh dwellings from 2020 to 2050. This leads to three limitations:

- All the limitations of a process-based LCAs (such as the cut-off) are also relevant for the LCA of the supply scenarios, since these are based on the EEI figures for single products.
- Scaling up the EEI of an 'average' product does not take into account the marginal improvement of EEI per FU which could result from economies of scale.
- Scaling up single products to model the entire supply requires data for single products to be good representatives of their product types, i.e. with properties close to the 'average product'. However, it would be virtually impossible to determine the

properties of the ‘average product’, for example stone wool insulation, as it would require knowing properties and quantities of all the stone wool sold in a region during a period of time. Pragmatically, only typical ranges of values can be identified, and therefore a degree of uncertainty remains.

- Consequential aspects are not modelled in the LCA, and therefore it must be remembered that the impact figures refer to an average impact as assessed under current conditions, and that large increases (or decreases) in production might results on a smaller or larger impact.

Minimum and maximum EEI of products were used to take into account the uncertainties associated with LCA by providing a range of possible variations based on existing LCA sources (sections 4.3.10 and 4.3.11). Applying these EEI variations to the supply scenarios allowed estimating the potential deviations of the results within a range of best and worst cases, although it does not provide information on the distribution of value within this range.

The impact of the end-of-life stage was assessed by modelling ‘typical’ shares of disposal options for each product and adopting the ‘recycled content’ approach. Using a different mix of disposal options may produce very different results, especially if the share of recycling is increased. The 12% ‘standard’ practice for recycling taken as main reference in this research can be considered a conservative figure. Its is possible that in period 2020-2050 the recycling rates for insulation waste will increase due to legal pressure, thus decreasing the overall impact of the end-of-life stage for all alternative scenarios. The ‘recycled content’ approach can also be considered as a ‘conservative’ perspective on the impact of the disposal options, as it excludes the benefits of offsetting material and energy use. It is possible that the inclusion of these benefits would result in a smaller impact of the end-of-life stage of biomass products, making the difference with conventional products less marked. Since there are more uncertainties and limitations associated with the end-of-life stage LCA, the cradle-to-grave results were evaluated separately from the cradle-to-site results in order to maintain a clear distinction between the two.

Limitations of the second component

The limitations of the second research component are associated with:

- surveying product prices and
- conducting LCA through I-O analysis.

Limitations associated with the survey of product prices

Prices of insulation products were surveyed to compare products in terms of affordability and were also used as inputs in the I-O LCA procedure. Prices and physical properties of products were collected through a web search from several UK retailers (see Appendix III). The survey produced minimum, average and maximum prices per m^2K/W for each product type. It must be stressed that these results should be considered as approximations of the hypothetical minimum, average and maximum values. Calculating the actual minimum, average and maximum prices per m^2K/W would require a complete record of all insulation sold over a period of time, categorised by product type. As mentioned earlier, it is theoretically possible to build such record, although it would be time-consuming and possibly incomplete due to the business-sensitive nature of this information. It should also be noted that prices are only valid for specific times and geographical areas and can be affected by several factors, such as inflation, business conditions and subsidies on manufacture or primary materials, therefore the validity of the results is limited to the time and area of the survey.

Limitations associated with I-O analysis and LCA

The broad limitations of I-O analysis have been introduced in section 2.2.2. A complete discussion of these limitations is beyond the scope of this research, however three main relevant issues are:

- I-O analysis is based on assumptions of fixed technology and prices, and therefore cannot model the effects of economies of scale, price variation, etc. (Lenzen, 2001a; Miller and Blair, 2009).
- Economic activity is aggregated by industry sectors, and therefore specific activities (such as insulation manufacture) can only be approximated (Giesekam et al., 2014). The Eora dataset (Lenzen et al., 2012; Lenzen et al., 2013) used in this research to perform the I-O analysis disaggregates the UK economy into a large number (512) of industry sectors, however this was not sufficient to distinguish different products within two groups of insulation products: plastic types (PUR, phenolic and EPS) and non-woven types (hemp fibre and sheep wool).
- Outcomes of I-O analysis (such as multiplier effects) are subject to change and therefore only valid for a limited period (Miller and Blair, 2009). However, the time series of multiplier effects (section 5.2.2) showed that although relative figures have changed over time, relative positions between the industry sectors associated with manufacturing insulation have remained quite stable. Thus the outcomes of a comparison between sectors (such as in this research) is less affected by the limits of the time period.

These issues are inherent to the technique of I-O analysis and could only be partially addressed in his research. Using economic I-O analysis to conduct LCA at the product level presents one additional significant issue, namely the necessity to rely on product prices to convert from monetary to physical units. This implies a direct proportionality between the price of a product and its 'impact' in terms of embodied work and generated GVA. This is better explained through a basic example, assuming that one FU of glass wool 'A' costs £2 while one FU of glass wool 'B' costs £4, although the manufacturers of 'A' and 'B' belong to the same industry sector (i.e. glass wool). According to how I-O LCA works, one FU of glass wool 'B' is associated with two times the embodied work of one FU of glass wool 'A'. Although the higher price of product 'B' might indicate a higher requirement of labour per FU than product 'A', in real conditions a higher price cannot always be assumed to imply a directly proportional input of labour, because product price can be affected by other factors beside the costs of production inputs. Therefore, using product prices to conduct I-O LCA can only provide an approximation of the (hypothetical) average embodied work per FU of glass wool. However, it can be argued that using an *average* price per FU of glass wool would provide a better approximation by balancing out the different prices of glass wool products. This is the approach taken in this research, but since average prices of insulation products can only be approximated (as discussed earlier), a degree of uncertainty remains.

Given the focus of this research on Wales, using data at the UK level can be questionable, as the two economies have different scales and there might be differences in technology and purchasing propensities. An I-O analysis of the Welsh economy exists for the year 2000 (Munday et al., 2004), but it is not adequate for the purpose of this research as the level of industry disaggregation was low and multiplier effects were not calculated. I-O analysis is used in this research to assess differences between industry sectors and not between economic regions, and therefore the capacity of a dataset to distinguish between sectors is more important than its capacity to reflect specific aspects of the regional economy. It can be argued that potential differences between the UK and Welsh economy in terms of technology and purchasing propensities are unlikely to be significant for the industry sectors studied in this research. This is because the Welsh economy is part of the UK economy and therefore it is unlikely for insulation manufacturers located in Wales to be *significantly* different in their technology and purchasing propensities from manufacturers of the same products located in England or Scotland. For the purpose of this research, it is assumed that technology and purchasing propensities of industries at the regional level of Wales are not significantly different from those at the wider UK level. Pragmatically, this assumption does not limit the validity of the results: the "system" modelled by the I-O tables used in this research is the whole UK economy, and therefore the resulting multiplier effects refer to UK boundaries and not Welsh ones.

Limitations of the third component

The limitations of the third research component are associated with assessing the potential supply of regional resources. This assessment was conducted by comparing the demand for resources determined by the alternative scenarios to indicators of the potential capacity of the Welsh territory and economy to supply such resources. Indicators were based on forecasts and historical records of agricultural activity. Each of the three biomass products requires a different primary material, and therefore the resulting demand was compared to a specific indicator. This method enables environmental and economic aspects to be integrated into the indicators but does not allow for a straight-forward comparison of potential *between* products, because the three indicators are not commensurable. Furthermore, hemp fibre is the primary product of industrial hemp cultivation (or at least co-product with shives) while raw wool and woodchips are, to different extents, by-products of their sectors. This difference adds to the ‘incommensurability’ of the three products supplies.

The assessment of potential capacity conducted in this research can be considered a preliminary evaluation. The economic and infrastructural aspects of establishing or enlarging the production of biomass insulation products in Wales were presented in the literature review and considered in the discussion of results, but a detailed study could investigate these aspects further.

7.3 Discussion

This discussion will present the complex picture of the benefits and drawbacks of a large uptake of biomass products in Wales by considering the outcomes of the three research components in their entirety. Section 7.3.1 defines the criteria used to evaluate product benefits and drawbacks following the ‘radical’ approaches to sustainability introduced in section 2.1. Benefits and drawbacks of biomass and conventional products are evaluated in sections 7.3.2 and 7.3.3. Sections 7.3.4, 7.3.5 and 7.3.6 discuss the price and resource constraints that have emerged from the research outcomes as factors which can hinder a large-scale uptake of biomass products in the future.

7.3.1 Criteria for sustainable products

There is a common preconception that biomass insulation products are more ‘natural’, less ‘processed’ and thus closer to the natural form of their primary material than plastic or mineral products, which leads to a better environmental performance and to these products being labelled as more sustainable. However, the reviewed literature and the research outcomes do not totally support this. The manufacture of hemp fibre, sheep wool and wood fibre insulation require several industrial processes, with additives required to ensure the performance of organic materials (sections 4.3.6 and 4.3.7), and the energy used in manufacturing is often higher than conventional products (Figure 4.67). Furthermore, the research outcomes show that there are significant differences across biomass products as well as conventional products in terms of their EEI (Figure 4.73). Therefore, the type of primary material is not a valid criterion to evaluate the environmental impact of a product. Assessing EEI across a number of impact categories provides a more accurate set of indicators for product assessment. Since sustainability is not limited to environmental impact, socio-economic factors should also be taken into account to provide a comprehensive assessment. As discussed in section 2.1, the choice of criteria to assess socio-economic impact is less standardised than the ones used to assess environmental impact and is significantly affected by the approach taken towards sustainability. In comparison to mainstream economics, radical approaches to sustainability have a stronger focus on the capacity to generate employment (Schumacher, 1938; Costanza et al., 1997a) and on the 'regional dimension' of its environmental and socio-economic impact (Graymore, 2005; North, 2010; Cato, 2011). This is the approach taken in this discussion to evaluate products sustainability and the benefits and drawbacks of a larger uptake. This discussion is also based on the understanding of relative product sustainability, i.e. it is not possible to say that product 'A' is sustainable in itself, it is only possible to say that product 'A' is more (or less) sustainable than product 'B'. From this perspective, a 'sustainable' product should satisfy the following criteria in comparison to a functionally-equivalent conventional product:

- lower resource use, possibly renewable and/or recyclable;
- regional manufacturing and supply chains;
- lower environmental pollution;
- higher embodied work;
- higher wealth generation;
- affordable price.

These criteria provide the basis to evaluate the benefits and drawbacks of the insulation products assessed in this research. While hemp fibre, wood fibre and, to a lesser extent, sheep wool satisfy most of these criteria in comparison to plastic products in the cradle-to-site stages fo the life-cycle, their advantage is less marked when compared to mineral products. If the impact of the end-of-life stage is taken into account, the environmental benefits of biomass products are less apparent, although hemp fibre remains the favourable alternative to mineral products in terms of GWP reductions.

The main criteria which is fully in favour of mineral and plastic products is affordability (section 5.1.2 and Figure 5. 1). This indicates that biomass products present a trade-off between price and positive impact in environmental and wider socio-economic terms, which poses an obstacle to a larger uptake of these products. Although there might be ways to reduce it (discussed in section 7.3.5), it is arguable that this trade-off is a consequence of the criteria for a ‘sustainable’ product identified above. All other things being equal, a product with higher embodied work can be expected to be more expensive than a ‘standard’ product, because the manufacturer spends more on salaries. Product price can also increase if a manufacturer internalises the costs of environmental externalities in order to have a product with lower environmental impact. The food industry provides a clear example: traditional products requiring labour-intensive processes and regional ingredients can be expected to be more expensive than products manufactured with imported ingredients and highly-industrialised processes. However, this should not lead to simplistic generalisations and to the assumption that ‘sustainable’ products are necessarily more expensive. In the context of this research, improved conventional products, such as glass wool with organic binder (see section 4.3.2), are less expensive than biomass products (Figure 5. 1) and can clearly ‘compete’ with them in terms of EEI reductions achievable through a large uptake (Figures 4.95 and 4.96).

7.3.2 Benefits and drawbacks of biomass products

Firstly, it must be clarified that this discussion focuses on the ‘Small level of substitution’ (modelled to progressively replace 25% of the market with biomass products) because it is the most realistic scenario among the four levels modelled, since it assumes the least deviation from the current market conditions. Achieving such a level of market penetration would represent a success for biomass products as they would effectively become comparable to conventional products in terms of volume of sales.

Based on the evidence collected in this research, the benefits of biomass products in comparison to conventional products have been identified as:

- lower EEI in terms of GWP and POCP, best achieved by a combination of hemp fibre and HD wood fibre (Figures 4.87, 4.88, 4.93 and 4.94), considering both cradle-to0ste and cradle-to-grave boundaries;
- higher capacity to generate local employment and wealth (Figure 5. 8 and Figure 5. 10);

- availability of local biomass resources for moderate levels of product uptake (Figure 6. 7 to Figure 6. 9).

Biomass products also present drawbacks:

- higher EEI in PEU, AP and EP, particularly in the case of sheep wool (Figures 4.85, 4.86, 4.89, 4.90, 4.91 and 4.92), and the issue of carbon release at the end of the product life-cycle;
- higher prices (Figure 5. 1);
- limits in local supply capacity of biomass to meet high levels of product uptake (Figure 6. 7 to Figure 6. 9).

Taking into account both benefits and drawbacks, it must be acknowledged that the evidence does not strongly support a large uptake of biomass insulation products in Wales:

- The first research component (chapter 4) has shown that the EEI of the future supply of insulation for Welsh dwellings can be reduced by increasing the use of biomass products, however these improvements are moderate in comparison to the required level of product substitution. In the cradle-to-site boundary, the Small level of substitution reduces the baseline EEI score of the supply of insulation by 6%-9% (Hemp fibre alternative scenario, Figures 4.95 and 4.96). The largest reductions are achieved for GWP (31%-41%, Figures 4.87 and 4.88) and POCP (around 15%, Figures 4.93 ad 4.94). These levels of GWP reductions are the largest achieved by any alternative scenario modelled in the research, and represent the most significant advantage of the Hemp fibre scenario (which combines hemp fibre with HD wood fibre). If the impact of the end-of-life is taken into account, this advantage in GPW reductions is significantly diminished (to 6%-7%). The POCP reductions are also quite significant, and less affected by the inclusion of the end-of-life stage, but it must be considered that other alternative scenarios achieve similar POCP reductions, and that results are affected by the problematic CML characterisation for POCP (Thinkstep, 2016b; see section 3.2.3). Overall, a lage scale uptake of hemp fibre and wood fibre insulation is justifiable in terms of environmental benefits only in conjunction with significant effort to reduce the impact of the end-of-life stage. This could be achieved by increasing the recycling rates and/or landlfilling rather than incinerating the waste which is not recycled, since landfilling releases less carbon (Norton, 2008). However, while it is likely that recycling rates will increase in the future due to legal pressure, for the same reason landfilling will probably become less viable than incineration. It must be also considered that the assessment of the end-of-life stage excludes the benefits from material and energy use offset by recycling and recovering energy during incineration. If these were to be taken into account (i.e. by adopting the 'avoided burden' approach to LCA), they might partially offset the negative impact of these disposal options.

- The second research component (chapter 5) has shown that biomass products have a high potential to generate socio-economic benefits in terms of local employment and wealth generation (Figure 5. 8 and Figure 5. 10), however the high price would continue to discourage the use of biomass products on a large scale in favour of less expensive conventional products.
- The third research component (chapter 6) has shown that primary materials necessary to sustain the Small level of substitution for biomass products could be sourced in Wales (Figure 6. 7 to Figure 6. 9), although this would require the establishment of regional supply chains (discussed further in section 7.3.6).

Overall, a large uptake of locally-manufactured biomass products in the domestic insulation market of Wales would generate a positive environmental and socio-economic impact, at least in the cradle-to-site stages, at the cost of capital investment on the supply side (to establish manufacturers and supply chains) and on the demand side (due to high product price). To provide a more comprehensive picture, the next sections consider whether conventional products might offer a better option, and discuss the opportunities to increase biomass product competitiveness and meet their supply chain requirements.

7.3.3 Benefits and drawbacks of conventional products

The research outcomes have highlighted the differences existing across conventional insulation products in terms of their EEI and socio-economic impact. Generally, mineral products have lower EEI and price than plastic products (Figures 4.72 and Figure 5. 1), but there are differences within these groups and products with similar primary materials cannot be assumed to have similar characteristics. This is particularly true in the case of EPS, as its environmental impact is quite different from that of the other two plastic products (Figure 4.72) and its price is much lower. In terms of employment and GVA generation per FU of product, PUR and phenolic have a higher potential than mineral products (Figure 5. 8 and Figure 5. 10). However, this is due exclusively to their high price, because on a monetary basis the employment and GVA generation of plastic manufacturers (i.e. their multiplier effect, see section 5.2.1) is lower than mineral products (Figure 5. 8 and Figure 5. 10). Since mineral products are more easily recycled and have higher fire resistance than plastic products (section 2.3.3), they can be considered more sustainable options. While the high EEI of plastic insulation (Figure 4.73) does not support a larger uptake, this does not imply that plastic products have no place on the insulation market. Plastic manufacturers could improve the performance of their products, and designers and contractors should limit their use to applications where technical requirements justify the choice of products with high EEI.

With regards to mineral products, the research outcomes show that an increase in the market share of glass wool and HD stone wool (as modelled by the Mineral alternative supply scenario) would reduce the EEI of the future supply of insulation in Wales. EEI reductions occur in different impact categories than the reductions achieved with biomass products, but they are comparable: implementing the Mineral scenarios at the Small level of substitution reduces the baseline EEI score of the supply of insulation by 5%-7% (Figures 4.95 and 4.96), and achieves the largest reduction in PEU (6%-8%, Figures 4.85 and 4.86) and POCP (8%-11%, see Figures 4.93 ad 4.94). In comparison, the Hemp fibre alternative scenario achieves higher POCP reduction (about 15%). Since the reliability of POCP results for biomass products is jeopardised by the problematic CML characterisation (Thinkstep, 2016b), it is arguable that the POCP 'performance' of the Hemp fibre alternative scenario should be considered equivalent to that of the Mineral alternative scenario (as discussed in section 4.4.2). Changes in AP and EP are similar for the Mineral and Hemp fibre alternative scenarios (Figures 4.89 to 4.92). Thus, the main difference between the Mineral and Hemp fibre alternative scenarios is in PEU and GWP reductions.

If only environmental impact is considered, the best option between Mineral and Hemp fibre alternative scenarios can be identified using PEU or GWP as the main EEI category to be reduced. In the cradle-sto-site stages, the Hemp fibre scenario sees a slight increase in PEU at the Small level of substitution (between 3% and 12%, Figures 4.85 and 4.86), but the reduction in GWP (31%-41%) is much larger than the Mineral scenario (2%-5%, Figures 4.87 and 4.88). The inclusion of the impact of the end-of-life stage decreases this advantage significantly (Hemp fibre reductions are only 6%-7%), and therefore mineral products can be considered more favourably. Moreover, since the Mineral scenario requires a smaller substitution of conventional products in comparison to the alternative scenarios for biomass products (see section 4.2.4), the environmental improvements of the Mineral scenario can be considered more easily obtainable, as they require a smaller deviation from current market conditions. Considering that mineral products are generally less expensive than biomass products (Figure 5. 1) and large mineral manufacturers are already established in Wales (see section 2.3.2), it is arguable that increasing the use of mineral products would be more feasible and less expensive than supporting a large uptake of biomass products. This is discussed further in section 7.3.7.

7.3.4 Challenges for biomass product uptake

As shown above, both Mineral and Hemp fibre alternative scenarios reduce EEI in some categories while causing increases in others (Figures 4.85 to 4.94). Beside prioritising PEU or GWP reductions, there are other factors such as socio-economic impact and local supply capacity, that should be taken into account when considering whether a large-scale uptake of biomass products is feasible and should be supported. These factors are discussed in the next sections in light of the research outcomes, but it must be clarified that qualitative aspects from the field of social sciences, such as the question of how innovations can escape the "technological lock-in" (Foxon, 2002; Perkins, 2003), are outside the scope of this research.

7.3.5 Increasing the competitiveness of biomass products

The outcomes of the second research component (socio-economic impact assessment) are contrasting. On one hand, biomass products are more expensive than most conventional ones (Figure 5. 1), however they are shown to have greater impact in terms of local employment and wealth generation (section 5.4, Figure 5. 8 and Figure 5. 10). This demonstrates a trade-off between affordability and wider socio-economic impact (adding to the trade-off between affordability and low EEI), and indicates price as the main obstacle to a larger uptake of biomass products. This section discusses the opportunities to decrease this trade-off by lowering the price of biomass products. If this price does not decrease, it remains the choice of the end-users (designers, contractors and property owners) to assess whether paying a higher retail price in return for the environmental and socio-economic benefits of biomass products. Thus, it is important for these benefits to be supported by evidence and be publicly acknowledged.

The current market of domestic insulation is occupied by five conventional products (section 2.3.2). Although some products might be prevalent in specific applications (such as glass wool in loft insulation), no single product occupies the absolute majority of the market. To reach a large share of the market, any newly introduced product would need to be highly competitive with conventional products in terms of price per FU (thermal resistance) and performance. The outcomes of the survey of product prices (section 5.1.2 and Figure 5. 1) show that this is not currently the case for biomass products:

- Price - Biomass products are disadvantaged in terms of price in comparison to stone wool, glass wool and EPS: although soft biomass products have similar thermal conductivity to these products, their price per FU is higher, therefore stone wool, glass wool and EPS achieve the same level of insulation at a lower cost. Hemp fibre and LD wood fibre have similar price ranges and would need to reduce average price per FU by 42% and 55% to become competitive with functionally-comparable products such as stone wool and EPS, respectively (Table 5. 1). Sheep wool insulation is slightly cheaper than hemp fibre and LD wood fibre, while HD wood fibre is the most expensive product and would need to reduce its price by 55% and 39% to become competitive with functionally-comparable products such as PUR and phenolic products, respectively (Table 5. 1).

- Performance - Biomass products are disadvantaged in terms of performance in comparison to PUR and phenolics: although soft biomass products have similar prices per FU to these products, their thermal conductivity is higher (section 2.3.1), therefore PUR and phenolics achieve the same level of insulation at the same cost but with a thinner layer of material. This can be particularly advantageous in applications such as IWI, where space is limited.

These disadvantages represent an obstacle for biomass products to reach a large share in the insulation market. To encourage a larger uptake of biomass products, market prices could be lowered by reducing production costs and through policy support.

Reducing production costs of biomass products

Production costs can be roughly divided between materials, and labour and operations.

- Materials costs may decrease for a number of reasons. According to the basic economic law of supply and demand (Greenlaw and Taylor, 2017, chapter 3), if the supply of goods becomes larger, their price will decrease. Thus, if a larger supply of primary materials for the manufacture of biomass insulation became available, insulation manufacturers would buy the primary materials at a lower cost, which would lower the price of the finished product. At the same time, a rise in the demand for biomass primary materials would tend to increase their prices. This highlights the need for a sufficient supply of primary materials to enable biomass insulation manufacturers to grow and become more economically competitive.
- Labour and operations costs can be reduced through technical improvements in the manufacturing process and the effects of economies of scale, i.e. by decreasing the inputs necessary to produce one unit of output (Greenlaw and Taylor, 2017). This generally requires capital investment to improve and upscale the manufacturing equipment. The outcomes of the I-O LCA indicate that biomass insulation products require a significant input of labour (Figure 5. 8), which can be identified as one of the reasons for their higher price, but also suggests an opportunity to decrease labour inputs per FU of product. However, a decrease in embodied work would also result in a

> reduction in the capacity of biomass products to generate local employment. More generally, if production costs of biomass products were to decrease to become more competitive with conventional ones, their capacity for employment and GVA generation per FU of product would also decrease, at least according to the outcome of I-O LCA (see minimum values in Figure 5. 8 and Figure 5. 10).

Given their high embodied work and GVA generation (Figure 5. 8 and Figure 5. 10) sourcing and manufacturing biomass insulation in Wales would generate more employment and wealth than mineral and plastic products, albeit at a higher capital cost. Localising production would allow the realisation of the benefits of local employment and GVA generation indicated by the socio-economic assessment (Figure 5. 8 and Figure 5. 10) and would minimise transportation costs, which are significant for insulation products (Office for Fair Trading, 2012a). However, it must be noted that the establishment of *local* insulation manufacturers cannot be supported on the basis of reducing environmental impact alone, since transportation distances do not significantly affect the EEI of products (Figure 4.72).

Policy support

The market price of biomass insulation products could be supported through subsidies, thus indirectly reducing production costs. To a certain extent this is already taking place, given the existing agricultural and forestry subsidies and the subsidies on natural fibre processing (section 2.3.4). The price of biomass insulation products could also be reduced via market-based policy instruments, such as tax discounts. This would require establishing criteria to identify eligible products. Rather than basing eligibility on product composition (i.e. the presence of biomass), rewarding product environmental performance (i.e. low EEI) would be fairer and more effective. As a policy initiative, this may not need to be restricted to insulation products but could be part of a general programme aimed at reducing EEI in the construction sector. The existing EPD methodology could be used to certify product EEI. In comparison to the GreenGuide framework (BRE, 2018) currently used in the UK to grade construction products, the EPD method (EPD International, 2017) is more transparent and widely adopted across Europe (see section 2.2.6). However, the current EPD methodology does not include information on the socio-economic impact of the product assessed. Adding socio-economic indicators to the EPD methodology could provide a more comprehensive assessment and enable policy-makers (and all other EPD users) to take a more holistic approach to sustainability. If a policy to support sustainable products in construction was to be established in Wales, it should be based on a reliable and transparent method to avoid basic simplifications (‘local’, ‘natural’, etc.) and ensure the best environmental and socio-economic outcomes. Furthermore, such a policy should be carefully structured to avoid potential conflicts with the general economic policy of the UK and its international trade agreements, such as disputes over subsidies to UK-based products.

In the absence of policy intervention, lower prices for biomass products would only be achievable through private investment from manufacturers to reduce production costs (as discussed above). With a policy to reward EEI performance, manufacturers of conventional as well as biomass insulation would be encouraged to reduce the EEI of their products, thus establishing a beneficial competition between firms to achieve lower impact. A similar effect would be achieved if products with high EEI were to be penalised under a regime of *Pigouvian taxation*, for example through a tax on carbon emissions. Manufacturers of biomass products would also be encouraged to increase the scale of production (e.g. opening new plants), thus potentially benefitting from economies of scale.

A policy supporting market prices of products with low EEI would likely impact on public revenue, depending on the combination of incentives and taxesd adopted. Following the principles of microeconomics (Hutchinson, 2017) if subsidies or incentives (e.g. tax reductions) were established for products with low EEI, there would be a reduction in public revenue. This could increase over time as manufacturers gradually improve the EEI of their products and gain access to the subsidies. Conversely, if financial penalties were established for products with high EEI, there would be an increase in public revenue, at least until the penalised manufacturers lower the EEI of their products.

Overall, the optimal way to increase the competitivity of biomass products on the market would be a combination of private efforts to reduce production costs and of public initiative to reward low EEI. A fair policy should aim to support manufacturers of products with low EEI as well as encourage manufacturers of product with high EEI to improve their production.

7.3.6 Potential to increase regional product supply

The outcomes of the third research component (comparing demand and supply of biomass resources) show that Welsh resources have the potential to supply ‘moderate’ levels of biomass product uptake (i.e. corresponding to the Small level of substitution), while this becomes increasingly difficult at higher levels of product uptake (i.e. higher levels of substitution), particularly for hemp fibre and sheep wool. This assessment is based on ‘quantitative requirements’ for regional resources (e.g. hectares of land), but other factors, such as the economic context and the necessity to establish local supply chains, can be discussed in light of the information on biomass production in the UK collected in section 2.3.4.

According to the principles of microeconomics (Greenlaw and Taylor, 2017), an increase in the demand for primary materials due to a large uptake of biomass products might initiate a series of economic dynamics. Manufacturers of biomass products would compete to access biomass resources against established manufacturers of other products based on the same resources. In general, increasing the demand of biomass as primary material for insulation could have consequences such as:

- in conditions of limited supply, a rise in the price of biomass and consequently a rise in the price of the related insulation product;
- lower availability of biomass for other industrial processes, due to the increase in competition;
- an increase in the regional output of biomass, if possible, in reaction to a higher demand;
- an increase in biomass imports from the rest of the UK or abroad, in reaction to a higher demand.

These economic consequences are particularly relevant in the case of wood fibre, since the market for its primary material (softwood chips) is already under pressure given the rising demand for this resource as biomass fuel (John Clegg Consulting, 2010; Europe Economics, 2010).

Regional supply of hemp fibre

Industrial hemp is grown in Wales in minimal quantities at present and no processing facilities are present within its borders, although a few fibre processing plants and two insulation manufacturers are located in England (section 2.3.4). If a significant part of the future demand for insulation in Wales were to be met with hemp fibre products, current agricultural output would need to increase. Assuming that hemp fibre products would fulfil one quarter of the demand for insulation of Welsh dwellings by 2040 (in combination with HD wood fibre, as modelled by the Small level of substitution), approximately 1,500 hectares of land would be required to be cultivated with industrial hemp (Figure 6. 7). Suitable land would be identified considering aspects such as soil, climate and accessibility. A consistent annual agricultural output could be provided by establishing a network of local hemp farmers growing industrial hemp either as main crop or ‘break crop’. Economic viability would be essential to make industrial hemp an attractive business for farmers. A rising demand for hemp fibre (and shives) as primary material for a number of end-products (including insulation) would provide an incentive for prospective industrial hemp farmers in addition to the presence of agricultural subsidies (see section 2.3.4). Local deposits and decortications facilities would be required to store seasonal harvest and process hemp straw (Springdale Crop Sinergies, 2006), and at least one manufacturing plant would be required, preferably in a location where transportation costs could be minimised to the whole of Wales.

Regional supply of sheep wool

Sheep wool is a traditional product of Wales, however its output has been declining in the last decade from around 10,000 to about 7,000 tonnes per year (section 2.3.4 and Figure 6. 4). Assuming that the use of sheep wool insulation products would rise to meet one quarter of the demand from Welsh dwellings by 2040 (in combination with HD wood fibre, as modelled by the Small level of substitution), about 30% of the current output of Welsh wool would be required (Figure 6. 8). Local supply of sheep wool for insulation is quantitatively feasible, however an increase in demand for sheep wool insulation would require scaling up current manufacturing facilities and establishing new ones. If a manufacturer of sheep wool insulation were to be located in Wales, an adequate scouring plant would be needed to ensure local supply of clean wool. As shown by Mitchell Associates (2005) and Quigley (2010) this would require initial capital investment (between £700,000 and £2 million, depending on plant size) but would be economically sustainable in the long-term.

Regional supply of wood fibre

Wood fibre insulation is currently manufactured in several European countries although not in the UK. Wood fibre manufacturers are particularly well established in countries with a tradition of timber production, such as Germany and Austria. The primary material (softwood) is locally available in Wales (Figure 6. 5) and is suitable for the manufacture of wood fibre insulation (Bryans, 2011; WoodKnowledge Wales, 2016). A newly-established wood fibre manufacturer in Wales could rely on the existing network of Welsh mills to provide softwood chips ‘ready’ to be processed into wood fibre insulation. If wood fibre products were introduced in the market to reach a “moderate” share of the Welsh market for domestic insulation (i.e. up to 25%, as modelled by the Small level of substitution), only up to 4% of the softwood chips forecasted to be available from Welsh mills (and sold to wood-processing industries) would be required to manufacture these products (Figure 6. 9). If wood fibre were to reach 100% of the market (as modelled by the Very Large level of substitution), only up to 14% of the forecasted availability of softwood chips would be affected.

Comparing supply chain requirements

Beside strictly quantitative requirements of biomass demand and supply (i.e. Figure 6. 7 to Figure 6. 9), the factors discussed above provide additional information to evaluate the opportunities for a large-scale uptake of biomass insulation products in Wales:

- Hemp fibre - Identifying adequate agricultural land location, establishing local depots, a fibre processing plant and an insulation manufacturer would ensure a local supply of hemp fibre insulation. Agricultural subsidies would affect prices and economic viability of industrial hemp as insulation material.
- Sheep wool - Establishing a local scouring plant and an insulation manufacturer would ensure a local supply of sheep wool insulation. Agricultural subsidies and trends in the meat sector would affect prices and economic viability of sheep wool as insulation material.
- Wood fibre - Establishing an insulation manufacturer would be sufficient to ensure local supply of wood fibre insulation. Agricultural subsidies and subsidies on biomass fuel would affect prices and economic viability of wood fibre as insulation material.

It can be concluded that developing a supply chain of wood fibre insulation in Wales would be less demanding in comparison to sheep wool and hemp fibre, because:

- it would only have a minor impact on its potential supply (i.e. softwood chips sold to wood processing industries, Figure 6. 9);
- it would use existing Welsh softwood mills as suppliers and only require the establishment of a local manufacturer for the final insulation product.

If a wider perspective is taken on the subject, there are additional arguments in favour of wood fibre insulation:

- The need to use agricultural land for a purpose different than food production might undermine the sustainability of a large uptake of hemp fibre insulation. Since fibres and shives are the main outputs of industrial hemp cultivation, producing hemp fibre implies a choice to exclude some agricultural land from food production. This is a similar issue to that arising from the use of agricultural land to produce biomass fuel instead of food (Tenenbaum, 2008; Thompson, 2012). It is argued that since food can only be 'produced' from agricultural land while fuels can be made from other resources, it is more sustainable to use land to produce food than fuels. In a similar way, it can be argued that using agricultural land for food production and making insulation from by-products of existing industries is a more sustainable option than using land to make insulation. This issue is less relevant when industrial hemp is cultivated as a break crop or on marginal land which is not used for food production.
- The environmental impact of sheep wool should be considered in the context of its production within the sheep meat sector (section litrev2.3.4 and Table 4.24). Because of its high environmental impact, it is arguable that sheep farming is the type of activity that a society aiming to become more sustainable should attempt to reduce

> (Williams et al., 2006; Monbiot, 2017). If Wales were to reduce the volume of its sheep meat industry, local supply of raw wool would decrease, therefore limiting the opportunities to use wool as insulation material. Given the reliance of the sheep meat sector on agricultural subsidies (O'Regan et al., 2017; section 2.3.4), it should also be considered that future changes in subsidy policy (for example after the UK leaves the EU) might affect sheep farming in Wales by making it less economically viable. This would impact on the long-term capacity to supply sheep wool for insulation products.

Wood fibre does not present this type of issues. As a by-product of the timber industry, woodchips are not associated with a high impacting sector (as in the case of sheep wool and the meat industry) and their production does not require excluding agricultural land from food production (as in the case of industrial hemp). Thus, wood fibre insulation has an advantage on hemp fibre and sheep wool products in terms of supply chain requirement as well as in terms of supply chain sustainability. However, a rise in the demand for woodchips could lead to an increase in their price. Considering that wood-processing industries have noted a rise in competition for woodchips due to their use as fuel in biomass boilers (John Clegg Consulting, 2010; Europe Economics, 2010), it is possible that this competition will continue to increase in the future and therefore provide an obstacle to a large-scale production of wood fibre insulation in Wales.

7.3.7 Achieveing regional self-reliance in the domestic insulation sector

Inspired by radical approaches to sustainability, this research has investigated the opportunities to reduce the embodied impact of domestic thermal insulation in Wales through regional biomass resources. The research outcomes enabled a more realistic evaluation of the sustainability of biomass insulation products in a regional context, and highlighted the difficulties of pursuing regional self-reliance in a relatively small sector such as domestic insulation.

In current conditions, complete self-reliance in the Welsh domestic insulation sector through biomass products could only be achieved at the cost of significant capital investment necessary to meet supply chain requirements and to lower the market price of these products. Complete self-reliance on biomass products also implies that manufacturers of conventional products currently occupying the market would see their business volume greatly reduced. While a reduction in the use of plastic products is favourable, the research outcomes showed that mineral products have relatively low EEI and high socio-economic impact (although not as high as biomass products). Since local mineral manufacturers already exist in Wales and across the English border and supply large shares of the market (section 2.3.2), mineral products have a clear advantage over biomass products in terms of local supply capacity. It is arguable that an increase in demand for mineral products could be met with a smaller capital investment in comparison to biomass products. If the presence of mineral manufacturers in Wales is weighed against the effort of establishing local biomass manufacturers and the potential consequences of increasing demand for biomass, the environmental (Figure 4.95 and 4.96) and socio-economic benefits (Figure 5. 1, Figure 5. 8 and Figure 5. 10) of mineral products can be considered a 'lower hanging fruit' than what is achievable through biomass products. However, this does not undermine the benefits that are achievable through a wider uptake of biomass products. Overall, a degree of self-reliance in the Welsh domestic insulation sector would be more easily pursued by supporting *both* mineral and biomass products, which would limit the demand for biomass within feasible levels and sustain local manufacturers of mineral products.

7.4 Conclusions

This research has investigated the opportunities to reduce the embodied impact of the future supply of domestic insulation in Wales through substitution with locally-sourced biomass products. The research process was divided into three components, each with its own objective, method and results.

- ~~First research component - The EEI of insulation products used in Welsh dwellings from 2020 to 2050 was assessed using process-based LCA results and modelling a series of alternative supply scenarios against a baseline business-as-usual scenario of the insulation market.~~
- ~~Second research component – The embodied socio-economic impact of insulation products was assessed using product prices and I-O multiplier effects to calculate embodied work and GVA generation.~~
- ~~Third research component – The demand for biomass resources determined by the alternative scenarios was compared to indicators of the potential capacity of the Welsh territory and economy to supply such resources.~~

The main findings are highlighted in section 7.4.1. The value of the research and its potential applications are discussed in section 7.4.2, while further research developments are outlined in section 7.4.3.

7.4.1 Main findings

The demand for insulation generated through the construction of new dwellings in Wales until 2050 is likely to be larger than the demand generated by dwelling retrofits in the same period. This leads to a larger EEI associated with the insulation products supplied to new dwellings. The most impacting conventional products across both retrofits and new constructions are EPS, PUR and stone wool.

The cradle-to-site EEI of the future supply of domestic insulation in Wales can be reduced by progressively increasing the share of biomass products in use, but to a lesser extent if the impact of the end-of-life stage is included. The largest EEI reductions are achieved in GWP and POCP through a combination of hemp fibre and HD wood fibre insulation. Increasing the use of specific mineral products can also decrease EEI, mostly in terms of PEU and POCP. Increasing the use of sheep wool insulation decreases the EEI only if the impact of the farming stage is not taken into account.

In terms of a large uptake, hemp fibre and wood fibre are preferable to sheep wool insulation as they have lower cradle-to-site EEI and are not related to a sector with high environmental impact (such as the sheep meat industry). A significant uptake of both products (i.e. up to 25% of the domestic insulation market) could be sustained using local Welsh resources. Neither hemp fibre nor wood fibre are currently manufactured in Wales, therefore establishing a local supply would require setting up local manufacturing plants. For hemp fibre, ensuring local supply would also require about 1,500 thousand hectares of industrial hemp cultivation - thus excluding at least a share of this land from food production - and the establishment of local depots and fibre processing facilities. A local wood fibre manufacturer would rely on existing Welsh softwood mills for its supply of primary material (softwood chips), which is a by-product of the timber industry. However, access to this resource might become increasingly difficult if its use as biomass fuel continues to increase. Overall, manufacturers of mineral insulation have a significant advantage since they are already established in Wales and supply large shares of the market.

Biomass insulation products, particularly hemp fibre and wood fibre, display environmental and socio-economic benefits in comparison to plastic ones, but these benefits are less marked in comparison to mineral products. The main obstacle to a large uptake of biomass products in Wales is the high price in comparison to most conventional products. Products such as stone wool, glass wool and EPS are markedly less expensive than biomass products, while PUR and phenolic products have similar price ranges but require a thinner layer of material than biomass ones. The high price of biomass products is counterbalanced by high levels of employment and wealth generation across their supply chain, which can be considered as positive socio-economic impact. In terms of end-of-life impact, biomass products are severely penalised by the potential release of the carbon stored in the natural fibres, and therefore the full realisation of their environmental benefits is linked to the viability of disposal practices (such as recycling and landfilling) which minimise the of carbon.

Overall, the research outcomes indicate that the best course of action to reduce the EEI of the future supply of domestic insulation in Wales is to reduce the use of plastic products in favour of products with lower EEI and higher socio-economic impact. These include hemp fibre and wood fibre as well as low-impact glass wool and HD stone wool. A policy instrument capable to recognise and reward the environmental and socio-economic benefits of these products without differentiating between biomass and non-biomass materials would ensure fair conditions for all manufacturers, supporting existing manufacturers of mineral products located in Wales as well as facilitating the establishment of new manufacturers of biomass products. This would result in a progressive reduction of the EEI of the domestic insulation used in Wales while increasing the positive local impact in terms of employment and business development.

7.4.2 Research value and application

The research conducted for this thesis brings several original contributions to the field of built environment sciences. It provides the first example of long-term assessment at the regional scale of the demand and supply of thermal insulation products for domestic buildings, connecting demand from construction activities to total EEI and local supply of resources. In comparison to the work conducted by Duijve (2012) in the Netherlands (reviewed in section 2.3.5), this research enlarged the scope of the assessment and increased its depth by:

- using thermal resistance (m^2K/W) as FU instead of m^3, thus enabling the comparison of products and scenarios on the basis of equal thermal resistance;
- investigating both retrofit and new construction sectors;
- investigating product mix in the insulation market for several specific envelope types;
- modelling progressive product substitution over time;
- assessing EEI changes achievable via progressive substitution of conventional insulation products over time in five impact categories;
- comparing demand and potential supply of biomass with higher detail, by using historical data and projections to estimate regional supply constraints determined by the Welsh territory and economy.

Palumbo et al. (2015) also compared the demand generated by insulation in dwellings and the regional supply of biomass (reviewed in section 2.3.4). In comparison to their study, this research provides a wider and more detailed set of outcomes by:

- including more products in the assessment;
- modelling demand for biomass resources with higher detail;
- assessing EEI and socio-economic impact at product level;
- assessing EEI changes at large scale.

With regards to single-product LCA, this research provides a detailed EEI assessment for hemp fibre and sheep wool products hypothetically manufactured in Wales with locally-sourced biomass. This was achieved by combining and modifying existing sources (van der Werf, 2004; Williams et al., 2006; Norton, 2008; Hutchings et al., 2013; Carus et al., 2013; Barth and Carus, 2015; Welsh Government, 2016) to create detailed models and LCIs of the hypothetical products. Figures to benchmark new LCA results against existing LCA sources were also developed for several products (stone wool, glass wool, PUR, EPS, phenolics, wood fibre). Existing figures were collected from different sources and expressed in the same FU, which can be used as benchmarks in future LCA of insulation.

With regards to the socio-economic assessment, a survey of prices of insulation products in the UK was developed using publicly-available sources of information such as retailers' websites. Since insulation products are generally priced and sold by volume (or number of panels), it is difficult to directly compare product price on the basis of product performance, i.e. thermal resistance. The survey conducted for this research addressed this problem by collecting several prices for each product type and generating minimum, average and maximum values of price per one unit of thermal resistance. Embodied work and GVA associated with insulation products were assessed via I-O LCA technique for the first time. In the context of the existing literature on the insulation products, a more holistic framework for sustainability assessment was adopted by using price and I-O outcomes as indicators of socio-economic impact at the product level in addition to the traditional indicators of environmental impact.

Regional validity of the research outcomes

Although the research was tailored to model demand and supply of insulation products in the Welsh context, several of the research outcomes are also relevant for other regions in the British Isles.

The demand and supply scenarios developed in the first research component are based on features of the Welsh dwelling stock and insulation market, therefore *in absolute figures* the resulting EEI assessment of baseline and alternative supply scenarios are applicable to Wales. However, since changes in EEI achieved by alternative supply scenarios are expressed *as relative figures* (i.e. percentage change from baseline), they can provide an indication of the EEI reduction which could be achieved in geographical areas with similar characteristics (such as dwelling stock and product mix) to Wales, such as England, Scotland, and Ireland, as well as the whole UK.

The socio-economic impact of insulation products developed in the second research component produced figures of product price, embodied work and GVA generation using UK data, therefore these results are fully valid at the UK level.

The comparison between demand and potential supply of biomass developed in the third research component is based on the outcome of the supply scenarios and on Welsh agricultural data, therefore its outcomes are valid strictly for Wales. However, they can provide an indication of the aspects that a similar assessment for another region would need to consider, such as land use, forestry and agricultural activity, presence of processing facilities, etc.

Research applications

This research has developed a combined methodology to assess large-scale EEI changes by using single-product LCA and by modelling demand and supply on the basis of the regional dwelling stock, construction activity and insulation market. This bottom-up type of model enabled disaggregating the results of the assessment into specific categories, such as envelope type, which would not have been possible using a top-down model. This method can be easily replicated in geographical regions such as England, Scotland, and Ireland due to their similarity to Wales in terms of dwelling stock, construction activity and insulation market, as well as to the availability of similar data sources (e.g. the NEED database). The replicability of this method in other countries/regions depends on the available data, especially with regards to the dwelling stock and insulation market. This method could also be adapted to assess other building components beside insulation products. This is discussed further in the next section (7.3.3).

This research presents a long-term forecast of insulation demand in Wales (subdivided by envelope type). Compared to the short-term perspective taken in most market research, this long-term forecast could provide useful information for strategic market planning and investment. The survey of product prices and the investigation of product market share in specific envelope types contain insights into the insulation market which can be of interest to retailers as well as existing and prospective manufacturers. As mentioned, the survey of product prices provides information to compare and benchmark product price on the basis of thermal resistance, while products are generally priced by volume, which does not allow a direct comparison of prices on the basis of equal thermal performance. For manufacturers of biomass products, this research provides a preliminary assessment of resource availability in Wales. In particular, the research outcomes highlight the untapped potential for introducing wood fibre manufacturing in Wales. Wood fibre insulation is a well-established product in many European countries and there are no significant technical obstacles to a large uptake of this product in UK construction (BRE and the University of Bath, 2011a). Welsh softwood is suitable for wood fibre manufacturing (WoodKnowledge Wales, 20) and there is a sufficient output of softwood chips from Welsh mills to sustain significant levels of regional production and uptake in the domestic market (Figure 6. 1).

For public bodies regulating the insulation sector, this research provides holistic evidence of the value of insulation products by bringing together aspects of environmental and socio-economic impact in addition to product price. This information can be used to support policy encouraging product substitution, for example a scheme rewarding the use of products with low EEI and high employment generation. Such a scheme should be based on quantitative indicators from a transparent assessment method (such as the EPD method) to avoid a bias towards conventional or alternative products. The evidence collected in this research can also be used to support supply chain development for manufacturing hemp fibre and wood fibre in Wales, as an opportunity to develop the local economy, since the outcomes of the socio-economic assessment indicate that the high price of biomass products is counterbalanced by high levels of work and GVA generation.

7.4.3 Future work

Several aspects of this research could be developed further as they could not be covered due to the limitations set by time and resource constraints. With regards to the scenarios developed to model demand and supply of insulation in the first research component (sections 4.1 and 4.2):

- The validity of the demand scenarios could be improved by increasing the number of scenarios modelled and variables taken into account, particularly with regards to the forecast of new constructions and retrofits.
- The accuracy of the business-as-usual mix of products used to model the baseline supply scenarios could be improved by gathering more information on specific sub-sectors (e.g. roofs in new dwellings), for example through site visits or by conducting a survey at the UK level.
- The outcomes of the first research component could be enriched by modelling additional alternative scenarios to investigate different options to reduce the total EEI

of the supply of products. These options could include new insulation products (e.g. cellulose, recycled PET) or accurately model substitution between specific products in specific applications.

With regards to the method and data used to assess the environmental and socio-economic impact embodied into insulation products (sections 4.3 and 5.2):

- The accuracy of product EEI figures obtained via aggregated LCI and EPD based outside the UK (stone wool, EPS, PUR, phenolics, wood fibre) could be improved by accessing disaggregated LCI and modelling UK energy mix for electricity.
- The reliability of the EEI assessment could be improved by analysing and quantifying the uncertainties associated with the LCA results using 'Monte Carlo' simulation (Lo et al., 2005) or other suitable methods.
- The end-of-life stage assessment could be improved by adopting the 'avoided burden' approach and producing a series of scenarios to investigate the effect of different mixes of end-of-life options.
- The scope of the environmental impact assessment could be enlarged by assessing impact in a larger number of categories.
- The overall completeness of the environmental impact assessment could be improved by including consequentai aspects, for example following Yang (2016).
- The 'depth' of the environmental impact assessment could be increased by using the Eora dataset to estimate product EEI through I-O LCA (at least for PEU and GWP) and comparing the resulting figures to the results of the process-based LCA. A more radical step to improve the accuracy of the assessment would be to combine process-based and I-O data to perform a hybrid LCA.
- The application of the I-O technique for LCA could be developed further by including other indicators of impact as well as by making full use of the multi-regional Eora model to investigate the embodied impact of insulation products that occurs outside UK boundaries.

With regards to the method used to assess regional supply capacity (section 6.1):

- The assessment of demand and supply capacity at the regional level could be enriched by estimating requirements and availability in terms of *land use* for the three biomass products, thus enabling direct comparison between the demand for resources generated by different products.

- The scope of the assessment could be enlarged to include conventional products by investigating resource demand and availability as well as provenance of primary materials.
- The necessity of ‘subtracting’ resources from other sectors in order to supply primary materials to produce insulation could be investigated in detail. For example, further research could assess whether using land to save energy (and store carbon) by making insulation is more sustainable, and economically viable, than using land to generate energy by producing biomass fuel.

Further possible development of this research includes the application of the methodology to other geographical areas, which would require obtaining appropriate data. The combination of methods used in this research could also be adapted to assess other types of construction products besides thermal insulation. For example, the potential to reduce the EEI of new dwellings by replacing high-impact structural materials such as steel and concrete with functionally-equivalent timber elements could be investigated together with the potential to locally source the required timber. This objective could be achieved with a combination of methods similar to that used for insulation products. The EEI of structural materials could be assessed via process-base and/or I-O LCA. A FU could be established on the basis of structural capacity, namely compression for pillars and flexion for beams. Data on recently-built dwellings could be used to associate building types with typical dimensions and loads for structural components, i.e. pillars and beams. Demand for structural materials could be estimated through a forecast of new construction activities by dwelling type. Using data from existing research on the sector, baseline scenarios could be created to model business-as-usual market conditions where conventional structural materials are used in new dwellings. The potential to reduce EEI could be explored by modelling a progressive uptake of materials such as timber as well as low-carbon concrete and steel (i.e. products with a high share of recycled materials and renewable energy). The research could also compare the demand for natural resources generated by different structural materials used in dwellings and the potential to supply these resources at the regional scale.

7.4.4 Final remarks

Beside the specific objectives, this research aimed to progress the debate on insulation products, and more generally on construction materials, moving away from easy generalisations and claims of sustainability. The outcomes show that assuming positive or negative impact on the basis of a general category - such as ‘natural’, ‘conventional’, or ‘alternative’ - does not reflect the reality of the industrial processes associated with the product, and therefore ideological oppositions between product categories - such as ‘conventional’ versus ‘alternative’ - should be avoided. Products should be evaluated by considering a larger spectrum of environmental impact categories (not only PEU and GWP) in conjunction with socio-economic aspects, resource availability and supply chain requirements. These can reveal differences between products which might appear very similar at a first glance, as in the case of hemp fibre and sheep wool insulation. ‘Natural’ products can have significant environmental impact and the regional capacity to supply a large uptake should not be taken for granted. The potential output of biomass might not be sufficient to ensure complete or partial self-reliance even for a relatively small industry sector such as domestic thermal insulation.

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Appendixes

Appendix I – LCA sources

Information and references of the LCA sources for insulation products cited in chapters 2 and 4 are shown inTable 1. The second column (“LCA source”) reports the name used in the graphs. The last column (‘Reference’) reports the citation as can be found in the bibliography.

In the table there is a distinction between “declared” and “calculation” values for density and thermal resistance of products. This is because some LCA sources:

a) either do not declare these properties;
b) or declare a range of values.

In this case, the ‘calculation’ values:

a) assumed based on typical values for the product;
b) chosen within the given range.

When the original LCA source uses a functional unit based on mass or volume, density values are needed to translate EEI figures into a functional unit based on thermal resistance (1 m^2K/W).

Table 1 – Information on LCA sources (next page)

Product type	LCA source	Declared values		Boundaries	Geographical area	Data sources	Calculation values		PEU	GWP	AP	EP	POCP	Reference
		Density	Thermal resistance				Density	Thermal resistance	MJ	kg CO2 eq	kg SO2 eq	kg (PO4)3- eq	kg ethene eq	
		kg/m3	W/mK				kg/m3	W/mK	/ m2K/W	/ m2K/W	/ m2K/W	/ m2K/W	/ m2K/W	
Mineral wool	Hammond and Jones 2011	various	various	CtG	various	various	25	0.039	16.2	1.2	n/a	n/a	n/a	Hammond and Jones, 2011
	EPD EURIMA 2012	not declared	0.035	CtG	EU	Specific+GaBi	23	0.035	27.2	1.5	8.80E-03	1.08E-03	5.40E-04	Eurima, 2012
	Oekobau.dat 2013	26.3	not declared	CtG	Germany	Specific+GaBi	26.3	0.039	20.8	1.6	7.41E-03	1.02E-03	5.54E-04	Oeokobau, 2013a
Stone wool	EPD Rockwool 2002, cited in Pargana 2012	not available	not available	CtGr	Denmark	Specific+various	45	0.04	27.0	2.2	1.82E-02	n/a	7.63E-03	Pargana, 2012
	Schmidt et al. 2004	32	0.037	CtG	Denmark	various	32	0.037	20.7	1.4	1.23E-02	1.18E-03	4.62E-03	Schmidt et al., 2004
	EPD Alphalene 2005, cited in Pargana 2012	not available	not available	CtGr	France	not specified	45	0.04	47.7	3.2	3.06E-02	n/a	8.71E-04	Pargana, 2012
	Papadopoulos and Giama 2007	not declared	not declared	CtS	USA/Greece	GEMIS	45	0.039	n/a	0.7	n/a	n/a	n/a	Papadopoulos and Giama, 2007
	EPD Confortpan 2008, cited in Pargana 2012	not available	not available	CtGr	Spain	not specified	45	0.04	24.7	3.2	1.78E-01	n/a	1.09E-03	Pargana, 2012
	EPD Ecose 2010, cited in Pargana 2012	not available	not available	CtGr	Belgium/Czech Republic	Specific+GaBi	45	0.04	47.1	2.6	2.70E-02	n/a	1.61E-03	Pargana, 2012
	Hammond and Jones 2011	various	0.034 - 0.037	CtGr	various	various	45	0.039	29.5	2.0	n/a	n/a	n/a	Hammond and Jones, 2011
	Briaban et al. 2011	60	0.04	CtGr	Spain	Ecoinvent	60	0.04	63.3	3.6	n/a	n/a	n/a	Briaban et al., 2011
	EPD Rockwool 2012	41	0.032 - 0.048	CtG	Germany	Specific+GaBi	41	0.039	23.8	1.3	1.07E-02	1.46E-03	6.24E-04	Rockwool, 2012
	Pargana 2012	140	0.044	CtG	Portugal	Specific+Ecoinvent	140	0.044	180.9	19.8	2.77E-02	n/a	1.39E-03	Pargana, 2012
	Oekobau.dat 2013 /1	130	not declared	CtG	Germany	Specific+GaBi	130	0.039	81.6	65.1	3.80E-02	5.58E-03	3.95E-03	Oeokobau, 2013b
	Oekobau.dat 2013 /2	41	not declared	CtG	Germany	Specific+GaBi	41	0.039	23.8	1.3	1.07E-02	1.46E-03	6.24E-04	Oeokobau, 2013c
	Baubook 2015	130	0.04	CtG	Austria	various	130	0.04	111.1	10.0	n/a	n/a	n/a	Baubook, 2015
	EPD Rockwool 2016	28	0.039	CtG	Poland	Specific+Ecoinvent	28	0.039	21.2	1.6	1.10E-02	1.70E-03	n/a	Rockwool, 2016
	GaBi aggregated LCI 2016	45	0.035	CtG	Germany	Specific	45	0.035	23.5	1.7	1.19E-02	1.34E-03	9.52E-04	Thinkstep, 2016
Glass wool	EPD Knauf Ecose 2011	8 - 20	0.04	CtG	Germany	Specific+GaBi	15	0.04	17.5	0.7	9.96E-03	5.22E-04	4.68E-04	Knauf, 2011
	Hammond and Jones 2011	various	various	CtS	various	various	20	0.039	21.8	1.1	n/a	n/a	n/a	Hammond and Jones, 2011
	Oekobau.dat 2013	7 - 100	not declared	CtG	Germany	Specific+GaBi	40	0.039	46.5	2.4	5.54E-03	8.74E-04	5.48E-04	Oeokobau, 2013d
	EPD Glava 2013	16.5	0.037	CtG	Norway	Specific	16.5	0.037	17.7	0.5	2.97E-	8.04E-	1.05E-	Glava, 2013

											03	04	04	
	EPD Ursa 2013	13	0.032 - 0.04	CtG	Slovenia	Specific+GaBi	13	0.039	10.4	0.8	1.44E-02	1.83E-03	4.77E-04	Ursa, 2014
	EPD Isover 2014	16.5	0.037	CtG	Austria	Specific+Ecoinvent	16.5	0.037	23.0	1.2	3.26E-03	1.97E-03	2.83E-03	Isover, 2014
	EPD Izocam 2015	13	0.043	CtG	Turkey	Specific+Ecoinvent	13	0.043	8.5	1.1	6.32E-03	2.12E-03	9.56E-04	Izocam, 2015
	Baubook 2015	68	0.035	CtG	Austria	various	68	0.035	110.1	5.8	n/a	n/a	n/a	Baubook, 2015
	EPD Knauf 2015	12 - 18	0.036 - 0.039	CtG	UK	Specific	15	0.039	15.1	0.7	3.65E-03	6.32E-04	1.36E-03	Knauf, 2015
	GaBi aggregated LCI 2016	n/a (FU=1kg)	not declared	CtG	Germany	Specific	20	0.039	43.1	2.2	1.18E-02	1.77E-03	6.95E-04	Thinkstep, 2016
EPS	EPD Stiropiuma 2010	not declared	0.036	CtG	Italy	Specific	20	0.036	n/a	2.8	1.02E-02	9.71E-04	1.50E-02	Sirap, 2010
	Hammond and Jones, 2011	various	various	CtG	various	various	15	0.036	47.8	1.8	n/a	n/a	n/a	Hammond and Jones, 2011
	Bribian et al. 2011	30	0.037	CtG	Spain	Ecoinvent	30	0.037	117.1	8.1	n/a	n/a	n/a	Briaban et al., 2011
	Pargana 2012	15	0.039	CtG	Portugal	Specific+Ecoinvent	15	0.039	61.8	3.2	8.78E-03	8.89E-04	4.72E-04	Pargana, 2012
	EPD Lape Greypor 2012	15 - 35	0.033	CtG	Italy	Specific	25	0.033	n/a	4.2	1.44E-02	1.32E-03	1.03E-02	Lape, 2012
	EPD Lape Disteso 2012	16	0.032	CtG	Italy	Specific	16	0.032	n/a	2.5	8.40E-03	8.19E-04	4.66E-03	Lape, 2012
	EPD Lape Greycycle 2012	21	0.032	CtG	Italy	Specific	21	0.032	n/a	2.3	8.40E-03	8.74E-04	8.06E-03	Lape, 2012
	EPD Isolconfort Ecoespanso 2014	15.5	0.036	CtG	Italy	Specific	15.5	0.036	31.2	2.3	1.70E-03	9.90E-04	1.60E-02	Isolconfort, 2014
	Oekobau.dat 2015 /1	18.5	0.04	CtG	Germany	Specific+GaBi	18.5	0.04	33.6	2.2	4.88E-03	4.48E-04	1.89E-02	Oeokobau, 2013e
	Oekobau.dat 2015 /2	16.6	0.04	CtG	Germany	Specific+GaBi	16.6	0.04	25.1	1.6	3.61E-03	3.35E-04	1.23E-02	Oeokobau, 2013f
	Baubook 2015	15	0.04	CtG	Austria	various	15	0.04	59.3	2.5	n/a	n/a	n/a	Baubook, 2015
	GaBi aggregated LCI 2016	15	0.037	CtG	EU	Specific	15	0.037	43.1	2.2	1.18E-02	1.77E-03	6.95E-04	Thinkstep, 2016
PUR	Knauf 2005, cited in Pargana 2012	not available	not available	CtGr	France	Generic	32	0.025	80.8	3.2	2.16E-02		1.41E-03	Pargana, 2012
	EPD Stiferite 2007	30	0.024	CtG	Italy	Specific+Boustead data	30	0.024	69.1	2.7	1.87E-02	2.59E-03	1.44E-03	Stiferite, 2007
	IVPU 2008, cited in Pargana 2012	not available	not available	CtGr	Germany	Specific+GaBi	32	0.025	75.1	3.6	1.15E-02	1.17E-03	1.89E-03	Pargana, 2012
	Hammond and Jones, 2011	30	0.028	CtG	various	various	30	0.028	85.3	3.6	n/a	n/a	n/a	Hammond and Jones, 2011
	Bribian et al. 2011	30	0.032	CtG	Spain	Ecoinvent	30	0.032	99.6	6.5	n/a	n/a	n/a	Briaban et al., 2011
	PU Europe 2011, cited in Pargana 2012	not available	not available	CtG	Europe	Specific+GaBi	32	0.025	68.2	3.0	1.08E-02	9.60E-04	1.75E-03	Pargana, 2012
	Pargana 2012	35	0.023	CtG	EU/Portugal	Specific+Ecoinvent	35	0.023	78.9	3.3	1.37E-02	1.32E-03	1.19E-03	Pargana, 2012
	EPD PU Europe 2014	31	0.028	CtG	EU	Specific	31	0.028	102.4	2.7	6.06E-	9.03E-	1.81E-	PU Europe, 2014

											03	04	03	
	Baubook 2015	40	0.03	CtG	Austria	n/a	40	0.03	112.8	5.2	n/a	n/a	n/a	Baubook, 2015
	EPD IVPU 2015	31	0.023	CtG	Gemany	Specific	31	0.023	64.1	2.9	8.43E-03	9.16E-04	1.77E-03	IVPU, 2015
Phenolic	Densley Tingley et al. 2014	40.5	not declared	CtG	UK	Specific+Ecoinvent	40.5	0.021	n/a	6.3	2.76E-02	n/a	3.12E-02	Densley Tingley et al., 2014
	EPD Kingspan 2014	35	0.021	CtG	UK	Specific+GaBi	35	0.021	59.3	2.0	4.80E-03	5.38E-04	1.98E-03	Kingspan, 2014
Hemp fibre	Norton 2008	35	0.039	CtS	UK/France	Specific+Ecoinvent	35	0.039	n/a	0.4	1.02E-02	1.80E-03	3.71E-04	Norton, 2008
	Biocompass 2009	35	0.039	CtG	UK/France	Specific+unknown database	35	0.039	63.6	2.3	n/a	n/a	n/a	Biocompass, 2009a
	Zampori et al. 2013	30	0.044	CtG	Italy	Specific+Ecoinvent	30	0.044	27.2	-0.9	n/a	n/a	n/a	Zampori et al., 2013
	Oekobau.dat 2013	38	not declared	CtG	Germany	GaBi	38	0.042	65.5	1.7	8.09E-03	1.23E-03	1.50E-03	Oeokobau, 2013g
	GaBi EU27 Hemp fibre 2015	38	not declared	CtG	EU	Specific	38	0.039	71.9	0.2	4.89E-03	2.01E-03	6.37E-04	Thinkstep, 2016
Sheep wool	Norton 2008	25	0.039	CtS	UK	Specific+Ecoinvent	25	0.039	n/a	-0.4	7.61E-03	1.13E-03	2.89E-04	Norton, 2008
	Biocompass 2009	25	not declared	CtG	UK	Specific+unknown database	25	0.039	44.8	0.7	n/a	n/a	n/a	Biocompass, 2009b
	CAP'EM 2012	25	0.035	CtG	Belgium	Specific+Ecoinvent	25	0.035	36.8	1.5	n/a	n/a	n/a	CAP'EM, 2012
	Baubook 2015	30	0.04	CtG	Austria	various	30	0.04	23.7	0.6	n/a	n/a	n/a	Baubook, 2015
LD wood fibre	EPD Pavaflex 2012	55	0.039	CtG	Germany	Specific+GaBi	55	0.039	74.1	-0.6	6.05E-03	6.67E-04	5.54E-04	Pavatex, 2012
	EPD Pavaflex 2014	55	0.038	CtG	Germany	Specific+GaBi	55	0.038	61.2	0.1	9.88E-03	8.97E-04	8.36E-04	Pavatex, 2014a
	EPD Steico 2016	50 - 265	0.038	CtG	France	Specific+GaBi	50	0.038	73.4	-2.3	4.06E-03	9.27E-04	8.98E-04	Steico, 2016
HD wood fibre	EPD Pavatex wet 2014	200 - 240	0.047	CtG	Switzerland	Specific+Ecoinvent	240	0.047	97.3	-6.3	7.03E-03	1.25E-03	6.08E-04	Pavatex, 2014b
	EPD Pavatex dry 2014	110 - 210	0.044	CtG	France	Specific	210	0.044	122.2	-6.3	1.11E-02	1.87E-03	4.28E-04	Pavatex, 2014c
	EPD Gutex 2015	80 - 250	0.037 - 0.05	CtG	Germany	Specific+GaBi	250	0.045	104.8	-6.4	8.71E-03	1.48E-03	6.54E-04	Gutex, 2015
	EPD Steico 2016	50 - 265	0.038	CtG	France	Specific+GaBi	265	0.038	224.9	-7.0	1.24E-02	2.84E-03	2.75E-03	Steico, 2016

Appendix II – Analysis of envelope construction

Table 2 shows the information about envelope construction reported in CSH case studies (DCLG 2009, 2010a, 2010b, 2013). Knowing the total envelope U-value and the material and thickness of the insulation layer were reported for most cases. Knowing this information, it is possible to estimate the R-value of the insulation layer and calculate its share in comparison to the total R-value of the envelope. This process is shown in Table 3, Table 4 and Table 5. The thermal conductivity of the insulation layers was assumed on the basis of the typical values shown in Table 2.2 (chapter 2).

Table 2 – Information on envelope construction given in CSH case studies (sources: DCLG 2009, 2010a, 2010b, 2013)

Case study	Code level	Information on external wall	Information on roof	Information on ground floor
1	5	The development was constructed with a thermally efficient timber cassette shell that was considered replicable for future projects. U-value of 0.14W/m2K	Engineered 'I' beams were used, filled with recycled newspaper insulation with 100mm woodfibre with OSB top and bottom and an internal vapour control layer to the underside of the OSB. U-value of 0.12W/m2K	The ground floor was constructed from concrete planks with 150mm foam insulation under a 50mm screed with 50mm edge upstands. U-value of 0.15W/m2K
2	5	Solid cross laminated timber panels with 290mm mineral fibre bat external insulation. U-value of 0.10W/m2K	Aluminium sheet, upstand seam, curved profile with 200mm mineral wool plus 100mm foam sheet insulation. U-value of 0.10 W/m2K	50% 99BS concrete slab with 165mm foamed sheet insulation and FSC raised timber floor. U-value 0.10 w/m2k
3	3	Timber frame with cement particle board sheathing and phenolic foam insulation – U-value of 0.29W/m2K	Timber frame with timber strand board and cut block foam insulation with a U-value of 0.20W/m2K	Proprietary concrete beam construction with polystyrene infill and concrete screed. The U-value for the floor is 0.21W/m2K
4	5	Structural Insulated Panel System (SIPS) with 50mm of external insulation – U-value of 0.14W/m2K	Timber frame with concrete tiles and 400mm mineral wool insulation – U-value of 0.13W/m2K	Beam-and-block with an additional 75mm insulation – U-value 0.14W/m2K
5	3	300mm cavity wall consisting of an external brickwork skin, 100m cavity fully filled with 100mm mineral wool insulation and an internal skin of 100mm ultra lightweight aggregate blocks, finished using standard plasterboard on dabs. U-value of 0.28W/m2k	Pitched timber truss, concrete interlocking tiles, 400mm mineral wool insulation laid in two layers with the first of 200mm laid between ceiling joists with second layer of 200mm laid at 90 degrees to first over ceiling joists. U-value of 0.17W/m2K	100mm concrete slab over a layer of 120mm urethane insulation. U-value of 0.15W/m2K
6	3	300mm cavity wall consisting of an external brickwork skin, 100m cavity fully filled with 100mm mineral wool insulation and an internal skin of 100mm ultra lightweight aggregate blocks, finished using standard plasterboard on dabs. U-value of 0.23W/m2K.	Pitched timber truss, concrete interlocking tiles, 450mm fibreglass insulation laid in layers with the first of 100mm laid between bottom trusses with the remaining 350mm cross layered. U-value of 0.09W/m2K	100mm concrete slab over a layer of 130mm urethane insulation. U-value of 0.13W/m2K
7	3	300mm cavity wall consisting of an external brickwork skin, 100m cavity fully filled with 100mm mineral wool insulation, an internal skin of 100mm lignacite blockwork. The external walls are finished using internal thermal enhancement comprising of thermal laminate plasterboard comprising of 35.5mm extruded polystyrene insulation bonded to 9.5mm wall board. U-value of 0.23W/m2K	Flat roof constructed using timber joist, plywood decking and a PVC single ply roof membrane. The Code Level 3 houses have 300mm mineral wool insulation laid in two layers with the first of 100mm insulation laid between ceiling ties to trusses with second layer of 200mm insulation laid at 90 degrees. U-value of 0.13W/m2K. The flats were provided with a standard 90mm rigid urethane board laid directly on the roof decking. U-value of 0.13W/m2K	Code Level 3 Houses – 65mm screed with 85mm urethane insulation. U-value of 0.15W/m2K. Flats – 65mm screed with 50mm urethane insulation. U-value of 0.2W/m2K.
8a	3	Code Level 3: 300mm cavity wall consisting of a thin joint external brickwork skin, 90mm cavity fully filled with 90mm mineral wool insulation and an internal skin of 100mm aircrete panels. U-value of 0.29W/m2K.	Code Level 3: Timber joists, 160mm rigid urethane insulation with low emissivity foil laid in two layers. U-value of 0.18W/m2K.	Code Level 3: Beam and block pre-cast floor system, 100mm thick polystyrene insulating board. U-value of 0.22W/m2K.
8b	6	Code Level 6: 200mm storey height aircrete panels and 200mm of external wall insulation. U-value of 0.09W/m2K	Code Level 6: Timber joists, 280mm rigid urethane insulation with low emissivity foil laid in three layers, 52.5mm insulating plasterboard layer. U-value of 0.12W/m2K.	Code Level 6: 300mm thick aircrete pre-cast flooring system with 110mm thick urethane insulation. U-value of 0.11W/m2K
9	6	The development was constructed using a glulam timber frame shell with 300mm of mineral wool insulation, eco-concrete panels and a breather membrane. U-value of 0.15W/m2K	Glulam timber frame in-filled with 250mm mineral wool insulation. This was covered with a breather membrane and a further layer of 50mm mineral wool insulation. U-value of 0.10W/m2K	Glulam timber joists in-filled with 300mm mineral wool insulation. This was covered with waxed slabs laid on an acoustic mat and plywood. U-value of 0.12W/m2K.
10	3	293 mm cavity wall consisting of an external brickwork skin, 90 mm cavity fully filled with blown bead insulation and an internal skin of 100 mm aggregate blocks, finished using standard plasterboard on dabs. U-value of 0.35 W/m2 K.	Pitched timber truss, concrete interlocking tiles, 300 mm quilt insulation laid in two layers with the first of 150 mm laid between ceiling joists with second layer of 150 mm laid at 90 degrees to cover ceiling joists. U-value of 0.16 W/m2 K.	200 mm concrete slab with a 65 mm floating screed over an acoustic layer. U-value of 0.25 W/m2 K
11	3	300 mm cavity wall consisting of an outer brickwork skin, 100 mm cavity filled with 50 mm celotex insulation and an internal skin of 100 mm blocks, finished using standard plasterboard on dabs. U-value of 0.32 W/m2 K. External fabric of flats upgraded to achieve a U-value of 0.16 W/m2 K through the use of a 100 mm insulated cavity	Plasterboard to underside of trusses with 150 mm thick mineral wool insulation between joists and an additional layer of 150 mm thick mineral wool cross-laid over joists. U-value of 0.14 W/m2 K. Roof of flats upgraded to achieve a U-value of 0.08 W/m2 K through the use of an additional 200 mm of insulation. Mixture of solar PV and concrete tiles	Suspended beam and block ground floor with 75 mm celotex insulation and 75 mm screed. Average gross internal floor area of 35.9 square metres. U-value of 0.21 W/m2 K. Floor of flats upgraded to achieve a U-value of 0.13 W/m2 K through the use of 130 mm of celotex insulation

12	3	rickwork outer leaf (103 mm), injected insulation (90 mm) and high density blocks (100 mm) finished with 12.5 mm plasterboard on 10 mm adhesive. U-value 0.30 W/m2K.	Minimum 400 mm thick glass fibre insulation in one 100 mm layer between rafters and one 300 mm layer, cross laid in opposite directions to achieve U-value of 0.11 W/m2K. Roof insulation lapped with wall insulation to limit air leakage. Sloping ceilings received 100 mm insulation between rafters, maintaining a minimum 50 mm air gap between insulation and underside of roofing felt. Insulation on the underside of rafters which consists of a composite board of 55.5 mm CFC-free foam insulation and 9.5 mm plasterboard with integral vapour check to achieve U-value of 0.20 W/m2K	Concrete beams with polystyrene block infill insulation covered with a concrete screed. U-value of 0.25 W/m2K
13	3	50 mm rigid polyurethane (PUR) foam board insulation. U-value of 0.23 W/m2 K for walls, 0.29 W/m2 K for a brickwall with a column and 0.27 W/m2 K for the rainwater cladding.	In situ and pre-cast concrete insulated with 150–180 mm extruded polystyrene (XPS) inverted roof board insulation. U-value of 0.16 W/m2 K. Terraced roofs achieve a U-value of 0.2 W/m2 K.	Concrete floor with 130 mm rigid insulation. U-value 0.25 W/m2 K
14	4	Render or weatherboard on 100mm concrete blockwork, lined with heat reflective membrane, 60mm internal cavity, 140mm timber frame, with insulation between timber studs, 50mm polyisocyanurate (PIR) insulation, then two layers of battens (at right angles to each other to reduce thermal bridging), then internal plasterboard	Timber deck, warm roof construction, with waterproof membrane and extensive sedum planting on top	63mm reinforced screed on 160mm thick insulation; on radon barrier; on 150mm concrete joists (suspended) with 150mm concrete block infil
15	4	200mm lightweight aerated concrete blocks, finished with polystyrene insulation batts and external render	Plain clay tiles	Beam and block floor with expanded polystyrene infill blocks
16	4	Lightweight aerated concrete blocks with thin joint mortar and 125mm of mineral wool insulation	Pitched concrete tile with 350mm glass wool insulation	Suspended concrete beam and block formation with insulated screed topping (chosen because there was a need for a ventilated sub-floor, following site remediation)
17	4	100mm lightweight aerated blocks	Concrete tiles	inverted concrete beams, infilled with expanded polystyrene blocks
18	4	100mm lightweight aerated concrete blocks, 100mm PIR insulation, 50mm clear cavity and 102.5mm facing brickwork	Concrete tiles	Standard beam and block with 150mm PIR insulation
19	4	190 mm lightweight aerated concrete blocks, 285mm external EPS insulation panels, external 8mm modified silicone resin render	Plain grey concrete tiles; timber trusses; 500mm glass fibre insulation to loft spaces	Ground floor slabs - 300mm reinforced concrete raft, on 50mm concrete blinding, on eco-membrane, on 400mm Styrofoam structural insulation, on 25mm 'fines' blinding, on compacted type 1 sub-base Ground floors - 65mm thick sand & cement screed, with fabric reinforcement, on 30mm thick expanded polystyrene insulation
20	4	Timber frame structure. Either Bath stone or render (on battened carrier board system). Both with structural insulated panels and two layers 15mm plasterboard. Properties are finished in Bath stone, which is sourced from a quarry less than two miles from the site	Timber framed, with biodiverse brown roofs incorporated on some blocks	200mm reinforced concrete raft slab with 60mm PIR insulation and 22mm chipboard flooring on timber battens
21	4	140mm timber frame structure insulated with 120mm polyisocyanurate (PIU) insulation, 50mm clear cavity plus external cladding, brick or render	Part sedum blanket, part concrete tiles	Screed on insulation laid on grouted beam and medium dense solid block flooring

Table 3 - Analysis of external wall construction

Case study	Wall U-value*	R-value	Net R-value	Insulation thickness*	Thermal conductivity	Insulation R-value	Share of insulation R-value in comparison to Net R-
	W/m²K	m²K/W	m²K/W	m	W/mK	m²K/W	%
1	0.14	7.14	6.99	n/a			
2	0.10	10.00	9.85	**0.29**	**0.036**	8.056	82
3	0.29	3.45	3.30	n/a			
4	0.14	7.14	6.99	n/a			
5	0.28	3.57	3.42	**0.1**	**0.038**	2.632	77
6	0.23	4.35	4.20	**0.1**	**0.038**	2.632	63
7	0.23	4.35	4.20	**0.1**	**0.038**	2.632	63
8a	0.29	3.45	3.30	**0.09**	**0.038**	2.368	72
8b	0.09	11.11	10.96	n/a			
9	0.15	6.67	6.52	**0.3**	**0.038**	7.895	121
10	0.35	2.86	2.71	**0.09**	**0.038**	2.368	87
11	0.32	3.13	2.98	**0.05**	**0.022**	2.273	76
12	0.30	3.33	3.18	**0.09**	**0.028**	3.214	101
13	0.23	4.35	4.20	**0.05**	**0.028**	1.7857	43
14	0.15	6.67	6.52	n/a			
15	0.18	5.56	5.41	n/a			
16	0.20	5.00	4.85	**0.125**	**0.038**	3.289	68
17	0.17	5.88	5.73	n/a			
18	0.18	5.56	5.41	**0.1**	**0.03**	3.333	62
19	0.09	11.11	10.96	**0.285**	**0.028**	10.179	93
20	0.25	4.00	3.85	n/a			
21	0.18	5.56	5.41	**0.12**	**0.03**	4.000	74

Table 4 - Analysis of roof construction

Case study	Roof U-value	R-value	Net R-value	Insulation thickness	Thermal conductivity	Insulation R-value	Insulation R-value in comparison
	W/m²K	m²K/W	m²K/W	m	W/mK	m²K/W	%
1	0.12	8.33	8.18	**0.3**	**0.048**	5.625	69
2	0.1	10.00	9.85	**0.3**	**0.035**	7.714	78
3	0.2	5.00	4.85	n/a			
4	0.13	7.69	7.54	**0.4**	**0.038**	9.474	126
5	0.17	5.88	5.73	**0.4**	**0.038**	9.474	165
6	0.09	11.11	10.96	**0.45**	**0.038**	10.658	97
7	0.13	7.69	7.54	**0.3**	**0.038**	7.105	94
8a	0.18	5.56	5.41	**0.16**	**0.028**	5.143	95
8b	0.12	8.33	8.18	**0.28**	**0.028**	9.000	110
9	0.1	10.00	9.85	**0.25**	**0.038**	5.921	60
10	0.16	6.25	6.10	**0.3**	**0.04**	6.750	111
11	0.14	7.14	6.99	**0.15**	**0.038**	3.553	51
12	0.11	9.09	8.94	**0.4**	**0.038**	9.474	106
13	0.2	5.00	4.85	**0.15**	**0.028**	4.821	99
14	0.15	6.67	6.52	n/a			
15	0.14	7.14	6.99	n/a			
16	0.11	9.09	8.94	**0.35**	**0.038**	8.289	93
17	0.1	10.00	9.85	n/a			
18	0.1	10.00	9.85	n/a			
19	0.08	12.50	12.35	**0.5**	**0.038**	11.842	96

Table 5 – Analysis of ground floor construction

Case study	*Ground floor U-value*	*R-value*	*Net R-value*	*Insulation thickness*	*Thermal conductivity*	*Insulation R-value*	*Share of insulation R-value in comparison to Net R-value*
	W/m²K	*m²K/W*	*m²K/W*	*m*	*W/mK*	*m²K/W*	*%*
1	0.15	6.67	6.43	**0.15**	**0.035**	3.857	60
2	0.10	10.00	9.76	**0.165**	**0.035**	4.243	43
3	0.21	4.76	4.52	n/a			
4	0.14	7.14	6.90	n/a			
5	0.15	6.67	6.43	**0.125**	**0.035**	3.214	50
6	0.13	7.69	7.45	**0.13**	**0.035**	3.343	45
7	0.15	6.67	6.43	**0.085**	**0.035**	2.186	34
8a	0.22	4.55	4.31	**0.1**	**0.033**	2.727	63
8b	0.11	9.09	8.85	**0.11**	**0.035**	2.829	32
9	0.12	8.33	8.09	**0.3**	**0.038**	7.105	88
10	0.25	4.00	3.76				
11	0.21	4.76	4.52	**0.075**	**0.022**	3.068	68
12	0.25	4.00	3.76	n/a			
13	0.25	4.00	3.76	**0.13**			
14	0.15	6.67	6.43	n/a			
15	0.14	7.14	6.90	n/a			
16	0.12	8.33	8.09	n/a			
17	0.14	7.14	6.90	n/a			
18	0.15	6.67	6.43	**0.15**	**0.03**	4.500	70
19	0.07	14.29	14.05	**0.4**	**0.033**	10.909	78

Appendix III – Insulation products price survey

The information collected by surveying product prices in 2015 and 2017 is shown in Table 6 and Table 7 respectively. All data was collected from the retailers' and manufacturers' websites, except for 'Price per cubic meter' and 'Price per Functional Unit' (FU). These are calculated from the collected data. Products are sold in units of panels or rolls, thus by knowing size and thermal conductivity, price per cubic meter can be calculated and successively price per FU.

Table 6 – Survey of product prices in 2015

Insulation product	Firm	Product type	Envelope application			Compressive strength at 10%	Quantity sold	Price	Price per cubic meter*	Thermal conductivity	Price per FU*	Weblink
			Wall	Roof	Floor	kPa	m^3	£	£ / m^3	W/mK	£ / m^2K/W	
EPS100 100 mm	Jablite	EPS	1	1	1	100	0.1	9.25	92.50	0.036	3.33	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
EPS100 50 mm	Jablite	EPS	1	1	1	100	0.05	4.51	90.20	0.036	3.25	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
EPS70 100 mm	Jablite	EPS	1	1	1	70	0.864	56.09	64.92	0.038	2.47	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
EPS70 25 mm	Jablite	EPS	1	1	1	70	0.864	56.83	65.78	0.038	2.50	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
EPS70 100 mm	Kay-Metzeler	EPS	1	1	1	70	0.1	4.33	43.30	0.038	1.65	http://www.just-insulation.com/001-eshop/buy-eps70-kay-metzeler-expanded-eps-polystyrene-insulation-boards.html
EPS70 100 mm	Kay-Metzeler	EPS	1	1	1	70	0.864	56.09	64.92	0.037	2.40	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
EPS70 25 mm	Kay-Metzeler	EPS	1	1	1	70	0.025	1.09	43.60	0.038	1.66	http://www.just-insulation.com/001-eshop/buy-eps70-kay-metzeler-expanded-eps-polystyrene-insulation-boards.html
EPS70 25 mm	Kay-Metzeler	EPS	1	1	1	70	0.864	56.83	65.78	0.037	2.43	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
Yelofoam X2i Cellecta 25 mm	Cellecta	EPS	1	1	1		0.025	11.15	446.00	0.029	12.93	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
Yelofoam X2i Cellecta 75 mm	Cellecta	EPS	1	1	1		0.075	21.71	289.47	0.029	8.39	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
Earthwool flexible 200 mm	Knauf	stonewool	1	1			0.288	21.01	72.95	0.036	2.63	http://www.lbsbmonline.co.uk/Knauf-200mm-Earthwool-Loft-Insulation-593m2-Price-Per-M2-IL0002704.asp
Earthwool flexible 140 mm	Knauf	stonewool	1	1			0.3024	14.75	48.78	0.037	1.80	http://www.insulation-online.com/rocksilk-rs45-rs60-rs100-slabs.html
Earthwool flexible 50 mm	Knauf	stonewool	1	1			0.432	22.03	51.00	0.037	1.89	http://www.insulation-online.com/rocksilk-rs45-rs60-rs100-slabs.html
Earthwool flexible 50 mm	Knauf	stonewool	1	1			0.432	21.28	49.26	0.037	1.82	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Earthwool loft 100 mm	Knauf	glasswool		1			1	12.3	12.30	0.044	0.54	http://www.lbsbmonline.co.uk/Knauf-100mm-Earthwool-Loft-Roll-44-Combi-Cut-IL0002501.asp
Earthwool loft 200 mm	Knauf	glasswool		1			0.2	2.48	12.40	0.044	0.55	http://www.lbsbmonline.co.uk/Knauf-200mm-Earthwool-Loft-Insulation-593m2-Price-Per-M2-IL0002704.asp
Earthwool loft 40 100 mm	Knauf	glasswool		1			1.2825	32.83	25.60	0.044	1.13	http://www.just-insulation.com/001-eshop/buy-knauf-loft-rolls-rafter-rolls-apr-acoustic-glass-mineral-wool.html
Earthwool loft 40 100 mm	Knauf	stonewool		1			1.398	22.62	16.18	0.035	0.57	http://www.planetinsulation.co.uk/store/index.php#Mineral_Wool
Earthwool loft	Knauf	stonewool		1			1.389	17.25	12.42	0.035	0.43	http://www.insulationgiant.co.uk/Products/Insulation/Loft-Insulation/c/1200034

40 100 mm												
Earthwool loft 40 200 mm	Knauf	stonewool		1			1.186	19.27	16.25	0.035	0.57	http://www.planetinsulation.co.uk/store/index.php#Mineral_Wool__
Earthwool loft 40 200 mm	Knauf	stonewool		1			1.186	15	12.65	0.035	0.44	http://www.insulationgiant.co.uk/Products/Insulation/Loft-Insulation/c/1200035
Earthwool loft 44 200 mm	Knauf	glasswool		1			1.186	24.73	20.85	0.044	0.92	http://www.just-insulation.com/001-eshop/buy-knauf-loft-rolls-rafter-rolls-apr-acoustic-glass-mineral-wool.html
Earthwool RS45 25 mm	Knauf	stonewool	1	1			0.36	26.86	74.61	0.035	2.61	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Eartwool RS60 100 mm	Knauf	stonewool	1	1			0.216	24.25	112.27	0.035	3.93	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Eartwool RS60 50 mm	Knauf	stonewool	1	1			0.324	24.25	74.85	0.035	2.62	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Earthwool RS100 50 mm	Knauf	stonewool	1	1	1		0.216	27.48	127.22	0.035	4.45	http://www.insulationexpress.co.uk/Product.asp?gclid=CKeYyKrhssYCFSLnwgodqmwIaw
Spacesaver roll 100 mm	Isover	glasswool		1			1.064	23.79	22.36	0.044	0.98	http://www.insulation-online.com/isover-spacesaver-loft-roll.html
Spacesaver roll 100 mm	Isover	glasswool		1			1.064	16.04	15.08	0.044	0.66	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Spacesaver roll 100 mm	Isover	glasswool		1			1.064	12.75	11.98	0.044	0.53	http://www.insulationgiant.co.uk/Products/Insulation/Loft-Insulation/c/1200032
Spacesaver roll 200 mm	Isover	glasswool		1			0.9	20.47	22.74	0.044	1.00	http://www.insulation-online.com/isover-spacesaver-loft-roll.html
Spacesaver roll 200 mm	Isover	glasswool		1			0.904	15.83	17.51	0.044	0.77	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Spacesaver roll 200 mm	Isover	glasswool		1			0.9	11.25	12.50	0.044	0.55	http://www.insulationgiant.co.uk/Products/Insulation/Loft-Insulation/c/1200033
Ursa 10 loft roll 100 mm	Ursa	glasswool		1			0.1	1.65	16.50	0.044	0.73	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
NatuHemp batts 100 mm	Black Mountain	hemp fibre	1	1			0.1	11.29	112.90	0.039	4.40	http://www.just-insulation.com/001-eshop/buy-natuwool-black-mountain-sheeps-wool.html
NatuHemp batts 150 mm	Black Mountain	hemp fibre	1	1			0.15	16.93	112.87	0.039	4.40	http://www.just-insulation.com/001-eshop/buy-natuwool-black-mountain-sheeps-wool.html
NatraHemp 100 mm	Thermafleece	hemp fibre	1	1			1.066	109.8	103.00	0.04	4.12	https://www.lime.org.uk/products/insulation/thermafleece-natrahemp-insulation/
NatraHemp 50 mm	Thermafleece	hemp fibre	1	1			1.066	120	112.57	0.04	4.50	http://www.celticsustainables.co.uk/thermafleece-natrahemp-thermal-acoustic-insulation/
NatraHemp 100 mm	Thermafleece	hemp fibre	1	1			1.094	107.05	97.85	0.04	3.91	http://ecomerchant.co.uk/walls/insulation/hemp-insulation/thermafleece-natrahemp-natural-insulation-batts.html
NatraHemp 100 mm	Thermafleece	hemp fibre	1	1			1.094	95.12	86.95	0.04	3.48	http://www.naturalinsulations.co.uk/index.php?location=ThermafleeceHemp
NatraHemp 50 mm	Thermafleece	hemp fibre	1	1			1.0655	104.26	97.85	0.04	3.91	http://ecomerchant.co.uk/walls/insulation/hemp-insulation/thermafleece-natrahemp-natural-insulation-batts.html
NatraHemp 50 mm	Thermafleece	hemp fibre	1	1			1.0655	92.8	87.10	0.04	3.48	http://www.naturalinsulations.co.uk/index.php?location=ThermafleeceHemp
K12 40 mm	Kingspan	Phenolic					0.1152	32.07	278.39	0.021	5.85	http://www.planetinsulation.co.uk/store/index.php#Kingspan_K3_Boards
K3 25 mm	Kingspan	Phenolic	1	1	1	120	0.072	19.36	268.89	0.022	5.92	http://www.planetinsulation.co.uk/store/index.php#Kingspan_K3_Boards
K7 140 mm	Kingspan	Phenolic	1	1			0.4032	77.34	191.82	0.021	4.03	http://www.planetinsulation.co.uk/store/index.php#Kingspan_K3_Boards
K7 40 mm	Kingspan	Phenolic	1	1			0.1152	25.29	219.53	0.021	4.61	http://www.planetinsulation.co.uk/store/index.php#Kingspan_K3_Boards
K3 Flooboard 25 mm	Kingspan	Phenolic	1	1	1	120	0.864	254.92	295.05	0.022	6.49	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/phenolic_rigid_insulation_boards.html
K3 Wallboard 20 mm	Kingspan	Phenolic	1	1			0.36	113.38	314.94	0.022	6.93	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/phenolic_rigid_insulation_boards.html
K7 Roofboard 25 mm	Kingspan	Phenolic	1	1			0.025	6.6	264.00	0.023	6.07	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/phenolic_rigid_insulation_boards.html

GA 4050 50 mm	Celotex	PUR	1	1	1		0.144	15.12	105.00	0.022	2.31	http://www.planetinsulation.co.uk/ZGA3012.php
GA 4090 90 mm	Celotex	PUR	1	1	1		0.2592	28.32	109.26	0.022	2.40	http://www.insulationgiant.co.uk/Products/Insulation/Internal-Wall-Insulation/c/1200049
GA 4100 100 mm	Celotex	PUR	1	1	1		0.288	28.3	98.26	0.022	2.16	http://www.insulationgiant.co.uk/Products/Insulation/Internal-Wall-Insulation/c/1200046
GA4050 50 mm	Celotex	PUR	1	1	1		0.05	5.59	111.80	0.022	2.46	http://www.just-insulation.com/001-eshop/buy-celotex-multi-purpose-rigid-pir-insulation-boards.html#tb4k
GA4050 50 mm	Celotex	PUR	1	1	1		0.144	18.5	128.47	0.022	2.83	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
GA4100 100 mm	Celotex	PUR	1	1	1		0.1	10.66	106.60	0.022	2.35	http://www.just-insulation.com/001-eshop/buy-celotex-multi-purpose-rigid-pir-insulation-boards.html#tb4k
GA4100 100 mm	Celotex	PUR	1	1	1		0.288	32.4	112.50	0.022	2.48	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
TB 4020 20 mm	Celotex	PUR	1	1	1		0.0576	8.85	153.65	0.022	3.38	http://www.planetinsulation.co.uk/ZGA3012.php
TB 4025 25 mm	Celotex	PUR	1	1	1		0.072	10.2	141.67	0.022	3.12	http://www.insulationgiant.co.uk/Products/Insulation/Internal-Wall-Insulation/c/1200048
TB4012 12 mm	Celotex	PUR	1	1	1		0.012	2.85	237.50	0.022	5.23	http://www.just-insulation.com/001-eshop/buy-celotex-multi-purpose-rigid-pir-insulation-boards.html#tb4k
TB4012 12 mm	Celotex	PUR	1	1	1		0.012	3.92	326.67	0.022	7.19	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
TB4012 12 mm	Celotex	PUR	1	1	1		0.03456	9.33	269.97	0.022	5.94	http://www.insulationexpress.co.uk/Insulation-Boards/Celotex-TB4000-Insulation-Board.htm
TB4040 40 mm	Celotex	PUR	1	1	1		0.04	4.59	114.75	0.022	2.52	http://www.just-insulation.com/001-eshop/buy-celotex-multi-purpose-rigid-pir-insulation-boards.html#tb4k
TB4040 40 mm	Celotex	PUR	1	1	1		0.1152	15.58	135.24	0.022	2.98	http://www.insulationexpress.co.uk/Insulation-Boards/Celotex-TB4000-Insulation-Board.htm
TB4045 45 mm	Celotex	PUR	1	1	1		0.045	6.71	149.11	0.022	3.28	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
XR4110 110 mm	Celotex	PUR	1	1	1		0.3168	33.41	105.46	0.022	2.32	http://www.insulation-online.com/celotex-xr4000-xtra-r-extra-previously-xr3000.html
XR4110 110 mm	Celotex	PUR	1	1	1		0.3168	34.53	109.00	0.022	2.40	http://www.just-insulation.com/001-eshop/buy-celotex-multi-purpose-rigid-pir-insulation-boards.html#tb4k
XR4110 110 mm	Celotex	PUR	1	1	1		0.3168	42.11	132.92	0.022	2.92	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
XR4110 110 mm	Celotex	PUR	1	1	1		0.3168	36.53	115.31	0.022	2.54	http://www.insulationexpress.co.uk/Solid-Wall-Insulation/Celotex-XR4000-Insulation-Board.htm
XR4165 165 mm	Celotex	PUR	1	1	1		0.4752	49.7	104.59	0.022	2.30	http://www.planetinsulation.co.uk/ZGA3012.php
XR4165 165 mm	Celotex	PUR	1	1	1		0.4752	49.8	104.80	0.022	2.31	http://www.insulationgiant.co.uk/Products/Insulation/Internal-Wall-Insulation/c/1200047
XR4200 200 mm	Celotex	PUR	1	1	1		3.456	371.95	107.62	0.022	2.37	http://www.insulation-online.com/celotex-xr4000-xtra-r-extra-previously-xr3000.html
XR4200 200 mm	Celotex	PUR	1	1	1		0.2	23.31	116.55	0.022	2.56	http://www.just-insulation.com/001-eshop/buy-celotex-multi-purpose-rigid-pir-insulation-boards.html#tb4k
XR4200 200 mm	Celotex	PUR	1	1	1		3.456	446.41	129.17	0.022	2.84	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
XR4200 200 mm	Celotex	PUR	1	1	1		0.576	71.49	124.11	0.022	2.73	http://www.insulationexpress.co.uk/Solid-Wall-Insulation/Celotex-XR4000-Insulation-Board.htm
TF70 150 mm	Kingspan	PUR	1	1	1	140	0.432	57.98	134.21	0.023	3.09	http://www.just-insulation.com/001-eshop/buy-kingspan-thermapitch-thermawall-thermafloor-insulation-boards.html#tp10
TF70 20 mm	Kingspan	PUR	1	1	1	140	0.0576	11.26	195.49	0.023	4.50	http://www.just-insulation.com/001-eshop/buy-kingspan-thermapitch-thermawall-thermafloor-insulation-boards.html#tp10
TP10 150 mm	Kingspan	PUR	1	1			0.864	115.96	134.21	0.023	3.09	http://www.insulation-online.com/kingspan-thermapitch-tp10.html
TP10 150 mm	Kingspan	PUR	1	1			0.432	57.98	134.21	0.023	3.09	http://www.just-insulation.com/001-eshop/buy-kingspan-thermapitch-thermawall-thermafloor-insulation-boards.html#tp10
TP10 150 mm	Kingspan	PUR	1	1			0.432	50.65	117.25	0.022	2.58	http://www.planetinsulation.co.uk/ZKSK1820.php
TP10 150 mm	Kingspan	PUR	1	1			0.432	52.1	120.60	0.022	2.65	http://www.insulationexpress.co.uk/Insulation-Boards/Celotex-TB4000-Insulation-Board.htm
TP10 20 mm	Kingspan	PUR	1	1			0.864	168.9	195.49	0.023	4.50	http://www.insulation-online.com/kingspan-thermapitch-tp10.html
TP10 20 mm	Kingspan	PUR	1	1			0.02	3.91	195.50	0.023	4.50	http://www.just-insulation.com/001-eshop/buy-kingspan-thermapitch-thermawall-thermafloor-insulation-boards.html#tp10
TP10 20 mm	Kingspan	PUR	1	1			0.0576	9.9	171.88	0.022	3.78	http://www.planetinsulation.co.uk/ZKSK1820.php
TP10 20 mm	Kingspan	PUR	1	1			0.0576	12.45	216.15	0.022	4.76	http://www.insulationexpress.co.uk/Insulation-Boards/Celotex-TB4000-Insulation-Board.htm

TP10 75 mm	Kingspan	PUR	1	1			0.864	118.2	136.81	0.023	3.15	http://www.insulation-online.com/kingspan-thermapitch-tp10.html
TW55 100 mm	Kingspan	PUR	1	1			0.288	38.42	133.40	0.022	2.93	http://www.just-insulation.com/001-eshop/buy-kingspan-thermapitch-thermawall-thermafloor-insulation-boards.html#tp10
TW55 150 mm	Kingspan	PUR	1	1			0.432	57.98	134.21	0.022	2.95	http://www.just-insulation.com/001-eshop/buy-kingspan-thermapitch-thermawall-thermafloor-insulation-boards.html#tp10
TW55 150 mm	Kingspan	PUR	1	1			0.432	51	118.06	0.022	2.60	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
TW55 25 mm	Kingspan	PUR	1	1			0.072	12.67	175.97	0.022	3.87	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
TW50 100 mm	Kingspan	PUR	1	1			0.27	41.48	153.63	0.022	3.38	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
TW50 25 mm	Kingspan	PUR	1	1			0.27	47.67	176.56	0.022	3.88	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
Xtratherm 150 mm	Xtratherm	PUR	1	1	1		0.432	49.37	114.28	0.022	2.51	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
Xtratherm 20 mm	Xtratherm	PUR	1	1	1		0.0576	12.5	217.01	0.022	4.77	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/pir_rigid_insulation_boards.html
SupaLoft roll 100 mm	Thermafleece	recycled PET		1			0.9	46.41	51.57	0.04	2.06	http://www.insulationgiant.co.uk/Products/Insulation/Natural+Sustainable-Insulation/c/1200021
SupaLoft roll 100 mm	Thermafleece	recycled PET		1			0.3	17.5	58.33	0.04	2.33	http://www.celticsustainables.co.uk/thermafleece-supaloft-green-polyester-insulation/
SupaLoft roll 100 mm	Thermafleece	recycled PET		1			0.9	52.92	58.80	0.04	2.35	https://www.lime.org.uk/products/insulation/new-supaloft-green/supaloft-green/
SupaLoft roll 100 mm	Thermafleece	recycled PET		1			0.9	42.5	47.22	0.04	1.89	http://www.naturalinsulations.co.uk/index.php?location=Supaloft
SupaLoft roll 150 mm	Thermafleece	recycled PET		1			0.9195	42.9	46.66	0.04	1.87	http://www.naturalinsulations.co.uk/index.php?location=Supaloft
Non-itch loft roll	YBS	recycled PET		1			0.1	6.3	63.00	0.0425	2.68	http://www.just-insulation.com/001-eshop/buy-natuwool-black-mountain-sheeps-wool.html
InnoTherm 200 mm	InnoTherm	recycled textiles	1	1			0.432	31.36	72.59	0.039	2.83	http://www.naturalinsulations.co.uk/index.php?location=Innotherm
InnoTherm 50 mm	InnoTherm	recycled textiles	1	1			0.432	31.36	72.59	0.039	2.83	http://www.naturalinsulations.co.uk/index.php?location=Innotherm
InnoTherm 200 mm	InnoTherm	recycled textiles	1	1			0.2	11.2	56.00	0.039	2.18	http://www.inno-therm.com/buy/specifications/
NaturePRO roll 100 mm	NaturePRO	sheep wool		1			0.552	46.71	84.62	0.04	3.38	http://www.insulationexpress.co.uk/Timber-Frame-Insulation/naturePRO-Sheep-Wool-Insulation.htm
NaturePRO roll 150 mm	NaturePRO	sheep wool		1			0.69	59.62	86.41	0.04	3.46	http://www.insulationexpress.co.uk/Timber-Frame-Insulation/naturePRO-Sheep-Wool-Insulation.htm
NatuWool batts 200 mm	Black Mountain	sheep wool	1	1			0.2	22.57	112.85	0.039	4.40	http://www.just-insulation.com/001-eshop/buy-natuwool-black-mountain-sheeps-wool.html
NatuWool batts 50 mm	Black Mountain	sheep wool	1	1			0.05	5.65	113.00	0.039	4.41	http://www.just-insulation.com/001-eshop/buy-natuwool-black-mountain-sheeps-wool.html
NatuWool roll 125 mm	Black Mountain	sheep wool		1			0.125	14.1	112.80	0.039	4.40	http://www.just-insulation.com/001-eshop/buy-natuwool-black-mountain-sheeps-wool.html
NatuWool roll 50 mm	Black Mountain	sheep wool		1			0.05	5.65	113.00	0.039	4.41	http://www.just-insulation.com/001-eshop/buy-natuwool-black-mountain-sheeps-wool.html
CosyWool 50 mm	Thermafleece	sheep wool	1	1			0.2405	17.5	72.77	0.039	2.84	http://www.celticsustainables.co.uk/thermafleece-cosywool-sheeps-wool-insulation/
CosyWool 100 mm	Thermafleece	sheep wool	1	1			0.7215	53	73.46	0.039	2.86	https://www.lime.org.uk/products/insulation/thermafleece-cosywool/ty-mawr-thermafleece-welsh-cosywool-insulation/
CosyWool 100 mm	Thermafleece	sheep wool	1	1			0.722	51.57	71.43	0.039	2.79	http://www.insulationgiant.co.uk/Products/Insulation/Natural+Sustainable-Insulation/c/1200021
CosyWool 140 mm	Thermafleece	sheep wool	1	1			0.7336	44.36	60.47	0.039	2.36	http://www.naturalinsulations.co.uk/index.php?location=PB21
CosyWool 150 mm	Thermafleece	sheep wool	1	1			0.7155	54.33	75.93	0.039	2.96	http://ecomerchant.co.uk/thermafleece-cosy-roll-sheeps-wool-insulation.html
CosyWool 50 mm	Thermafleece	sheep wool	1	1			0.7215	44.66	61.90	0.039	2.41	http://www.naturalinsulations.co.uk/index.php?location=PB20
CosyWool 50 mm	Thermafleece	sheep wool	1	1			0.7215	54.83	75.99	0.039	2.96	http://ecomerchant.co.uk/thermafleece-cosy-roll-sheeps-wool-insulation.html

Original (Welsh) 50 mm	Thermafleece	sheep wool	1	1			1.008	120	119.05	0.038	4.52	http://www.celticsustainables.co.uk/thermafleece-original-thermal-acoustic-wool-insulation/
Original (Welsh) 100 mm	Thermafleece	sheep wool	1	1			1.008	98	97.22	0.038	3.69	https://www.lime.org.uk/products/insulation/ty-mawr-thermafleece-welsh-wool-insulation/
Original (Welsh) 100 mm	Thermafleece	sheep wool	1	1			1.008	112.74	111.85	0.038	4.25	http://www.insulationgiant.co.uk/Products/Insulation/Natural+Sustainable-Insulation/c/1200021
Original (Welsh) 100 mm	Thermafleece	sheep wool	1	1			1.008	96.85	96.08	0.038	3.65	http://www.naturalinsulations.co.uk/index.php?location=Thermafleece
Original (Welsh) 100 mm	Thermafleece	sheep wool	1	1			1.008	109.1	108.23	0.038	4.11	http://ecomerchant.co.uk/thermafleece-cosy-roll-sheeps-wool-insulation-1.html
Original (Welsh) 50 mm	Thermafleece	sheep wool	1	1			1.008	97.09	96.32	0.038	3.66	http://www.naturalinsulations.co.uk/index.php?location=Thermafleece
Original (Welsh) 50 mm	Thermafleece	sheep wool	1	1			1.008	109.35	108.48	0.038	4.12	http://ecomerchant.co.uk/thermafleece-cosy-roll-sheeps-wool-insulation-1.html
UltraWool 50 mm	Thermafleece	sheep wool	1	1			0.702	110	156.70	0.035	5.48	http://www.celticsustainables.co.uk/thermafleece-ultrawool-high-density-wool-slabs-insulation/
UltraWool 50 mm	Thermafleece	sheep wool	1	1			0.702	104.6	149.00	0.035	5.22	https://www.lime.org.uk/products/insulation/thermafleece-ultrawool/
UltraWool 50 mm	Thermafleece	sheep wool	1	1			0.702	88.68	126.32	0.035	4.42	http://www.naturalinsulations.co.uk/index.php?location=UltraWool
UltraWool 90 mm	Thermafleece	sheep wool	1	1			0.765	96.12	125.65	0.035	4.40	http://www.naturalinsulations.co.uk/index.php?location=UltraWool
Flexi 100 mm	Rockwool	stonewool	1	1			0.432	29.35	67.94	0.038	2.58	http://www.planetinsulation.co.uk/store/index.php#Mineral_Wool__
Flexi 140 mm	Rockwool	stonewool	1	1			0.1008	6.12	60.71	0.038	2.31	http://www.just-insulation.com/001-eshop/buy-rockwool-mineral-flexi-slabs-semi-rigid-batts-glass-wool.html
Flexi 50 mm	Rockwool	stonewool	1	1			0.024	1.46	60.83	0.038	2.31	http://www.just-insulation.com/001-eshop/buy-rockwool-mineral-flexi-slabs-semi-rigid-batts-glass-wool.html
Flexi 50 mm	Rockwool	stonewool	1	1			0.432	24.48	56.67	0.038	2.15	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Flexi 50 mm	Rockwool	stonewool	1	1			0.432	29.99	69.42	0.038	2.64	http://www.planetinsulation.co.uk/store/index.php#Mineral_Wool__
Prorox SL 920 30 mm	Rockwool	stonewool	1	1			0.2592	13.63	52.58	0.042	2.21	http://www.insulation-online.com/rockwool-rwa45-rs3-slabs.html
Prorox SL 920 50 mm	Rockwool	stonewool	1	1			0.324	17.45	53.86	0.04	2.15	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Prorox SL 930 100 mm	Rockwool	stonewool	1	1			0.1	7.2	72.00	0.04	2.88	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Prorox SL 930 30 mm	Rockwool	stonewool	1	1			0.03	2.47	82.33	0.04	3.29	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Prorox SL 960 50 mm	Rockwool	stonewool	1	1			0.144	16.7	115.97	0.04	4.64	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Prorox SL 980 100 mm	Rockwool	stonewool	1	1			0.144	20.46	142.08	0.04	5.68	http://www.insulation-online.com/rockwool-rwa45-rs3-slabs.html
Roll loft 150 mm	Rockwool	stonewool		1			0.657	26.16	39.82	0.044	1.75	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
RollBatt 100 mm	Rockwool	stonewool	1	1			0.576	20.74	36.01	0.044	1.58	http://www.insulationshop.co/glass_and_mineral_wool_insulation.html
Styrozone H350R 120 mm	Kingspan	XPS	1	1	1		0.12	30.22	251.83	0.03	7.56	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
Styrozone H350R 80 mm	Kingspan	XPS	1	1	1		0.08	20.14	251.75	0.03	7.55	http://www.insulationshop.co/rigid_insulation_boards_kingspan_celotex_xtratherm/polystyrene_insulation_eps_70_online.html
Steico Flex 100 mm	Steico	wood fibre flex	1	1			0.28	25.62	91.50	0.038	3.48	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-flexible/steico-flex-wood-fibre-insulation-575mm.html
Steico Flex 100 mm	Steico	wood fibre flex	1	1			0.28	28.62	102.21	0.038	3.88	http://www.naturalinsulations.co.uk/product/steicoflex-insulation/

Steico Flex 100 mm	Steico	wood fibre flex	1	1			2.806	321	114.40	0.038	4.35	http://www.insulationgiant.co.uk/Steico-Flex-Wood-Fibre-Insulation-Slab-100mm-x-1150mm-x-1220mm-%281-Pallet-28-06m2%29/p/149812
Gutex Thermoflex 100 mm	Gutex	wood fibre flex	1	1			0.1	10.07	100.70	0.038	3.83	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Pavaflex	Gutex	wood fibre flex					0.1519	15.62	102.83	0.038	3.91	http://www.phstore.co.uk/pavatex-en/pavaflex.html
Steico Therm (S/E) Internal 100 mm	Steico	wood fibre rigid	1			50	0.081	14.32	176.79	0.039	6.89	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-rigid/steico-therm-wood-fibre-insulation-board.html
Steico Therm (T&G) Internal 40 mm	Steico	wood fibre rigid	1	1	1	50	0.0184	3.64	197.83	0.039	7.72	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-rigid/steico-therm-internal-wood-fibre-insulation-board.html
Steico Special Dry S&S 60 mm	Steico	wood fibre rigid	1	1	1	100	0.0636	15.66	246.23	0.041	10.10	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-rigid/steico-special-dry-wood-fibre-insulation-sheathing-board.html
Steico Special S&S 60 mm	Steico	wood fibre rigid	1	1	1	100	0.06768	20.18	298.17	0.046	13.72	http://www.naturalinsulations.co.uk/product/steico-rigid-wood-fibre-insulation/
Steico Therm 100 mm	Steico	wood fibre rigid	1	1	1	50	0.081	15.04	185.68	0.039	7.24	http://www.naturalinsulations.co.uk/product/steico-rigid-wood-fibre-insulation/
Steico Universal 52mm	Steico	wood fibre rigid	1	1	1	200	0.078	25.68	329.23	0.048	15.80	http://www.naturalinsulations.co.uk/product/steico-rigid-wood-fibre-insulation/
Gutex Multiplex-top 35 mm	Gutex	wood fibre rigid		1		200	0.035	9.03	258.00	0.044	11.35	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Gutex Ultratherm 100 mm	Gutex	wood fibre rigid		1		150	0.1	22.67	226.70	0.042	9.52	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Gutex Thermosafe homogen 100 mm	Gutex	wood fibre rigid	1	1		40	0.1	15.34	153.40	0.037	5.68	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Gutex Thermosafe 100 mm	Gutex	wood fibre rigid	1	1		20	0.1	14.76	147.60	0.037	5.46	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Gutex Multitherm 100 mm	Gutex	wood fibre rigid	1	1		70	0.1	19.51	195.10	0.039	7.61	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Gutex Thermoroom 100 mm	Gutex	wood fibre rigid	1	1		50	0.1	22.86	228.60	0.038	8.69	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Gutex Thermosafe wd 100 mm	Gutex	wood fibre rigid		1	1	70	0.1	17.46	174.60	0.039	6.81	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Gutex Thermofloor 30 mm	Gutex	wood fibre rigid			1		0.03	7.96	265.33	0.039	10.35	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Gutex Thermowall 100 mm	Gutex	wood fibre rigid	1			100	0.1	28	280.00	0.042	11.76	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Gutex Thermowall gf 60 mm	Gutex	wood fibre rigid	1			200	0.06	17.35	289.17	0.046	13.30	http://gutex.de/fileadmin/uploads/Downloads/GUTEX_EN_BR_Preisliste_2015-12.pdf
Pavatherm Plus 100 mm	Pavatex	wood fibre rigid	1	1	1	70	0.12324	40.05	324.98	0.044	14.30	http://www.womersleys.co.uk/shop/natural_insulation/60mm_pavatherm_plus_insulation_board_1580_x_780_mm
Pavatherm Plus 100 mm	Pavatex	wood fibre rigid	1	1	1	70	0.1044	22.46	215.13	0.044	9.47	http://www.phstore.co.uk/wood-fibre-insulation/nbt-wood-fibre/pavatherm-plus.html
Pavatherm 100 mm	Pavatex	wood fibre rigid	1	1	1	20	0.0612	8.5	138.89	0.038	5.28	http://www.phstore.co.uk/pavatex-en/pavatherm.html

Isolair S&S	Pavatex	wood fibre rigid	1	1		175	1.9635	429.76	218.87	0.047	10.29	http://www.phstore.co.uk/pavatex-en/isolair.html
Diffutherm 100 mm	Pavatex	wood fibre rigid	1			80	0.0841	19.14	227.59	0.043	9.79	http://www.phstore.co.uk/pavatex-en/diffutherm.html

Table 7 – Survey of product prices in 2017

Insulation product	**Firm**	**Product type**	**Envelope application**			**Compressive strength**	**Quantity sold**	**Price**	**Price per cubic meter**	**Thermal conductivity**	**Price per FU**	**Weblink**
			Wall	Roof	Floor	kPa	m3	£	£ / m3	W/mK	£/m2K/W	
30mm Rockwool RW3 Slab (Prorox SL930)	Rockwool	stone wool	1	1	1		0.03	2.47	82.33	0.034	2.80	http://www.insulationshop.co/30mm_rockwool_prorox_sl930_formerly_known_as_rw3_slab.html
100mm Rockwool RW3 Slab (Prorox SL 930)	Rockwool	stone wool	1	1	1		0.1	9.65	96.50	0.034	3.28	http://www.insulationshop.co/100mm_rockwool_prorox_sl930_formerly_known_as_rw3_slab.html
150mm Rockwool Roll Loft Insulation	Rockwool	stone wool		1			13.14	559.8	42.60	0.044	1.87	http://www.insulationshop.co/rockwool_roll_loft_insulation_150mm.html
150mm Earthwool Loft Roll 44	Knauf	glass wool		1			27.54	504.8	18.33	0.044	0.81	http://www.insulationshop.co/150mm_earthwool_loft_roll_44.html
200mm Earthwool Loft Roll 44	Knauf	glass wool		1			23.72	448.4	18.90	0.044	0.83	http://www.insulationshop.co/200mm_earthwool_loft_roll_44.html
100mm Isover Spacesaver Loft Roll	Isover	glass wool		1			21.28	266	12.50	0.043	0.54	http://www.insulationshop.co/100mm_isover_spacesaver.html
200mm Isover Spacesaver Loft Roll	Isover	glass wool		1			18	316.6	17.59	0.043	0.76	http://www.insulationshop.co/200mm_isover_spacesaver.html
100mm Rockwool RollBatt Loft Insulation	Rockwool	stone wool		1			11.52	499.2	43.33	0.044	1.91	http://www.insulationshop.co/rockwool_rollbatt_loft_insulation_100mm.html
170mm Rockwool RollBatt Loft Insulation	Rockwool	stone wool		1			13.056	502.02	38.45	0.044	1.69	http://www.insulationshop.co/rockwool_rollbatt_loft_insulation_170mm.html
100mm Superglass Multi Roll 44 Loft Insulation	Superglass	glass wool		1			0.1	1.28	12.80	0.044	0.56	http://www.insulationshop.co/100mm_superglass_multi_roll_44_loft_insulation.html
200mm Superglass Multi Roll 44 Loft Insulation	Superglass	glass wool		1			0.2	2.35	11.75	0.044	0.52	http://www.insulationshop.co/200mm_superglass_multi_roll_44_loft_insulation.html
100mm URSA 10 Loft Roll	Ursa	glass wool		1			21.66	336.4	15.53	0.044	0.68	http://www.insulationshop.co/100mm_loft_insulation_roll_ursa.html
200mm URSA 10 Loft Roll	Ursa	glass wool		1			25.08	358.4	14.29	0.044	0.63	http://www.insulationshop.co/200mm_loft_insulation_roll_ursa.html
12mm Celotex TB4000 PIR Insulation Board	Celotex	PUR	1	1	1	120	1.03	291	282.52	0.022	6.22	http://www.insulationshop.co/12mm_celotex_tb4000_pir_insulation.html
45mm Celotex TB4000 PIR Insulation Board	Celotex	PUR	1	1	1	120	2.592	437.6	168.83	0.022	3.71	http://www.insulationshop.co/45mm_celotex_tb4000_pir_insulation.html
50mm Celotex GA4000 PIR Insulation Board	Celotex	PUR	1	1	1	140	2.88	347.2	120.56	0.022	2.65	http://www.insulationshop.co/50mm_celotex_ga4000_pir_insulation.html
100mm Celotex GA4000 PIR Insulation Board	Celotex	PUR	1	1	1	120	8.64	664.8	76.94	0.022	1.69	http://www.insulationshop.co/100mm_celotex_ga4000_pir_insulation.html
110mm Celotex XR4000 PIR Insulation Board	Celotex	PUR	1	1	1	140	6.336	723	114.11	0.022	2.51	http://www.insulationshop.co/110mm_celotex_xr4000_pir_insulation.html
200mm Celotex XR4000 PIR Insulation Board	Celotex	PUR	1	1	1	140	13.824	1722	124.57	0.022	2.74	http://www.insulationshop.co/200mm_celotex_xr4000.html
20mm Kingspan Thermapitch TP10	Kingspan	PUR		1		140	1.152	249.4	216.49	0.022	4.76	http://www.insulationshop.co/20mm_kingspan_thermapitch_tp10_pitched_warm_roof_insulation_board.html

Pitched Warm Roof Insulation Board												
50mm Kingspan Thermapitch TP10 Pitched Warm Roof Insulation Board	Kingspan	PUR		1		140	8.64	1091.5	126.33	0.022	2.78	http://www.insulationshop.co/150mm_kingspan_thermapitch_tp10_pitched_warm_roof_insulation_board.html
20mm Thermawall TW55 PIR Insulation Board Kingspan	Kingspan	PUR	1			140	1.728	371.1	214.76	0.022	4.72	http://www.insulationshop.co/20mm_thermawall_tw55_pir_insulation_board_kingspan.html
150mm Thermawall TW55 PIR Insulation Board Kingspan	Kingspan	PUR	1			140	8.64	1091.4	126.32	0.022	2.78	http://www.insulationshop.co/150mm_thermawall_tw55_pir_insulation_board_kingspan.html
20mm Thermafloor TF70 PIR Insulation Board Kingspan	Kingspan	PUR			1	140	1.728	371.1	214.76	0.023	4.94	http://www.insulationshop.co/20mm_Thermafloor_TF70.html
150mm Thermafloor TF70 PIR Insulation Board Kingspan	Kingspan	PUR			1	140	12.96	1637.1	126.32	0.023	2.91	http://www.insulationshop.co/150mm_Thermafloor_TF70.html
100mm Kingspan Thermaroof TR24	Kingspan	PUR		1		150	7.2	1265.8	175.81	0.025	4.40	http://www.insulationshop.co/100mm_kingspan_thermaroof_tr24.html
150mm Kingspan Thermaroof TR26	Kingspan	PUR		1		150	17.28	3553.8	205.66	0.022	4.52	http://www.insulationshop.co/150mm_kingspan_thermaroof_tr26.html
25mm Kingspan Thermaroof TR27	Kingspan	PUR		1		150	4.32	919.8	212.92	0.025	5.32	http://www.insulationshop.co/25mm_kingspan_tr27.html
130mm Kingspan Thermaroof TR27	Kingspan	PUR		1		150	5.616	1240.6	220.90	0.024	5.30	http://www.insulationshop.co/130mm_kingspan_tr27.html
15mm Xtratherm PIR Rigid Insulation Board	Xtratherm	PUR	1	1	1		1.296	324.3	250.23	0.022	5.51	http://www.insulationshop.co/15mm_xtratherm_pir_insulation_board_thin_r.html
150mm Xtratherm PIR Rigid Insulation Board	Xtratherm	PUR	1	1	1		8.64	947	109.61	0.022	2.41	http://www.insulationshop.co/150mm_xtratherm_pir_insulation_board_thin_r.html
50mm Flat Roof Insulation Board Xtratherm FR-BGM	Xtratherm	PUR		1		150	7.2	1098.2	152.53	0.025	3.81	http://www.insulationshop.co/50mm_xtratherm_frbg_flat_roof_insulation_board.html
150mm Flat Roof PIR Insulation Board Xtratherm FR-BGM	Xtratherm	PUR		1		150	6.48	1039.4	160.40	0.025	4.01	http://www.insulationshop.co/150mm_xtratherm_frbg_flat_roof_insulation_board.html
25mm Kingspan Kooltherm K3 Floorboard	Kingspan	phenolic			1	120	17.28	4546	263.08	0.02	5.26	http://www.insulationshop.co/25mm_kooltherm_k3_floorboard_pack_of_12.html
100mm Kingspan Kooltherm K3 Floorboard	Kingspan	phenolic			1	120	17.28	3333.4	192.91	0.02	3.86	http://www.insulationshop.co/100mm_kooltherm_k3_floorboard_pack_of_12.html
20mm Kooltherm K5 External Wall Board Kingspan	Kingspan	phenolic	1			120	7.2	2426.4	337.00	0.023	7.75	http://www.insulationshop.co/20mm_kooltherm_k5_external_wall_kingspan.html
80mm Kooltherm K5 External Wall Board Kingspan	Kingspan	phenolic	1			120	0.08	26.29	328.63	0.023	7.56	http://www.insulationshop.co/80mm_kooltherm_k5_external_wall_kingspan.html
25mm Kooltherm K7 Pitched Roof Board Kingspan	Kingspan	phenolic		1		125	17.28	4598	266.09	0.021	5.59	http://www.insulationshop.co/25mm_kooltherm_k7_pitched_roof_kingspan.html
140mm Kooltherm K7 Pitched Roof Board Kingspan	Kingspan	phenolic		1		125	16.128	3050	189.11	0.021	3.97	http://www.insulationshop.co/140mm_kooltherm_k7_pitched_roof_kingspan.html
25mm Kingspan Kooltherm K103 Floorboard	Kingspan	phenolic			1	120	3.456	1015.64	293.88	0.018	5.29	http://www.insulationshop.co/25mm_kingspan_kooltherm_k103_floorboard.html
100mm Kingspan Kooltherm K103 Floorboard	Kingspan	phenolic			1	120	3.456	768	222.22	0.018	4.00	http://www.insulationshop.co/100mm_kingspan_kooltherm_k103_floorboard.html

10mm Grey Polystyrene (Graphite EPS) for External Wall Insulation	Styropoz	EPS	1			72	0.01	0.86	86.00	0.031	2.67	http://www.insulationshop.co/10mm_grey_polystyrene_ewi_graphite.html
150mm Grey Polystyrene (Graphite EPS) for External Wall Insulation	Styropoz	EPS	1			70	6	398	66.33	0.031	2.06	http://www.insulationshop.co/150mm_grey_polystyrene_ewi_graphite.html
10mm White Polystyrene Board (EPS) for External Wall Insulation	Styropoz	EPS	1			75	9	507	56.33	0.042	2.37	http://www.insulationshop.co/10mm_white_polystyrene_board_for_external_wall_insulation.html
150mm White Polystyrene Board (EPS) for External Wall Insulation	Styropoz	EPS	1			75	9	525	58.33	0.042	2.45	http://www.insulationshop.co/150mm_white_polystyrene_board_for_external_wall_insulation.html
25mm EPS70 Polystyrene Insulation Board Kay-Metzeler	Kay-Metzeler	EPS	1	1			17.28	814.4	47.13	0.037	1.74	http://www.insulationshop.co/25mm_polystyrene_insulation_eps_70.html
100mm EPS70 Polystyrene Insulation Board Kay-Metzeler	Kay-Metzeler	EPS	1	1			17.28	820.2	47.47	0.037	1.76	http://www.insulationshop.co/100mm_polystyrene_insulation_eps_70jablite.html
25mm EPS70 Polystyrene Insulation Board Jablite	Jablite	EPS	1	1		70	17.28	814.4	47.13	0.038	1.79	http://www.insulationshop.co/25mm_polystyrene_insulation_eps_70jablite.html
100mm EPS70 Polystyrene Insulation Board Jablite	Jablite	EPS	1	1		70	17.28	1121.8	64.92	0.038	2.47	http://www.insulationshop.co/100mm_polystyrene_insulation_eps_70.html
100mm ThermaFleece SupaLoft	ThermaFleece	sheep wool		1			0.1	6.25	62.50	0.04	2.50	http://www.insulationshop.co/100mm_thermafleece_supaloft_loft_insulation_roll_370mm_wide.html
150mm ThermaFleece SupaLoft	ThermaFleece	sheep wool		1			0.15	9.38	62.53	0.04	2.50	http://www.insulationshop.co/150mm_thermafleece_supaloft_loft_insulation_roll_370mm_wide.html
50mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool	1	1	1		0.05	4	80.00	0.039	3.12	http://www.insulationshop.co/50mm_thermafleece_eco_roll_370mm_wide_pack_of_3.html
140mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool	1	1	1		0.14	11.16	79.71	0.039	3.11	http://www.insulationshop.co/140mm_thermafleece_eco_roll_570mm_wide_pack_of_2.html
50mm ThermaFleece CosyWool Flexible Slab	ThermaFleece	sheep wool	1	1	1		0.05	6.01	120.20	0.038	4.57	http://www.insulationshop.co/50mm_thermafleece_cosywool_flexible_slab_390mm_x_1200mm.html
140mm ThermaFleece CosyWool Flexible Slab	ThermaFleece	sheep wool	1	1	1		0.14	16.81	120.07	0.038	4.56	http://www.insulationshop.co/140mm_thermafleece_cosywool_flexible_slab_390mm_x_1200mm.html
50mm ThermaFleece NatraHemp Flexible Slab	ThermaFleece	hemp fibre	1	1	1		0.05	5.88	117.60	0.04	4.70	http://www.insulationshop.co/50mm_thermafleece_natrahemp%20_flexible_slab_370mm_x_1200mm.html
100mm ThermaFleece NatraHemp Flexible Slab	ThermaFleece	hemp fibre	1	1	1		0.1	11.76	117.60	0.04	4.70	http://www.insulationshop.co/100mm_thermafleece_natrahemp%20_flexible_slab_370mm_x_1200mm.html
50mm ThermaFleece UltraWool Flexible Slab	ThermaFleece	sheep wool	1	1	1		0.05	7.85	157.00	0.035	5.50	http://www.insulationshop.co/50mm_thermafleece_ultrawool_flexible_slab_390mm_x_1200mm.html
90mm ThermaFleece UltraWool Flexible Slab	ThermaFleece	sheep wool	1	1	1		0.09	14.12	156.89	0.035	5.49	http://www.insulationshop.co/90mm_thermafleece_ultrawool_flexible_slab_390mm_x_1200mm.html
25mm Rockwool RWA45 slab	Rockwool	stone wool	1	1	1		0.025	1.08	43.20	0.035	1.51	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
100mm Rockwool RWA45 slab	Rockwool	stone wool	1	1	1		0.1	4.46	44.60	0.035	1.56	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
25mm Rockwool RW3 slab	Rockwool	stone wool	1	1	1		0.025	1.6	64.00	0.034	2.18	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
100mm Rockwool RW3 slab	Rockwool	stone wool	1	1	1		0.1	5.81	58.10	0.034	1.98	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
50mm Rockwool RW4 slab	Rockwool	stone wool	1	1	1		0.05	4.28	85.60	0.034	2.91	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
50mm Rockwool RW4 slab	Rockwool	stone wool	1	1	1		0.1	8.56	85.60	0.034	2.91	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
50mm Rockwool RW5 slab	Rockwool	stone wool	1	1	1		0.025	2.78	111.20	0.034	3.78	https://just-insulation.com/buy-mineral-wool-building-slabs.htm

100mm Rockwool RW5 slab	Rockwool	stone wool	1	1	1	0.1	10.52	105.20	0.034	3.58	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
50mm Rockwool Flexi	Rockwool	stone wool		1		0.05	2.47	49.40	0.038	1.88	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
140mm Rockwool Flexi	Rockwool	stone wool				0.14	7.85	56.07	0.035	1.96	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
40mm Knauf Earthwool RS33	Knauf	stone wool	1	1	1	0.04	2.69	67.25	0.035	2.35	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
100mm Knauf Earthwool RS33	Knauf	stone wool	1	1	1	0.1	6.31	63.10	0.035	2.21	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
25mm Knauf Earthwool RS45	Knauf	stone wool	1	1	1	0.025	1.27	50.80	0.035	1.78	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
100mm Knauf Earthwool RS45	Knauf	stone wool	1	1	1	0.1	5.05	50.50	0.035	1.77	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
25mm Knauf Earthwool RS60	Knauf	stone wool	1	1	1	0.025	1.62	64.80	0.035	2.27	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
100mm Knauf Earthwool RS60	Knauf	stone wool	1	1	1	0.1	6.22	62.20	0.035	2.18	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
25mm Knauf Earthwool RS100	Knauf	stone wool	1	1	1	0.025	3.45	138.00	0.035	4.83	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
100mm Knauf Earthwool RS100	Knauf	stone wool	1	1	1	0.1	13.93	139.30	0.035	4.88	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
30mm Knauf Earthwool RS140	Knauf	stone wool	1	1	1	0.03	5.87	195.67	0.035	6.85	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
100mm Knauf Earthwool RS140	Knauf	stone wool	1	1	1	0.1	19.35	193.50	0.035	6.77	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
50mm Knauf Earthwool Flexi	Knauf	stone wool		1		0.025	3.09	123.60	0.037	4.57	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
140mm Knauf Earthwool Flexi	Knauf	stone wool		1		0.14	8.71	62.21	0.035	2.18	https://just-insulation.com/buy-mineral-wool-building-slabs.htm
100mm Isover Spacesaver Loft Roll	Isover	glass wool		1		0.1	1.27	12.70	0.043	0.55	https://just-insulation.com/buy-glass-mineral-wool-rolls.html
200mm Isover Spacesaver Loft Roll	Isover	glass wool		1		0.2	2.58	12.90	0.043	0.55	https://just-insulation.com/buy-glass-mineral-wool-rolls.html
100mm Knauf Earthwool Loft roll 44	Knauf	glass wool		1		0.1	1.18	11.80	0.044	0.52	https://just-insulation.com/buy-glass-mineral-wool-rolls.html
200mm Knauf Earthwool Loft roll 44	Knauf	glass wool		1		0.2	2.53	12.65	0.044	0.56	https://just-insulation.com/buy-glass-mineral-wool-rolls.html
100mm Knauf Earthwool Loft roll 40	Knauf	glass wool		1		0.1	2.56	25.60	0.04	1.02	https://just-insulation.com/buy-glass-mineral-wool-rolls.html
200mm Knauf Earthwool Loft roll 40	Knauf	glass wool		1		0.2	5.22	26.10	0.04	1.04	https://just-insulation.com/buy-glass-mineral-wool-rolls.html
50mm Knauf Earthwool rafter roll 32	Knauf	glass wool		1		0.05	7.33	146.60	0.032	4.69	https://just-insulation.com/buy-glass-mineral-wool-rolls.html
100mm Knauf Earthwool rafter roll 32	Knauf	glass wool		1		0.1	13.52	135.20	0.032	4.33	https://just-insulation.com/buy-glass-mineral-wool-rolls.html
50mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool	1	1	1	0.05	3.65	73.00	0.038	2.77	https://just-insulation.com/thermafleece-cosywool-sheeps-wool.html
150mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool	1	1	1	0.15	10.75	71.67	0.038	2.72	https://just-insulation.com/thermafleece-cosywool-sheeps-wool.html
25mm Kooltherm K103	Kingspan	phenolic			1	0.025	8.08	323.20	0.018	5.82	https://just-insulation.com/buy-phenolic-rigid-board.html
100mm Kooltherm K103	Kingspan	phenolic			1	0.1	23.89	238.90	0.018	4.30	https://just-insulation.com/buy-phenolic-rigid-board.html
20mm Kooltherm K5	Kingspan	phenolic	1			0.02	6.7	335.00	0.023	7.71	https://just-insulation.com/buy-phenolic-rigid-board.html
70mm Kooltherm K5	Kingspan	phenolic	1			0.07	15.23	217.57	0.02	4.35	https://just-insulation.com/buy-phenolic-rigid-board.html
25mm Kooltherm K7	Kingspan	phenolic		1		0.025	6.73	269.20	0.021	5.65	https://just-insulation.com/buy-phenolic-rigid-board.html
150mm Kooltherm K7	Kingspan	phenolic		1		0.15	29.16	194.40	0.02	3.89	https://just-insulation.com/buy-phenolic-rigid-board.html

25mm Kooltherm K12	Kingspan	phenolic	1				0.025	7.33	293.20	0.021	6.16	https://just-insulation.com/buy-phenolic-rigid-board.html
140mm Kooltherm K12	Kingspan	phenolic	1				0.14	33.71	240.79	0.02	4.82	https://just-insulation.com/buy-phenolic-rigid-board.html
25mm Kooltherm K15	Kingspan	phenolic	1				0.025	7.17	286.80	0.021	6.02	https://just-insulation.com/buy-phenolic-rigid-board.html
140mm Kooltherm K15	Kingspan	phenolic	1				0.14	29.72	212.29	0.02	4.25	https://just-insulation.com/buy-phenolic-rigid-board.html
25mm Celotex TB4025	Celotex	PUR	1	1	1		0.072	11.13	154.58	0.022	3.40	http://www.planetinsulation.co.uk/ZGA3012.php
150mm Celotex TB4150	Celotex	PUR	1	1	1		0.432	45.33	104.93	0.022	2.31	http://www.planetinsulation.co.uk/ZGA3012.php
15mm Celotex PL 4015	Celotex	PUR	1	1	1		0.0432	25.97	601.16	0.022	13.23	http://www.planetinsulation.co.uk/ZPL4025.php
60mm Celotex PL 4060	Celotex	PUR	1	1	1		0.1728	37.3	215.86	0.022	4.75	http://www.planetinsulation.co.uk/ZPL4025.php
50mm Celotex CW4050	Celotex	PUR	1				0.298	35.34	118.59	0.022	2.61	http://www.planetinsulation.co.uk/store/index.php#Celotex_Cavity_Wall_Boards
100mm Celotex CW4100	Celotex	PUR	1				0.324	37.15	114.66	0.022	2.52	http://www.planetinsulation.co.uk/store/index.php#Celotex_Cavity_Wall_Boards
25mm Kooltherm K3	Kingspan	phenolic			1	120	0.072	20.91	290.42	0.02	5.81	http://www.planetinsulation.co.uk/store/index.php#Kingspan_K3_Boards
100mm Kooltherm K3	Kingspan	phenolic			1	120	0.288	65.12	226.11	0.02	4.52	http://www.planetinsulation.co.uk/store/index.php#Kingspan_K3_Boards
40mm Kooltherm K7	Kingspan	phenolic		1		125	0.1152	27.31	237.07	0.02	4.74	http://www.planetinsulation.co.uk/ZKSK740.php
140mm Kooltherm K7	Kingspan	phenolic		1		125	0.432	83.52	193.33	0.02	3.87	http://www.planetinsulation.co.uk/ZKSK740.php
40mm Kooltherm K12	Kingspan	phenolic	1				0.1152	32.07	278.39	0.02	5.57	http://www.planetinsulation.co.uk/store/index.php#Kingspan_K12_Boards
60mm Kooltherm K12	Kingspan	phenolic	1				0.1728	47.45	274.59	0.02	5.49	http://www.planetinsulation.co.uk/store/index.php#Kingspan_K12_Boards
50mm Rockwool Flexi	Rockwool	stone wool		1			0.432	32.5	75.23	0.038	2.86	http://www.planetinsulation.co.uk/store/index.php#Mineral_Wool_
100mm Rockwool Flexi	Rockwool	stone wool		1			0.432	32.5	75.23	0.038	2.86	http://www.planetinsulation.co.uk/store/index.php#Mineral_Wool_
100mm Earthwool Loft Roll 44	Knauf	glass wool		1			1.389	22.63	16.29	0.044	0.72	http://www.planetinsulation.co.uk/store/index.php#Mineral_Wool_
200mm Earthwool Loft Roll 44	Knauf	glass wool		1			1.186	19.27	16.25	0.044	0.71	http://www.planetinsulation.co.uk/store/index.php#Mineral_Wool_
50mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool		1			0.741	59.27	79.99	0.039	3.12	http://www.insulationgiant.co.uk/Thermafleece-Cosywool-50mm-Natural-Sheeps-Wool-Insulation-570mm-Split/p/174327
100mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool		1			0.722	57.09	79.07	0.039	3.08	http://www.insulationgiant.co.uk/Thermafleece-Cosywool-100mm-Natural-Sheeps-Wool-Insulation-370mm-Split/p/174329
25mm EPS70 Polystyrene Insulation Board Kay-Metzeler	Kay-Metzeler	EPS	1	1			0.072	3.75	52.08	0.037	1.93	http://www.insulationgiant.co.uk/Kay-Metzeler-Eps70-Expanded-Polystyrene-Insulation-Board-2400mm-x-1200mm-x-25mm/p/277187
100mm EPS70 Polystyrene Insulation Board Kay-Metzeler	Kay-Metzeler	EPS	1	1			0.28	15	53.57	0.037	1.98	http://www.insulationgiant.co.uk/Kay-Metzeler-EPS70-Expanded-Polystyrene-Insulation-Board-2400mm-x-1200mm-x-100mm/p/277202
40mm Rockwool RW5 slab	Rockwool	stone wool	1	1	1		0.1728	16.33	94.50	0.034	3.21	http://www.insulationgiant.co.uk/Rockwool-RW5-Slab-1200mm-x-600mm-x-40mm/p/767883
100mm Rockwool RW5 slab	Rockwool	stone wool	1	1	1		0.144	13.15	91.32	0.034	3.10	http://www.insulationgiant.co.uk/Rockwool-RW5-Slab-1200mm-x-600mm-x-100mm/p/767886
50mm Rockwool Flexi	Rockwool	stone wool		1			0.05	2.56	51.20	0.038	1.95	http://www.insulationgiant.co.uk/Rockwool-Flexi-50mm-Insulation-Slab-1200mm-x-600mm/p/665442
140mm Rockwool Flexi	Rockwool	stone wool		1			0.4032	22.68	56.25	0.038	2.14	http://www.insulationgiant.co.uk/Rockwool-Flexi-140mm-Insulation-Slab-1200mm-x-600mm/p/665447
150mm Naturepro roll	Naturepro	sheep wool	1	1	1		0.69	71.54	103.68	0.039	4.04	http://www.insulationexpress.co.uk/Natural%2DInsulation/naturePRO%2DSheep%2DWool%2DInsulation.htm
50mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool	1	1	1		0.741	63.94	86.29	0.039	3.37	http://www.insulationexpress.co.uk/Natural%2DInsulation/Thermafleece%2DCosyWool%2DInsulation.htm
20mm Steico Therm Rigid S/E	Steico	wood fibre	1	1	1	50	0.0162	2.79	172.22	0.039	6.72	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-rigid/steico-therm-wood-fibre-insulation-board.html
100mm Steico Therm Rigid S/E	Steico	wood fibre	1	1	1	50	0.081	14.32	176.79	0.039	6.89	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-rigid/steico-therm-wood-fibre-insulation-board.html
40mm Steico Therm Rigid T&E	Steico	wood fibre	1	1	1	50	0.01736	4.03	232.14	0.039	9.05	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-rigid/steico-therm-internal-wood-fibre-insulation-board.html

60mm Steico Therm Rigid T&E	Steico	wood fibre	1	1	1	50	0.02604	6.04	231.95	0.039	9.05	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-rigid/steico-therm-internal-wood-fibre-insulation-board.html
40mm Steico Flex	Steico	wood fibre		1			0.28	25.62	91.50	0.038	3.48	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-flexible/steico-flex-wood-fibre-insulation-575mm.html
140mm Steico Flex	Steico	wood fibre		1			0.392	40.12	102.35	0.038	3.89	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-flexible/steico-flex-wood-fibre-insulation-575mm.html
100mm Steico Flex	Steico	wood fibre		1			0.18	19.84	110.22	0.038	4.19	http://www.ecomerchant.co.uk/walls/insulation/wood-fibre-flexible/steico-flex-wood-fibre-insulation-385mm.html
100mm Natrahemp	ThermaFleece	hemp fibre	1	1	1		1.094	129.95	118.78	0.04	4.75	http://www.ecomerchant.co.uk/walls/insulation/hemp-insulation/thermafleece-natrahemp-natural-insulation-batts.html
50mm Natrahemp	ThermaFleece	hemp fibre	1	1	1		1.0655	126.57	118.79	0.04	4.75	http://www.ecomerchant.co.uk/walls/insulation/hemp-insulation/thermafleece-natrahemp-natural-insulation-batts.html
50mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool	1	1	1		0.741	59.06	79.70	0.038	3.03	http://www.ecomerchant.co.uk/walls/insulation/thermafleece-range/thermafleece-cosy-wool-sheeps-wool-insulation-1.html
150mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool	1	1	1		0.735	58.54	79.65	0.038	3.03	http://www.ecomerchant.co.uk/walls/insulation/thermafleece-range/thermafleece-cosy-wool-sheeps-wool-insulation-1.html
50mm ThermaFleece UltraWool Roll	ThermaFleece	sheep wool	1	1	1		0.702	110	156.70	0.035	5.48	http://www.ecomerchant.co.uk/walls/insulation/thermafleece-range/thermafleece-ultra-wool-sheeps-wool-insulation.html
90mm ThermaFleece UltraWool Roll	ThermaFleece	sheep wool	1	1	1		0.7578	118.66	156.58	0.035	5.48	http://www.ecomerchant.co.uk/walls/insulation/thermafleece-range/thermafleece-ultra-wool-sheeps-wool-insulation.html
50mm Natrahemp	ThermaFleece	hemp fibre	1	1	1		1.0655	111.59	104.73	0.04	4.19	http://www.naturalinsulations.co.uk/product/thermafleece-natrahemp/
100mm Natrahemp	ThermaFleece	hemp fibre	1	1	1		1.066	111.64	104.73	0.04	4.19	http://www.naturalinsulations.co.uk/product/thermafleece-natrahemp/
40mm Steico Flex	Steico	wood fibre		1			0.2808	33.19	118.20	0.038	4.49	http://www.naturalinsulations.co.uk/product/steicoflex-insulation/
140mm Steico Flex	Steico	wood fibre		1			0.392	41.4	105.61	0.038	4.01	http://www.naturalinsulations.co.uk/product/steicoflex-insulation/
50mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool	1	1	1		0.983	99.28	101.00	0.038	3.84	http://www.naturalinsulations.co.uk/product/thermafleece-cosywool-sheep-wool-insulation-slabs/
140mm ThermaFleece CosyWool Roll	ThermaFleece	sheep wool	1	1	1		0.9912	100.01	100.90	0.038	3.83	http://www.naturalinsulations.co.uk/product/thermafleece-cosywool-sheep-wool-insulation-slabs/
50mm Natrahemp	ThermaFleece	hemp fibre	1	1	1		1.0655	122.58	115.04	0.04	4.60	http://www.phstore.co.uk/insulation/hemp-insulation-cellulose-insulation-recycled-insulation/thermafleece-natrahemp
100mm Natrahemp	ThermaFleece	hemp fibre	1	1	1		1.066	122.64	115.05	0.04	4.60	http://www.phstore.co.uk/insulation/hemp-insulation-cellulose-insulation-recycled-insulation/thermafleece-natrahemp
22mm Steico Universal	Steico	wood fibre	1	1	1		0.022	6.17	280.45	0.048	13.46	http://www.phstore.co.uk/insulation/steico/steico-universal.html
52mm Steico Universal	Steico	wood fibre	1	1	1		0.052	13.84	266.15	0.048	12.78	http://www.phstore.co.uk/insulation/steico/steico-universal.html
40mm Steico Therm	Steico	wood fibre	1	1	1		0.04	6.65	166.25	0.039	6.48	http://www.phstore.co.uk/insulation/steico/steico-therm.html
100mm Steico Therm	Steico	wood fibre	1	1	1		0.1	16.1	161.00	0.039	6.28	http://www.phstore.co.uk/insulation/steico/steico-therm.html
40mm Steico Therm internal	Steico	wood fibre	1	1	1		0.04	7.66	191.50	0.039	7.47	http://www.phstore.co.uk/insulation/steico/steico-therm-internal.html
60mm Steico Therm internal	Steico	wood fibre	1	1	1		0.06	11.9	198.33	0.039	7.74	http://www.phstore.co.uk/insulation/steico/steico-therm-internal.html
50mm Steico Flex	Steico	wood fibre		1			0.05	5.41	108.20	0.038	4.11	http://www.phstore.co.uk/insulation/steico/steico-flex.html
140mm Steico Flex	Steico	wood fibre		1			0.14	13.8	98.57	0.038	3.75	http://www.phstore.co.uk/insulation/steico/steico-flex.html
40mm Steico Floor	Steico	wood fibre			1		1.532	318.88	208.15	0.04	8.33	http://www.phstore.co.uk/insulation/steico/steico-floor.html
60mm Steico Floor	Steico	wood			1		1.476	305.34	206.87	0.04	8.27	http://www.phstore.co.uk/insulation/steico/steico-floor.html

		fibre									
40mm Pavatherm	Pavatex	wood fibre	1	1	1	0.02448	3.86	157.68	0.038	5.99	http://www.phstore.co.uk/insulation/nbt-wood-fibre/pavatherm.html
100mm Pavatherm	Pavatex	wood fibre	1	1	1	0.0612	8.62	140.85	0.038	5.35	http://www.phstore.co.uk/insulation/nbt-wood-fibre/pavatherm.html
40mm Pavatherm combi	Pavatex	wood fibre	1	1	1	0.039872	7.76	194.62	0.041	7.98	http://www.phstore.co.uk/insulation/nbt-wood-fibre/pavatherm-combi.html
120mm Pavatherm combi	Pavatex	wood fibre	1	1	1	0.119616	20.46	171.05	0.041	7.01	http://www.phstore.co.uk/insulation/nbt-wood-fibre/pavatherm-combi.html
40mm Diffutherm	Pavatex	wood fibre	1			0.03364	7.25	215.52	0.043	9.27	http://www.phstore.co.uk/insulation/nbt-wood-fibre/diffutherm.html
120mm Diffutherm	Pavatex	wood fibre	1			1.7292	446.4	258.15	0.043	11.10	http://www.phstore.co.uk/insulation/nbt-wood-fibre/diffutherm.html
50mm Pavaflex	Pavatex	wood fibre		1		0.152	14.85	97.70	0.038	3.71	http://www.phstore.co.uk/insulation/nbt-wood-fibre/pavaflex.html
140mm Pavaflex	Pavatex	wood fibre		1		0.1414	17.07	120.72	0.038	4.59	http://www.phstore.co.uk/insulation/nbt-wood-fibre/pavaflex.html

Appendix IV – Extended results of environmental impact

Tables 8 to 19 report the total EEI figures of the baselines and alternative supply scenarios for each envelope type. For the alternative scenarios, only the EEI figures of the 'Small' level of substitution are reported. For new dwellings, only the EEI figures of for the demand scenario 'D1' are reported. All EEI figures reported here are normalised. Total EEI figures obtained by using maximum and minimum EEI figures for single products (used to calculate maximum and minimum ranges) are indicated respectively with 'EI+' and 'EI-'. The supply scenarios are named as follows:

Base.1 - Primary baseline Scenario

Base.2 - Secondary baseline Scenario

Min - Mineral alternative scenario

ShW - Sheep wool alternative scenario

HeF - Hemp fibre alternative scenario

WoF - Wood fibre alternative scenario

Table 8 – EEI figures of the baseline supply scenarios for EWI in retrofitted dwellings

	Base.1	Base.2	Base.1 EI+	Base.1 EI-	Base.2 EI+	Base.2 EI-
PEU	43,135	52,287	61,707	26,703	65,081	28,882
GWP	16,701	16,474	38,485	13,488	38,965	13,312
AP	11,547	7,539	39,184	8,561	27,507	5,002
EP	1,919	1,181	3,726	1,650	3,404	981
POCP	54,118	77,890	121,896	28,501	163,506	40,788

Table 9 – EEI figures of the alternative supply scenarios for EWI in retrofitted dwellings at “small” level of substitution

	Min	ShW	HeF	WoF	Min EI+	ShW EI+	HeF EI+	WoF EI+	Min EI-	ShW EI-	HeF EI-	WoF EI-
PEU	4,705	11,278	12,726	16,391	13,067	16,541	17,932	22,133	3,587	8,453	10,382	13,349
GWP	2,790	-1,055	-4,519	-4,690	6,720	1,453	-7,027	-2,606	1,390	-5,214	-4,225	-6,774
AP	2,976	5,119	2,462	2,370	9,942	7,237	3,527	3,214	2,400	1,275	1,946	1,508
EP	574	6,708	678	550	1,404	10,154	1,100	745	498	301	505	408
POCP	2,928	749	809	1,834	9,289	1,662	1,472	3,060	891	491	498	1,188

Table 10 - EEI figures of the baseline supply scenarios for IWI in retrofitted dwellings

	Base.1	Base.2	Base.1 EI+	Base.1 EI-	Base.2 EI+	Base.2 EI-
PEU	12,868	13,075	18,621	9,823	21,366	9,990
GWP	4,655	5,157	8,470	3,892	11,038	4,527
AP	2,460	2,815	5,884	1,903	7,600	2,144
EP	428	487	853	351	1,171	399
POCP	6,663	6,482	11,474	4,133	11,126	3,793

Table 11 - EEI figures of the alternative supply scenarios for IWI in retrofitted dwellings at “small” level of substitution

	Min	ShW	HeF	WoF	Min EI+	ShW EI+	HeF EI+	WoF EI+	Min EI-	ShW EI-	HeF EI-	WoF EI-
PEU	1,138	2,728	3,079	3,965	3,161	4,001	4,338	5,354	868	2,045	2,511	3,229
GWP	675	-255	-1,093	-1,135	1,625	351	-1,700	-630	336	-1,261	-1,022	-1,639
AP	720	1,238	595	573	2,405	1,751	853	777	581	308	471	365
EP	139	1,623	164	133	340	2,456	266	180	120	73	122	99
POCP	708	181	196	444	2,247	402	356	740	216	119	120	287

Table 12 - EEI figures of the baseline supply scenarios for loft insulation in retrofitted dwellings

	Base.1	Base.1 EI+	Base.1 EI-
PEU	18,644	41,963	12,403
GWP	8,209	21,494	6,131
AP	6,302	21,591	5,043
EP	1,389	3,869	1,162
POCP	14,997	32,076	4,471

Table 13 - EEI figures of the alternative supply scenarios for loft insulation in retrofitted dwellings at “small” level of substitution

	Min	**ShW**	**HeF**	**WoF**	**Min EI+**	**ShW EI+**	**HeF EI+**	**WoF EI+**	**Min EI-**	**ShW EI-**	**HeF EI-**	**WoF EI-**
PEU	2,467	4,348	6,188	10,585	7,354	4,715	6,482	11,539	1,448	3,646	6,098	9,632
GWP	1,145	3,022	-1,379	-1,559	3,586	5,326	-5,449	165	762	-1,381	-123	-3,282
AP	948	5,331	1,954	1,795	3,596	7,714	3,000	2,540	780	778	1,631	1,049
EP	248	8,188	527	355	824	12,393	888	426	205	156	415	285
POCP	2,258	96	172	1,439	4,701	-7	-248	1,727	173	293	302	1,151

Table 14 - EEI figures of the baseline supply scenarios for wall insulation in new dwellings, demand scenario D1

	Base.1	Base.2	Base.1 EI+	Base.1 EI-	Base.2 EI+	Base.2 EI-
PEU	74,269	90,029	106,248	45,978	112,056	49,730
GWP	28,756	28,365	66,264	23,224	67,090	22,921
AP	19,882	12,981	67,467	14,740	47,362	8,612
EP	3,305	2,034	6,416	2,840	5,861	1,690
POCP	93,180	134,111	209,881	49,073	281,525	70,229

Table 15 - EEI figures of the alternative supply scenarios for wall insulation in new dwellings at “small” level of substitution, demand scenario D1

	Min	**ShW**	**HeF**	**WoF**	**Min EI+**	**ShW EI+**	**HeF EI+**	**WoF EI+**	**Min EI-**	**ShW EI-**	**HeF EI-**	**WoF EI-**
PEU	6,318	13,672	16,641	24,153	18,021	18,480	21,331	29,944	4,408	10,614	14,569	20,651
GWP	3,447	1,966	-5,135	-5,485	9,082	6,272	-11,112	-2,048	1,898	-5,725	-3,697	-8,922
AP	3,417	9,384	3,935	3,749	11,821	13,434	5,827	5,186	2,771	1,816	3,193	2,295
EP	721	13,434	1,073	811	1,968	20,334	1,772	1,044	616	402	821	622
POCP	4,614	726	848	2,949	12,313	1,402	1,012	4,267	919	694	708	2,123

Table 16 - EEI figures of the baseline supply scenarios for roof insulation in new dwellings, demand scenario D1

	Base.1	Base.2	Base.1 EI+	Base.1 EI-	Base.2 EI+	Base.2 EI-
PEU	51,538	61,988	105,525	36,869	117,393	47,272
GWP	22,259	28,022	55,269	18,096	64,963	23,725
AP	15,146	19,977	48,640	11,909	61,216	15,600
EP	3,091	3,665	8,431	2,568	8,195	3,084
POCP	32,523	32,053	64,720	12,186	67,947	15,503

Table 17 - EEI figures of the alternative supply scenarios for roof insulation in new dwellings at “small” level of substitution, demand scenario D1

	Min	**ShW**	**HeF**	**WoF**	**Min EI+**	**ShW EI+**	**HeF EI+**	**WoF EI+**	**Min EI-**	**ShW EI-**	**HeF EI-**	**WoF EI-**
PEU	5,872	12,664	15,454	22,512	16,764	17,066	19,745	27,838	4,084	9,844	13,560	19,275
GWP	3,195	1,927	-4,745	-5,075	8,443	5,957	-10,377	-1,861	1,765	-5,284	-3,378	-8,288
AP	3,159	8,795	3,676	3,501	10,942	12,596	5,448	4,846	2,562	1,691	2,985	2,141
EP	668	12,617	1,002	756	1,832	19,097	1,656	971	571	374	767	580
POCP	4,309	666	782	2,755	11,439	1,278	913	3,971	846	646	659	1,989

Table 18 - EEI figures of the baseline supply scenarios for ground floor insulation in new dwellings, demand scenario D1

	Base.1	Base.2	Base.1 EI+	Base.1 EI-	Base.2 EI+	Base.2 EI-
PEU	42,012	40,264	72,491	32,961	62,739	28,245
GWP	17,161	15,035	38,537	15,625	34,405	13,253
AP	8,972	7,421	24,064	6,780	21,781	5,408
EP	1,530	1,241	4,059	1,239	3,455	1,008
POCP	16,152	31,166	23,540	9,811	58,493	17,101

Table 19 - EEI figures of the alternative supply scenarios for ground floor insulation in new dwellings at “small” level of substitution, demand scenario D1

	Min	**ShW**	**HeF**	**WoF**	**Min EI+**	**ShW EI+**	**HeF EI+**	**WoF EI+**	**Min EI-**	**ShW EI-**	**HeF EI-**	**WoF EI-**
PEU	2,811	2,670	3,800	19,223	7,930	2,896	3,981	27,777	2,037	2,239	3,744	14,989
GWP	1,590	1,856	-847	-6,471	4,030	3,271	-3,346	-4,277	839	-848	-76	-8,666
AP	1,628	3,274	1,200	2,606	5,545	4,737	1,842	3,462	1,317	478	1,002	1,719
EP	330	5,028	323	646	860	7,610	545	910	284	96	255	464
POCP	1,926	59	106	1,982	5,508	-4	-153	3,753	461	180	185	1,140

Appendix V – Benchmarking EEI against LCA sources

Stone wool

The EEI figures used in this research to represent conventional stone wool insulation are compared (on a FU basis) to the results found in the available sources in the following Figures

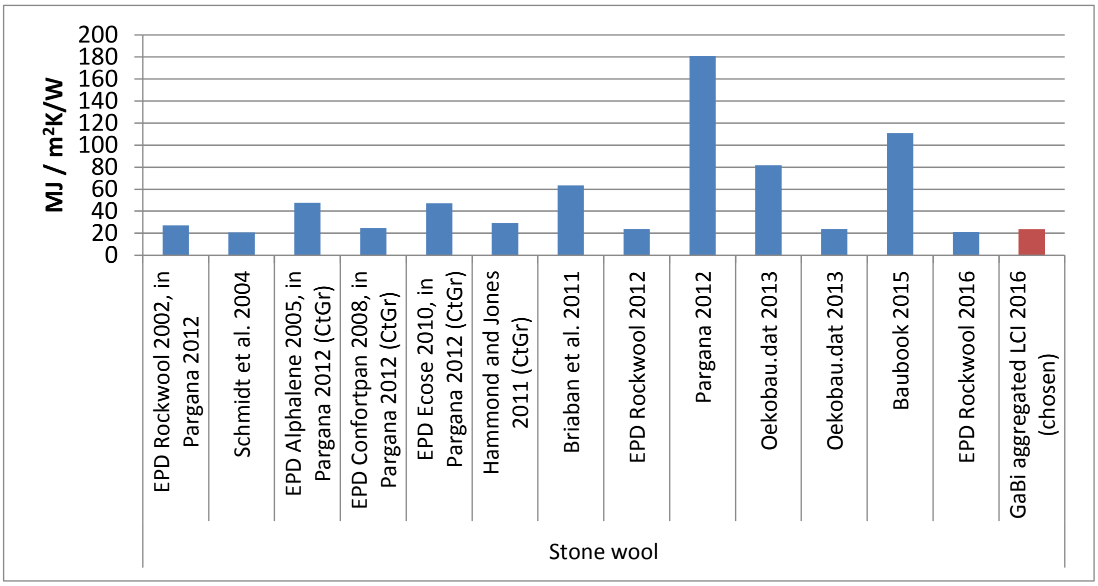

Figure 1 – Comparison between the PEU used in this research for stone wool and the results of other LCA studies

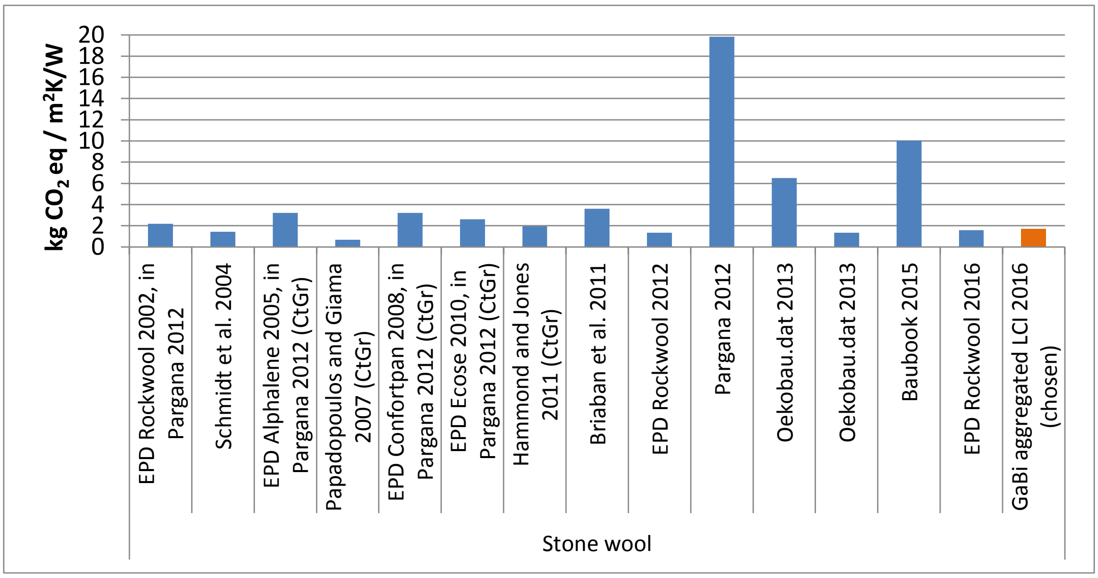

Figure 2 - Comparison between the GWP used in this research for stone wool and the results of other LCA studies

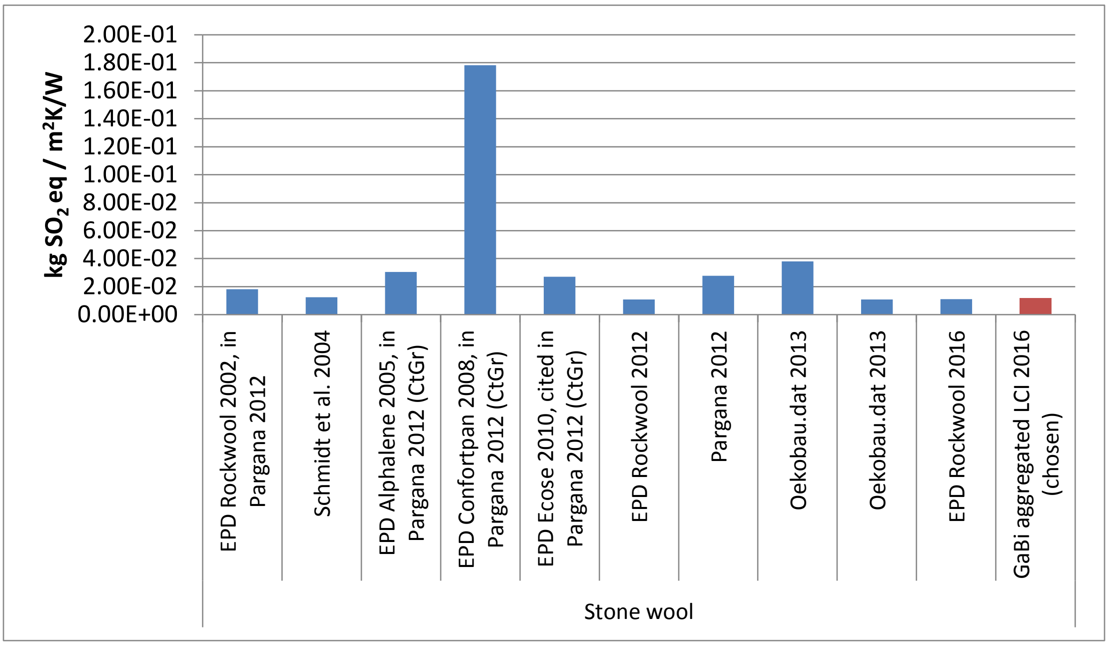

Figure 3 - Comparison between the AP used in this research for stone wool and the results of other LCA studies

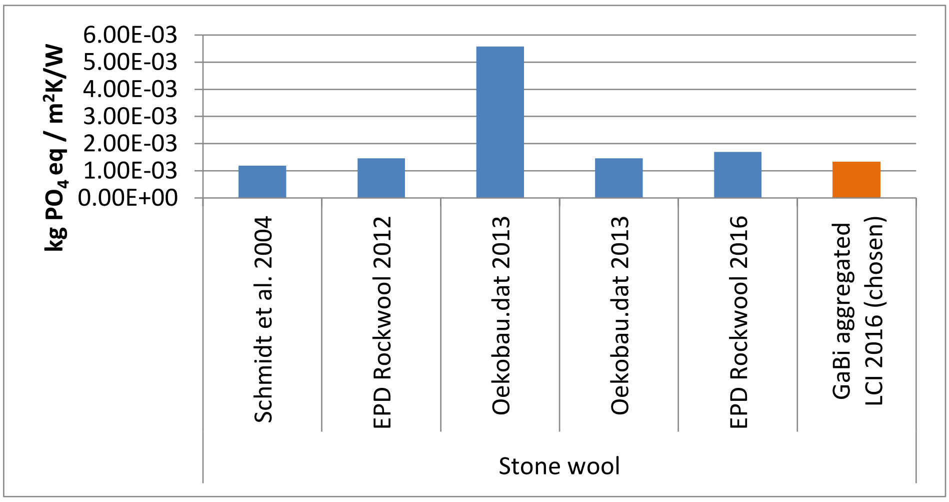

Figure 4 - Comparison between the EP used in this research for stone wool and the results of other LCA studies

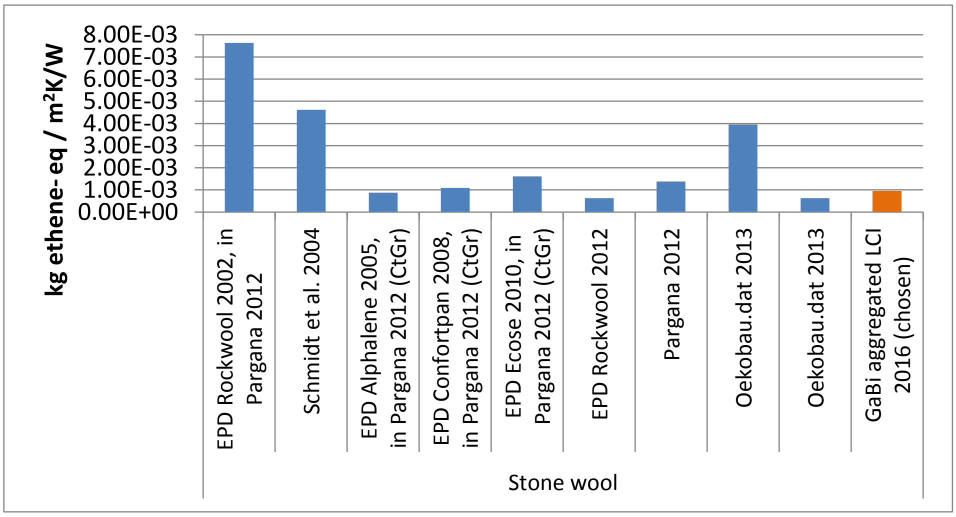

Figure 5 – Comparison between the POCP used in this research for stone wool and the results of other LCA studies

Glass wool

The EEI figures for glass wool insulation (Knauf, 2015) are compared (on a FU basis) to figures found in existing sources in the following Figures.

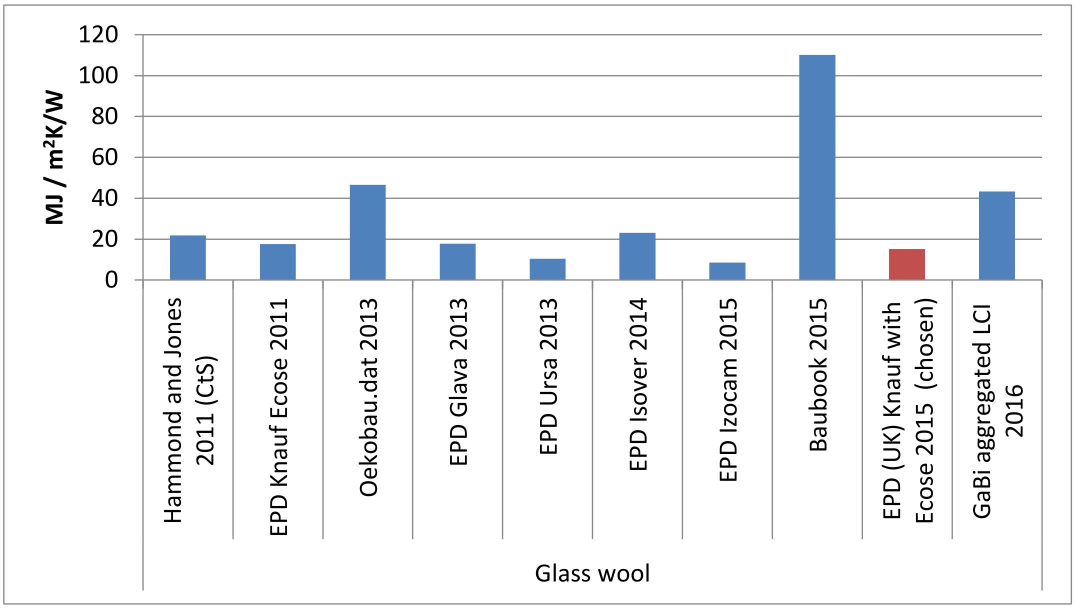

Figure 6 - Comparison between the PEU used in this research for glass wool and the results of other LCA studies

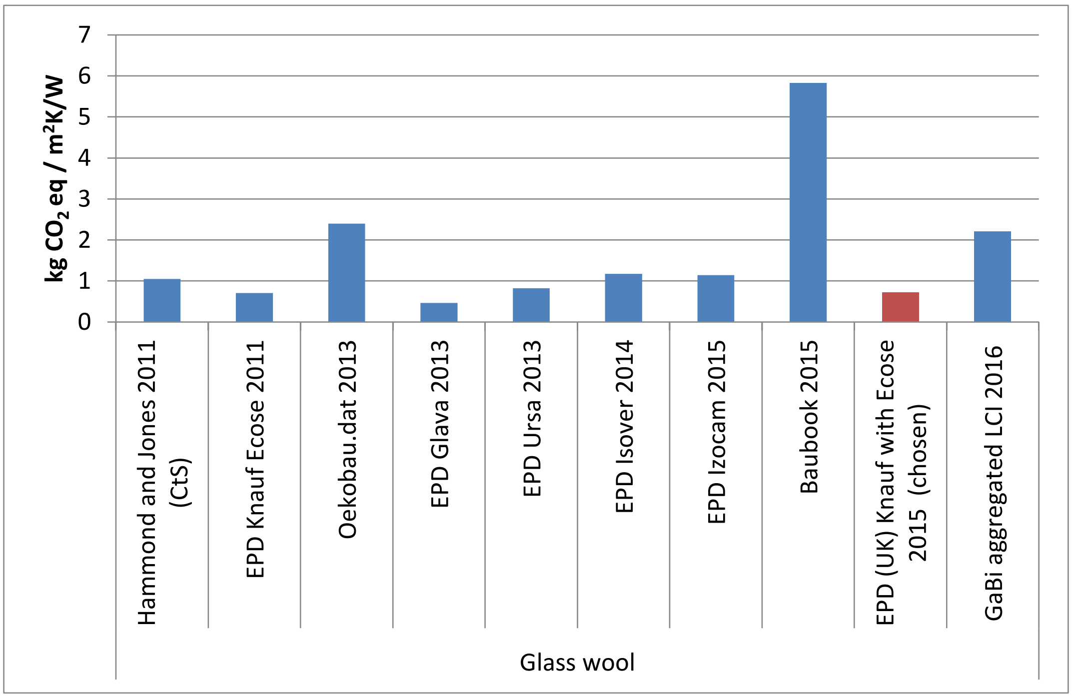

Figure 7 - Comparison between the GWP used in this research for glass wool and the results of other LCA studies

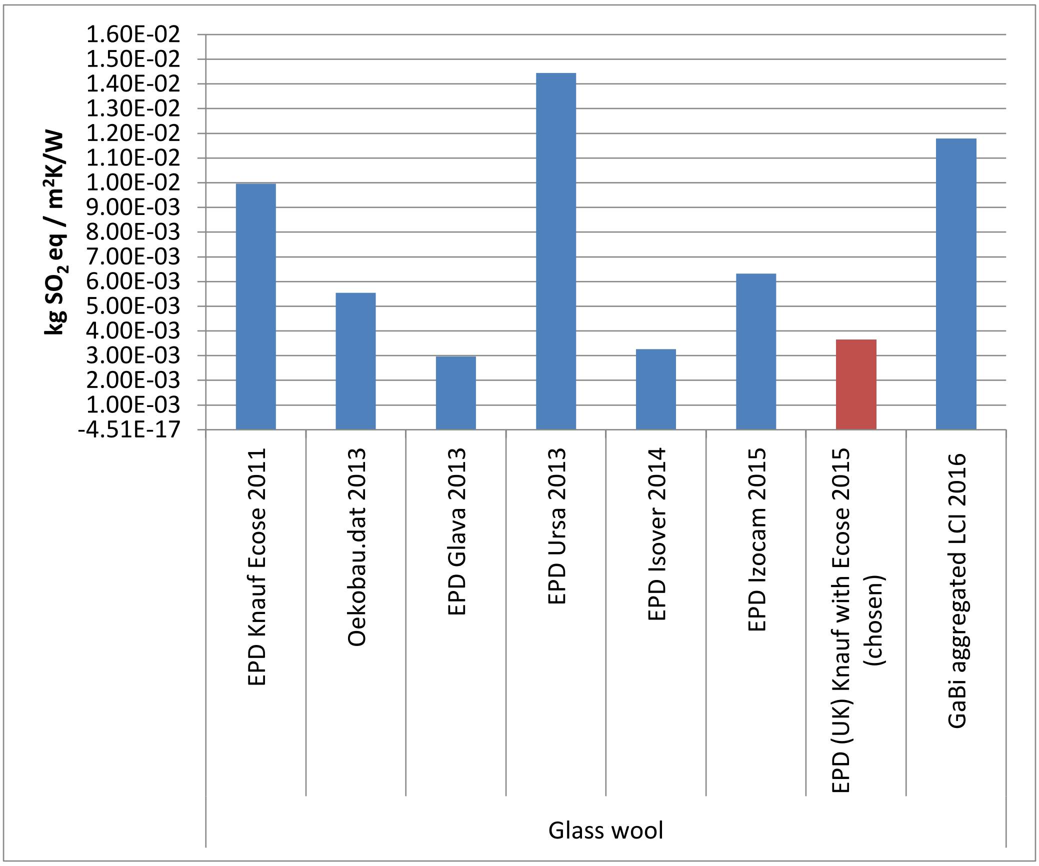

Figure 8 - Comparison between the AP used in this research for glass wool and the results of other LCA studies

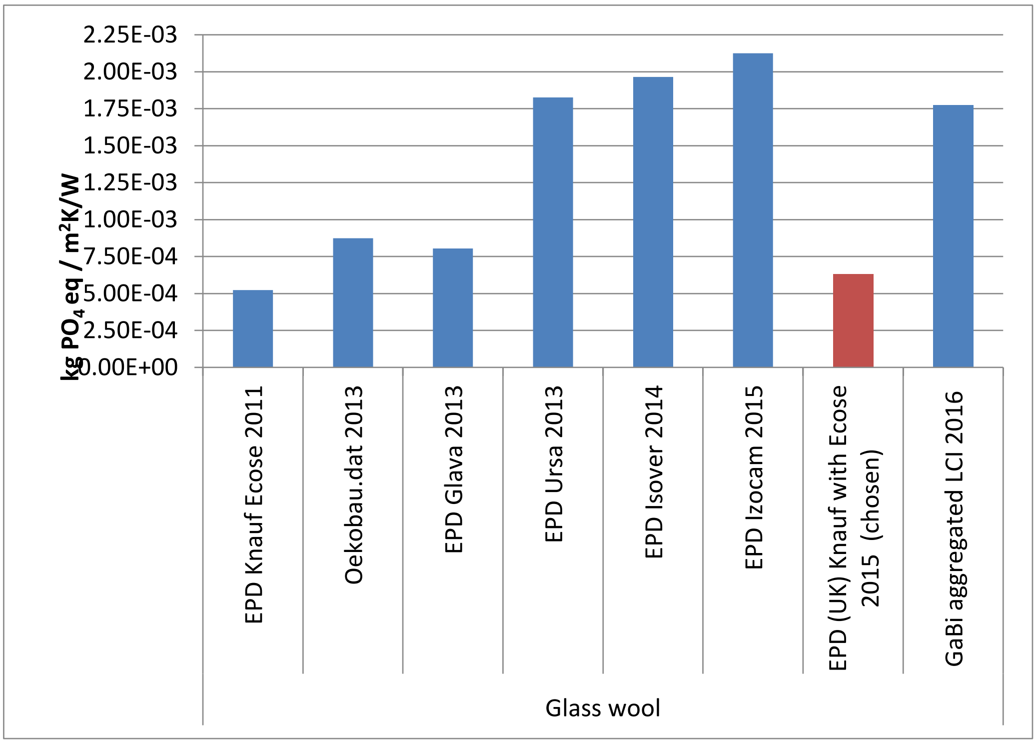

Figure 9 - Comparison between the EP used in this research for glass wool and the results of other LCA studies

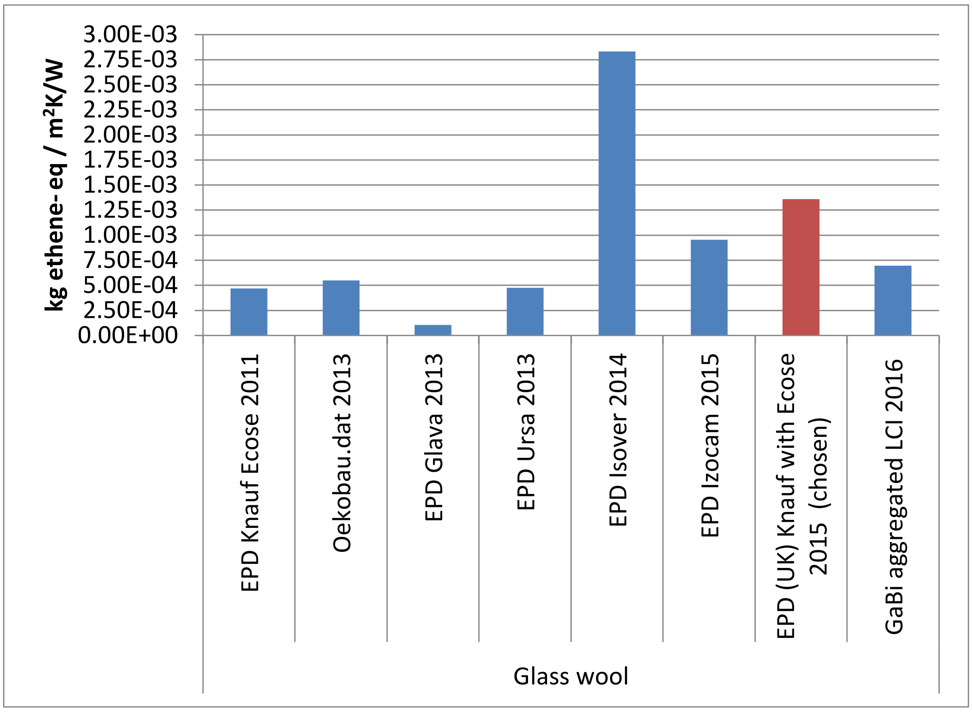

Figure 10 - Comparison between the POCP used in this research for glass wool and the results of other LCA studies

EPS

The EEI figures used in this research for EPS products (Thinkstep, 2016a) are compared (on a FU basis) to the figures found in the existing studies in the following Figures.

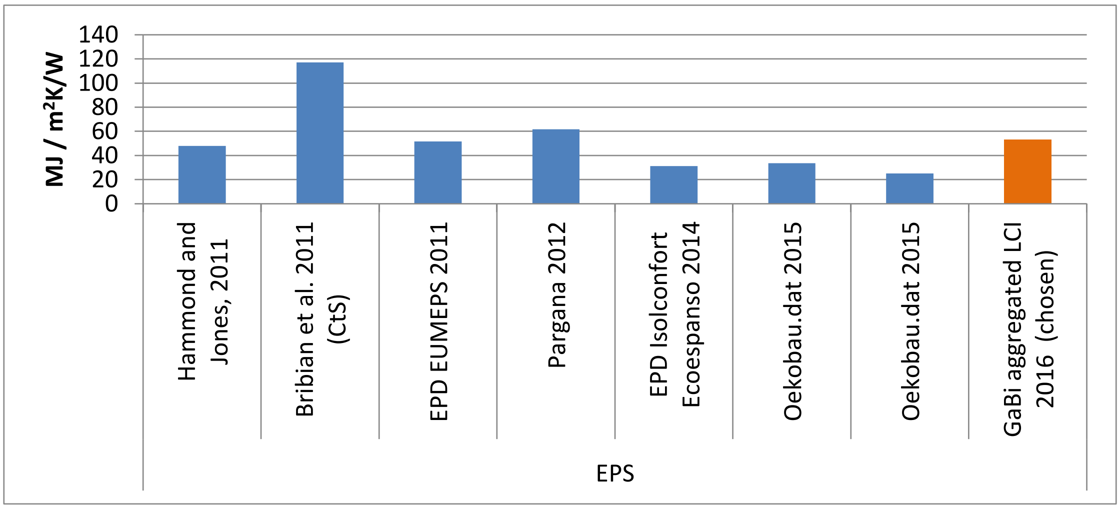

Figure 11 - Comparison between the PEU used in this research for EPS and the results of other LCA studies

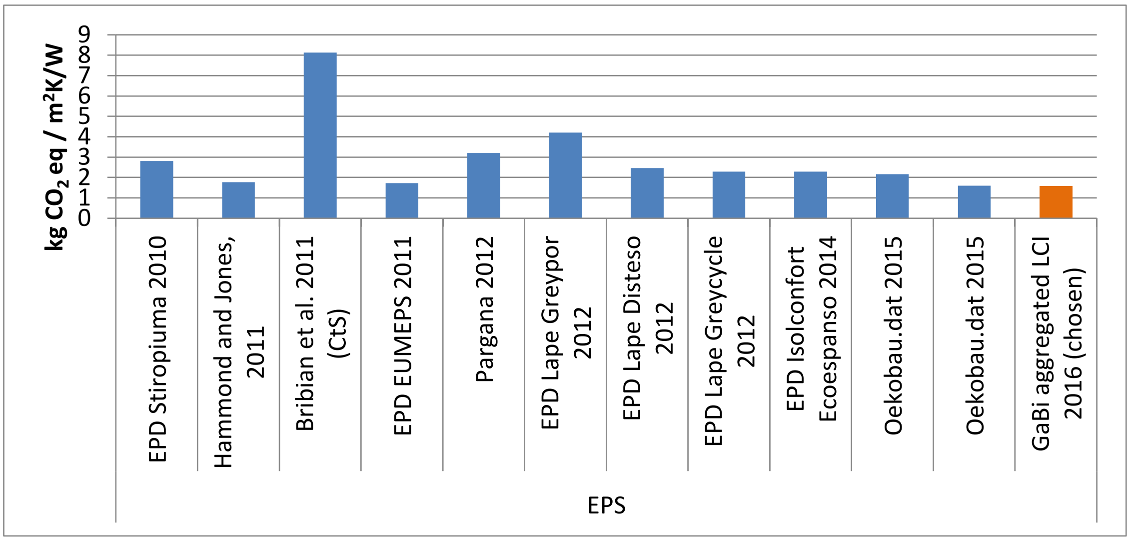

Figure 12 - Comparison between the GWP used in this research for EPS and the results of other LCA studies

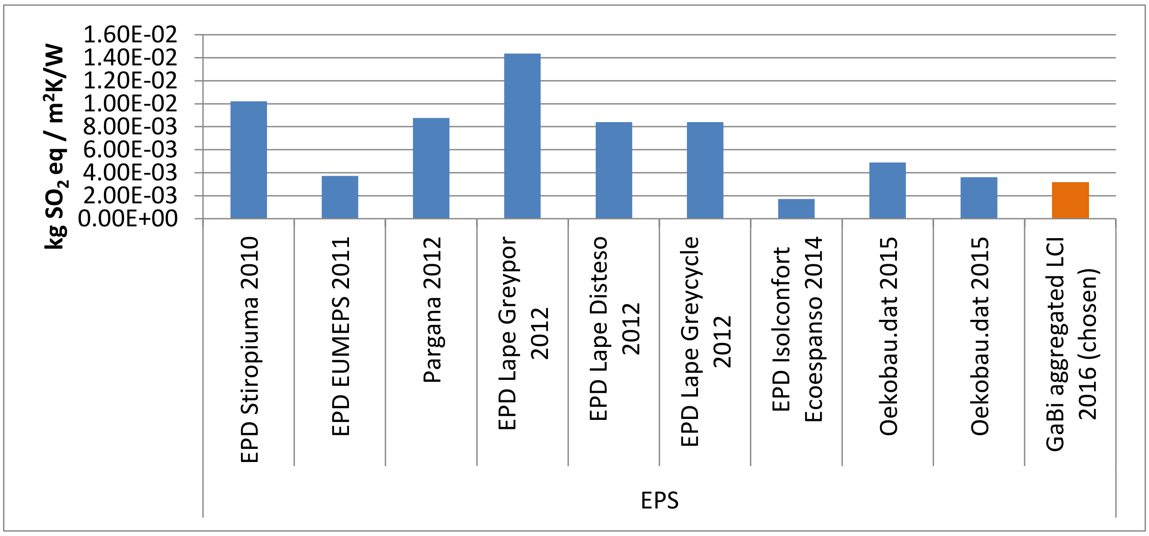

Figure 13 - Comparison between the AP used in this research for EPS and the results of other LCA studies

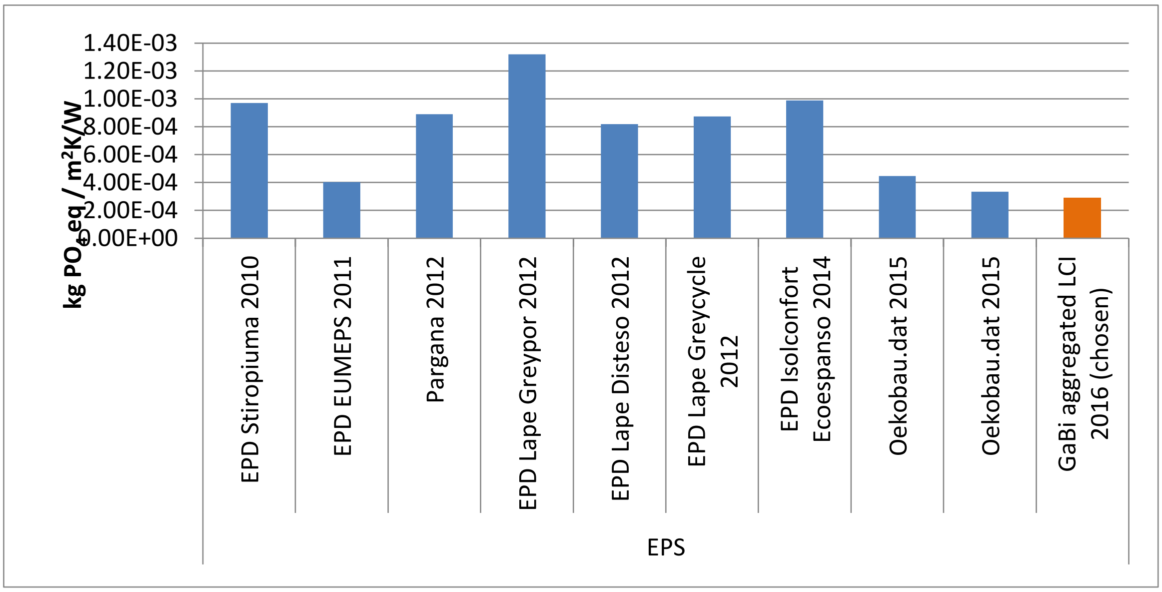

Figure 14 - Comparison between the EP used in this research for EPS and the results of other LCA studies

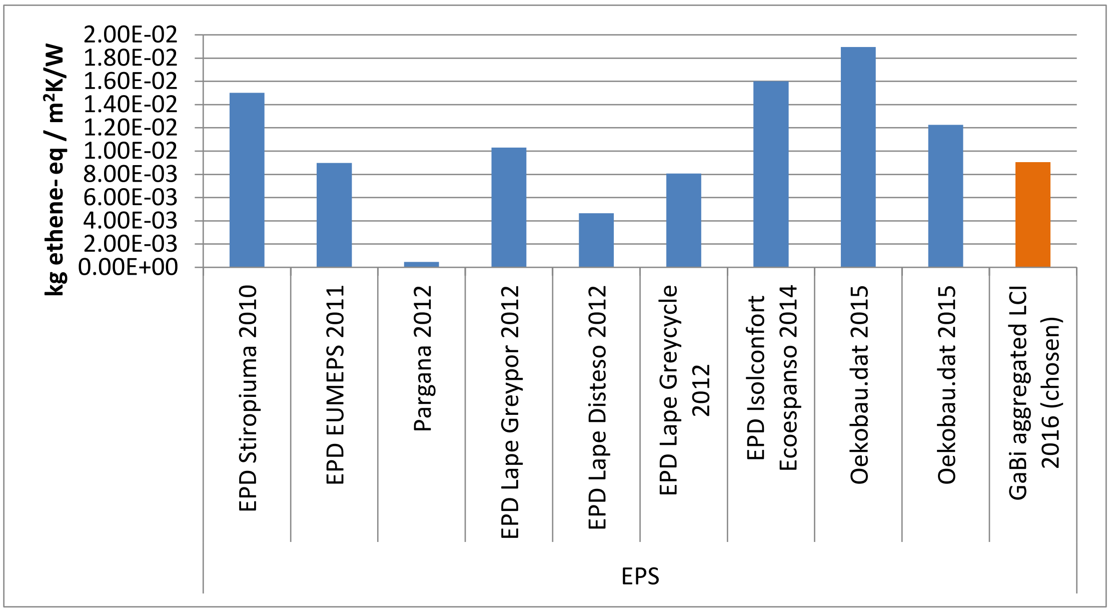

Figure 15 - Comparison between the PEU used in this research for POCP and the results of other LCA studies

PUR and phenolic foam

The EEI figures used in this research for PUR and phenolic products are compared (on a FU basis) to figures found in existing studies from

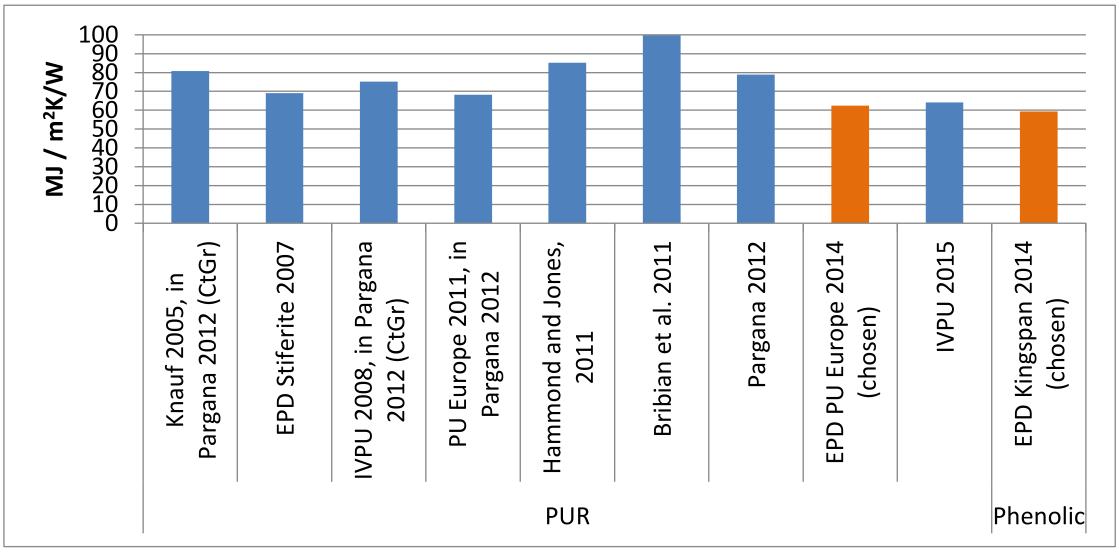

Figure 16 - Comparison between the PEU used in this research for PUR and phenolic products and the results of other LCA studies

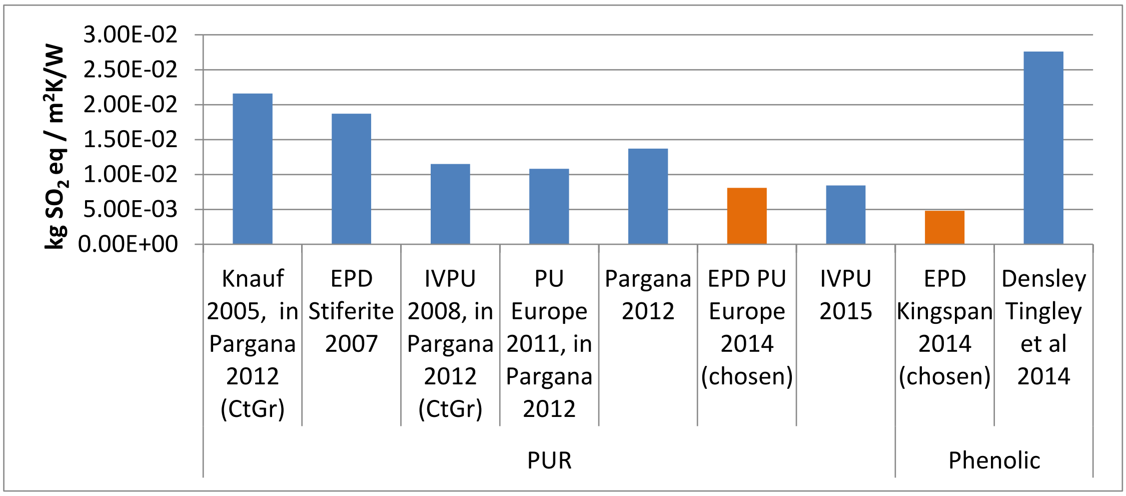

Figure 17 – Comparison between the GWP used in this research for PUR and phenolic products and the results of other LCA studies

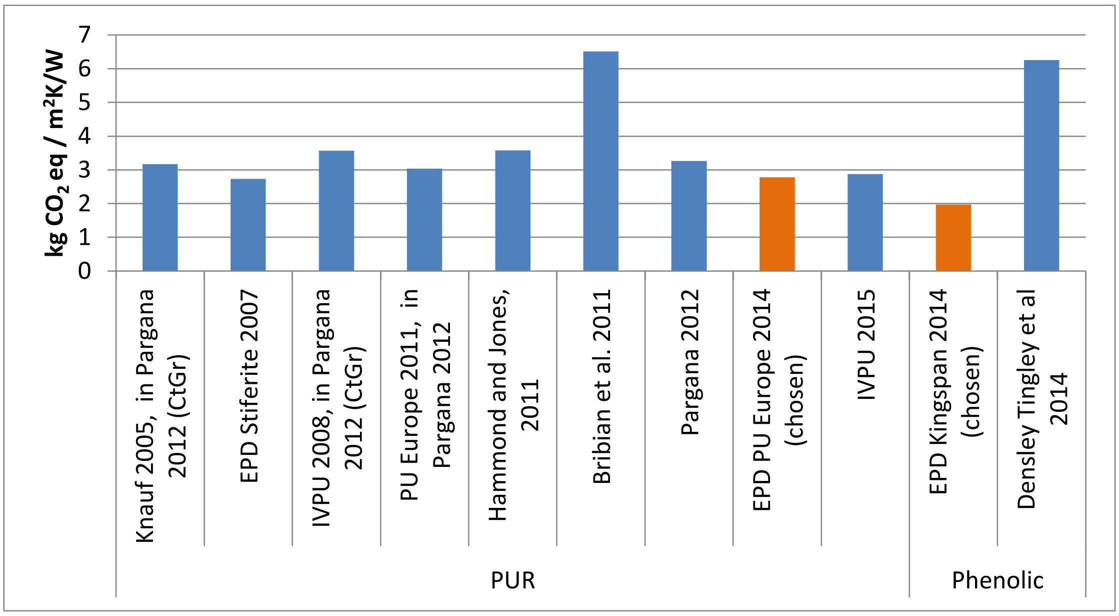

Figure 18 – Comparison between the AP used in this research for PUR and phenolic products and the results of other LCA studies

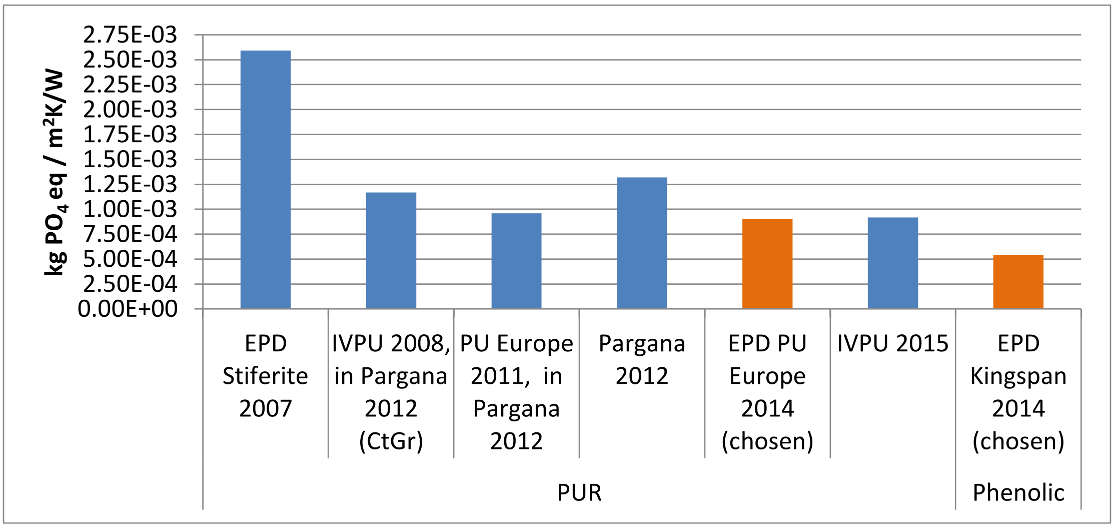

Figure 19 – Comparison between the EP used in this research for PUR and phenolic products and the results of other LCA studies

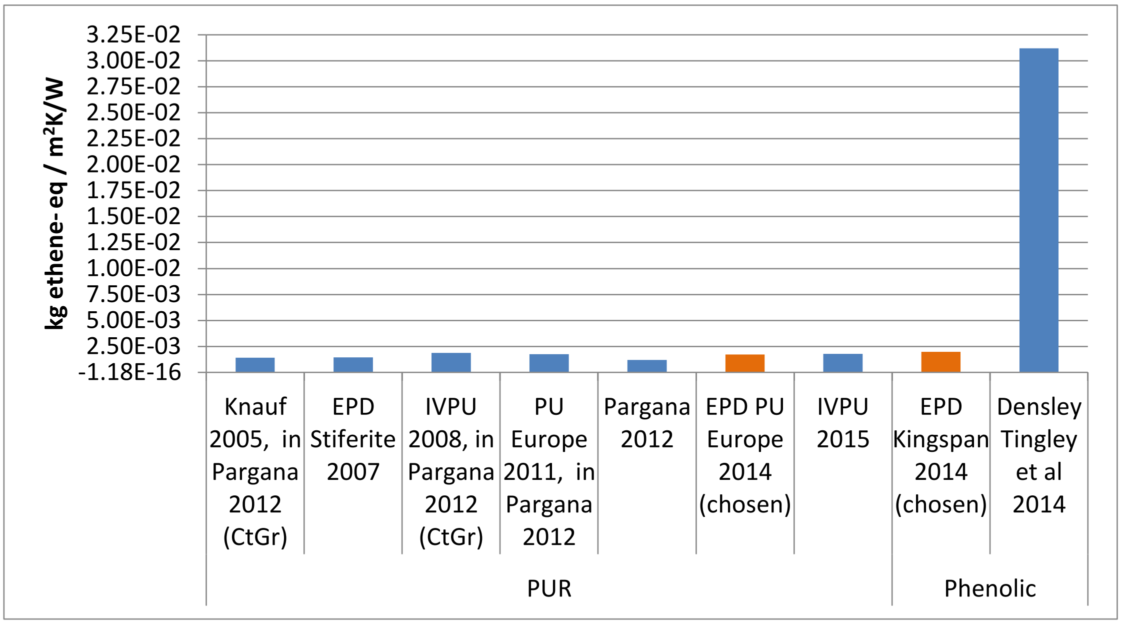

Figure 20 – Comparison between the POCP used in this research for PUR and phenolic products and the results of other LCA studies