Embodied Energy Data implications for Optimal Specification of Building Envelopes

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Abstract

Highly insulated building envelopes have become more commonplace as environmental imperatives require reduction of building carbon footprints. Whilst increased insulation levels reduce operational energy demand, the additional embodied energy investment can increase the buildings' overall environmental impact. The embodied energy consideration can determine whether, and to what extent, additional insulation is justified. The following paper investigates the impact of uncertainties of embodied energy data on the cumulative operational and embodied energy analyses and holistically appraises its implications for different stakeholders involved with the construction sector. Limitations in current LCA calculation methods and high uncertainty of available data are recognised and reflected in the analyses through studying available EPDs of various types of insulation materials and by modelling a typical semi-detached residential building in the UK as the case study. The results of such approach illustrate 'optimum insulation thicknesses' beyond which the embodied energy penalty outweighs operational energy savings. These essentially represent idealised levels of building envelope insulation that can inform the development of future standards for low energy/carbon buildings and support the adoption of LCAs as decision making tools in informing the urgent debate of optimal insulation requirements of buildings.

Keywords: Building Regulations; Building Envelope; Embodied Energy; Life Cycle Assessment; Insulation sector; Combined Operational and Embodied Carbon

Introduction

This paper seeks to highlight the implications of uncertainties/inconsistencies associated with embodied energy data generated from LCA analyses for the building construction industry and its impact on informing related policies and standards. Historically, the international building standards approach to low energy design have consistently sought to reduce the energy burdens by requiring better standards of operational energy efficiency. The background to this approach is relatively clear and is essentially one where the biggest and most serious energy issues were addressed first. In the 1980s when carbon emissions came under increased scrutiny, the operational energy of buildings (the energy used to operate heating and cooling and lighting systems) was assumed to be around ten times greater than the embodied energy (the energy invested into building materials) (Koezjakov, Urge-Vorsatz, Crijns-Graus, & van den Broek, 2018). It was, therefore, reasonable that this was given priority. This trend has been cemented in the UK and other countries around the world, for example, by statutory requirements that have progressively required lower building envelope U-values with every successive iteration of Building Regulations (Table 1).

[Table 1 near here]

Hence relatively little attention has been given to embodied energy contribution (Anastaselos, Giama & Papadopoulos (2009), Ramesh, Prakash & Shukla (2010), Hafliger et al. (2017), Szalay (2007)). However, as building energy efficiencies have improved, the 'embodied: operational' energy ratio has shifted very considerably (Cole and Fedoruk, 2014). Regulatory requirements and the increased use of renewable energy sources have reduced operational energy supply from the grid whilst embodied energy has increased due to increased quantities of insulation and energy efficiency measures. This trend is set to continue and so future low and zero energy buildings look highly likely to achieve relative parity between operational and embodied energy or even embodied energy exceeding operational energy (Figure 1) (RICS, 2012).

[Figure 1 near here]

A significant number of studies have demonstrated the crucial impact that the embodied energy contribution can have on buildings' overall energy consumption. Sartori and Hestnes (2007) demonstrated in their study that, while highly insulated buildings benefit from reduced overall operational energy demand, higher embodied energy burdens would be unavoidable. Their findings concluded that embodied energy values were up to 46% of the overall energy consumption for low-energy buildings. Thormak (2002) has also studied energy efficient buildings in Sweden and concluded that over a 50 year design life, the embodied energy contribution was up to 40% of the overall life cycle energy consumption. Kristjansdottir et al., (2017) demonstrated in their research for Norwegian zero energy buildings that embodied impacts were up to 75%. According to the RICS Information Paper '*Methodology to Calculate the Embodied Carbon of Materials*', the embodied energy of materials and products accounted for more than a third of the total energy consumption associated with housing over a 30 year service life. Similarly, the ratio of embodied to operational energy for office buildings is shown to be around 1:3, and for typical supermarkets 1:5. On a global or national scale, the materials' embodied energy can be much higher than 30% of the total energy demand of the building sector, due to a growing population and hence a growing demand for buildings (Treloar, Love & Holt. 2001). The embodied energy contribution in this context has been addressed in several other studies including Dixit (2017), Chau, Leung & Ng (2015), Stephan, Crawford & Myttenaere (2013), Gustavsson and Joelsson (2010) and many more.

The desire and attempt to quantify the environmental impact of buildings through life cycle assessment (LCA) analyses in recent years has resulted in various environmental certification systems such as the Environmental Product Declaration (EPD) (Tettey, Dodoo & Gustavsson, 2014). EPDs are type III environmental declarations based on European standard's core product category rules (PCR) and are intended to independently verify documents which transparently and accurately communicate the environmental impact of different products in compliance with EN 15804 and ISO 14025.

According to the EN 15804, the core PCRs define:

- The parameters to be declared and reported,
- Stages and processes of a product's life cycle considered in the EPD (the information modules groups A1-A3, A4-A5, B1-B5, B6-B7, C1-C4 and module D if included),
- Scenarios development rules and those for calculating the Life cycle Inventory (LCI) (detailed tracking of all the flows in and out of the product system, including raw resources or materials, energy by type, water, and emissions to air, water and land by specific substance) (Athenasmi.org, 2018) and,
- LCIA (environmental impact analysis of the LCI).

The current French and Belgian legislations in Europe and LEED rating system in the US are also good examples of the move to mandate consideration of embodied energy and the disclosure of Environmental Product Declarations for construction materials. This is still relatively obscure in Europe (manufacturers are only obliged to carry out an LCA if they include an environment message on their product), but it is a major step towards regulating embodied energy in buildings (Eurima, 2017). Other examples of gradual regulation of embodied energy include Austrian, the Netherlands and German legislation within Europe. The Australian National Construction Code, although recognises the issue of embodied energy, focuses on operational energy only. There are also several databases and inventories around the world that intend to facilitate the consideration of embodied energy in the construction sector including BRE's Green Guide and the Inventory of Carbon and Energy (ICE) developed at the University of Bath in the UK, the US National Renewable Energy Laboratory's U.S. Life Cycle Inventory Database and the Canadian Athena Sustainable Materials Institute's Building Material Life Cycle Inventory Database.

Despite improvements, embodied energy is currently not comprehensively regulated. This situation has been analysed from different points of view in the literature including mainly difficulties around the reliability and consistency of existing embodied energy data used to perform LCA analysis, and inconsistent modelling methodologies generating outputs with high level of uncertainty. The following section investigates the challenges LCA approach is facing at present in relation to data reliability and methodological choices and lays the foundation for further analyses presented in the ‘Results and Discussions’ section.

Methodological Challenges Associated with LCA Studies

In theory the EPDs using common PCRs should facilitate effective comparison between different building materials in terms of their environmental impact. In practice however, while it may be possible to make choices based upon the environmental impacts associated with different stages and processes considered in the EPDs, the assumptions adopted in model such as the service life of the product, maintenance requirements especially with respect to the impact on the operating energy of the building and different system boundary choices can consequently have a critical impact upon the outcome of the LCA results (Hill and Zimmer, 2018).

LCA is an intensively data-driven approach which relies on availability of adequate and high quality data (Takano, Hughes & Winter, 2014). Finding reliable data however has been an issue for LCA practitioners (De Wolf, Pomponi & Moncaster, 2017). This lack of availability of consistent data can be associated with confidentiality issues for manufacturers, the time consuming process of generating reliable data and different methodological approaches to data treatment (Soust-Verdaguer, Llatas & Garcia-Martinez (2016), Lotteau, Loubet, Pousse, Dufrasnes & Sonnemann (2015)). This is also confirmed in Moncaster and Song (2012) technical paper which associated the wide range of calculated embodied energy values with the use of different LCA methodologies, different boundaries and often for specific manufacturers, which are therefore non-comparable; different calculation methodologies for the LCA of the whole building; and different building construction and designs. The UK Green Building Council 2015 report ‘Tackling Embodied Carbon From Buildings’ states that the complexity of embodied energy data arises from the fact that sources of accurate and exhaustive data are based on different parameters of assessment. It is also stated that according to EN 15804, the information module approach for materials/products can consider different life cycle stages i.e. ‘cradle to gate’, ‘cradle to gate with options’ and ‘cradle to grave’, which adds to the inconsistency of results.

The methodological differences are well studied in the literature and are associated with several factors including functional units (Cabeza, Rincón, Vilariño, Pérez & Castell, 2006), system boundaries (Silvestre, De Brito & Pinheiro (2014), Rauf and Crawford (2015)), the LCI databases (Takano et al 2014, Anand and Amor 2017) and those used for the End-of-Life (EoL) modelling (Frischknecht, 2010). Soust-Verdaguer et al (2016) state in their study that procedures such as ISO 14040, EN 15804 or ISO 13315, although limit these modelling choices, do not facilitate mechanisms to ensure consistency. De Wolf et al. (2017) reviewed several studies highlighting the inconsistencies associated with available LCA data. For example, Clark (2013) reviewed calculations for embodied CO_2eq for office buildings using different methodologies and presented a broad range of results from 300 to 1650 kgCO_2eq/m^2 and Eaton and Amato (1998) who in a similar approach compared embodied CO_2eq of steel, composite, reinforced and precast concrete office buildings, demonstrating a wide range of results from 200 to 350 $kgCO_2eq/m^2$ for the structure and between 600 and 850 $kgCO_2eq/m^2$ for the whole building.

The LCI techniques are also heavily referenced in the literature as the discrepancies associated with data generated using different LCI techniques for the same case study are considerable. The available LCI techniques include process, input-output and hybrid methods. Process analysis is formulated by breaking down the life cycle of a product into a series of representative processes. The production process data are collected from manufacturers or rely on existing databases such as ecoinvent and GaBi. The data generated using process analysis however is known to suffer from the 'truncation error' which can considerably underrepresent requirements (Crawford (2008), Crawford, Bontinck, Stephan, Wiedmann & Yu (2018), Lenzen (2000), Majeau-Bettez, Strømman & Hertwich (2011)). Input – output technique considers matrices of all financial transactions between different sectors assigning an energy intensity value to each sector (Stephan et al., 2013). The embodied energy values can be calculated on that basis using their price and energy intensity accordingly, although this correlation needs to be holistically studied in more detail (Dixit (2016) and Jiao, Lloyd & Wakes (2012)). The input–output analysis is also criticised for assigning the same energy intensity value to all products within a sector, known as the aggregation error (Säynäjoki, Heinonen, Junnila & Horvath, 2017). Hybrid analysis combines the two techniques and aims to eliminate the shortcomings of the two methods (Stephan et al., 2013).

The studies relying on process analysis do not consider environmental impacts associated with inputs and outputs located outside the system boundaries. For instance, in their studies on whole buildings, Crawford (2011), Stephan et al. (2013) and Stephan and Stephan (2014) have demonstrated that input-output-based hybrid analysis can produce embodied energy figures four times higher than process-based analysis, for the same building. Similarly, Wiedmann et al. (2011) studied wind turbines in the UK using process and hybrid analysis. They found that hybrid analysis data resulted in environmental impacts double that when using process data. Bontinck, Crawford & Stephan (2017) have studied SIPS panels using hybrid technique with the hybrid coefficient calculated for these panels was composed of 25% process and 75% input-output data. The resulting hybrid coefficient was demonstrated as 159% higher than its process equivalent and 46% lower than its input-output equivalent. Guan, Zhang & Chu (2016) also demonstrate a 100% gap between the process and hybrid LCAs for a building in China. Findings similar to the examples presented are also confirmed in Lenzen and Dey (2000), Omar, Doh, Panuwatwanich & Miller (2014) and Jiang, Li, Liu, Zhang & Ren (2014).

Discrepancies of this nature simply draw attention to the fact that inconsistencies associated with LCA results can have significant implications for its end users when using it as a decision making tool to assist in the early stages of building design, informing policy or planning future strategies for different stakeholders.

Gelowitz and McArthur (2017) conducted a review of published EPDs for building products and came to the following conclusions:

- Discrepancies between life cycle inventory methodology, environmental indicators and life cycle inventory databases were a barrier to making comparisons between EPDs;
- There was a high level of incomparability between EPDs using the same PCR, which was unexpected and should not occur;
- There was evidence of poor verification practices, demonstrated by a high proportion of EPDs containing contradictory data;

The EN 15804 harmonisation standard has not been entirely successful. The proportion of valid comparisons was much higher with EN 15804-compliant EPDs, but the overall level of comparability was still low.

Several studies have been conducted considering the uncertainties associated with embodied energy data ranging from introducing simplified approaches (Soust-Verdaguer et al, 2016), data uncertainty analysis (Groen, Heijungs, Bokkers & De Boer, 2014) and building element sensitivity analysis to changes (cellura, Longo & Mistretta (2011), Hafliger et al (2017)). These studies can be used to provide a valuable basis for the application of LCA analyses to inform decision making, and communicate findings more meaningfully. LCA by its nature is a tool for assessing the environmental impact of products and services and should be adopted in a way that supports industry and policymakers in making reasonable decisions concerning products, processes and environmental strategies.

Despite all the studies carried out to support the LCA concept, the LCA based decision making is currently mainly limited to academic research (Anand and Amor, 2016), and is not widely adopted by industries (Eurima, 2017). This is attributed in the literature to various factors including the lack of integration of LCA methodologies in commonly used building related tools (Anand and Amor (2016), Means and Guggemos (2015)), the high level of expertise required to undertake LCA analyses (Means and Guggemos, 2015) and the priority level LCA holds for different stakeholders (Han and Srebric, 2015). This lack of adoption may mean that environmental strategies and many of the assumptions on which regulations are based, may not truly reflect energy and its subsequent carbon burdens. For example, it is questionable as to whether currently accepted definitions of ‘low energy’ as meaning ‘low operational energy’, as opposed to ‘low combined operational and embodied energy’, are strategically acceptable in terms of future policy. This has been studied by several researchers including Chastas, Theodosiou, Bikas & Kontoleon (2017), cellura, Guarino, Longo & Mistretta (2014) and Moran, Goggins & Hajdukiewicz (2017).

The majority of the existing LCA studies reviewed, address buildings as a whole without focusing on individual building elements, however the following research seeks to use the LCA findings to inform policy makers and manufacturers of building products and materials directly with clear messages. This study, based on a combined operational and embodied energy analysis, demonstrates the effect that uncertainties associated with LCA results can have on informing the end users of LCA as a design tool within the construction sector with a specific view of individual building elements and materials. The presented analysis can uniquely assist the policy makers, building designers and product developers to develop a practical understanding of their offerings and foresee the environmental and financial (in a wider context) implications associated with their services. This is demonstrated through analysing the sensitivity of optimum environmental design of building's thermal envelope to the uncertainties of embodied energy data. The analyses are demonstrated in the context of UK domestic dwellings but are not limited to it and are applicable to the wider international context. The study in particular uses insulation materials as case study examples given that Insulation materials have been referred to in the literature as one of the key building materials affecting the uncertainties associated with buildings' environmental impacts (Hoxha, Habert, Lasvaux, Chevalier & Le Roy, 2017). Hafliger et al (2017) also listed insulation materials alongside wood products, windows and doors as building elements demonstrating a strong sensitivity to embodied energy calculation choices.

Methodology

The methodology section comprises three main topics of operational energy (including the case study building), the embodied energy data sources and the associated combined operational and embodied carbon (total carbon curve).

Operational Energy/Carbon Data

According to the UK Office for National statistics, 26% of the UK existing houses are semi-detached with the trend applicable to the new build dwellings. Hence, a typical three bedroom semi-detached with a total floor area of approximately 80m^2 has been used for the analyses as demonstrated in Figure 2. The analyses were carried out using EnergyPlus based dynamic thermal simulation software. The ratio of roof to wall insulation thicknesses (and U-values) is the same as that of the backstop values in current UK Building Regulations (reflecting the higher heat losses that occur through roofs compared to walls). The case study building is in accordance with the UK's latest Building Regulations as presented in L1A Conservation of fuel and power in new dwellings (2013) document. Other simulation assumptions are as presented in Table 2. The analysis uses the external walls as the varying element and assumes a fixed U-value for all other building elements. The analysis is applied to the new build dwellings but is applicable to retrofit cases with appropriate adjustments made to the assumptions such as service life maintenance and other limitations associated with existing buildings.

[Figure 2 near here]
[Table 2 near here]

A conventional brick and block with filled cavity wall layout has been used for the case study as presented in Figure 3. The structural and other wall layout layers except insulation are fixed and the insulation materials' impacts in terms of embodied energy and carbon are investigated for different thicknesses.

[Figure 3 near here]

Embodied Energy/Carbon Data

The Global Building Thermal Insulation market is accounted for $24.65 billion in 2015 and is expected to reach $34.41 billion by 2022. Mineral and glass wool insulation account for largest market share globally with plastic foam witnessing highest growth (Trent, 2019). According to Trent (2019), the Insulation materials with the highest market share within the construction sector are the following materials: Expanded Polystyrene (EPS), Polyurethane Foams (PU), Extruded Polystyrene (XPS), other Plastic Foams, Phenolic Foams (PF), Polyisocyanurate Insulation (PIR), Mineral Wool (MW), Glass Wool (GW). This study therefore included these materials in addition to two other types including Cellulose based insulations (CEL) and novel materials at the verge of upscaling such as Vacuum Insulation Panels (VIP) for the analyses.

A considerable number of EPDs have been studied for these insulation types and filtered into 66 EPDs used directly in the analysis based on their consistency and applicability to building applications. Most EPDs were available from the operators' websites including IBU, BRE and Norge. The collected EPDs are also cross checked with those presented in Hill, Norton & Dibdiakova (2018), Schiavoni, Bianhci & Astrubali (2016) and Karami, Al-Ayish & Gudmundsson (2015). There are a few EPDs publicly available for VIPs which present radically different results. Karami et al (2015) referenced three EPDs in accordance with EN 15804, from VIP manufacturers in Germany (producer I), USA (producer II) and Belgium (producer III). The EPDs referenced in their study are used as the basis for the analysis in this paper. In some studied EPDs, the energy used for the maintenance of the product is also included, although this should be reported separately as the recurring embodied energy. This is distinct from the initial embodied energy, which is constant once the product is manufactured and installed (Hill and Zimmer 2018, Ramesh et al. 2010, Chau et al. 2015). Only EPDs with Modules A1-A3 have been used for the comparison purposes to reduce the uncertainties associated with assumptions concerning service life and different end of life scenarios. Global Warming potential (GWP) and Embodied Energy (EE) values are used as proxies to compare the materials. EN15804 requires the reporting of energy inputs as primary energy and the categories describing resource use as:

- Use of renewable primary energy excluding renewable primary energy resources used as raw materials;
- Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials.

Embodied Energy in this study is therefore defined as the primary energy used for the production of the insulation material from cradle to factory gate (including both renewable and non-renewable primary energy). This is particularly important to be clearly determined as some LCA practitioners do not include renewable energy in their definition of embodied energy. It was demonstrated in Dixit, Fernández-Solís, Lavy & Culp (2012) that the use of different information sources and failure to distinguish between primary or secondary energy could lead to errors as high as 40% when reporting embodied energy. The results are based on a 50 year service life for all cases for comparison purposes. This although is not taking into account the unique service life and durability characteristics of each insulation material, facilitates investigating different insulation materials on a comparative basis. This can be further studied as a limitation of the study.

Total Carbon Curve

The energy analysis in this paper is based on combined operational and embodied energy values. The primary energy for the operational phase has been converted to greenhouse gas (GHG) emissions using UK conversion factors as referenced in Defra's 'environmental reporting guidelines'. Natural gas to GHG emission conversion factor was used as 0.184 (kWh to $kgCO_2eq$). The GWP values of the insulation materials are the ones quoted in the EPDs and are used for the embodied CO_2 figures in this study.

[Figure 4 near here]

Whilst considering incremental increases in the U-values, a combined operational and embodied carbon curve is formed which demonstrates optimum U-value points beyond which embodied carbon investment outweighs operational carbon savings (triangular point on the total carbon line in Figure 4). Figure 4 describes a typical relationship between combined operational and embodied carbon and building element U-values for a selected building example. The total carbon curve (solid line on the graph) demonstrates the progressively diminishing return in terms of improved U-value for each unit increase in insulation thickness. Reductions in combined operational and embodied carbon therefore, become more difficult to achieve. The optimum points (sweet spots) on the total carbon curves reflect assumptions built into the modelling and will change as these assumptions are adjusted (such as reference service life, climatic conditions, type of insulation materials, energy source and operational schedules). Key, however, is the illustration of the relationship of the three lines. This becomes a classic arrangement that repeats in all such analyses and is reflected in the specific instances presented subsequently in this paper. Curves of this nature tend to flatten as service life increases or as a result of the use of lower embodied energy insulation. Both of these factors increase the optimum insulation thicknesses.

Factoring embodied carbon into an aggregated analysis serves to limit the minimum carbon levels that can be justified. A more detailed analysis of the total carbon curve in Figure 4 reveals that due to the nature of graphs of this type, the total carbon curves tend to flatten as the level of insulation increases. This implies that the minimal savings are achieved for each scenario as more insulation is added after a certain point. The highlighted areas on the two sides of the optimum point on the graph in Figure 5 are pointing towards the levels of insulation that would allow 5% higher or lower total carbon investment compared with the optimum points on each line. These points are of identical total carbon investment and therefore from a carbon saving point of view are of significant importance (i.e. 100mm and 300mm having identical carbon impact in this example). The 'operational carbon only' approach for the same range however, demonstrates a 50% carbon saving (dash-dotted line).

This is of particular significance in the near future where most operational energy demand is electricity based with the prospect of a decarbonised grid.

[Figure 5 near here]

This suggests that if embodied carbon and specifically a total carbon approach is applied to early decision making stages, more effective environmental scenarios can be investigated with a true representation of the situation. On a combined operational and embodied carbon approach, optimum U-value ranges are much higher than the values recommended by existing standards on an operational carbon only approach. This will have inevitable cost, policymaking and manufacturing implications for the construction industry and all other stakeholders/end users involved with it for both new build and retrofit cases. All values presented in this paper, therefore, follow a combined operational and embodied carbon approach taking into account values within 5% of the optimum points.

The study is limited to the range of assumptions applied and can be expanded to include more insulation materials, building types, occupancy patterns and climates for further studies. However, although the optimum points on the total carbon curve can shift, the approach will be valid for all scenarios.

Results and Discussion

Materials' Thermal and Environmental Properties:

The thermal and environmental properties associated with the selected EPDs are presented in Table 3 below.

[Table 3 near here]

Figures 6 and 7 demonstrate a box and whisker plot of the GWP/kg and EE/kg data respectively from the published EPDs presented in Table 3. The box represents the interquartile range (IQR) between the 25th and 75th percentiles with the line and the whiskers as median and standard deviation values respectively. The IQR is used to present the probability distribution for the values studied for each insulation material.

Analysing the GWP results (Fig 6) demonstrate that there is a clear distinction between different insulation groups (e.g. MW and GW with similar values compared with hydrocarbon based insulation materials such as EPS, XPS, PU and PF). Amongst each group there is no significant statistical difference in the median GWP per unit weight values. This is also in line with the findings in the Hill (2018) study. It is evident that although median points are very close in all groups, the ranges of probability distribution for PU and MW are considerably larger than those for XPS and GW respectively. The EE values however show slightly different scenarios. For example, the associated EE values for EPS are significantly higher than those of the same nature such as XPS and PU. Also the median EE values for cellulose insulation escalate to almost similar values to MW median points. The probability distribution for EE values for cellulose products cover a wider range compared with all other insulation types due to the distinct nature of the products categorised under the same insulation group.

[Figure 6 near here]

[Figure 7 near here]

In order to put the insulation materials in the context of their environmental performance relative to their thermal properties, the GWP and EE values per m^2 material achieving R-value of 6.6 m^2.K/W have been studied and presented in Figures 8 and 9. R-value or thermal resistance is a measure of a material's resistance to heat transfer relative to a given thickness. R-value of a building element with the addition of surface resistances is reciprocal to the total heat transmittance known as U-value, measured in W/m^2.K. The assumed resistance is equal to 0.15 W/m^2.K U-value which is considered as a well-insulated building element for stricter building codes and standards.

Although the GWP and EE values per unit weight of GW and MW were evidently lower than the hydrocarbon based materials and VIPs, the median values per specific R-values are closer for the majority of insulation groups. The spread of EE values for MW becomes considerably larger when this is calculated in terms of the studied R-value (87-500 MJ/m^2 for R=6.6 m^2.K/W with a median value of 164.7 MJ/m^2), whereas these values for GW maintains relative stability (65-146 MJ/m^2 R=6.6 m^2.K/W with a median value of 102.86 MJ). These values for the hydrocarbon based materials are very close and within the range of 215 to 660 MJ/m^2 for R=6.6 m^2.K/W with a median value of 300 MJ/m^2). These values are competitive with many of the MW materials, although higher than the GW products. The glass wool EE values referenced in Schiavoni et al. (2016) are an order of magnitude larger than those used by Hill et al. (2018). These values have been discounted from the database. Cellulose insulation material's EE figures spread across a wide range of values from the highest EE/m^2 for R=6.6 m^2.K/W of all materials (after VIPs) to the lowest of all. Hill et al. (2018), associate this wide range to the nature of the products used for cellulose based EPDs including refined virgin wood chips as a source of fibre (median 25.1 MJ/kg) and the blown recycled cellulosic products, such as wastepaper (median EE of 4.3 MJ/kg). These products although cellulose based, require distinct processing procedures and therefore can be categorised under different insulation groups.

In terms of EE values of VIPs, although they still demonstrate considerably higher values than other insulation groups, their significantly better thermal properties, bridges the gap partially. The system boundaries of the studied EPDs only cover cradle to gate stages. This will have a significant implication on the VIPs' contribution to the overall embodied energy measures, as the core material is the key contributor to the environmental impact of VIPs. This is investigated in studies such as in Schonhardt, Binz, Wohler & Dott (2003) (referenced in Karami et al. (2015)) which have demonstrated that the core material in VIPs (fumed silica) is responsible for over 90% of the embodied energy. This correlates directly with the data presented in one of the only available EPDs for VIPs which considered the end of life scenarios in which recycling the core material reduces the environmental impact by about

95% in all impact categories. Such huge impact would certainly need to be included in any energy/carbon impact analysis. This is also true in case of other insulation materials such as cellulose based ones.

[Figure 8 near here]

[Figure 9 near here]

Optimum Combined Operational and Embodied Carbon Analysis

All values presented in this section are based on the total carbon approach introduced in the previous section. Figure 10 demonstrates the range of optimum combined operational and embodied carbon points for the studied insulation materials. In defining the optimum points on the total carbon curve, Insulation R-values relative to their embodied carbon intensity are of particular significance. This is particularly important as the thickness of all insulation materials were adjusted based on their thermal conductivities to achieve specific U-values. This implies that the differences in the optimum points in the graph above are purely based on the carbon intensity of each material. For example, the relative carbon intensity of PUR and glass wool insulations calculated as a measure of R6.6/m^2 insulation, on the basis of their median GWP values, are 18.94 kgCO$_2$-eq/m^2 and 5.17 kgCO$_2$-eq/m^2 respectively. This equates to a factor of 3.66 in favour of glass wool, hence the lower optimum points achievable using glass wool.

This suggests that insulation materials with low embodied carbon, coupled with high R-value will achieve carbon minima more effectively than other insulation materials. The slimness of the external walls in particular is also crucial as more insulation is required. The super insulation materials (SIMs) are being developed to achieve the thermal and environmental demands with the slimness conceptin mind. VIPs for example, depending on the recycled content of the core material, can cover a range of values between 7.5 kgCO$_2$ (100% recycled core) to 100.19 kgCO$_2$ (no recycled core) as a measure of R6.6/m^2 insulation carbon intensity. With proper consideration of embodied carbon, VIPs can offer 3 to 4 times thinner panels than conventional insulation materials for the same thermal and environmental performance. It is evident that the optimum carbon saving points for VIPs are very close to those of all other insulation types relative to their significantly higher GWP and EE values presented in the previous section.

[Figure 10 near here]

Figure 11 demonstrates the range of optimum U-value points associated with different insulation types and their studied GWP values. The results clearly present the wide range of optimum points that can be achieved using either the same or different insulation types. This is particularly important when it comes to using LCA studies as decision making tools at early stages of design. Only cellulose insulation alone covers values from 0.15 W/m^2.K to 0.35 W/m^2.K with a median value of 0.22 W/m^2.K which demonstrates the extent of uncertainty associated with the current practice. This figure for the most commonly used materials in the building application such as MW and PU is 0.16 – 0.25 W/m^2.K and 0.21 – 0.29 W/m^2.K respectively.

[Figure 11 near here]

Comparing VIP values with the PU results demonstrate that on average the optimum U-values achieved for both insulation types match perfectly but due to higher GWP values of VIPs, their optimum carbon points are higher than PU. The interquartile range for VIPs is almost double of those for PU. This is aligned with the findings of the literature where high uncertainty of data is referred to when VIPs are investigated, highlighting the need for further studies to be carried out.

The results considering higher embodied energy values associated with different LCI techniques, as discussed in the theory section, are even more extreme and demonstrate even higher ranges of optimum U-values for all insulation types with larger uncertainties associated with the results (the graphs not included to avoid repetition). The results generally demonstrate that whilst different insulation types can justify specific ranges of U-values in their unique ways (as assessed using cumulative operational and embodied carbon analyses), the results are highly sensitive to the assumptions applied to the LCA study.

[Figure 12 near here]

Figure 12 demonstrates that a combined embodied and operational carbon approach will have considerable impact on the amount of material used in buildings. In the graph above, the solid squares are representing the insulation thicknesses required for optimum cumulative carbon saving points (as in Figure 4) and the outlined squares are the thicknesses associated with savings within 10% of the points as illustrated in Figure 3. The differences in the amount of insulation for the median points of each insulation group (illustrated as wide rectangles) are significant. For example, the median points for GW insulation show a wide range between 200-360mm as optimum points with identical level of carbon saving potentials. This figure for MW, EPS, XPS and PU as the most commonly used insulation materials in building applications are in range of 180-320mm, 170-310mm, 130-220mm and 90-200mm respectively.

To quantify the significance of this analysis on a national scale, potential material savings associated with PU insulation is reflected in a hypothetical UK housing scenario as an example. UK needs to build around 250,000 new homes every year to meet its growing housing market. According to different surveys undertaken by RIBA and LABC Warranty, the average new home size in the UK is about 70m^2. This equates to roughly 150m^2 insulation used in walls and roofs (average areas for terraced, semi-detached and detached houses assumed). The difference in the GWP values for PU insulation, associated with the upper and lower end of the thickness ranges presented above, based on the current trend of new homes scenario in the UK, will be equal to the total carbon emission from 150,000 households in the UK per year (based on circa 4 tonnes CO_2/ household per annum (UK energy facts 2013)).

Analyses of this nature can be expanded to retrofit scenarios in the UK, across Europe and globally and are crucial in achieving the energy thrift targets as more buildings are being built every day to the highest energy performance standards, and specifically very low U-values, without a proper appraisal of optimal building envelope designs. LCA studies that communicate the findings clearly and effectively are key in pushing the building designers and practitioners towards accounting for cumulative energy and carbon emissions in their design. This is only feasible if current limitations of LCA as a decision making tool is addressed effectively within the LCA community.

This study's findings support the rich body of literature considering the importance of an aggregated operational and embodied carbon analyses in demonstrating the effectiveness of carbon reduction strategies and provides further evidence suggesting the shift away from 'operational carbon only' methods. The total carbon curve approach introduced in this paper however, presents insight into how effective additional insulation levels would be and whether and to what extent carbon savings are occurring. Through the total carbon curve it has been demonstrated that current building energy codes and regulations, which focus mainly on space heating and operational energy aspects, do not necessarily result in a lower overall energy consumption when compared with less energy efficient buildings without including embodied energy contribution. This has also been evidenced in Mohazabieh, Ghajarkhosravi & Fung (2015), Gul and Patidar (2015) and Stephan et al (2013). If the regulations are aiming to reduce buildings energy consumption and associated greenhouse gas emissions, wider system boundaries must be adopted, including the embodied energy in building materials. Giesekam et al. (2016) highlight in their study the need for new regulatory drivers to complement changing attitudes if embodied carbon is to be established as a mainstream construction industry concern.

Lutzkendorf (2018) believes that the discussion is no longer about whether environmental performance considerations can or should be included in the design process but it has shifted to the challenges and practices of how, when and by what means this can be achieved. The analyses presented here, therefore are aimed at highlighting the implications of the environmental impacts of building products for policy makers and subsequent future regulatory requirements, and building product manufacturers. This is facilitated through using LCA analyses as design tools providing clear and meaningful messages to the relevant stakeholders.

Although there are several studies considering the application of LCA as such tools, more comprehensive communication and evaluation of environmental impacts is required to effectively integrate this information with buildings' design and performance criteria, example of which could be LCA integration with BIM, as suggested by Malmqvist et al. (2011). These criteria, backed up by analyses that can inform building designers and specifiers of environmental implications of their choices, are to assist decisions made during a building's early design stages which practically determine the buildings environmental impact (Basbagill, Flager, Lepech & Fischer, 2013) (designers tend to defer decisions related to the environmental impacts to later stages of the design process). The analyses presented in this study demonstrate that deferring decisions considering environmental impacts of materials and products when designing buildings (in particular building fabric performance) can significantly mislead the design choices and result in total carbon disbenefit particularly in case of insulation materials. Analyses of this nature can be used to identify likely requirements of the future standards, and can indicate limits to the amount by which current approaches to energy thrift can be escalated using specific products.

However, Moreno, Rohmer & Ma (2015) suggest that the availability of reliable building product level data for assisting LCA in design phase seems to be limited. Malmqvist et al. (2011), suggest the use of simplified LCA results during the design phase. Simplification, although suggested by many other researchers as well, may affect the results relative to the level of simplification applied (Lewandowska and Noskowiak, 2015). Wallhagen, Glaumann & Malmqvist (2011), demonstrate that the results associated with simplified methodologies can be up to 50% different compared with a comprehensive LCA study. However, despite the discrepancies in results, a simplified approach encourages the users in the building design to use LCA (Anand and Amor, 2017).

Prior to effective application of LCA as tools assisting in decision/policy making, the fundamental methodological inconsistencies of LCAs need to be addressed. Lutzkendorf et al. (2014) state in their research that the development of a life cycle approach needs strong support from a wide range of stakeholders including product manufacturers, data analysts and providers, technical experts and researchers, professional bodies, designers, software tool developers, regulators and policy-makers, amongst others. This is also reflected in Säynäjoki, Heinonen, Junnila & Horvath (2017) research that currently the level of unreliability of data and inconsistency of methodological approaches in LCA analyses are to a level which cannot effectively and fully support decision-making in the building sector without further improvements. Arbuckle and Kahn (2017) also confirm this view that if LCA is to be used to influence policy making, the results of analyses must be transparent and reproducible. In doing so, it is critical to realise that without consistent and harmonised data/methodologies, uncertainties of data can have significant implications for the end users. It has been demonstrated in this study that data uncertainty and variation can be larger than emissions reductions targets in some cases (also confirmed in Venkatesh, Jaramillo, Griffin & Matthews, 2011). The policy implications will generally be very different for the construction industry if lower or higher end values are used.

Considering the uncertainties, referenced in several studies, is crucial to any practical application of LCAs in general. In the specific case of insulations in this study, the combined operational and embodied carbon curve has demonstrated that the insulation materials have generally higher optimum U-values than expected within 5% carbon savings of the optimum points. Given that a broad range of values was used for embodied energy figures, some overlaps/similarities in the optimum ranges between the insulation materials is demonstrated. This needs to be further studied with different climatic conditions, operational regimes, primary energy sources, and building types as it will have significant implications for policymaking and future standards. However, given that buildings are already being specified to considerable efficiency levels, the optimum U-value ranges seem unlikely to shift dramatically.

The findings also support the case for development of novel insulation technologies with low levels of embodied energy relative to their R-values. The analyses have demonstrated that if appropriate attention is given to the use of recycled content of the core material used in VIPs, the technology can outperform the existing materials based on a cumulative carbon approach. Perhaps these results strengthen the case for finding new VIP core materials or for finding manufacturing techniques to reduce the energy required to produce fumed silica. It must be noted that the issues with VIPs such as the longevity and practical on site constraints need to be addressed more effectively before a major uptake in the construction sector.

Failure to consider embodied energy in future strategies, particularly in relation to low and zero carbon building envelopes has potential to create escalating issues in terms of buildings having significantly greater carbon footprints that they require for their design and operation, as compared to that suggested by conventional operational energy analysis only. The situation is further complicated by the possible effects of imminent climate change. For instance, in the UK it has been estimated that future (2030) domestic heating demand may be at least 25% lower (Kendrick, Ogden, Wang & Baiche, 2012), leading to a different approach for both new build and retrofit as regards insulation requirements. With UK conditions, the primary heat gains are within the building (solar, people, electrical) and added insulation could lead to additional overheating, with a consequent rise in demand for air conditioning if passive strategies are not sufficient.

Conclusions

Although there are several shortcomings associated with the existing approaches, the number of studies and initiatives taking place in different countries demonstrate that the Life Cycle Assessment of buildings will be part of the future assessment of the environmental impacts of buildings. The driver for increased uptake of assessments of this nature should come from regulations incentivising more stakeholders to adopt these approaches, supported also in Eurima (2017). This adoption however needs to be informed and supported by analyses which could generate clear and simple messages to the relevant end users/stakeholders of the analysis, assisting them in making decisions to their best interest and in developing effective business models. A deeper understanding of the limitations associated with the LCA sector, is a necessary prerequisite for development of a robust and consistent methodology.

Consideration of cumulative operational and embodied carbon has been shown to generate graphs that indicate optimal minima in terms of the amounts of operational carbon saved relative to the embodied carbon invested in insulation materials. The theoretical minima are the product of various factors including embodied energy data uncertainties, insulation type and service life, operational assumptions and climate. Optimum specifications cannot therefore be set for all buildings of a particular type, but rather require proper analytical and predictive understanding.

Practice and standards based on such analyses however, could realistically deliver very significant energy/carbon savings across the life of a building. Such analyses can contribute to informing the maximum levels of insulation that can be incorporated into buildings or that may in the future be required by standards, and can indicate limits to the amount by which current approaches to energy thrift can be escalated using specific products. Its associated implications, directly affect various stakeholders involved with the construction industry including the policy makers addressing future energy thrift targets, building designers aware of the environmental burdens of their buildings and product developers/manufacturers affected by the environmental performance of their products in the current competitive market.

The current uncertainties associated with embodied energy/carbon values can affect the end users of LCA analyses and provide the relative stakeholders with misleading messages, although the LCA thinking is finding its way into standards and regulations. The research demonstrates compelling evidence supporting the demand for harmonisation and standardisation of LCA and LCI databases and methodologies.

It has been demonstrated in this paper that the evident flatness of the combined operational and embodied carbon curves can accommodate a relatively high level of variation in the LCA analyses (due to current discrepancies in methods, assumptions and carbon data) and still be within 5% of the optimum points. The approach can thus be used as useful guidance currently, whilst the onus is still upon the LCA experts and practitioners and other relevant beneficiaries to harmonise the science across all sectors and indeed software.

References

Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renewable and sustainable energy reviews*, *67*, 408-416.

Anastaselos, D., Giama, E., & Papadopoulos, A. M. (2009). An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions. *Energy and Buildings*, *41*(11), 1165-1171.

Arbuckle, P., Kahn, E., & Kriesberg, A. (2017). Challenge paper: Challenges to sharing data and models for life cycle assessment. *Journal of Data and Information Quality (JDIQ)*, *9*(1), 6.

Athenasmi.org. (2018). *LCA, LCI, LCIA, LCC: What's the Difference?* Athena Sustainable Materials Institute. Available at: http://www.athenasmi.org/resources/about-lca/whats-the-difference/

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, *60*, 81-92.

Bontinck, P. A., Crawford, R. H., & Stephan, A. (2017). Improving the uptake of hybrid life cycle assessment in the construction industry. *Procedia engineering*, *196*, 822-829.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and sustainable energy reviews*, *29*, 394-416.

Cellura, M., Guarino, F., Longo, S., & Mistretta, M. (2014). Energy life-cycle approach in Net zero energy buildings balance: Operation and embodied energy of an Italian case study. *Energy and Buildings*, *72*, 371-381.

Cellura, M., Longo, S., & Mistretta, M. (2011). Sensitivity analysis to quantify uncertainty in life cycle assessment: the case study of an Italian tile. *Renewable and Sustainable Energy Reviews*, *15*(9), 4697-4705.

Chastas, P., Theodosiou, T., Bikas, D., & Kontoleon, K. (2017). Embodied energy and nearly zero energy buildings: A review in residential buildings. *Procedia environmental sciences*, *38*, 554-561.

Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Applied energy*, *143*, 395-413.

Clark, D. H. (2013). *What Colour is your Building?: Measuring and reducing the energy and carbon footprint of buildings*. London: RIBA Publishing.

Raymond J. Cole & Laura Fedoruk (2015) Shifting from net-zero to net-positive energy buildings, *Building Research & Information*, 43:1, 111-120, DOI: 10.1080/09613218.2014.950452

Crawford, R. (2011). *Life cycle assessment in the built environment*. Routledge.

Crawford, R. H. (2008). Validation of a hybrid life-cycle inventory analysis method. *Journal of environmental management*, *88*(3), 496-506.

Crawford, R. H., & Stephan, A. (2013, January). The significance of embodied energy in certified passive houses. In *Proceedings of World Academy of Science, Engineering and Technology* (No. 78, p. 453). World Academy of Science, Engineering and Technology (WASET).

Crawford, R. H., Bontinck, P. A., Stephan, A., & Wiedmann, T. (2017). Towards an automated approach for compiling hybrid life cycle inventories. *Procedia Engineering*, *180*, 157-166.

Crawford, R. H., Bontinck, P. A., Stephan, A., Wiedmann, T., & Yu, M. (2018). Hybrid life cycle inventory methods–a review. *Journal of cleaner production*, *172*, 1273-1288.

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings*, *140*, 68-80.

Ding, G. K. C. (2004). *The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities* (Doctoral dissertation).

Dixit, M. K. (2017). Embodied energy and cost of building materials: correlation analysis. *Building Research & Information*, *45*(5), 508-523.

Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2012). Need for an embodied energy measurement protocol for buildings: A review paper. *Renewable and sustainable energy reviews*, *16*(6), 3730-3743.

Eurima (2017) *Life Cycle Assessment of Buildings – A Future-proofed Solution in the Digitalised World of Tomorrow*. [ebook]. doi:

https://www.eurima.org/uploads/ModuleXtender/Publications/170/Eurima_LCA_WhitePaper_Final_20170915.pdf

European Committee for Standardisation (2012), *CEN Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculations Method EN 15978*

European Committee for Standardisation (2012), *CEN Sustainability of Construction Works – Environmental Product Declarations – Core Rules for the Product Category of Construction Products EN 15804*

FPS Public Health. (2018). *The Belgian framework for environment messages concerning construction products and environmental product declarations (EPD).* Available at: https://www.health.belgium.be/en/belgian-framework-environment-messages-concerning-construction-products-and-environmental-product#Document

Frischknecht, R. (2010). LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. *The International Journal of Life Cycle Assessment*, *15*(7), 666-671.

Gelowitz, M. D. C., & McArthur, J. J. (2017). Comparison of type III environmental product declarations for construction products: Material sourcing and harmonization evaluation. *Journal of Cleaner Production*, *157*, 125-133.

Groen, E. A., Heijungs, R., Bokkers, E. A. M., & De Boer, I. J. (2014). Methods for uncertainty propagation in life cycle assessment. *Environmental modelling & software*, *62*, 316-325.

Guan, J., Zhang, Z., & Chu, C. (2016). Quantification of building embodied energy in China using an input–output-based hybrid LCA model. *Energy and Buildings*, *110*, 443-452.

Gul, M. S., & Patidar, S. (2015). Understanding the energy consumption and occupancy of a multi-purpose academic building. *Energy and Buildings*, *87*, 155-165.

Gustavsson, L., & Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings*, *42*(2), 210-220.

Häfliger, I. F., John, V., Passer, A., Lasvaux, S., Hoxha, E., Saade, M. R. M., & Habert, G. (2017). Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials. *Journal of cleaner production*, *156*, 805-816.

Han, G., & Srebric, J. (2015). Comparison of survey and numerical sensitivity analysis results to assess the role of life cycle analyses from building designers' perspectives. *Energy and Buildings*, *108*, 463-469.

Hill, C., Norton, A., & Dibdiakova, J. (2018). A comparison of the environmental impacts of different categories of insulation materials. *Energy and Buildings*, *162*, 12-20.

Hill, C., Zimmer, K. (2018). *The environmental impacts of wood compared to other building materials*. Norwegian Institute of Bioeconomy Research (NIBIO)

International Organization for Standardisation (2006), *ISO 14040: Environmental management-Life cycle assessment-Principles and framework.*

Jiang, Q., Li, T., Liu, Z., Zhang, H., & Ren, K. (2014). Life cycle assessment of an engine with input-output based hybrid analysis method. *Journal of cleaner production*, *78*, 131-138.

Jiao, Y., Lloyd, C. R., & Wakes, S. J. (2012). The relationship between total embodied energy and cost of commercial buildings. *Energy and Buildings*, *52*, 20-27.

Karami, P., Al-Ayish, N., & Gudmundsson, K. (2015). A comparative study of the environmental impact of Swedish residential buildings with vacuum insulation panels. *Energy and Buildings*, *109*, 183-194.

Kendrick, C., Ogden, R., Wang, X., & Baiche, B. (2012). Thermal mass in new build UK housing: a comparison of structural systems in a future weather scenario. *Energy and buildings*, *48*, 40-49.

Koezjakov, A., Urge-Vorsatz, D., Crijns-Graus, W., & van den Broek, M. (2018). The relationship between operational energy demand and embodied energy in Dutch residential buildings. *Energy and Buildings*, *165*, 233-245.

Kristjansdottir T.F., Heeren N., Andresen I. & Brattebø H. (2018) Comparative emission analysis of low-energy and zero-emission buildings, *Building Research & Information*, 46:4, 367-382, DOI: 10.1080/09613218.2017.1305690

Lenzen, M. (2000). Errors in conventional and Input-Output—based Life—Cycle inventories. *Journal of industrial ecology*, *4*(4), 127-148.

Lenzen, M., & Dey, C. (2000). Truncation error in embodied energy analyses of basic iron and steel products. *Energy*, *25*(6), 577-585.

Lewandowska, A., Noskowiak, A., Pajchrowski, G., & Zarebska, J. (2015). Between full LCA and energy certification methodology—a comparison of six methodological variants of buildings environmental assessment. *The International Journal of Life Cycle Assessment*, *20*(1), 9-22.

Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E., & Sonnemann, G. (2015). Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. *Building and Environment*, *93*, 165-178.

Lützkendorf T. (2018). Assessing the environmental performance of buildings: trends, lessons and tensions. *Building Research and Information*, 46:5, 594-614, DC 10.1080/09613218.2017.1356126

Lützkendorf T., Foliente G., Balouktsi M. & Wiberg A. H. (2015) Net-zero buildings: incorporating embodied impacts, *Building Research & Information*, 43:1, 62-81, DOI: 10.1080/09613218.2014.935575

Majeau-Bettez, G., Strømman, A. H., & Hertwich, E. G. (2011). Evaluation of process-and input–output-based life cycle inventory data with regard to truncation and aggregation issues. *Environmental science & technology*, *45*(23), 10170-10177.

Malmqvist, T., Glaumann, M., Scarpellini, S., Zabalza, I., Aranda, A., Llera, E., & Díaz, S. (2011). Life cycle assessment in buildings: The ENSLIC simplified method and guidelines. *Energy*, *36*(4), 1900-1907.

Means, P., & Guggemos, A. (2015). Framework for life cycle assessment (LCA) based environmental decision making during the conceptual design phase for commercial buildings. *Procedia engineering*, *118*, 802-812.

Mohazabieh, S. Z., Ghajarkhosravi, M., & Fung, A. S. (2015). Energy consumption and environmental impact assessment of the energy efficient houses in toronto, canada. *Procedia engineering*, *118*, 1024-1029.

Moncaster A. M. & Song J-Y. (2012) A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings, *International Journal of Sustainable Building Technology and Urban Development*, 3:1, 26-36, DOI: 10.1080/2093761X.2012.673915

Moran, P., Goggins, J., & Hajdukiewicz, M. (2017). Super-insulate or use renewable technology? Life cycle cost, energy and global warming potential analysis of nearly zero energy buildings (NZEB) in a temperate oceanic climate. *Energy and Buildings*, *139*, 590-607.

Moreno, P. R., Rohmer, S., & Ma, H. W. (2015). Analysis of potential relationships between functional analysis and life cycle assessment. *Procedia CIRP*, *29*, 390-395.

Omar, W. M. S. W., Doh, J. H., Panuwatwanich, K., & Miller, D. (2014). Assessment of the embodied carbon in precast concrete wall panels using a hybrid life cycle assessment approach in Malaysia. *Sustainable Cities and Society*, *10*, 101-111.

Pavel, C. C., & Blagoeva, D. T. (2018). Competitive Landscape of the EU's Insulation Materials Industry for Energy-Efficient Buildings. *Publications Office of the European Union: Luxembourg*.

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and buildings*, *42*(10), 1592-1600.

Rauf, A., & Crawford, R. H. (2015). Building service life and its effect on the life cycle embodied energy of buildings. *Energy*, *79*, 140-148.

RICS (2012), *Methodology to calculate embodied carbon of materials*, RICS information paper, IP32/2012, Coventry

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and buildings*, *39*(3), 249-257.

Säynäjoki, A., Heinonen, J., Junnila, S., & Horvath, A. (2017). Can life-cycle assessment produce reliable policy guidelines in the building sector?. *Environmental Research Letters*, *12*(1), 013001.

Schiavoni, S., Bianchi, F., & Asdrubali, F. (2016). Insulation materials for the building sector: A review and comparative analysis. *Renewable and Sustainable Energy Reviews*, *62*, 988-1011.

Schonhardt, U., Binz, A., Wohler, M., & Dott, R. (2003). Ökobilanz eines Vakuum-Isolations-Paneels (VIP). *University of Applied Sciences, Institute of Energy, Basel, German*.

Silvestre, J. D., De Brito, J., & Pinheiro, M. D. (2014). Environmental impacts and benefits of the end-of-life of building materials–calculation rules, results and contribution to a "cradle to cradle" life cycle. *Journal of Cleaner Production*, *66*, 37-45.

Simmler, H., Brunner, S., Heinemann, U., Schwab, H., Kumaran, K., Mukhopadhyaya, P., and Stramm, C. (2005). Vacuum Insulation Panels. Study on VIP-components and panels for service life prediction of VIP in building applications (Subtask A). *IEA/ECBCS Annex*, *39*.

Soust-Verdaguer, B., Llatas, C., & García-Martínez, A. (2016). Simplification in life cycle assessment of single-family houses: A review of recent developments. *Building and Environment*, *103*, 215-227

Stephan, A., & Stephan, L. (2014). Reducing the total life cycle energy demand of recent residential buildings in Lebanon. *Energy*, *74*, 618-637.

Stephan, A., Crawford, R. H., & De Myttenaere, K. (2013). A comprehensive assessment of the life cycle energy demand of passive houses. *Applied energy*, *112*, 23-34.

Szalay, A. Z. Z. (2007). What is missing from the concept of the new European Building Directive?. *Building and Environment*, *42*(4), 1761-1769.

Takano, A., Hughes, M., & Winter, S. (2014). A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context. *Building and Environment*, *82*, 526-535.

Tettey, U. Y. A., Dodoo, A., & Gustavsson, L. (2014). Effects of different insulation materials on primary energy and CO2 emission of a multi-storey residential building. *Energy and buildings*, *82*, 369-377.

Thormark, C. (2002). A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and environment*, *37*(4), 429-435.

Treloar, G. J., Love, P. E., & Holt, G. D. (2001). Using national input/output data for embodied energy analysis of individual residential buildings. *Construction Management and Economics*, *19*(1), 49-61.

Trent N. (2019) Global Building Insulation Market Report 2019 - Market Size, Share, Price, Trend and Forecast, *Wise Guy Research Consultants Pvt Ltd*

Venkatesh, A., Jaramillo, P., Griffin, W. M., & Matthews, H. S. (2010). Uncertainty analysis of life cycle greenhouse gas emissions from petroleum-based fuels and impacts on low carbon fuel policies.

Wallhagen, M., Glaumann, M., & Malmqvist, T. (2011). Basic building life cycle calculations to decrease contribution to climate change–Case study on an office building in Sweden. *Building and Environment*, *46*(10), 1863-1871.

Wiedmann, T. O., Suh, S., Feng, K., Lenzen, M., Acquaye, A., Scott, K., & Barrett, J. R. (2011). Application of hybrid life cycle approaches to emerging energy technologies–the case of wind power in the UK. *Environmental science & technology*, *45*(13), 5900-5907.