RENEWABLE VERSUS NON-RENWABLE BUILDING FABRIC: A COMPARATIVE STUDY ON THE EFFECT OF MATERIAL CHOICE ON THE EMBODIED ENERGY AND GLOBAL WARMING POTENTIAL OF LOW ENERGY DWELLINGS

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Abstract: The built environment causes damaging environmental impacts through processes such as material extraction, manufacture, transport, construction, maintenance, demolition and disposal, and the operational energy of buildings. Building and fabric design is driven by statutory requirements to conserve operational energy in response to climate change mitigation. Very low energy in use building standards such as Passive House have been developed and these standards require careful and rigorous design incorporating heavily insulated fabric, solar heat gains, heat recovery, and non conventional heat distribution systems.

This paper examines how material choice can contribute to overall thermal performance and also potentially sequester carbon within the building fabric which in turn might offset operational energy emissions. A house is modelled with two different specifications of fabric design, both achieving the Passive House standard. The implications of material choices on energy in use and the Embodied Energy and Global Warming Potential (both positive and negative) are explored.

1. Introduction:

The life cycle of buildings accounts for 40% of the total global energy demand (Dixit et al. 2010). Reducing energy to heat buildings is well established, but what about all the other stages of a buildings lifecycle? There will be energy inputs to make, package and transport materials. There will be energy required to construct, maintain and eventually deconstruct and dispose of the building.

In a recent study the Embodied Energy (EE) and Global Warming Potential (GWP) due to the fabric of a 222m^2 low operational energy dwelling (41.9kWh/m^2/a) was examined. Fabric EE accounted for 30% of the total primary energy requirement over 50 years and fabric GWP accounted for 41% of the total GWP (Bribian et al. 2009). Another study (Monahan and Powell, 2011) examined an 88m^2 low Energy in Use (EIU) dwelling considering fabric EE and GWP between non-renewable or renewable material selection. The prefabricated timber frame construction resulted in a GWP 34% less than masonry cavity wall construction.

This study examines construction material choice from a designer's perspective and the potential opportunities to positively guide design by measuring the quantities, the EE and the GWP of materials used in low energy houses. The study will compare two different approaches to fabric material choice: non-renewable or renewable.

1.1. Climate Change:

Atmospheric Green House Gas (GHG) emissions can cause a warming influence or positive radiative forcing in the atmosphere. The 1997 Kyoto Protocol set binding targets

to be met between 2008 and 2012 based on a 5% reduction in emissions on 1990 levels (UN 1998). The Protocol identified relevant GHG emissions and how their affect on radiative forcing would be measured. The GWP index expresses the radiative forcing effect of 1 kg of a GHG relative to 1 kg of $C0_2$ over 100 years (IPCC, 2007).
In 2002 the EU published a directive requiring that all member states set and measure targets in relation to the energy performance of buildings in use (EU, 2002). There is no such legislation regarding specification of materials with respect to EE or GWP in Europe (Bribian et al. 2009). Engagement with material choice and GHG mitigation in building design is voluntary.

2. Materials and Life Cycle Analysis:

2.1. Non-Renewable and Renewable Building Materials:

Non-renewable materials are finite and can be extracted once or develop very gradually over time (Berge, 2009) and include minerals such as rock, metals and fossil fuels.
Renewable materials are plant derivatives and thus can be regenerated over again after the initial crop has been harvested (Berge, 2009). A renewable material must not be consumed more quickly that it can regenerate (Chambers et al. 2004). Sustainable production cannot be assumed because a material is renewable and the quantity of renewable materials the earth can support is limited (Chambers et al. 2004).
The attractive characteristic of renewable material is its potential to store or sequester $C0_2$ through the process of photosynthesis. This property can be assigned a corresponding negative GWP.

2.2. Life Span and Longevity:

The lifespan of buildings storing Carbon in the fabric is critical when considering GWP. $C0_2$e sequestered in materials must remain intact for 100 years in order to be accounted in climate change reduction (Berge, 2009). Discounting the possibility $C0_2$e sequestration in fabric on the grounds of longevity could be a missed opportunity. It could be addressed in design by assigning a particular type of future recycling or reuse.
Longevity of individual materials within the fabric is an important consideration and the service life of a particular component must be considered within the context of the all materials comprising it and how they are assembled (Anderson, Clift et al. 2009).

2.3. Life Cycle Analysis:

Life Cycle Analysis (LCA) considers the environmental effects of a product over its life time e.g. extraction, production, utilization and eventual disposal. LCA can include data in relation to EE and GWP. International Standard ISO 14044:2006 sets out an approach to the complex business of carrying out LCA. Individual assessments can vary greatly in scope and comparisons are difficult given the extent of inputs and processes associated with any product. Designers are not qualified to properly assess and understand the full implications of LCA (Anderson, Shiers et al. 2009). A simplified LCA of houses to assess EE and GWP could be adopted as part of the overall statutory approach of building energy rating as required by EU directive 2002/91/EC (Bribian et al. 2009).
A manufacturer can voluntarily state certain Environmental Product Declarations (EPD) including data in relation to EE and GWP. International standard ISO 14025:2010 (ISO

2010) requires that EPD are subject to prescribed third party verification. This standard requires that product categories are selected according to specific rules to ensure comparability i.e. functional units, system boundaries, data description, input/outputs and data quality are the same between product categories in addition to complying with ISO 14044 LCA. A statutory requirement for EPD would encourage a wider application of comparative LCA data in relation to construction materials (Bribian et al. 2008).

2.4. Embodied Energy:

Embodied Energy is defined as the total primary energy to produce a material (Boyle et al. 2004). There is no one accepted methodology to measure EE. Current EE databases are mired by variability, discrepancy and are not analogous (Dixit et al. 2010). The overall consistency between results can suffer e.g. the system boundary adopted might differ between materials. Inconsistent system boundaries are the most crucial parameter when making comparisons (Dixit et al. 2010).

2.5. Global Warming Potential:

2.5.1 Embodied $C0_2$. Embodied carbon dioxide (EC) represents the total GWP of all the GHG emissions in the manufacture of a product. A precise definition is required depending on the system boundary adopted in each individual case. The EC is directly related to the energy type used in manufacture. In calculating EC invariably a whole range of different energy fuels, sources and generation techniques might have been utilised each with its own GWP.

2.5.2 Sequestered $C0_2$. Sequestered carbon dioxide (SC) represents the measure of $C0_2e$ that can be stored as carbon (C0) within plant based renewable materials through the process of photosynthesis. There is much variation between how much carbon different plants contain and associated growth rates (Stanley, 2008). This property of storing $C0_2e$ could reduce or offset the overall GWP of plant based building materials.

2.6. Construction Material Inventories:

There are several inventories of construction materials detailing data such as EE and EC. Some also take account of SC. Some Material Inventories deliberately do not balance EC with SC for a number of reasons. The Inventory for Carbon and Energy (ICE) database developed by Hammond and Jones lists several reasons for not including SC. The science required to evaluate materials within the carbon cycle is considered insufficiently developed. Calculation of GWP including both EC with SC is considered inappropriate unless the supply of timber is matched by equal regeneration. This is not supported by the current trend of worldwide deforestation. Renewability is not considered to necessarily mean sustainability (Hammond and Jones, 2008).
Inventories are usually based on secondary data gathered from sources such as LCA studies. Data in relation to EE and GWP can be very diverse and dependent of a range of factors thus should not be considered definitive or comparable.

3. Passive House:

Passive House (PH) design requires minimised energy use for space heating through maximised fabric and services insulation, minimised or thermal bridge free design, maximised fabric air tightness, maximised passive heat gains (e.g. solar), and installation of mechanical ventilation with heat recovery (MVHR) (SEI, 2008). PH is conceived as an energy balance between passive heat gains and losses to achieve a targeted maximum heat demand (CEPH Developing Group, 2010). Thus PH requires a very low heating load which can be delivered by MVHR (Schnieders and Hermelink, 2006). The annual space heating demand must not exceed 15 kWh/(m^2a) (SEI, 2008). Passive House Planning Package (PHPP) is a Microsoft Excel based spreadsheet program developed to verify the PH standard by inputting values for all the relevant building parameters and equipment of a building. It performs a steady state analysis in accordance with EN 832 (Schnieders and Hermelink, 2006).

4. Methodology:

PH is selected for this study because it is a very 'low energy' approach to building design, represents optimum thermal transmittance performance and reduced energy demand, and is widely adopted in Europe at present. A single house design has been modelled in PHPP using two different materials specifications, non-renewable and renewable.

4.1. House Design:

The model is based on a two storey four bedroom detached house with a Treated Floor Area of 155.23m^2 with a hipped pitched roof.

Using the PHPP software the house fabric was specified to meet the PH specific space heat demand standard for both the non-renewable and renewable materials. The heat loss calculations include heat loss through floors, walls, roof, windows, doors and related thermal bridges. This study was confined to the building fabric associated with external heat loss and heat gains only.

4.2. Data Sources

The designs were based on the construction details, material inventories and other pertinent information contained in the catalogue: "IBO Details for Passive House: A catalogue of ecologically rated constructions" (Waltjen et al. 2009). The fabric build-ups and connections are specifically generated to achieve PH standard under central European climatic conditions. The material inventory section contains tables with the density, thermal conductivity, primary embodied energy and GWP of each material. LCA data is based on ISO 14040 and EPD data is based on ISO 14025. The characterization factors selected to measure global warming are non renewable primary energy content (EE) measured in MJ and GWP_{100} measured in kg$C0_2$e/kg. The net $C0_2$ factor could be positive or negative i.e. the ability to sequester $C0_2$ is included in the catalogue. The LCA system boundaries adopted are cradle to gate.

Calculation of individual material volume was made and fabric weight, EE and GWP were calculated by applying the relevant inventory data from the Catalogue.

Some of the IBO catalogue data could be considered quite definitive such as density and thermal conductivity. However some of the data could be considered more uncertain such as EE and GWP. It was not within the scope of this study to research the original LCA for each individual material. .

The study included a simplistic verification the IBO GWP data for timber: planed spruce air dried: -1.436 kg $C0_2$eq/kg. 1 kg of dried timber can contain 1.8kg of $C0_2$eq/kg (Berge 2009). In the ICE database (where SC is not considered) sawn soft wood is attributed a GWP of between 0.20-0.59 $C0_2$eq/kg (Hammond and Jones, 2011). Based on a subtraction of the Berge figures from the ICE figures, softwood could have a GWP range between -1.6 and -1.21 $C0_2$eq/kg. Thus the IBO GWP factor could be considered potentially realistic depending on how the timber is grown and processed.

4.3 Specifications:

Two generic construction types, non-renewable (NR) and renewable (R), in relation to floor, wall and roof constructions (table 1; figures 1 and 2) were selected from a palette of 27 materials contained in the IBO component catalogue (table 3). The Catalogue provides the U-values and principle linear thermal bridge coefficients. Standard proprietary products with Passivhaus Institute (PHI) certification were selected for windows, doors, glazing and MVHR units.

Table 1: Non-renewable and Renewable materials

	NR model	R model
Ground Floor: U-Value: 0.15 W/m^{2}k	Ground supported concrete slab insulated with petrochemical based insulation.	Suspended timber floor insulated with plant based insulation.
Wall: U-Value: 0.12 W/m^{2}k	Honeycomb block wall insulated externally with petrochemical based insulation with plaster finish.	Double timber T beam stud wall insulated with plant based insulation with external timber cladding.
Roof: U-Value: 0.10 W/m^{2}k	Double T beam pitched roof with non renewable insulation with concrete tiles.	Double T beam pitched roof with plant based insulation with concrete tiles.

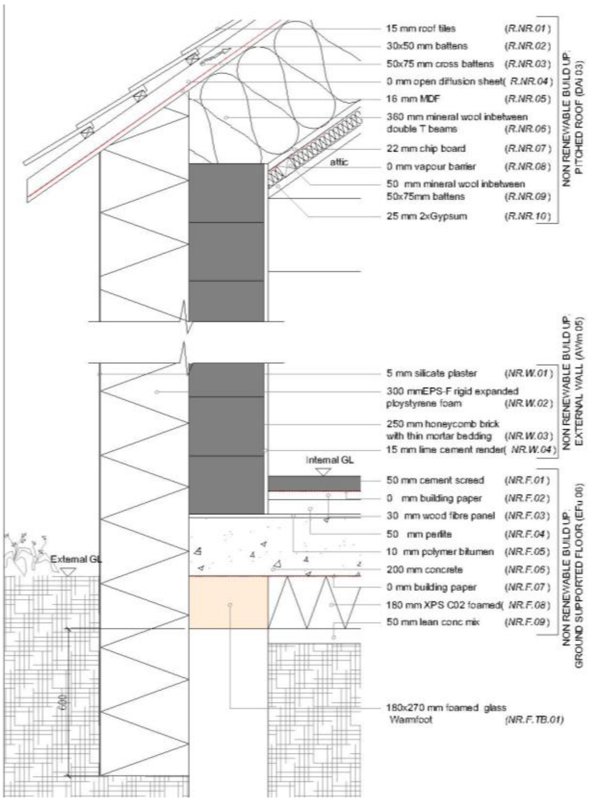

Figure 1: Non-renewable Section

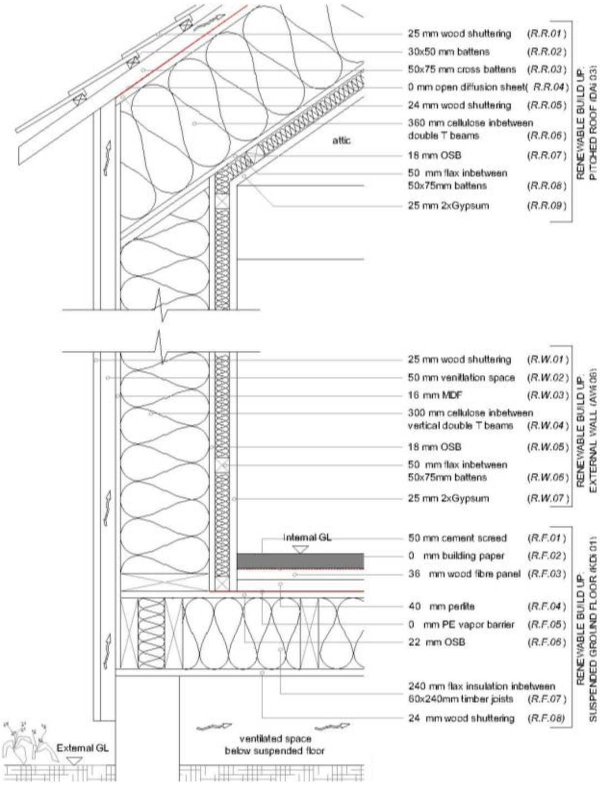

Figure 2: Renewable Section

Table 2: Fabric Material Inventory Data (Waltjen et al. 2009)

	Density	Primary Energy Content NR	GWP
Material:	Kg/m^3 (*Kg/m^2)	MJ/Kg	Kg $C0_2$ eq/Kg
Battens/joists (spruce planed technically dried)	500.000	3.860	-1.436
Building Paper*	0.100	15.100	-0.975
cellulose flakes	35.000	7.030	-0.907
Cement Screed	2000.000	0.880	0.102
Chipboard	690.000	13.350	-1.296
Concrete	2300.000	0.690	0.103
EPS-F rigid expanded polystyrene foam	18.000	98.500	3.350
Flax insulation (without fibres)	30.000	34.000	0.121
Foamed glass	105.000	15.700	0.943
Gypsum plasterboard	850.000	4.340	0.203
Honeycomb bricks	800.000	2.490	0.176
Lean concrete mix	2000.000	0.440	0.060
Lime cement Mortar	1800.000	1.790	0.168
MDF panel	780.000	11.900	-1.040
Open diffusion sheet*	0.080	77.000	2.020
OSB	660.000	9.320	-1.168
PE vapour barrier*	0.200	93.400	2.550
Perlite	85.000	9.350	0.493
polymer bitumen*	4.300	50.000	0.987
Reinforcement to concrete	7800.000	22.700	0.935
Rock wool MW-PT	130.000	23.300	1.640
Roof tiles	1800.000	4.560	0.200
Sheeps wool	30.000	14.700	0.045
Silicate Plaster	1800.000	12.100	0.485
Vapour Barrier*	0.200	93.400	2.550
Wood fibre panels	270.000	13.700	-0.183
XPS C02 foamed	38.000	102.000	3.440

There is numerous energy performance criteria required to achieve the PH standard. The principal specifications are detailed on Table 3.

Table 3: Non renewable and Renewable Performance specifications

	Non-renewable	Renewable
Floor:	U-Value: 0.15 W/m^2k	
Wall:	U-Value: 0.12 W/m^2k	
Roof:	U-Value: 0.10 W/m^2k	
Windows	uPVC $U_{install}$-Value: 0.80 W/m^2k	Timber $U_{install}$-Value: 0.79 W/m^2k
Door	uPVC $U_{install}$-Value: 0.79 W/m^2k	Timber $U_{install}$-Value: 0.73 W/m^2k
Glazing	4/16/4/16 90% Argon U_{centre}-Value: 0.69 W/m^2k G Value: 67%	
MVHR	N_{HR}: 93%	
Air tightness	N_{50} = 0.3	

4.4. Operational Primary Energy and GWP

Three options in relation to fuel choice were considered: gas powered condensing boiler (93% efficient), electric heater to the MVHR supply air or biomass stove in addition to the energy required to power heat distribution and ventilation via MVHR. Table 4 gives both primary energy and GWP emission factors for each fuel selected applied to the PHPP results regarding operational energy.

Table 4: Irish Fuel Primary Energy Factors (SEAI 2009)

Fuel type	Primary Energy Factor	$C0_2$ Emission Factor ($kgC0_2/kWh$)
Natural gas	1.1	0.2030
Electricity	2.7	0.6430
Biomass	1.1	0.0250

5. Results and Discussion:

5.1 PHPP Calculation:

PHPP calculations of each model were made to determine the annual specific heat demand and verify substantial compliance with PH standard (Table 4).

Table 4: PHPP Results

House Type:	Total Annual Heat Demand:	Specific Space Heat Demand Per m^2 TFA:
Non-Renewable:	1663 kWh/a	11 kWh/(m^2a)
Renewable:	1869 kWh/a	12 kWh/(m^2a)

The individual transmission losses of each element are illustrated in Figure 3. Both models are performing almost identically from a heat loss perspective thus setting the scene for the fabric comparisons.

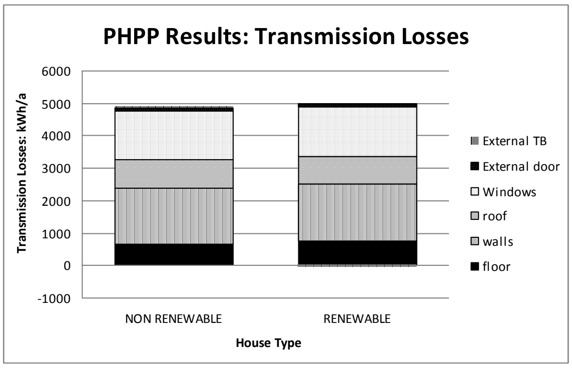

Figure 3: Heat Loss/Gain balance

5.2. Fabric Weight

Figure 4 illustrates that there is a very substantial difference between the fabric weights. The renewable fabric weighs about one third of the non-renewable fabric.

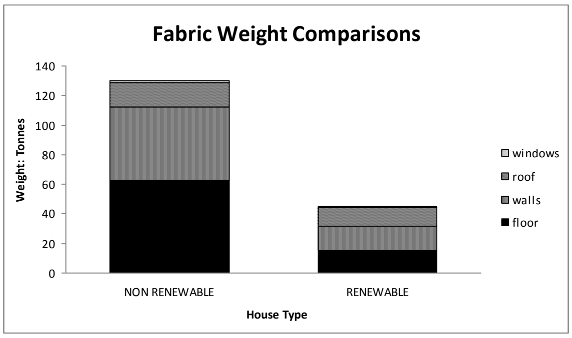

Figure 4: Comparison of fabric weight

5.3. EE Fabric and EE Operational Results:

Despite reaching the minimum annual Space heat demand of 15kWh/m^2/a, Figures 5 and 6 illustrates that the overall primary energy differs significantly depending on fuel choice. This illustrates that while the space heat demand is indeed very low for each house type, the primary energy demand can vary enormously. When considering EE in this case the most efficient choice is the renewable fabric with gas fuelled heating.

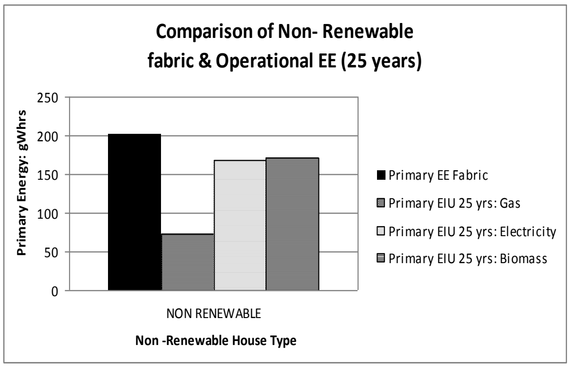

Figure 5: Non-Renewable fabric and Operational EE

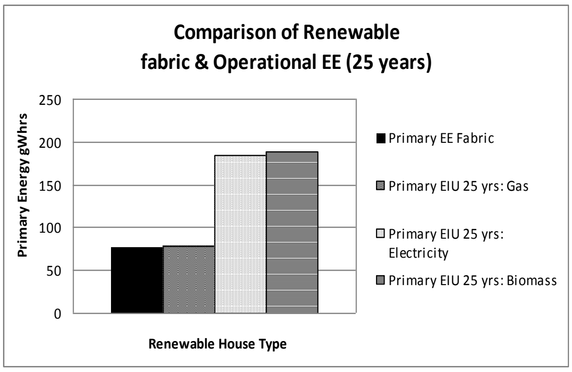

Figure 6: Renewable fabric and Operational EE

5.4. GWP fabric and GWP in use Results:

Figure 7 and 8 shows that over a 25 year life span it is possible to balance the negative GWP of renewable building fabric with the positive GWP of either gas or biomass. The GWP of electricity is very high in comparison.

Table 5 explores the metric of offsetting the positive material GWP of the renewable model against the negative fuel GWP as a tool to measure potential zero carbon design e.g. the negative GWP of the renewable fabric is the equivalent of 28 years positive operational GWP if the primary fuel is gas, 7.5 years if the primary fuel is electricity and 41 years if the primary fuel is biomass.

In terms of offering a reduction in GWP the fabric would need to survive for 100 years. Design for longevity and future recyclability of the renewable fabric to ensure the $C0_2$e storage is maintained is a possible solution. Ensuring the material continues to store carbon for 100 years is probably impossible to administer.

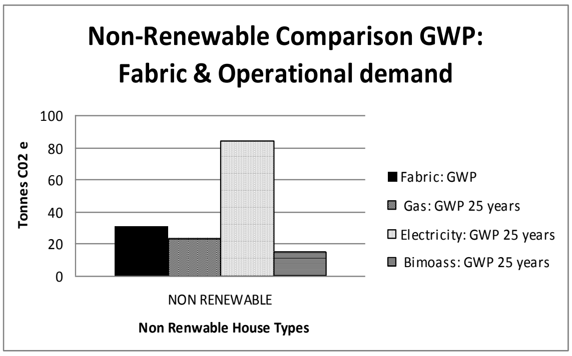

Figure 7: Non Renewable GWP fabric and EIU

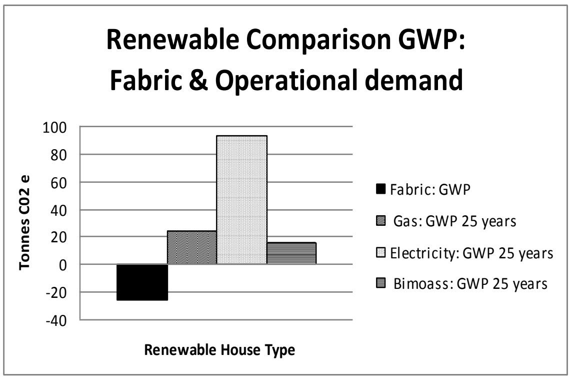

Figure 8: Renewable GWP fabric and EIU

Table 5: Renewable Fabric GWP

Total GWP Fabric ($TC0_2e$)	Total GWP Fuel over 25 Years of operation ($TC0_2e$)		Equivalent operational (years)
-26	Gas	24	28
	Electricity	93	7.5
	Biomass	16	41

6. Conclusion:

PH design requires development of detailed specification early in design. Subject to access to some basic data points such as density, EE and GWP factors, relatively simple assessment of building fabric design in tandem with detailed PH specifications can potentially offer substantial savings on EE and GWP.

The results indicate that as very low EIU buildings become the norm, quantities of fabric EE and GWP becomes significant.

In terms of potential positive and negative GWP the concurrent fabric and operational calculations can present an opportunity to offset one against the other when selecting renewable plant based building materials with the property of biogenic carbon storage. Based on the IBO catalogue material inventory data a negative GWP is possible in the renewable house types achieving the PH standard.

This study is limited to the heat loss fabric. Thus if the entire building is considered in terms of substructure, internal fabric and all those other elements not included these issues will become further pronounced.

This study indicates that both fabric specifications can achieve comparable thermal performance, yet the renewable fabric weighs one third of the non renewable fabric and contributes -26 $TC0_2e$ GWP whereas the non-renewable fabric is three times heavier than the renewable fabric and contribute +31 $TC0_2e$ GWP.

This study illustrates that it could be worthwhile to set targets in relation to the EE and GWP of fabric in tandem with operational standards such as PH. The targets could then be used for specific material choices e.g. a high impact material could be used in appropriate locations because it is offset elsewhere in the design.

PH might have a very low specific heat demand but can still contribute significantly to GWP depending on fuel choice. This study used a 25 year operational lifespan for comparative purposes with fabric EE and GWP. Modelling EIU over a longer period is considered prone to inaccuracy as fuel sources and generation techniques are likely to change significantly. EE and GWP related to the operational use i.e. space heating can be low in PH design depending on fuel choice with substantial levels accruing over long periods of time. However the EE and GWP associated with the fabric will occur prior to completion of the building. Thus in terms of ambitious climate change mitigation targets EE and GWP associated with fabric should be prioritised.

6.1 Limitations:

The results presented in this study are only as robust as the data source. The literature review indicated that data gathered from LCA can be prone to inaccuracy and is not necessarily comparable. The study hinges almost exclusively a single source of data: the IBO catalogue. Thus the study relies on stated methodologies, secondary and tertiary data sources. It was not possible to access and investigate the data in detail. The results in relation to negative GWP in particular were not adequately verified. The unavailability of any similar studies measuring SC exacerbates these shortcomings. However the calculation of the negative global warming *potential* through the carbon storage properties of plant based materials could be a strategy to incentivise sustainable renewable building fabric specification.

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