Passivhaus Trust
The UK Passive House Organisation

Passivhaus and embodied carbon

May 2022

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Introduction

It is estimated that buildings are responsible for over one third of greenhouse gas emissions globally. There are six ways buildings can cut these emissions:

- reduce operational energy use
- decarbonise operational energy use
- reduce construction material use
- decarbonise the manufacture of construction materials
- reduce activities on construction sites
- decarbonise activities on construction sites.

As buildings become more energy efficient, and with a rapidly decarbonising National Grid, the balance between the carbon emitted when running a building (operational carbon) and the carbon emitted to build it (embodied carbon) is changing. The whole life carbon footprint is a way to assess both operational and embodied carbon. It runs from "cradle to grave", that is, from product material extraction to ultimate building demolition (or better still deconstruction). The whole life carbon footprint thus gives a good indication of the carbon impact of a building though its lifetime.

In new buildings, embodied carbon can represent as much as 40-70% of a building's whole life carbon footprint. Both the RIBA 2030 Climate Challenge and the LETI Climate Emergency Design Guide have set minimum standards for embodied carbon, and the lack of embodied carbon calculations in UK Building Regulations is being challenged through the proposed introduction of a Part Z in England.

Passivhaus buildings are optimised for net zero, providing the best route to minimise whole life carbon. Outstanding levels of building performance minimise operational carbon, while the Passivhaus design methodology encourages optimisation of embodied carbon through efficient use of materials and radically reducing the heat and cooling plant.

The government's approach to achieving zero carbon homes in the UK is based on the decarbonisation of the grid and the switch to heat pumps (which have their own embodied carbon implication as shown later). This will require a huge increase in grid capacity to meet the electrical needs of housing alone, unless we continue to drive down the operational energy used in our buildings. Passivhaus buildings are optimised for a decarbonised grid, by slashing the peak energy demand, thus facilitating a smooth transition to renewable energy for all sectors, not just buildings. In addition, well insulated buildings also allow for 'load shifting' which means you can be more flexible with the timing of heating while still retaining comfortable internal temperatures. This means you can heat your home outside of peak times, when energy prices will be cheaper[1].

Consequently, we need to rethink how we design, construct and supply energy to our buildings. Once the grid has completely decarbonised, the only emissions associated with a building will be the whole life carbon of its construction materials, component replacement and the infrastructure needed to generate and supply its energy demand.

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[1] See *Passivhaus: A route to net zero – Operational Carbon*, Passivhaus Trust 2022

Building to Passivhaus does not increase overall embodied carbon

Building to the Passivhaus standard is the proven route to reducing operational carbon in buildings and whilst Passivhaus does not include an embodied carbon analysis, this was an integral part of the background that informed the Standard. However, it has sometimes been argued that designing to decrease operational carbon emissions increases embodied carbon emissions .

This however is not the case. Figure 1 compares the whole life carbon footprint (measured over 60 years) of a house built to comply with building regulations, which was then upgraded to meet the Passivhaus standard just by increasing the insulation, window specification and airtightness, without any further design optimisation.

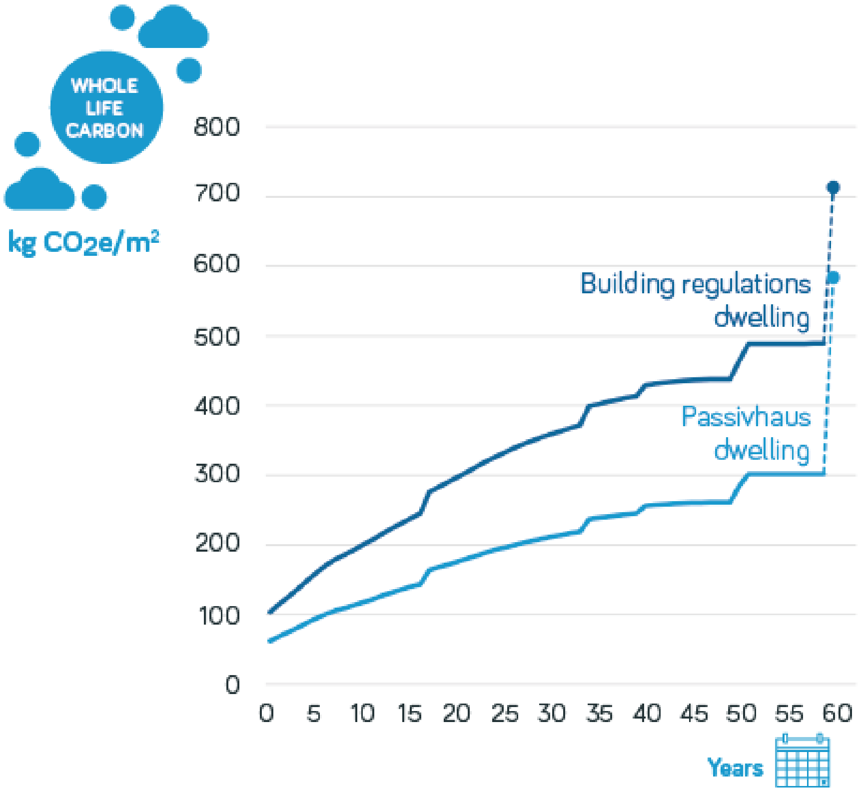

Figure 1 - *Whole life carbon emissions of a Building Regulations dwelling and the same building upgraded to the Passivhaus Standard*

The modelling shows that even with additional building elements (a heat recovery ventilation system, higher performance windows, more insulation), the Passivhaus has a lower initial embodied carbon and less operational carbon over its lifetime, leading to a smaller whole life carbon footprint, because :

1. A Passivhaus has a reduced space heating load and therefore will need a smaller heat pump and radiators. This will reduce the embodied carbon emissions both from the initial installation and from subsequent renewals during the building lifetime. This carbon saving then 'pays' for the additional Passivhaus elements.

2. Passivhaus buildings have a lower space heating demand and have been proven not to have the same performance gap issues as a typical building. The performance gap in non-Passivhaus new-build homes is well documented and is estimated on average to add 60% to space heating demand which we have added to the space heating demand of our Building Regulations home[2].

3. More carbon is sequestrated in the additional cellulose insulation at the construction phase (which is released at end of life at 60 years).

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[2] In England the new building regulations, which come into force in June 2022, may have some impact on the performance gap, this will only be established once post occupancy evaluation is available from homes built to the new standards. Once available the Passivhaus Trust will review this data.

In addition, the assessment was based on exactly the same building design. In reality a Passivhaus planned from first principles would be constructed differently to maximise energy and resource efficiency, through optimisation of the form factor, orientation, fenestration design, etc., which is not factored into this calculation. A better form factor can significantly reduce the amount of construction materials. The assessment was also based on both buildings using ASHPs. In reality a Passivhaus could have utilised a classic compact heat pump system (taking the place of the MVHR and ASHP) to deliver both the ventilation and heating, potentially reducing the embodied carbon further. Also not factored into the calculation are the additional whole life carbon co-benefits Passivhaus is likely to bring:

- Lower replacement and maintenance emissions throughout the building's life owing to the quality of build and quality assurance on site (for the purposes of this assessment identical product lifespans have been assumed).

- Well designed, well-built, quality assured buildings such as a certified Passivhaus should last well beyond the 60 years assumed in an embodied carbon calculation.

- A Passivhaus new build will not require further fabric retrofit to meet any future zero carbon standards. This is unlikely to be the case for a Building Regulations building.

And we must also consider other sustainability benefits beyond simply carbon, including improved air quality, acoustics, thermal comfort and protection against fuel poverty[3].

Glazing choice and embodied carbon

For most new build homes supplied by the electrical grid, the amount of embodied carbon in the building's materials and services is greater than the operational carbon over its lifetime. This demonstrates how critical it is that 'zero carbon' homes account for both sources of emissions, rather than only focusing on carbon emissions in use.

The transition from gas to a decarbonising grid means that we need to consider the embodied carbon of our construction elements carefully. However, this calculation is not simple, as highlighted in recent research by Mark Siddall from LEAP that examined the upgrade from single glazed sash window to double or triple glazed windows, using emission figures from a decarbonising electricity supply.

The results show that window orientation affects the calculations. The heat losses are greater on the north façade compared to the gains and therefore the operational carbon has greater significance than embodied. This is reversed on the south façade, where the embodied carbon has greater significance.

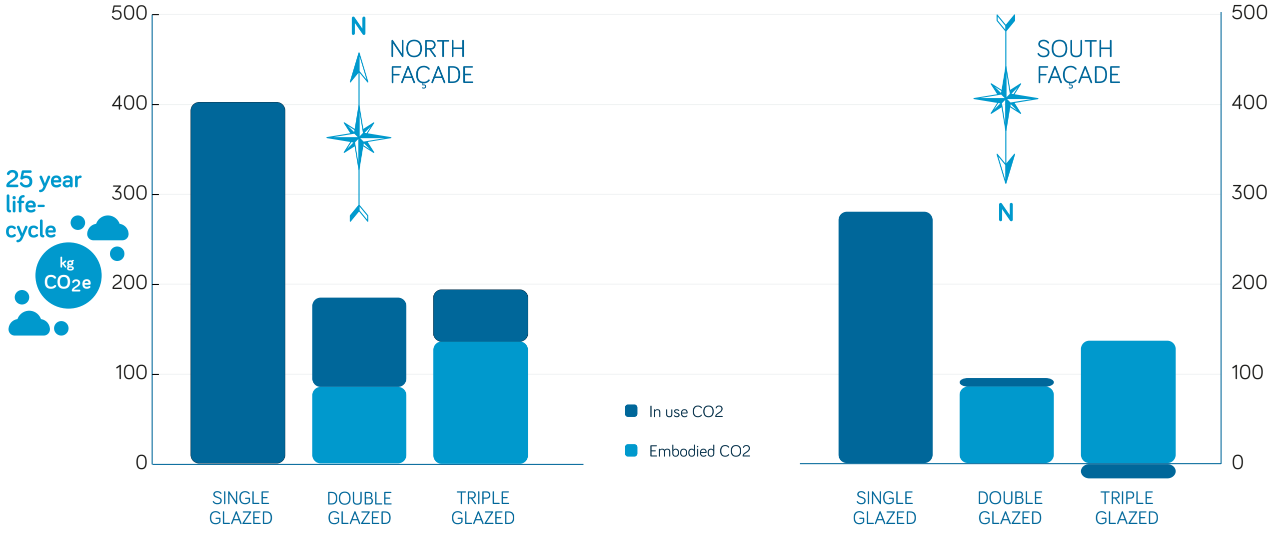

Figure 2 *- Comparison of the embodied and operational emissions from three glazing types in a north and south façade*

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[3] See *Passivhaus Benefits Guide*, Passivhaus Trust, 2021

The whole life carbon of building components, including windows, will also be affected by material choices. Using the north facing window as the example, Figure 3 shows that frame choice is more important than glazing type.

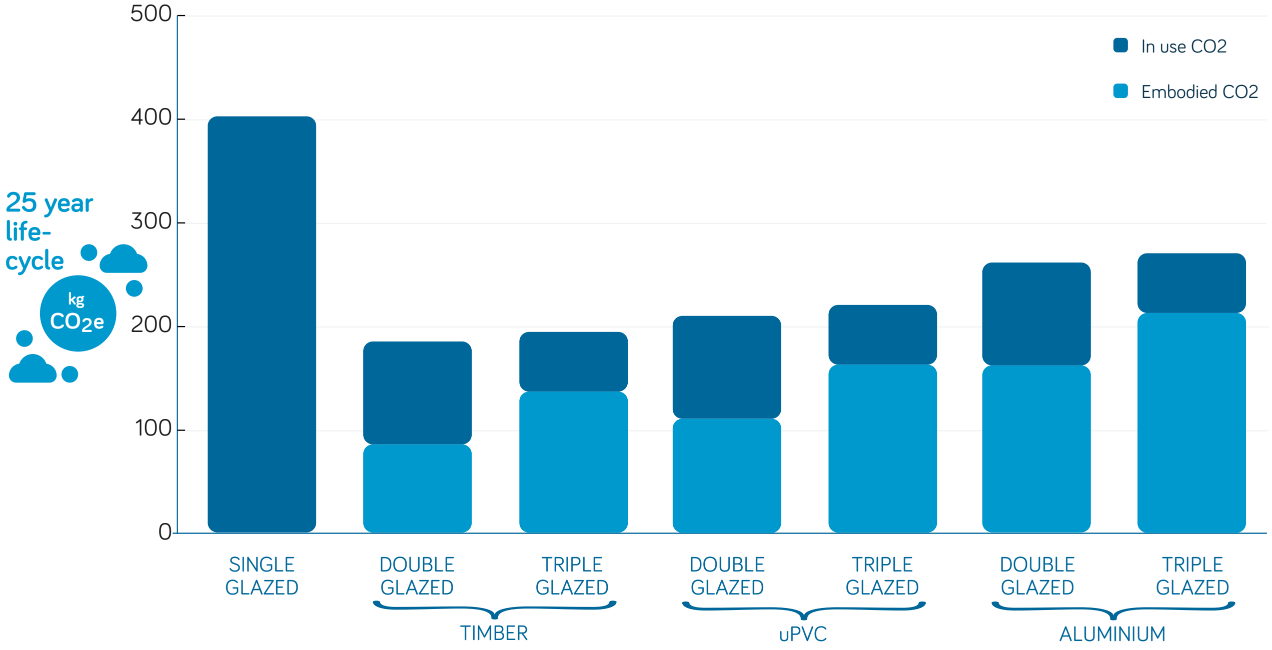


Figure 3 - *The impact of frame type on whole life carbon calculations*

In this example, we can see that over the lifespan of the window the frame material choice makes as much, if not more, difference to the overall emissions, than does the glazing choice. But the orientation of the window makes more difference than either. Embodied carbon assessments are continually envolving and changing and often a triple glazed timber window will now outperform a double glazed UPVC window, so lowering emboded carbon within the building.

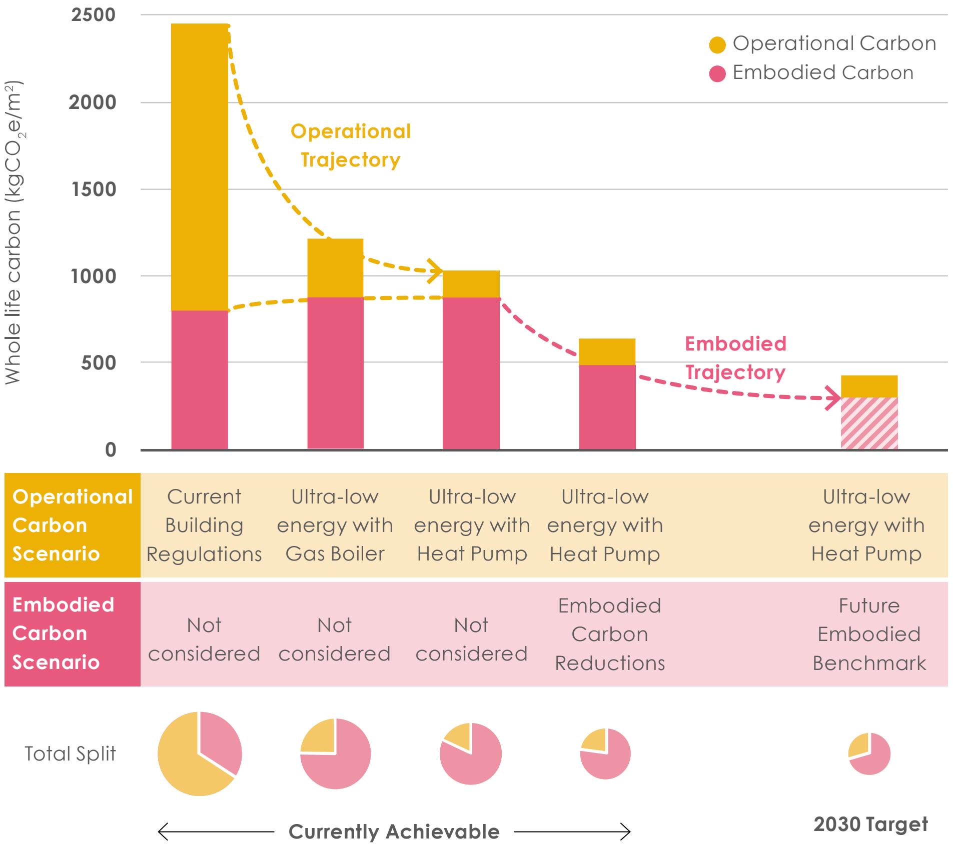
In addition, there are also other factors beyond carbon to consider when installing glazing, which include:

- Winter comfort – only a triple glazed window can achieve this in the UK
- Energy costs – a triple glazed window reduces operational energy use
- Optimisation of total window area, daylighting and frame factor
- The cumulative impact of peak load on the national grid

Therefore the calculations are not straightforward and should be considered alongside other sustainability factors. The research concludes by reminding us that there is still uncertainty about the rate at which the grid will actually be decarbonised and that, rather than looking to downgrade building components, we should be looking to decarbonise manufacture to reduce embodied carbon, while still ensuring our buildings are comfortable, affordable to run, and reduce peak load on the grid.

Low embodied carbon design

As shown, the choice of materials, the nature of their manufacture, and the thoughtfulness of the structural and architectural design, will have a greater impact on the whole life carbon footprint than the performance upgrade to meet the Passivhaus standard. Indeed, when the Passivhaus standard was being developed, embodied energy analysis was an integral part of the background that informed it, especially insulation choices.



Operational Carbon Scenario	Current Building Regulations	Ultra-low energy with Gas Boiler	Ultra-low energy with Heat Pump	Ultra-low energy with Heat Pump	Ultra-low energy with Heat Pump
Embodied Carbon Scenario	Not considered	Not considered	Not considered	Embodied Carbon Reductions	Future Embodied Benchmark

Figure 4 - *Reducing embodied and operational carbon from the LETI Climate Emergency Design Guide*

The graph in Figure 4, drawn from the LETI Climate Emergency Design Guide[4], shows the reduction in operational carbon as we transition away from fossil fuels and increase energy efficiency, and illustrates the opportunities for embodied carbon savings through material choices and good design.

Embodied carbon in the built environment can be reduced by using the following principles:

1. *Reuse existing buildings rather than rebuilding, as most of the embodied carbon is located in the foundations and the superstructure*
2. *Extend the life of the building though better-quality construction*
3. *Use products with longer lifetimes*
4. *Reduce or eliminate building materials with high embodied carbon*
5. *Use durable materials that are easy to maintain*
6. *Buy local materials where possible to reduce transport*
7. *Reuse building materials at deconstruction*
8. *Design for disassembly and the circular economy*

In addition to carbon emissions, the extraction, use and disposal of construction materials have severe environmental consequences to air, land and water pollution.

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[4] *Climate Emergency Design Guide*, London Energy Transformation Initiative, 2020

This comprehensive strategy to reducing embodied carbon is summarised in figure 5 below.

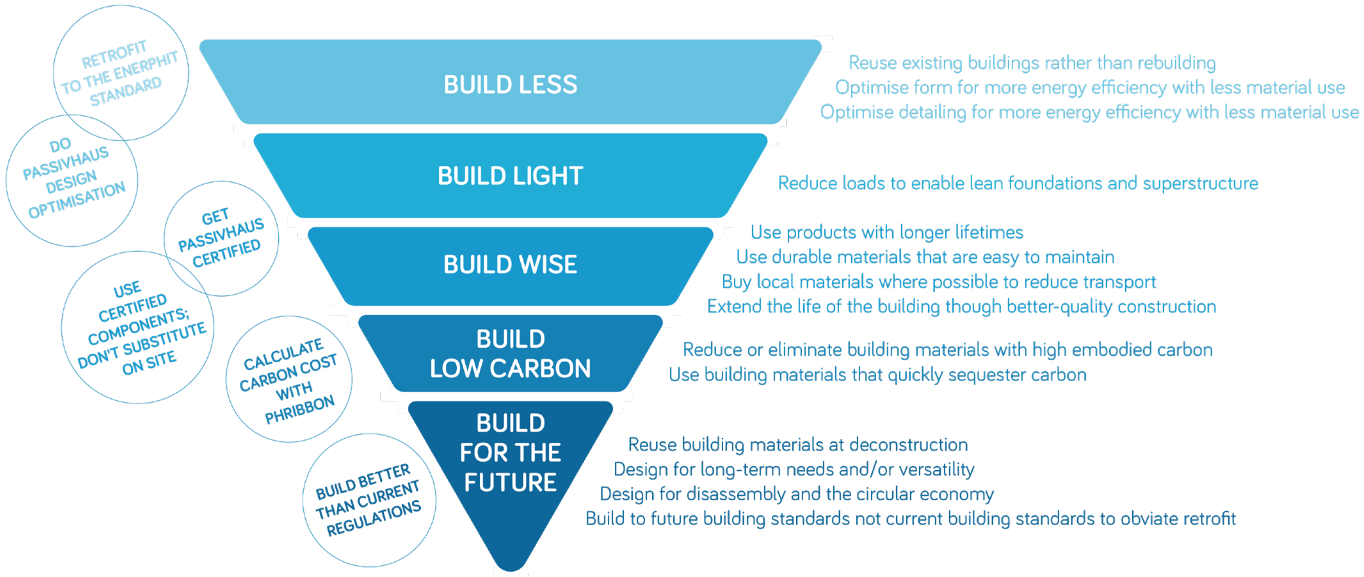

Figure 5 - *Strategy to reduce carbon emissions (based on concept from KLH Sustainability)*

Therefore, resource efficiency and creating a circular economy are also critical to reducing the environmental impact of materials.

Two of the most common materials in construction, steel and concrete, are responsible for 15% of global carbon emissions. Demand for construction materials is also predicted to more than double by 2060[5]. Steel is the most carbon intensive material, and whilst the embodied carbon of concrete is lower, considerably more volume and weight is needed to achieve the same structural outcome and it is by far the most widely used construction material globally. Steel design makes a significant impact on embodied carbon - a recent study on light gauge steel frame dwellings showed that the embodied carbon can be lower than a traditional masonry cavity wall alternative[6]. However, steel frame is particularly challenging to design thermal bridge free and without thermal bypass, meaning that it is not always an appropriate choice for a Passivhaus building[7].

Reducing the use of these materials will impact on embodied carbon emissions. What are the alternatives? Typically, timber is being promoted to lower carbon impact. However, wood also has embodied carbon content. Through sequestration, namely the intake of carbon dioxide during the growth of the tree, timber construction does have the potential to be a temporary carbon store. But how the timber is grown, harvested, manufactured and dealt with at end of life (reused, taken to landfill or incinerated) can result in both up-front emissions and in any temporarily stored carbon being released back into the atmosphere. Therefore, exchanging timber for concrete and steel is not a straightforward solution.

Irrespective of the choice of materials, what will reduce embodied carbon is designing and building resource efficient buildings through Passivhaus design principles such as:

- Rationalising the form factor to reduce the amount of materials used overall in the building[8]
- Designing in structural efficiency, to simplify airtightness and thermal bridges, which also reduces material use

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[5] OECD 2018 'Global material resources outlook to 2060 – economic drivers and environmental consequences'

[6] Carbon Assessment by Collida (a Willmott Dixon Company) and Architype, 2021

[7] See *Modelling assumptions for steel projects*, Passivhaus Trust 2022 and *Steel in Passivhaus construction: technical position paper*, forthcoming

[8] Form factor study for South Yorkshire Housing Association, Qoda Consulting, 2021

The additional elements needed for a compliant Passivhaus design (triple glazing, MVHR) only account for a small percentage of the overall whole life carbon footprint. Other factors, such as reducing steel and concrete and embedding circular design principles, are more important. After tackling these elements, simplification and rationalistion of form factor and the reduction in size of heating systems found in a Passivhaus lead to a reduction in embodied carbon.

We can see the impact of a reduced heating system when we compare the embodied carbon breakdown of the construction elements of the Building Regulations house and the same building upgraded to the Passivhaus standard (using the same model as in Figure 1 above).

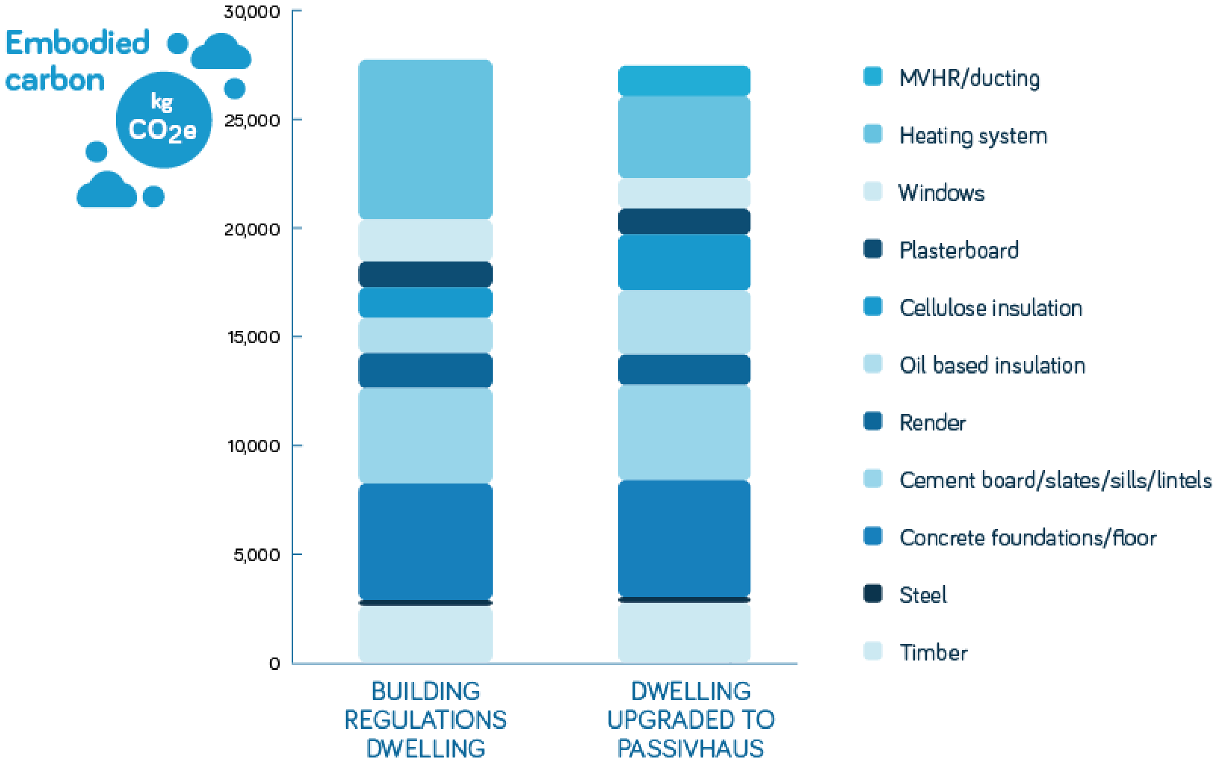

Figure 6 *- comparison of embodied carbon of construction elements. Building Regulations house vs Passivhaus house*

Here we can see that the materials which contribute most to embodied carbon are concrete, concrete products and the heating system. In our example the timber triple glazed windows have less embodied carbon than the UPVC double glazed unit used in the Building Regulations option, supporting the argument that frame choice is more important than glazing type. Reducing the size of the heating system by reducing energy demand more than 'pays' for the embodied carbon in the MVHR unit and additional insulation materials.

Retrofit

Whole life carbon calculations are also important when considering retrofit. Improving the energy performance of a building will add to the embodied carbon (additional insulation and building services) but this can be offset against operational carbon improvements or the embodied carbon cost of demolition and replacement.

A planned refurbishment of St Sophia's primary school in Scotland found that reducing space heating from 210 to 22 kWh/m2a using EnerPHit added an additional 162 tCO2e of upfront embodied carbon, and 4.1tCO2e lifetime embodied carbon on average per year in maintenance/replacement, of which just over half was attributed to the building services[9].

Quite rightly there is concern about the embodied carbon in the construction materials used in a retrofit, but as Figure 7 shows, the embodied carbon impacts of fabric improvements are less than half those required for new mechanical, electrical and plumbing (MEP) services . This proportion would be even higher if heating demand was not significantly reduced using the EnerPHit methodology. This reminds us that simply changing the heating systems in our existing buildings without insulating and tackling air tightness means locking in high levels of embodied carbon into equipment that needs regular replacement and relies wholly on a decarbonising grid. Investing in the building fabric means less embodied and operational carbon, which results in a faster carbon payback.

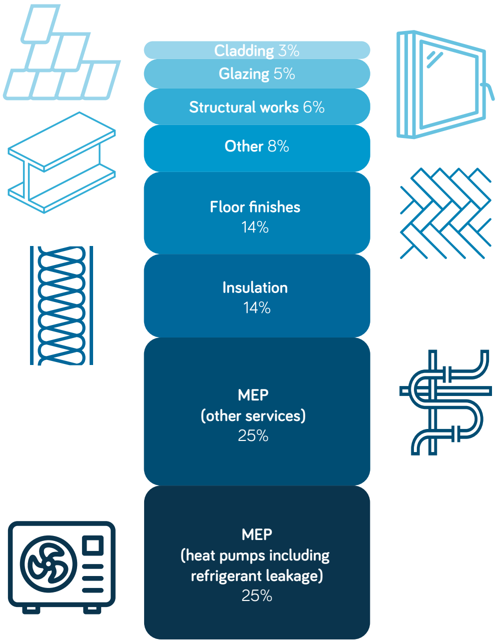

Figure 7 *- Embodied carbon breakdown at design stage of an EnerPHit retrofit at St Sophia's school, analysis by Useful Projects*

Using our example of the school, the carbon payback period (where the embodied carbon is offset by the savings in operational carbon) was 6-7 years using National Grid's FES - see figure 8[10]. In addition, the school has all the benefits of new sustainable building – that is, summer and winter comfort, reduced running costs, and good indoor air quality - without the need for a costly and carbon intensive demolition and rebuild process. By retrofitting rather than rebuilding, the embodied carbon of the project was cut by 40%, largely through the reuse of the foundations and superstructure, two of the highest embodied elements in a new building.

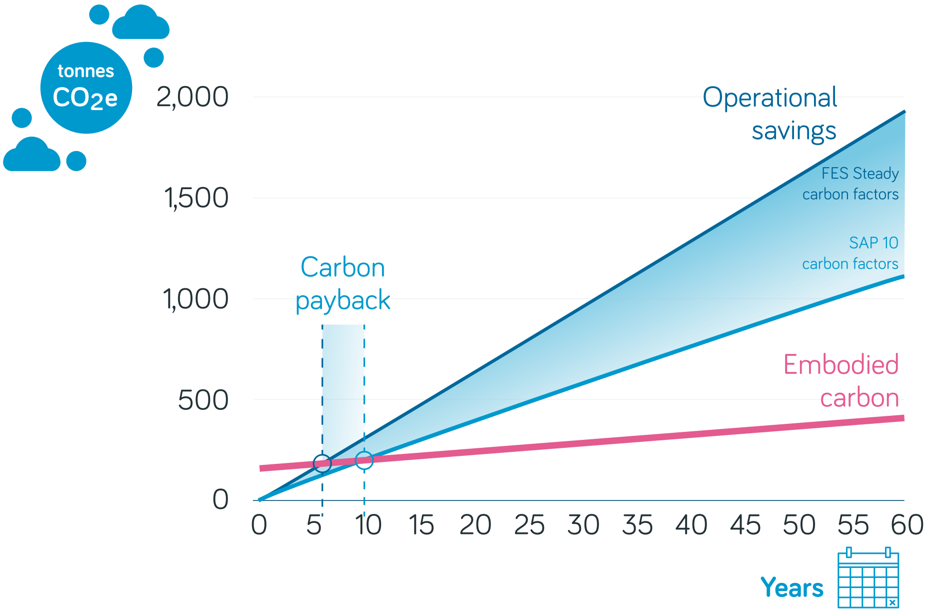

Figure 8 *- Embodied carbon vs operational carbon savings St Sophia's school, analysis by Useful Projects*

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[9] Assessment undertaken in accordance with BS EN 15978 and RICS Professional Statement, 2020. Reference area for refurbishment = 981 m² GIA.

[10] The 'Steady Progression' FES is used for this model as this is the scenario recommended by the RICS in their professional statement *Whole life carbon assessment for the built environment.*

On-site renewable energy

A rapidly decarbonising grid is also changing the embodied /operational calculations for on-site renewable technologies. If energy demand using the building fabric is not fully optimised, bolt-on technologies such as photovoltaics (PV) are often used to 'offset' carbon emissions. However, these technologies also have embodied carbon implications. Figure 9 below gives the current embodied carbon calculations per kWh of electricity generated for on-site photovoltaics and offshore wind, compared to the National Grid carbon intensity predictions for 2020 -2050[11].

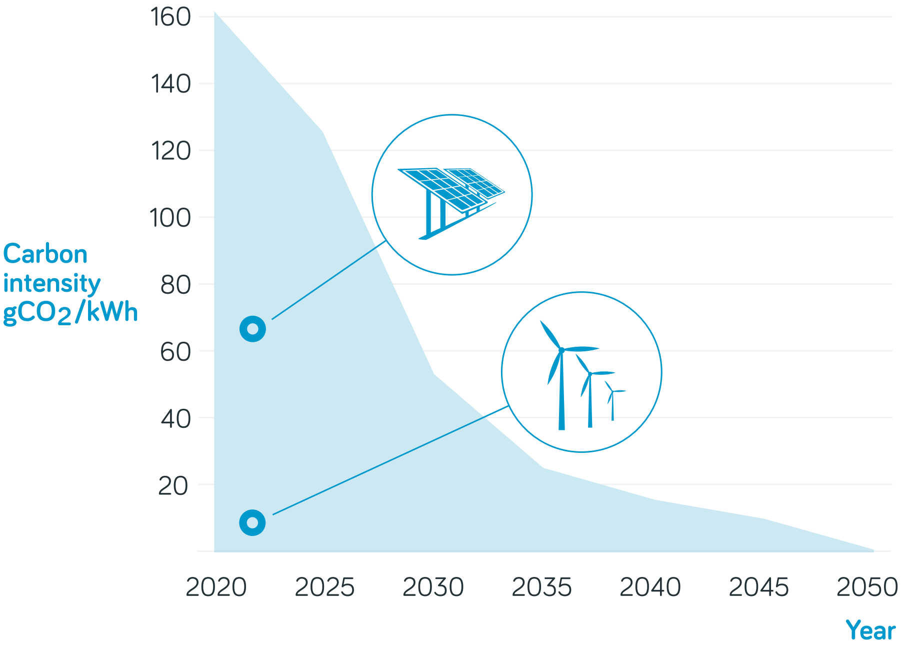

Figure 9 *- Comparison of the average embodied carbon of photovoltaics and offshore wind compared to the carbon intensity of the National Grid 2020-2050*

The whole life carbon emissions of bolt-on technologies need to be less than the carbon intensity of the National Grid to be able to truly offset emissions. There is a large variation in the carbon calculations for PV, which depend on the panel type chosen and energy used to manufacture that panel, and can range between 22-109 kg CO2 per kWh. As a comparison, the whole life carbon of offshore wind has a smaller variation, between 5 - 13 kg CO2 per kWh.

As the energy supply decarbonises, so will the embodied carbon of construction materials. However, this reduction will not be uniform. For example, it is predicted that the carbon intensity of aluminium will reduce significantly, but much less so for concrete. What this tells us is that reliable and up-to-date data is needed to allow these calculations and comparisons to be made, and that these assessments will change over time as process emissions intensities change.

In addition, the carbon intensity of the grid does not include the embodied carbon of the infrastructure to generate electricity[12]. To allow a true comparison, this needs to be factored into the calculations.

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[11] Greenbook 2021 grid emission factors to 2050 BEIS

[12] NationalgridESO carbon intensity forecast methodology 2021

Whole life carbon calculations

There is a standard for embodied carbon calculations in the UK, the RICS Professional Statement on Whole Life Carbon, which is based on EN 15978 and is used by RIBA, CIBSE and IStructE.

This standard is embedded in AECB PHribbon, the optional extra for Passive House Planning Package (PHPP), which can be used to assess the whole life carbon footprint of a building. PHribbon, written by Tim Martel and the AECB, calculates embodied CO2 from Cradle to Grave, covering stages A-C (and D where information is available).

This therefore includes :

Stage A, A1-A3 Manufacture including A4 Transport to site and A5 Construction

Stage B, Use of the building including B4 Replacement

Stage C, Demolition and Disposal of the building

Stage D covers the Reuse and Recycling potential of materials post demolition. This calculates the credit from reuse and is quoted separately from the main calculation.

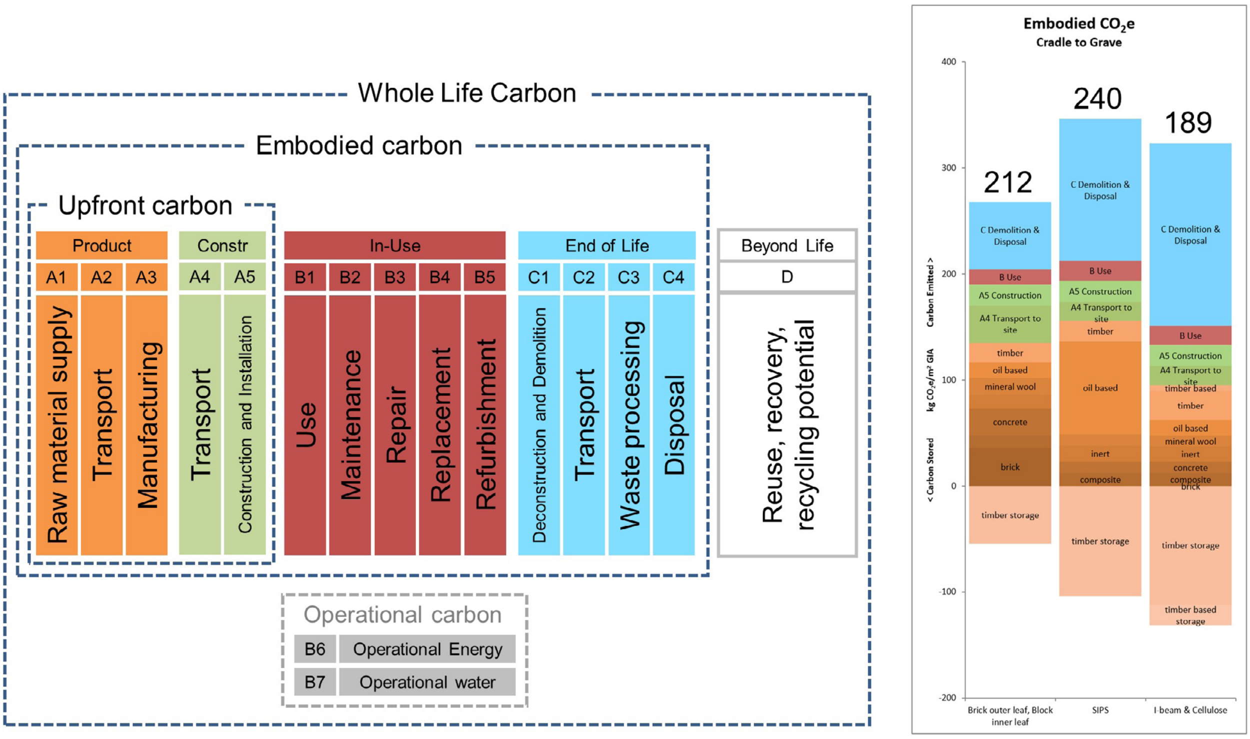

Figure 10 - *Extract from AECB PHribbon showing the stages and outputs*

Figure 10 shows these stages and how they are calculated in PHribbon, which makes whole life carbon calculations relatively quick to calculate using the material quantities embedded in a PHPP assessment and is suitable for whole life carbon initial estimates for both the RIBA 2030 Challenge and LETI. More about PHribbon can be found at phribbon.co.uk.

Conclusion

The relationship between embodied and operational carbon is rapidly changing, as energy supplies decarbonise worldwide. The embodied carbon of construction materials is locked into a building, based on the energy supply conditions now, whereas operational carbon changes as energy supplies change and, at the moment, is steadily decarbonising. However, continuing to reduce energy demand is still important as it reduces peak loads and shrinking our collective winter energy demand will reduce the level of future zero carbon energy infrastructure and storage needed.

Emerging research shows that designing to the Passivhaus standard, be that for new or existing buildings, does not need to result in increased embodied carbon and that choice of materials, rationalisation of build form and reduction of building services play a significant part in reducing whole carbon. Therefore, with a Passivhaus you get the multiple benefits of:

- Reduced operational carbon
- Reduced whole life carbon
- Reduced operational and maintenance costs
- Increased summer and winter comfort
- Increased indoor air quality

Therefore, we should not be looking to reduce either operational or embodied carbon, but to tackle both and these can be done simultaneously.

Passivhaus buildings are optimised for net zero, providing the best route to minimise whole life carbon. Outstanding levels of building performance minimise operational carbon, while the Passivhaus design methodology encourages optimisation of embodied carbon through efficient use of materials and radically reducing the heat and cooling plant.

As shown, reliable accurate and up to date information on the whole life carbon assessment of building materials, services and the national grid is vital to allow comparisons and informed choices to be made. To assist with this, the Passivhaus Trust is planning to undertake further research in this area to help fully understand the interrelationship of these complex elements .

Acknowledgements

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