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Study of embodied energy and carbon for indoor living walls

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Abstract

Indoor living walls are becoming increasingly popular in buildings as they can provide good aesthetic effects and other environmental benefits. Understanding of their environmental impacts is important for planning and designing effective living walls. The main objective of this research is to apply the theory of embodied energy and carbon for assessment of indoor living walls. The principle and calculation methods of embodied energy and carbon are studied with the aim to develop analytical models for evaluating different types of indoor living wall systems for the major applications in buildings. The technical details and design considerations of indoor living walls are examined to investigate the practical parameters for the analysis. The major issues and key factors for reducing their embodied energy and carbon are assessed so as to identify effective design strategies and study the environmental performance criteria. To assess the environmental impacts of indoor living walls, a system of accounts is constructed based on an input-output model and the total direct and indirect energy and carbon requirements for each output made by the system are estimated. It is found that the indoor living walls could be more environmentally sound if recycled materials, renewable energy and sustainable design and maintenance practices are applied.

Keywords

Indoor living walls; embodied energy and carbon; life cycle environmental impacts.

1. Introduction

Living wall is a form of vegetated wall surfaces acting as an additive material to increase the functionality of building facades (Dunnett and Kingsbury, 2008; Mir, 2011; Ottelé, *et al.*, 2011). Adopting indoor living walls has many advantages (Binabid, 2010; Choi, 2013; Köhler, 2008). The wall greenery improves visual and aesthetic aspects of indoor spaces. The vegetation plants help to ameliorate the effects of air pollution, trap dust, absorb noise and recycle carbon dioxide by photosynthesis (Feng and Hewage, 2014; Perini, *et al.*, 2011b). The vegetation can also help to modulate indoor climate of buildings by evapotranspiration and thermal insulation (Fernández-Cañeroa, Urrestarazu and Salas, 2012). In some buildings, indoor living walls can also be designed to act as a filter for air-conditioning system and/or a negative ion generator.

The main objective of this research is to apply the theory of embodied energy and carbon for assessment of indoor living walls. The principle and calculation methods of embodied energy and carbon are studied with the aim to develop analytical models for evaluating different types of indoor living wall systems for the major applications in buildings. The technical details and design considerations of indoor living walls are examined to investigate the practical parameters for the analysis. The major issues and key factors for reducing their embodied energy and carbon are assessed so as to identify effective design strategies and study the environmental performance criteria.

Embodied energy and carbon is an accounting method which aims to find the sum total of the energy and carbon (dioxide) emission necessary for an entire product life-cycle (Cabeza, *et al.*, 2013b; Chau, Leung and Ng, 2015; Dixit, *et al.*, 2012; Hammond and Jones, 2008). This includes assessing the relevance and extent of energy and carbon emission into raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction and/or decomposition as well as human and secondary resources. To evaluate the environmental impacts of indoor living walls in this research, a system of accounts is constructed based on an input-output model and the total direct and indirect energy and carbon requirements for each output made by the system are estimated. It is hoped that the analysis can provide hints for understanding the environmental performance and sustainable design considerations of indoor living walls.

2. Indoor Living Walls

Living walls are vertical greening systems which cover walls or other structures with vegetation that are either rooted within those structure or are able to survive independently on the structure without the need to root in surrounding soil (Dunnett & Kingsbury, 2008). Living walls may be formed by panels and/or geotextile felts, sometimes pre-cultivated, and are fixed to a vertical support or on the wall structure (Pérez, *et al.*, 2011). The panels and geotextile felts provide support to the vegetation by upholstering plants, ferns, small shrubs, and perennial flower. Panels of varying sizes and types, with holes in which the substrate and plants are located, are fixed to the wall.

Indoor living walls are becoming increasingly popular in buildings (such as shopping malls, offices and airports) as they can provide good aesthetic effects and other ecological and environmental benefits (Choi, 2013). Figure 1 shows two examples of indoor living walls. Understanding of their environmental impacts is important for planning and designing effective living walls (Ottelé, *et al.*, 2011; Perini and Rosasco, 2013). However, as indoor living walls require materials to build and resources to maintain, there are practical questions from sustainability point of view on whether they are really worthy for adoption into building design and how to enhance their environmental performance.

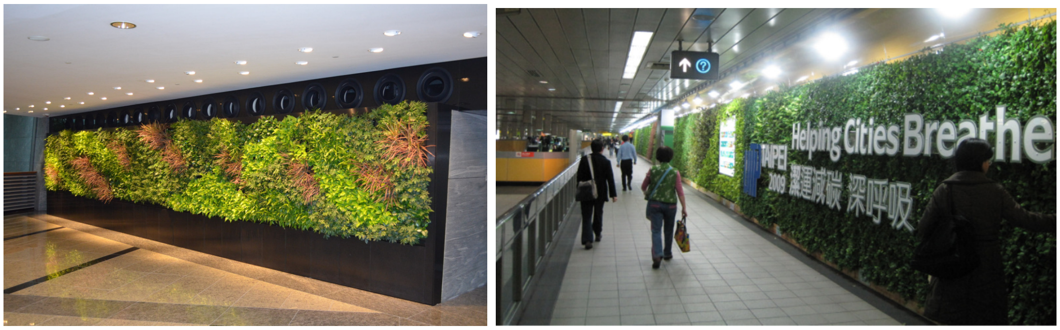

Figure 1. Examples of indoor living walls (in Hong Kong and Taipei)

Ottelé, *et al.* (2011) have performed a comparative life cycle analysis for green facades and living wall systems in the Netherlands to identify environmentally preferable choice. Perini and Rosasco (2013) presented a cost-benefit analysis of different vertical greening systems to determine which ones are more economically sustainable. Feng and Hewage (2014) have conducted a lifecycle assessment of living walls based on air purification and energy performance. But they all focused mainly on outdoor façade greening.

In some situations, the indoor living walls may have access to natural daylight and air through windows and/or skylights; but in most cases they are located in a completely enclosed environment and thus special considerations for plant growth and maintenance are needed, such as artificial lighting and irrigation. Technical studies of indoor living walls can be found on issues such as lighting systems (Egea, *et al.*, 2014), cooling potential (Fernández-Cañeroa, Urrestarazu and Salas, 2012) and indoor pollutant removal (Wolverton and Wolverton, 1993). There is a need to develop systematic methods for assessing the environmental performance of indoor living walls.

3. Embodied Energy and Embodied Carbon

Embodied energy (EE) is the amount of energy consumed to extract, refine, process, transport and fabricate a material or product (Cabeza, *et al.*, 2013b; Hammond and Jones, 2008). In practice, depending on the life cycle boundary, it is often measured from cradle to (factory) gate, cradle to site (of use), or cradle to grave (end of life).

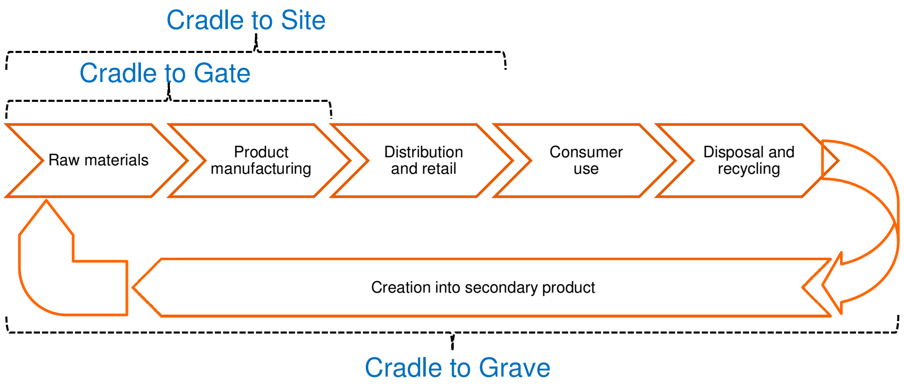

Figure 2. Life cycle boundary

Figure 2 shows the life cycle boundary for defining EE. Similarly, embodied carbon (EC) is the amount of carbon dioxide (CO_2) or carbon dioxide equivalent (CO_2e) emission to produce a material or product.

3.1 Measurement of Embodied Impact

Typical measurement units of EE and EC are MJ/kg (megajoules of energy needed to make a kilogram of product) and tCO_2/kg (tonnes of carbon dioxide created by the energy needed to make a kilogram of product). Converting MJ to tCO_2 is not straightforward because different types of energy (coal, oil, gas, wind, solar and nuclear) emit different amounts of carbon dioxide, so the actual amount of carbon dioxide emitted when a product is made depends on the type of energy used in the manufacturing process.

In many researches, EE and EC are closely related to each other and often interchanged. Gonzalez and Navarro (2006) indicated that building materials possessing high embodied energy could possibly result in more carbon dioxide emissions than materials with low embodied energy. Ibn-Mohammed, *et al.* (2013) argued that EE and EC do not have a direct relationship because material processes can both emit and sequester carbon. In fact, EC is the carbon associated with embodied energy use, and each embodied energy expenditure varies depending on its fuel type used. Therefore, it is important to distinguish between carbon and energy when describing embodied impact of a product as opposed to the operational impacts.

Dixit, *et al.* (2012) pointed out that an EE measurement protocol can be applied to buildings to help assess the environmental impacts. It is believed that EE and EC constitute a considerable amount of the total energy and carbon of buildings. Sartori and Hestnes (2007) found that for a conventional building the embodied energy could account for 2 to 38% of the total life cycle energy and for a low energy building, this could range from 9 to 46%. Another research by Thormark (2007) determined that the embodied energy of a low energy house could be equal to 40 to 60% of the total life cycle energy. Jiao, Ye and Li (2011) found that embodied carbon could contribute up to 60% of the whole life carbon. Practical ways of achieving carbon reduction in the building industry require attention be paid to embodied energy and carbon, in order to assess and engage the full supply chain (Buchanan, and Honey, 1994).

3.2 Accounting Methods

Estimating embodied energy and carbon requires an accounting method which aims to find the sum total of the energy and carbon emission necessary for an entire product life-cycle. Determining what constitutes this life-cycle demands assessing the relevance and extent of energy into raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction and/or decomposition as well as human and secondary resources. At present, different methodologies use different scales of data to calculate the embodied energy and carbon (Moncaster and Song, 2012); this will produce diverse understandings of the scale and scope of application and the type of embodied values and results. The main methods of embodied impact accounting today come from an input-output model analysis (Bullard, Penner and Pilati, 1978; Lenzen, 2000; Nassen, *et al.*, 2007).

Usually, EE includes renewable and nonrenewable sources and does not consider the carbon dioxide emissions associated with the energy production, which is why it is important to consider the EC separately (Tingley and Davison, 2011). EE can be divided into two categories: initial embodied energy and recurring embodied energy (Chau, Leung and Ng, 2015). Initial embodied energy is the sum of the energy required for extraction and manufacture of a material together with the energy required for transportation of the material used for the initial construction. The recurring embodied energy represents the sum total of the energy embodied in the material use due to maintenance, repair, restoration, refurbishment or replacement during the service life of building components.

Jiao, Ye and Li (2011) indicated that the carbon emissions of building materials are made up of direct and indirect carbon emissions. Cabeza, *et al.* (2013a) further explained that the carbon emissions of raw materials and the manufacturing process of building materials are two important parts to evaluate the direct carbon emission. On the other hand, the indirect carbon emission was generated from depreciation of equipment and buildings, management in each link and environmental process of garbage processing and transportation. It is believed that consideration of EE and EC of building projects and building products will promote the importance of taking a whole life-cycle approach for achieving sustainability of buildings.

4. Life Cycle Assessment

The ISO Standards (ISO, 2006a & b) provided a general framework of life cycle assessment (LCA). LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal, i.e. a ‘cradle to grave’ approach. Normally, LCA consists of four phases including goal and scope definition, inventory analysis, impact assessment, and interpretation. The scope (including definition of system boundary) and level of detail of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA may differ considerably depending on the goal.

4.1 LCA with Embodied Energy and Carbon

LCA with embodied energy and carbon approach still follows the general frameworks of LCA stages (Chau, Leung and Ng, 2015; Scheuer, Keoleian and Reppe, 2003; Suh and Huppes, 2005). But as compared with a normal LCA, its focus on data inventory is different (Lamnatou, *et al.*, 2014; Menzies, Turan and Banfill, 2007). The input-output data inventory of normal LCA is based on the major environmental impacts identified to investigate at the scope stage, which may include effects of global warming, smog, acidification, natural resources depletion, ozone depletion, etc. However, the LCA adopting embodied energy and carbon approach has only the inventory data of EE and EC as the major concern in environmental impacts.

Some researchers called LCA with embodied energy and carbon approach as life cycle energy analysis (LCEA). Menzies, Turan and Banfill (2007) has distinguished the difference between LCA and LCEA and stated that whereas LCA assesses the overall impact, on the contrary, a derivative LCEA focuses on energy as the only measure of environmental impact of buildings or products. They also explained that the purpose of LCEA is to present a more detailed analysis of energy attributable to products, systems or buildings, to enable decision-making strategies concerning energy efficiency and environmental protection. Chau, Leung and Ng (2015) also supported this interpretation and pointed out that LCEA is a simplified version of LCA which focuses only on the evaluation of energy inputs for different phases of the life cycle. They mentioned that 'bottom-up' technique, sometimes called process-based approach proposed by González and Navarro (2006) and Peuportier (2001), can be a methodology for embodied evaluation, but it relies heavily on the energy databases for construction materials as well as drawings, specifications and/or data from actual buildings.

4.2 Practical Considerations

It should be noted that LCEA is not developed to replace LCA, but to compare and evaluate the initial and recurrent EE in materials, energy used during its life cycle stages, in order to estimate the energy use and savings over the product's or building's life, and more importantly, to find out the energy/CO_2 payback period (Menzies, Turan & Banfill, 2007). LCA with embodied carbon approach is similar to LCEA, and relies on prevailing energy structures to convert mega joules of EE to kilograms of carbon for assessing total carbon impact (Chau, Leung and Ng, 2015).

Unfortunately there are very few large scale databases listing the embodied energy and carbon data for various construction materials. Some popular databases include the Inventory of Carbon & Energy (ICE) (Hammond and Jones, 2011) and the New Zealand Building Materials Embodied Energy Coefficients Database (Alcorn, 2003). Some researchers such as Buchanan and Honey (1994), Adalberth (1997), and Pullen (2000) have also provided data lists showing the EE and EC data for construction activities. In this research, reference has been made to these databases and sources. The EE and EC calculations were built up by each of the life cycle stages for the indoor living wall systems and components. For every life cycle stage the embodied energy and carbon values for each type of living walls are calculated.

5. Comparison of Different Types of Living Walls

In this research, the embodied energy and carbon of four types of indoor living walls have been evaluated and compared with a bare brick wall. The facades being investigated included:

(a) Bare wall (brick)
(b) Planter boxes type living wall system + bare wall
(c) Felt layers type living wall system + bare wall
(d) Mineral wool type living wall system + bare wall
(e) Foam type living wall system + bare wall

All the living walls selected here have been defined before by Ottelé, et al (2011) and Mir. (2011) for their LCA analyses. The functional unit adopted is 1 m^2 of wall area and a fictitious façade of 100 m^2 (20 m length × 5 m height) is used as the basis for calculating the materials and products involved in every system. The wall structural materials, plants, irrigation systems and lighting systems have been considered in the analysis. However, as the embodied energy and carbon data for the materials and components forming the irrigation and lighting systems are difficult to evaluate, not all the materials in these systems have been included in the analysis. For the irrigation system, only the water pipes have been evaluated; for the lighting system, only the linear aluminium luminaire framework and LED lamps are included in the analysis.

5.1 Boundary and Scope Definition

The initial embodied energy and carbon is measured from "cradle to gate", that is from raw materials extraction to the supply at factory gate. Energy consumption and carbon emission embedded in the transportation process of materials from countries of origin (factory gate) to ports in Hong Kong have been included in the analysis. However, the embodied energy and carbon emission associated with transportation of materials from ports in Hong Kong to the construction site, transportation of waste materials after decommissioning, the recycle, reuse and land filling processes of the waste materials have not been included in the analysis.

At the construction stage, the embodied energy and carbon associated with labour, equipment and machinery for the living wall installation were ignored because it is difficult to estimate them and they are usually negligible as found out from other research such as Gaspar and Santos (2015). The energy and carbon embedded in construction waste during the construction processes have been calculated by the waste factors for different materials. The replacement of materials during operational life span of the living wall systems has been considered and the embodied energy and carbon have been examined. But the embodied energy and carbon associated with demolition processes of the living walls were neglected.

5.2 Summary of the Analysis Results

Summaries of the analysis results for the bare wall and the four living wall systems are shown in Tables 1 and 2. The calculations are divided into three main life cycle stages including embodied stage, construction stage and operation stage. For the embodied stage, it can be further broken down into material, transportation, and recurrent energy/carbon. The material and transportation constitute the initial energy/carbon. About the embodied stage, Figures 3 and 4 shows the comparison results of EE and EC for the four living wall systems and the bare wall. It is found that the transportation energy/carbon is negligible because the materials transport (from countries of origin to ports in Hong Kong) is assumed to be using costal vessels which does not contribute much energy/carbon. Also, it can be seen that the felt layers type and the foam type living walls have higher embodied energy and carbon values than the other two living wall systems because of their large recurrent impacts.

Table 1. LCA with embodied energy analysis

Life Cycle Stages	**Energy Breakdown** (MJ/m²)	**Types of Living Walls**				
		1. Bare Wall	**2. Planter Boxes**	**3. Felt Layer**	**4. Mineral Wool**	**5. Foam**
Embodied Stage	Material (initial)	743.05	2017.30	1620.37	1533.17	1655.41
	Transportation (initial)	20.06	27.71	20.67	20.66	20.67
	Recurrent Energy	0.00	301.33	2751.22	683.86	2891.41
Construction	Construction Energy	23.15	89.75	71.61	70.41	73.36
Operation	Operation Energy	0.00	5466.38	5466.67	5466.53	5466.38
Total Life Cycle Energy (MJ/m²)		786.26	7902.48	9930.54	7794.63	10107.24

Table 2. LCA with embodied carbon analysis

Life Cycle Stages	**Carbon Breakdown** (kg CO₂/m²)	**Types of Living Walls**				
		1. Bare Wall	**2. Planter Boxes**	**3. Felt Layer**	**4. Mineral Wool**	**5. Foam**
Embodied Stage	Material (initial)	88.27	141.47	142.24	147.28	135.17
	Transportation (initial)	0.50	1.39	0.57	0.57	0.57
	Recurrent Carbon	0.00	32.15	136.48	50.32	108.22
Construction	Construction Carbon	2.81	5.40	5.52	5.92	5.21
Operation	Operation Carbon	0.00	622.56	622.59	622.58	622.56
Total Life Cycle Carbon (kg CO₂/m²)		91.58	802.97	907.42	826.67	871.73

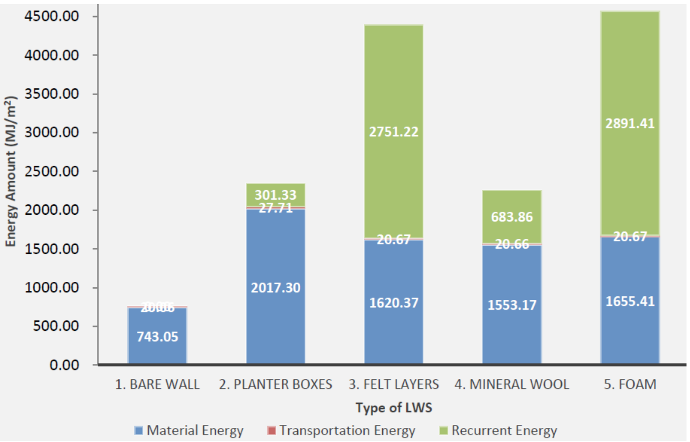

Figure 3. Comparison of embodied energy for living wall systems

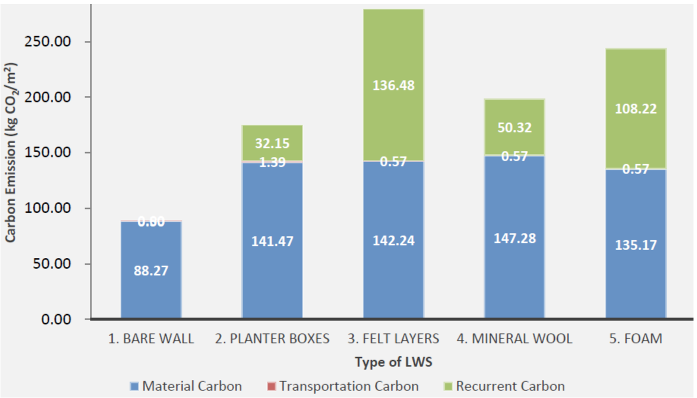

Figure 4. Comparison of embodied carbon for living wall systems

From sustainability point of view, the planter boxes type and mineral wool type living walls are preferred. From the life cycle point of view, as the operation energy and carbon of indoor living walls are quite large, the effect of the embodied stage is relatively small. It is believed other sustainable design strategies may be considered to reduce the overall environmental impacts of all these living wall systems. This point will be evaluated in the next section.

6. Effects of Sustainable Design Strategies

In order to study the effects of some sustainable design strategies for reducing environmental impacts of indoor living walls, the models of LCA with embodied energy and carbon developed in the previous section were modified to form several scenario cases as shown below.

(a) Case 0 – Original (baseline) (see Tables 1 and 2)
(b) Case 1 – Recycling Materials
(c) Case 2 – Renewable Energy (used in the operation stage)
(d) Case 3 – Substitution of Materials (by Hardwood)
(e) Case 4 – Substitution of Materials (by HDPE)
(f) Case 5 – Substitution of Materials (by Stainless Steel)

6.1 Effects of Recycling Materials

Case 1 changes some of the construction materials of the living walls from primary-use materials to recycling materials. Recycling materials means the building product is partly or totally manufactured from the disassembled materials (Gao, *et al.*, 2001). For the four living wall systems under the present study, the virgin steel, aluminium and high-density polyethylene (HDPE) have been changed to recycling materials of the same type. Figures 5 and 6 shows the effects on EE and EC of changing to recycling materials for the living walls.

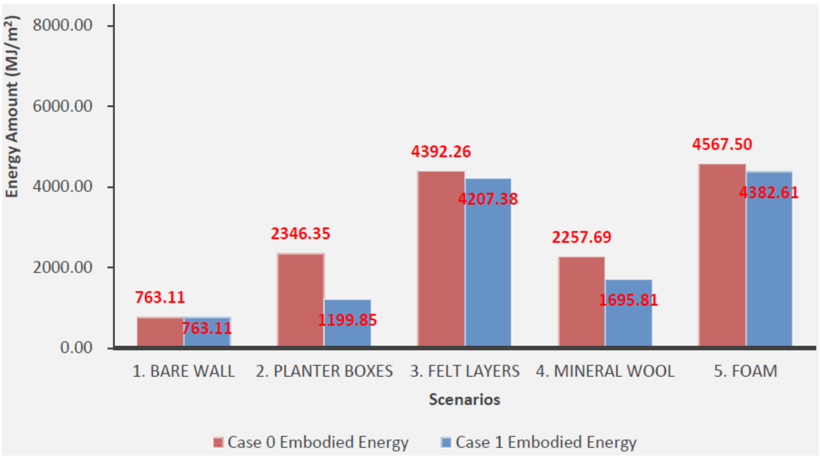

Figure 5. Effects of recycling materials on embodied energy for living wall systems

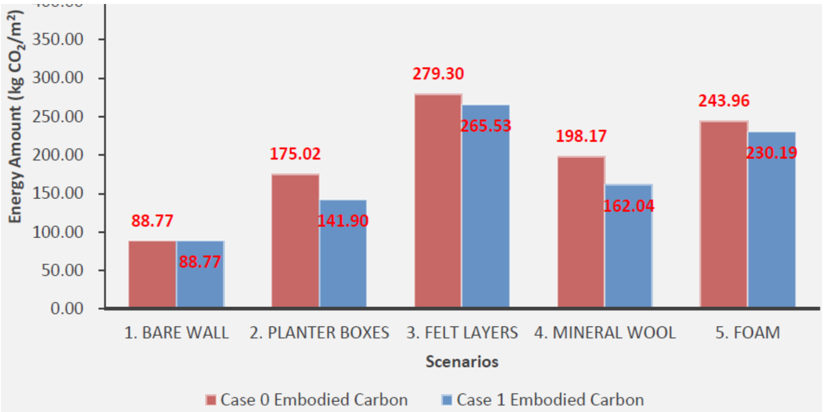

Figure 6. Effects of recycling materials on embodied carbon for living wall systems

It is found that the embodied energy and carbon have dropped for all the four living wall systems. The planter boxes type living wall has the largest embodied energy reduction because HDPE is the main material for this system (for making the planter boxes) and using recycling material for HDPE has significantly decreased the total embodied energy. As for embodied carbon, the reduction effect is not so large for this system because the material carbon value has not decreased very much.

6.2 Effects of Renewable Energy Used in the Operation Stage

Case 2 utilizes the current trend of energy and carbon emission optimization in buildings, by using renewable energy to fulfill part of the building energy consumption. It is proposed that solar photovoltaic panels are installed on the building roof to provide electricity to the building's electrical supply system. It is assumed that solar electricity can supply 15% of the total operation energy of the living wall systems (including lighting and water pumps). Therefore, the operation energy in the previous analysis is reduced by 15%. There is no change in the data at the embodied and construction stages. Figures 7 and 8 shows the effects on total life cycle energy and carbon by using renewable energy in the operation stage.

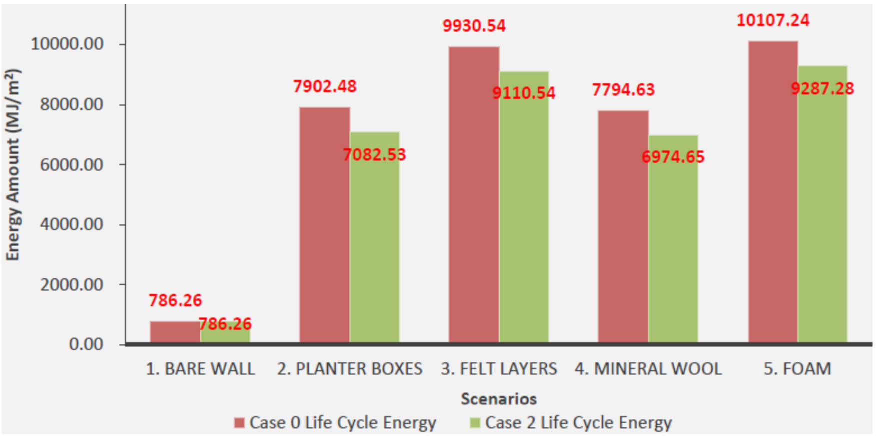

Figure 7. Effects of renewable energy for operation stage on life cycle energy for living wall systems

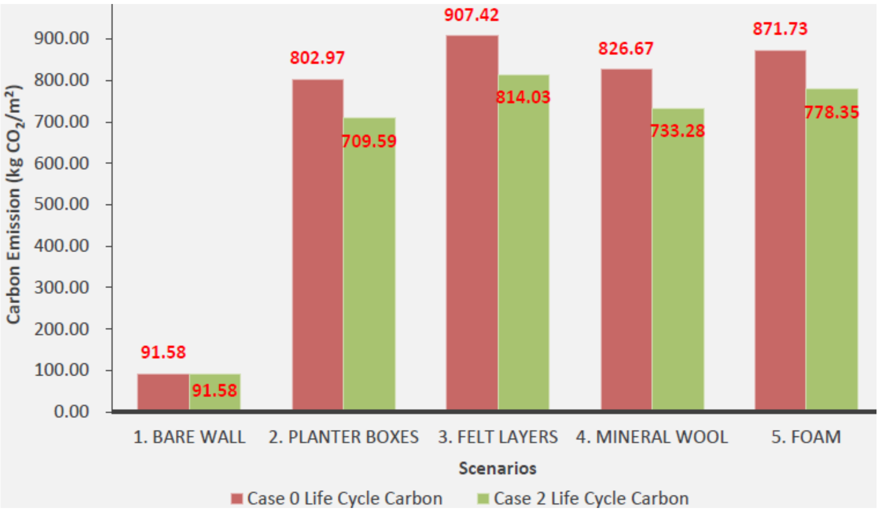

Figure 8. Effects of renewable energy for operation stage on life cycle carbon for living wall systems

From Figures 7 and 8, it is obvious that the four living wall systems have the same amount of reduction. If more renewable energy is applied to the building, say 50% of the total operation energy, then the effects will be very significant. However, it should be noted that the environmental impacts of the renewable energy system (such as solar photovoltaic) have not been considered in the present analysis.

6.3 Effects of Material Substitution of Support Structural Frame

Since all the four living wall systems require a support structural frame to set up the vertical greening, a practical design consideration is to select suitable material for this structural frame. Case 3 to Case 5 tried to substitute the original materials (ordinary steel) used for constructing the structural frame by other alternative materials (such as hardwood, HDPE and stainless steel). For the sake of comparison, it is assumed that the amount of materials in terms of weight remains unchanged after the substitution. Also, the construction and operation stages are not affected by this change.

Figures 9 and 10 shows the effects at the embodied stage of material substitution of support structural frame on embodied energy and carbon for the living walls. Because the alternative materials selected (hardwood, HDPE and stainless steel) have different coefficients of embodied energy and carbon, they exhibit different effects in the analysis. From Figure 9, for all four living wall systems, hardwood can help decrease the total embodied energy but HDPE and stainless steel will increase the values. From Figure 10, both hardwood and HDPE can help decrease the total embodied carbon but stainless steel will increase the values. In practice, other factors such as the design of the support structural frame, safety issues, costs and maintenance have to be considered carefully when selecting the materials for the construction (González and Navarro, 2006).

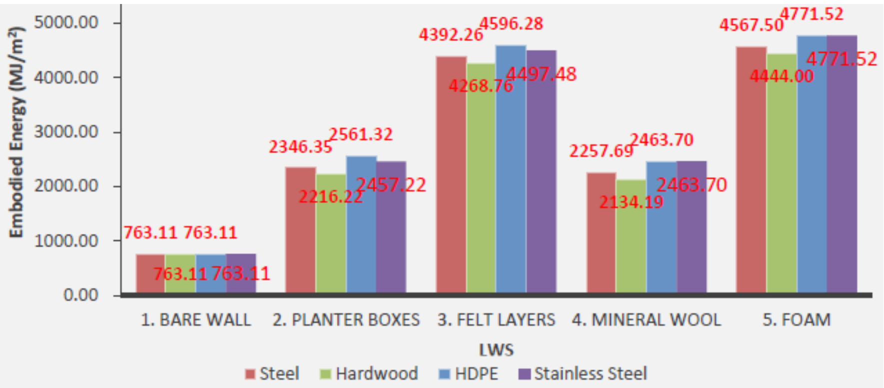

Figure 9. Effects of material substitution of support structural frame on embodied energy for living wall systems

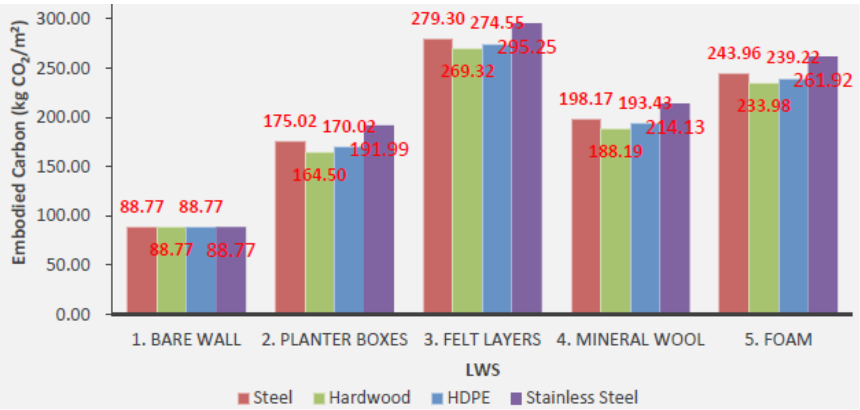

Figure 10. Effects of material substitution of support structural frame on embodied carbon for living wall systems

7. Discussions

Like other LCA research, the main limitation of this study is the difficulty of finding accurate and reliable data to be used in the life cycle inventory for the energy and carbon calculations, especially concerning complex materials and products, such as the components of living wall systems. Lack of information through the supply chain concerning the product has made it unfeasible to obtain the materials' breakdown. It is not uncommon that embodied carbon and energy data are not available for some products or materials of living walls. To resolve this problem, the embodied carbon/energy is approximated as the sum of their constituent materials or elements; this may overlook the impacts from manufacturing and transport processes.

It is clear that the present study is conducted with a high level of uncertainty for the calculation of embodied energy and carbon at different lifecycle stages of the indoor living walls. Reference to popular databases and study of the technical details and practical design considerations of typical indoor living wall systems can help manage the uncertainties and ensure the comparative analyses are meaningful and reasonably. The goal of this research is not to determine the precise embodied impacts, but to demonstrate the theory of embodied energy and carbon for the assessment of indoor living walls or other similar systems. It is hoped that the research findings could provide hints for improving the data quality and developing human skills on sustainable building design and analysis.

In fact, the full benefits of indoor living walls include consideration of many environmental and social effects, such as air purification to improve indoor air quality, thermal performance to enhance the efficiency of cooling and heating systems, and growing of edible plants to supply vegetation and food. At present, it is very difficult to comprehend all these effects and quantify the energy and carbon impacts without over generalization. More research efforts are needed to investigate the real benefits in different applications and develop scientific methods to evaluate the consequences.

8. Conclusions

Indoor living walls are becoming increasingly popular in buildings as they can provide good aesthetic effects and other environmental benefits. This research applies the theory of embodied energy and carbon for the assessment of indoor living walls. A system of accounts is constructed based on an input-output model and the total direct and indirect energy and carbon requirements for each output are estimated. The energy and carbon calculations are divided into three main life cycle stages including embodied stage, construction stage and operation stage. For the embodied stage, it is further broken down into material, transportation, and recurrent energy/carbon.

It is found that the indoor living walls could be more environmentally sound if recycled materials, renewable energy and sustainable design and maintenance practices are applied. In order to reduce the carbon footprint of such living wall systems, it is important to consider and account for the energy/carbon that is embodied in the materials being used. The energy and carbon content can be reduced by specifying the materials properly and sourcing them responsibly. From the life cycle point of view, as the operation energy and carbon of indoor living walls are quite large (for lighting, pumps, maintenance, etc.), the effect of the embodied stage is relatively small. It is believed other sustainable design strategies may be considered to reduce the environmental impacts of the living wall systems. For example, design for deconstruction, reuse and recovery, renewable resources should be considered for the living walls because it will effectively increase the life-span and energy efficiency of the systems and components.

Interestingly, it is observed that the worldwide research on vertical greening systems begins with outdoor greening (green façades and living walls). In the past, many people were doubtful about the benefits and potential of indoor greening applications. But nowadays the indoor living walls are well accepted and growing very fast in the market. Therefore, it is essential to develop a better understanding of them and improve their performance since we all can enjoy the greening and people spend most of the time staying indoor.

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