Balancing embodied and operation carbon

Introduction

The material and products used within building facades contribute directly to the embodied carbon of a project. Furthermore, the façade system plays a key role in the regulation of the building's energy use and operational carbon.

Changing the design of the façade by, for example, increasing the thickness of insulation, will increase the embodied carbon of the façade but in many cases will reduce the operational carbon of the building. If we are to minimise carbon emissions, then we need to be able to balance the effect of our design decisions on both the embodied and operational carbon of the building.

As a result, today's façade designers must balance both the embodied and operational carbon of their design decisions in the pursuit of minimising whole life carbon.

To this end, this article introduces the idea of Carbon Payback Periods (CPP) as a metric for assessing the relative carbon benefits of design decisions whose scope spans both the embodied and operational carbon. A number of equations are presented which will aid designers wishing to implement the described approach on a project.

An approach for calculating the CPP is presented, and the need to account for the building performance gap and decarbonisation is highlighted. This paper also introduces the concept of the 'time value of carbon' with a short discussion on how this may be accounted for within the assessment of the CPP.

Sustainable design encompasses more than just minimising carbon emissions and requires consideration for resilience, passive-capacity, circularity, biodiversity and more. For this reason, designers should note that the CPP should not be used blindly and should inform design decision making as part of holistic approach.

The façade as a skin

'The façade is the *skin* of the building' is an analogy well-used by architects and façade designers. The analogy is good because it provides a very intuitive relationship easily understood by specialists and laypersons alike.

The skin, technically an organ, provides the human body with a primary level of protection against the external environment, it also acts to insulate the body by provision of fat near to the surface and regulate internal body temperature via hairs and sweat glands.

In kind, the façade keeps the inside environment in and the outside environment out, whilst helping to protect and regulate the internal environment of a building through a variety of passive and active measures.

Traditionally, the key performance parameters through which facades regulate the internal environment are (1):

- U-value: a measure of steady-state heat transfer through a facade element. A higher U-value indicates a greater level of heat transfer through an element;.
- Thermal bridging ψ- and χ-values: a measure of the additional steady-state heat transfer associated with interfaces between facade elements, structural and services penetrations and changes of geometry;

- Airtightness: a measure of the amount of uncontrolled air leakage through the facade;
- g-value: a measure of the amount of solar radiation energy transmitted through glazing and other translucent or transparent elements. A low g-value indicates that a glazing unit lets through a low percentage of the radiative solar energy;
- Shading: the use of fixed or deployable elements external or internal to the façade to control solar radiation;.
- Light transmission: a measure of the amount of visible light transmitted through a glazing unit;
- Form factor: the ratio of a building's external surface area to its internal floor area.

Designers specify these parameters to both moderate internal environment and minimise the operational energy demand of the building. For this reason, facades have a strong, albeit indirect, influence on the operational carbon of a building. This influence is recognised most notably in the Passivhaus standard which promotes a 'fabric first' approach to managing building energy use.

The façade as a structure

There are many different forms of façade system available. These include large format precast concrete panels, off-site manufactured unitised curtain walling, on-site installed stick-system curtain walling and various kinds of rainscreen cladding and over-cladding.

The façade of a building is a structure in and of itself. Exposed to external loads, most commonly wind and self-weight, the façade must provide a stable, stiff and robust load path back to the supports. The façade must also accommodate the movement of the supporting structure and be able to expand and contract in response to changes in temperature and moisture content. The strength and stiffness of the facade elements are amongst the many design criteria that the façade must satisfy.

The greenhouse gas (GHG) emissions associated with the production, transport and assembly of the materials and products that form façade systems contribute to its upfront embodied carbon. As a result, the façade contributes to the wider embodied carbon of the project. For many façade systems, components will need to be replaced during the design life of the building and therefore additional embodied carbon emissions associated with lifecycle module B4 need to be considered.

Estimating the whole life carbon emissions from buildings in the UK is complicated, with no single agreed figure. Figures published by LETI (2) suggest buildings account for 49% of annual carbon emissions in the UK. Of these emissions, 20% is attributed to the embodied carbon of new construction (2). A recent report (3) by the World Business Council for Sustainable Development suggests that the façade may contribute between 10 to 31% of the embodied carbon of a building (life cycle stages A – C). From these figures it may be understood that the embodied carbon of new build facades contributes in the order of 1-3% of annual UK emissions.

This proportion is substantial and anticipated to increase due to improvements in building efficiency and energy grid decarbonisation (as operational carbon is reduced so the contribution of embodied carbon becomes proportionally greater). If this proportion were extrapolated globally it would represent the size of emissions from a medium-sized country, say South Africa or Canada (4). This highlights the responsibility of the façade industry in this climate emergency.

Balancing embodied and operational carbon

In recent decades, ever-tightening Building Regulations have significantly improved the operational efficiency of buildings, in part through the specification of minimum requirements for the aforementioned façade performance parameters. However, the façade industry has often met these requirements at the expense of unregulated embodied carbon emissions. Figure 1 illustrates this trade-off through development of glazed façade systems from single glazing through to double-skin systems.

It should be noted that Figure 1 is intentionally simplified to illustrate need for a balance, in practice considerations for overheating risk, condensation, security and more factor into the selection of the most suitable façade system. Notwithstanding, today's designers must balance both the embodied and operational carbon of design decisions in the pursuit of truly low carbon design. The need to consider this trade-off has not gone unnoticed in the wider press. In a Guardian article on a proposed office in Salford, the journalist quotes *"Triple-glazed windows might reduce heating requirements, but their embodied carbon is vast*" (5).

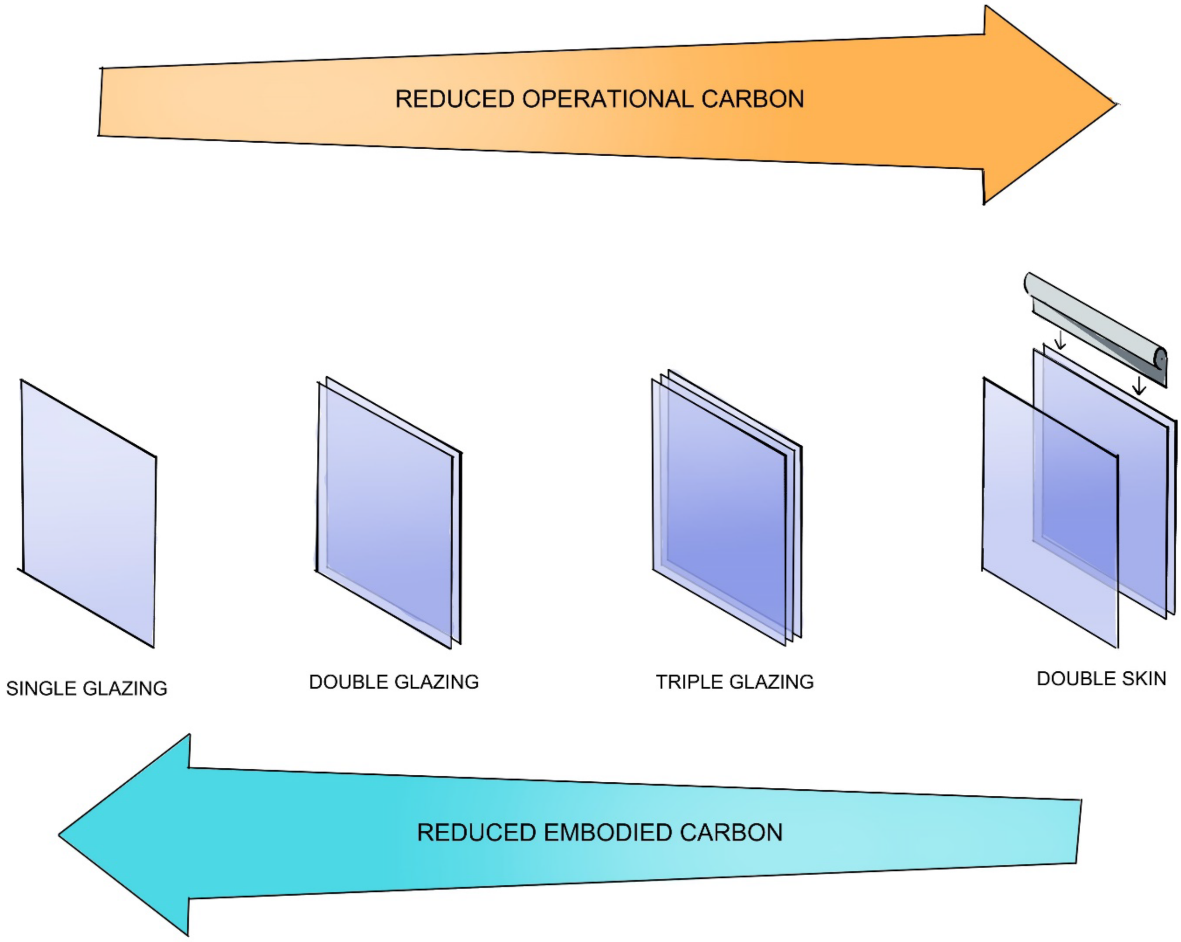


Figure 1: Illustrative development of glazed facades to meet operational energy regulations at the expense of embodied carbon.

Carbon payback period

The concept of a Carbon Payback Period (CPP) is more comprehensible when considering renewable energy generation systems (e.g., photovoltaic, wind or tidal power generation) whereby the energy generated saves a certain amount of emitted carbon compared to an alternative fossil-fuel-based energy generation system. The CPP identifies a point in time in the future at which these savings compensate for the additional emissions required to manufacture the renewable energy system.

The embodied carbon associated with manufacture, transport and installation of the energy generation system is always positive and can be represented as a step value ΔEC occurring at, or near, the commencement of operation. The carbon saving in operation is a certain amount ΔOC per accounting period. The process of carbon payback can then be illustrated as in Figure 2.

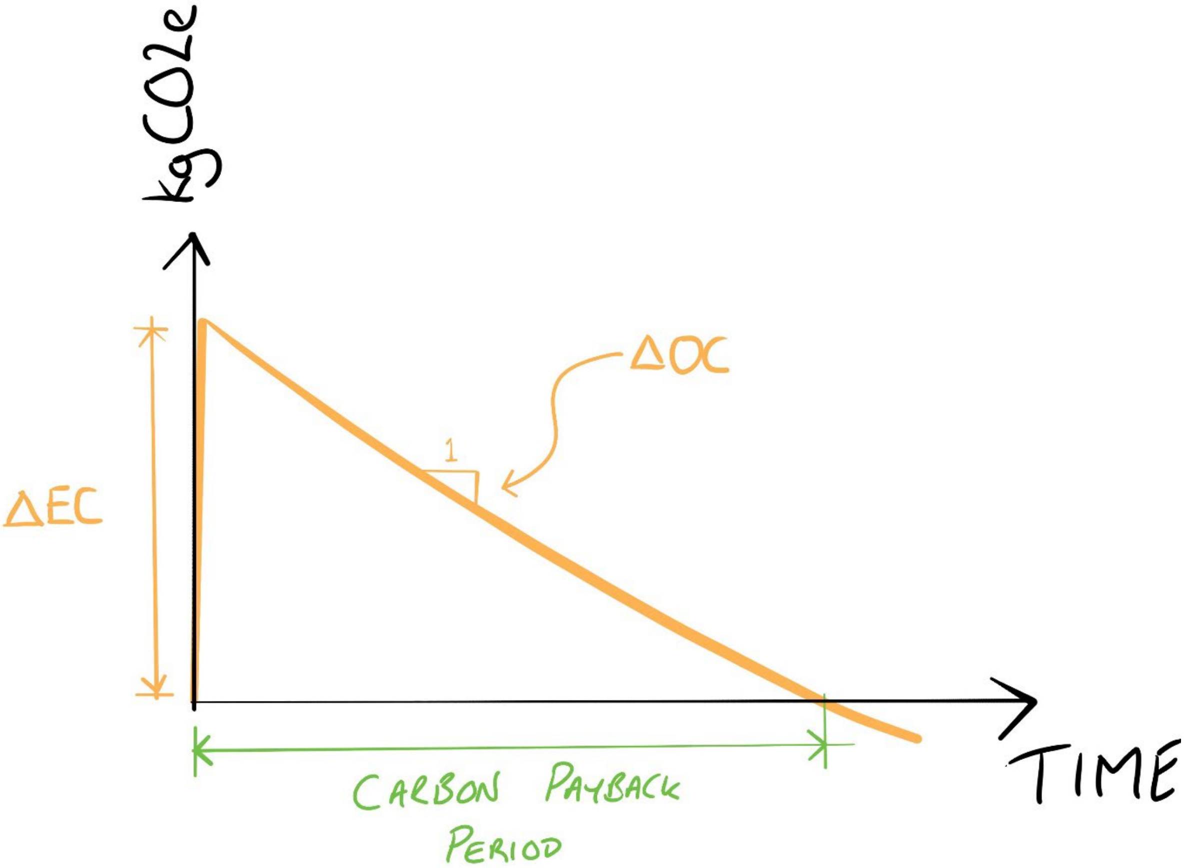


Figure 2: Figurative illustration of the CPP

The shorter the Carbon Payback Period (CPP) is, the greater the benefit over the life of the system, provided the CPP is shorter than the service life of the system.

The same concept can be applied when comparing any façade component or system to any other. For example, design decisions for which a CPP may be calculated include:

- The adoption of triple glazing over double glazing;
- The use of external solar shading devices or not;
- The adoption of one façade system over another;
- Or more generally, design option A or design option B.

Embodied carbon increment (ΔEC)

Calculating the change (increment) in embodied carbon of a design decision is simply a case of determining the difference in embodied carbon associated with each design option (equation 1).

$$\Delta EC_{AB} = EC_{B,y} - EC_{A,y} \tag{1}$$

Where:

ΔEC_{AB}	change in embodied carbon from option ‘A’ to option ‘B’ (kgCO$_2$e)
$EC_{B,y}$	embodied carbon of option B (kgCO$_2$e)
$EC_{A,y}$	embodied carbon of option A (kgCO$_2$e)

Considering Figure 2, the CPP approach is easiest to understand if the embodied carbon increment (ΔEC) is positive. If there are several options to be compared, designers should define the option with the lowest embodied carbon as Option A, this ensures ΔEC remains positive.

A future CWCT publication will provide further guidance on calculating embodied carbon for façade systems.

Operational carbon increment (ΔOC)

Calculating the change in operational carbon ($\Delta\mathrm{OC}_{\mathrm{AB,y}}$) associated with a given design decision (i.e., moving from option A to option B) for any given year is the difference between the operational carbon of the building with option A and option B (equation 2) in that year.

$$\Delta OC_{AB,y} = (OC_{B,y} - OC_{A,y}) \cdot W_y \tag{2}$$

Where:

$\Delta OC_{AB,y}$	change in operational carbon from option A to option B on year ’y’ (kgCO$_2$e)
$OC_{B,y}$	annual operational carbon on year ‘y’ of option B (kgCO2e)
$OC_{A,y}$	annual operational carbon on year ‘y’ of option A (kgCO2e)
W_y	Weighting factor for year ‘y’. This factor accounts for the ‘time value of carbon’.

An additional weighting factor may be included to account for the ‘time value of carbon’. In principle this factor allows for the diminishing significance of future carbon emissions:

- The embodied carbon associated with a building is expended at, or near to, year 0;
- Each kilogram of operational carbon that is saved at year 1 has much greater significance at, say year 50, than each kilogram of operation carbon that is saved at, say, year 41;
- The diminishing significance of operational carbon emissions as the building ages is accounted for by means of the weighting factor (W_y).

The justification for the diminishing significance considered by the ‘time value of carbon’ are discussed later in this paper.

The operational carbon of each option on any given year may be calculated as the product of the annual energy use of each source (e.g., electricity or gas) and the respective emissions factor (equation 3). Data on the emissions factor may be found at the BEIS greenhouse gas conversion factors (6) or Carbon Footprint (7).

$$OC_{A,y} = \sum_i EU_{A,i} \cdot EF_{i,y} \tag{3}$$

Where:

$OC_{A,y}$ annual operational carbon on year ‘y’ of option A (kgCO2e)

$EU_{A,i}$ operational energy use per annum of the *i*th energy source of option A (kWh)

$EF_{i,y}$ emissions factor associated with the *i*th energy source (kgCO2e/kWh) on a given year ‘y’. Note the emissions factor should explore decarbonisation discussed later in this guide.

$\sum_{i}$ Represents the sum over each energy source, typically electricity and natural gas in the UK.

Over time the balance of energy sources used to supply the UK electricity grid will change, and so this approach can also take account of the long-term transition away from traditional fossil-fuel-based energy sources. Accounting for decarbonisation in the assessment of the CPP is discussed later in this paper.

Evaluating the CPP

The CPP is a useful metric to guide designers wishing to reconcile embodied and operational carbon. A CPP is associated with a given design decision. CPP may be usefully applied to design decisions at a component level or a system level.

The CPP is defined as the time over which the benefits on a building’s Operational Carbon (ΔOC) offset the burden associated with an increased Embodied Carbon (ΔEC) as depicted in Figure 2. Whilst Figure 2 provides a useful depiction, designers should take care not to be misled in inferring that the downward slope represents an actual reduction in carbon emissions, this is not true. The downward slope represents a lower rate of operational emissions between the two options considered.

The line shown on Figure 2 can be expressed from equation 4.

$$C_y = \Delta EC_{AB} + \sum_{y=1}^{y} \Delta OC_{AB,y} \tag{4}$$

Where:

C_y net carbon emissions up to year ‘y’ (kgCO$_2$e)

ΔEC_{AB} difference in embodied carbon from option ‘A’ to option ‘B’ (kgCO$_2$e)

$\Delta OC_{AB,y}$ difference in operational carbon from option A to option B on year ’y’ (kgCO$_2$e)

The CPP is the time at which the plotted line crosses the x-axis in Figure 2. This occurs when equations 5 and 6 are satisfied.

$$CPP > 0 \tag{5}$$

$$C_{CPP} = \Delta EC_{AB} + \sum_{y=1}^{y} \Delta OC_{AB,y} = 0 \tag{6}$$

Finally, the designer must compare the CPP with the Estimated Service Life (ESL) of the associated components:

- If the CPP is positive and less than the ESL of the element it relates to, this implies that Option B has a net carbon benefit on the project (payback is achieved before the element needs to be replaced);
- Conversely, when the CPP exceeds the ESL of the components, this indicates that option B will have a net carbon burden on the project.

It is worth noting that the CPP will depend on the overall energy performance of the building, which in turn may depend upon the type of building. This is best illustrated with an example:

Consider the decision to adopt triple-glazing over double-glazing on a project, the CPP will vary significantly depending on the building in which it is being considered:

- A new-build residential building in the UK is likely to have its energy use dominated by space heating requirements, which in turn may be provided by electric air source heat pumps. In such an example the CPP would be greater than the same building with a gas-powered heating system. This is because the reduction in energy use afforded by the triple-glazing saves more operational carbon in a gas-powered heating system than an electric-heating system due to the greater carbon intensity of the fuel source;
- A modern high-rise glazed office in the UK is likely to have its energy use dominated by space cooling requirements. In such a circumstance the additional insulation afforded by triple-glazing may act to increase the overall energy use, thus resulting in a theoretically infinite CPP.

Further considerations

The following section presents an introduction to a number of further considerations designers should be aware of when evaluating the CPP. Moreover, advice is given to how these considerations, and the associated uncertainty they bring, may be accounted for.

Calculating operational energy use

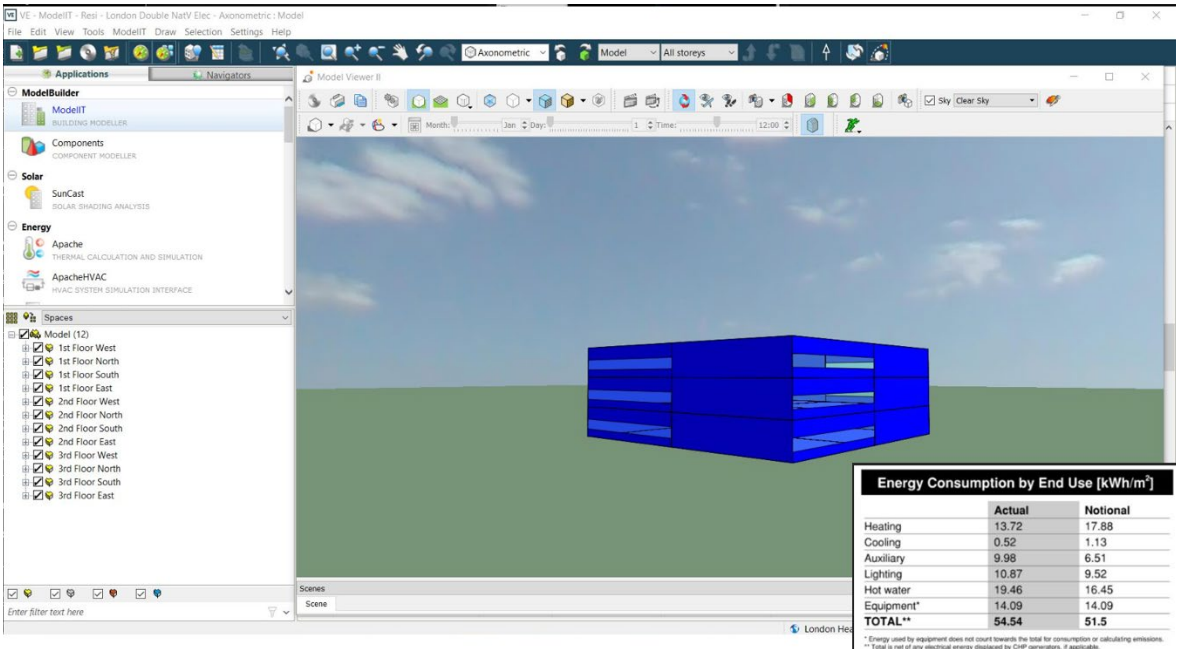
Determining the operational energy use is achieved through Building Energy Modelling (BEM). BEM is a common tool for building mechanical engineers and is already used to demonstrate compliance with Part L of Building Regulations through tools such as SBEM (8) and SAP (9).

BEM is the practice of using computer-based simulation software to perform a detailed analysis of a building's energy use and energy-using systems. The software uses mathematic models, based on thermodynamic and building science equations, to represent the actual building (10). Over time these models have become more complex, taking more variables into account and moving from a pure steady-state analysis into a quasi-steady-state approach with some dynamic elements accounted for.

Building energy models require inputs including geometry, materials, building systems, external climate files and component efficiencies. In approximating real conditions, models also incorporate schedules for occupancy, lighting and thermostat settings (11). The results of an energy model are reported in the annual energy consumption for space cooling and heating, lighting and auxiliary power. Typically in units of kWh/yr/m^2 GIA.

To assess the CPP multiple models are required, one for each design option. For this reason, any work that can be done to eliminate unsuitable design options in advance of developing a full building energy model is highly advantageous.

The models should be identical in all aspects except for the proposed design change, this ensures that the difference in energy use determined is only that which results from the proposed design change. Designers should work closely with their facades and mechanical engineering colleagues during the development of these models to ensure the inputs adopted for the envelope truly reflect the façade performance.



Energy Consumption by End Use [kWh/m²]

	Actual	Notional
Heating	13.72	17.88
Cooling	0.52	1.13
Auxiliary	9.98	6.51
Lighting	10.87	9.52
Hot water	19.46	16.45
Equipment*	14.09	14.09
TOTAL**	**54.54**	**51.5**

* Energy used by equipment does not count towards the total for consumption or calculating emissions.
** Total is net of any electrical energy displaced by CHP generators, if applicable.

Figure 3: Extract from Building Energy Model

Currently there exists a difference between the amount of energy our models predict buildings use and their actual energy use. This difference is termed the ‘building performance gap’. Designers assessing CPP based on predicted energy demand should be cognizant of the building performance gap and how it may impact the calculated CPP.

The building performance gap

The building performance gap refers to the disparity between the predicted energy consumption of buildings and their actual energy consumption. Many studies have been undertaken to try to quantify the gap (12). A literature review undertaken and reported in UKGBC Whole Life Carbon Roadmap Technical Report suggests a space heating performance gap for domestic buildings retrofit in the order of 15 to 35% (13). Data at carbonbuzz.org (14) suggests actual overall energy consumption may be two times higher (100%) than predicted.

The disparity is understood to result from both inaccuracies in the modelling and uncertainties in the environmental conditions, workmanship and occupant behavior (15). These include, but are not limited to (1):

- Model inaccuracies of the building envelope (incorrect calculation of U-values, ignoring or miscalculating repeating thermal bridges, underestimation of thermal bridging at interfaces, and lack of consideration for solar control devices);
- Poor detailing and installation of air barriers leading to poor airtightness;
- Modelling assumptions lack an understanding of how users operate (or do not operate) solar control devices and blinds in practice;
- Modelling assumptions regarding the efficiency of plant equipment are often exaggerated as in practice these are reduced by a lack of upkeep on building maintenance, or an incomplete understanding on how these are to be operated;
- Weather and climate data, used to simulate the external environment, may be taken from a source that does not accurately represent the local microclimate or context at the site of the building.

Reducing the building performance gap can be achieved in part through more advanced BEM, and studies have recognised the value Passivhaus design offers in reducing the building performance gap (16).

The reporting of actual energy consumption of buildings, as promoted in the NABERS energy efficiency rating scheme (17), will help researchers identify sources of the gap. Currently, most energy efficiency schemes are based on predicted performance and the rating achieved lasts the lifetime of the building. In contrast, NABERS requires an annual reaccreditation to ensure the building and plant are still operating as efficiently and as intended during the life of the asset.

Designers wishing to calculate CPPs cannot ignore the building performance gap. Where the design decision considered reduces the operational energy use of the building, accounting for the building performance gap will act to reduce the CPP, as shown indicatively in Figure 4.

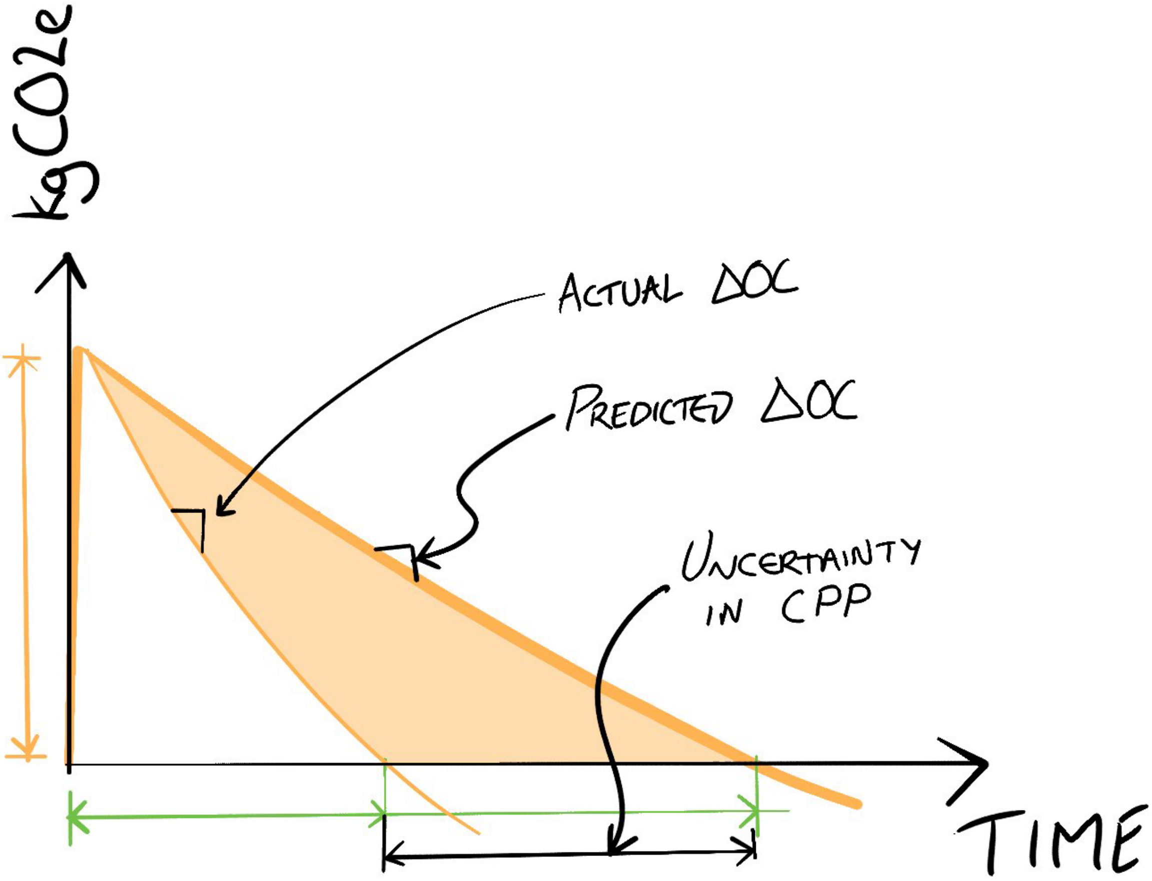


Figure 4: illustrative plot showing the indicative effect of accounting for the building performance gap on the CPP

Decarbonisation

In recent decades the UK energy grid has demonstrated a slow but growing trend towards decarbonisation. The UK energy supply is forecast to decarbonise as the country aims to meet the Net Zero Carbon target set into law in 2019 (18). Designers exploring CPPs that extend beyond a few years into the future will need to consider the influence decarbonisation will have.

Decarbonisation can be accounted for using an emissions factor (EF) for a given energy source in accordance with those forecasted. In the UK, the HM Treasury Green Book guidance (19) provides data for grid emissions projections. Alternatively, the National Grid provides a range of future energy scenarios (FES) designers can use (20). It is worth noting that the modelling behind the FES data assumes renewable energy will be used if it is available. In practice there may be network constraints that limit this assumption and so the emissions factors presented might be slightly lower than seen in reality.

Designers are advised to explore the sensitivity of the results to the specific emissions factors assumed. The Greater London Authority's draft guidance (21) advises designers to consider both a 'baseline' case, where no decarbonisation is assumed, and the FES Steady Progression scenario.

Where the design decision considered reduces the energy use of a building, taking account for decarbonisation will act to increase the CPP.

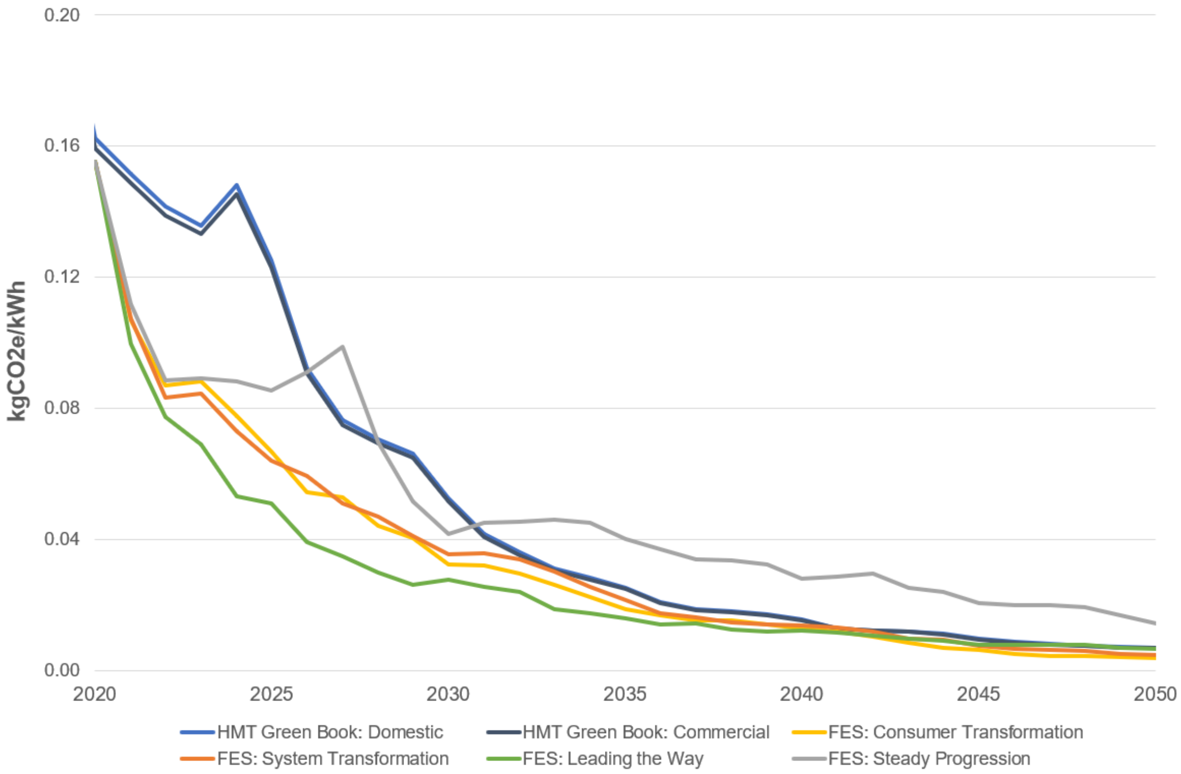


Figure 5: Forecast grid emissions factors (Data from National Gird (20) and HMT guidance (19))

The time value of carbon

Is carbon emitted today more impactful than carbon emitted tomorrow? This question gets at the roots of what is known as the 'time value of carbon'.

Delaying carbon emissions may be thought as a 'temporary sink', whereby the emissions are held out of the atmosphere for a period of time. In practice, this may be achieved through the process of sequestration in the use of timber (22). Alternatively, in the tradeoff between additional upfront carbon, released near the time of construction, against future operational emissions during the buildings' life.

There are multiple reasons why delaying carbon emissions with temporary sinks is beneficial for climate change mitigation (22) (23):

- They decrease the cumulative impact of raised temperatures at a given time in the future;
- They delay or avoid climate tipping points (i.e., disintegration of polar ice sheets, shifting monsoon rains and dieback of the Amazon rainforest). Albeit these thresholds are hard to predict;
- They preserve the opportunity of permanent storage through "buying time" to learn and develop.

Conventional life cycle assessments (LCAs) undertaken to BS EN 15978 (24) take no account for the time value of carbon and implicitly assume the time at which carbon is released does not influence its impact. Some methods exist which attempt to account for the benefits associated with delaying emissions. One example, Annex E of PAS 2050 (25), adopts a linear weighting factor which reduces to zero over a fixed time horizon of 100 years (equation 7).

$$W_y = \frac{100 - (y - y_0)}{100} \tag{7}$$

Where:

W_y	Weighting factor for year 'y'.
y	Year in which emissions occur.
y_0	Year of upfront carbon emissions.

The application of the weighting factor to future operation emissions acts to increase the CPP (see Figure 6).

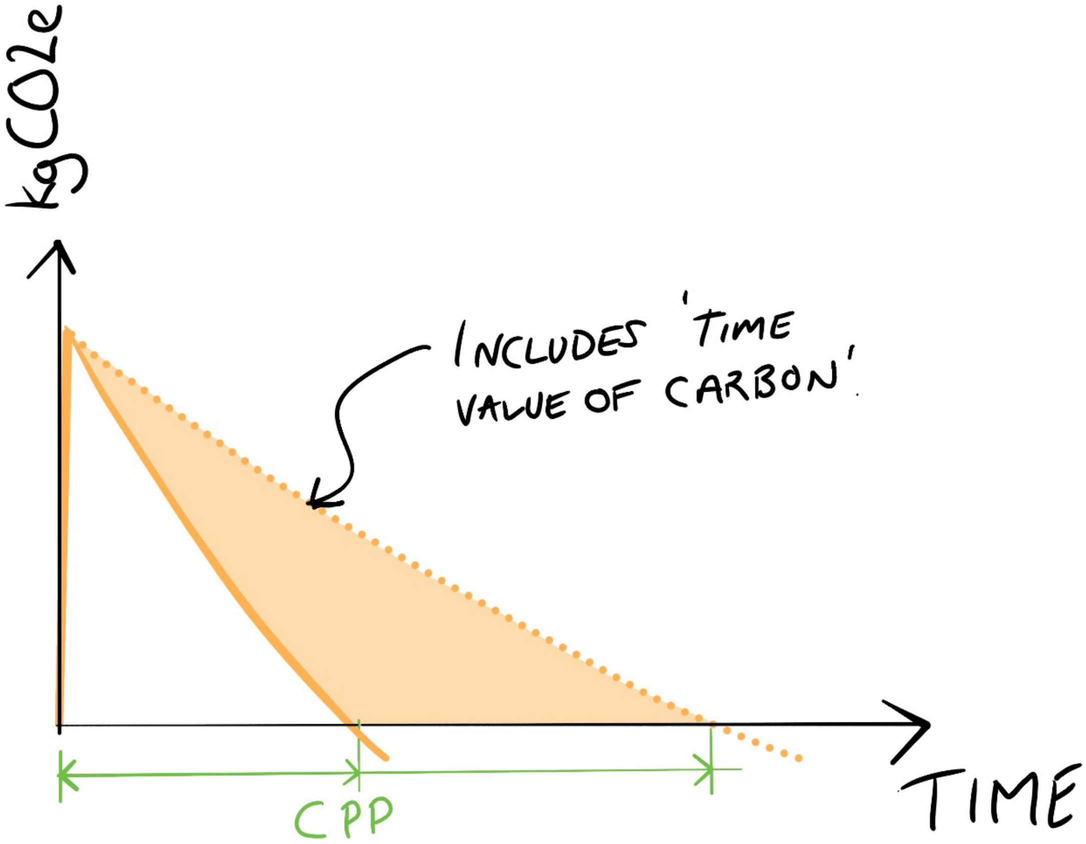


Figure 6: Sketch showing the indicative effect of accounting for the time value of carbon on the CPP

Complex interactions

When the CPP is used to evaluate system level decisions (e.g., façade system A or façade system B), designers should take care to include any complex indirect embodied carbon increments in the assessment. For example:

- A heavier façade system will require additional primary structure to support it, the embodied carbon of which should also be considered in the assessment;

- Where a façade system provides a significant improvement in the operational energy demand this may reduce the requirement for mechanical servicing equipment. This reduced embodied carbon should be considered in the assessment.

Future embodied carbon emissions

When designers are using the CPP to compare options of differing service life, there is the need to consider embodied carbon emissions associated with the manufacture of replacement components at some time in the future. The embodied carbon of future components is likely to be less than the same component manufactured today as the supply chain decarbonises. The extent to which future embodied carbon emissions are reduced is inherently uncertain and hard to predict. The UKGBC Whole Life Carbon Roadmap (13) offers a forecast of future carbon intensity of materials which can be used to guide estimates, but as with all considerations, the sensitivity of the CPP to the assumptions should be explored.

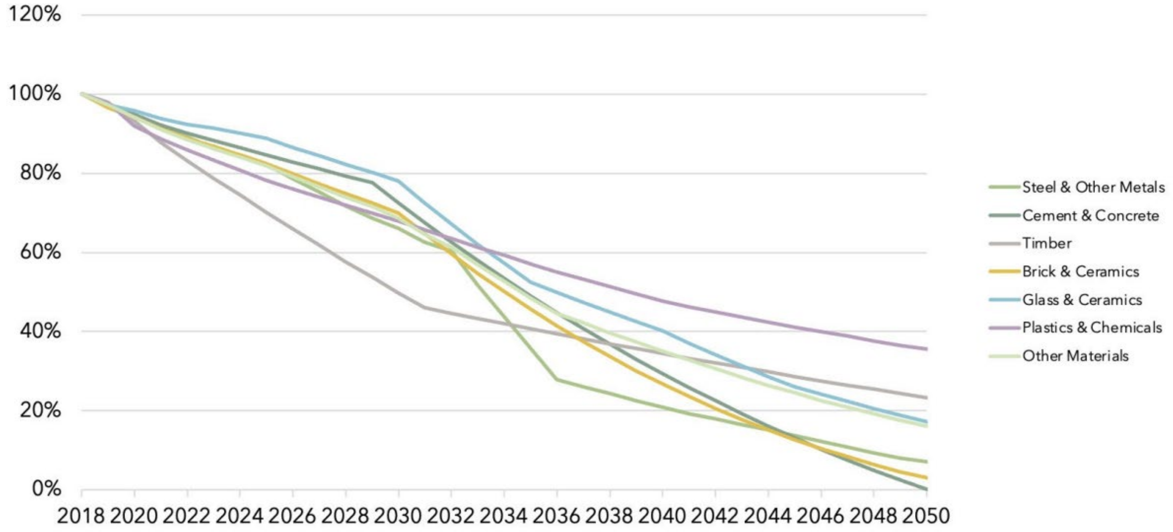


Figure 7: Carbon intensity (non-electricity emissions) per material category
Source: UKGBC Whole Life Carbon Roadmap, Figure 30 (13)

Dealing with uncertainty

Each of the variables used in the assessment of the CPP have a level of uncertainty. Key areas of uncertainty include the alternative decarbonisation forecasts, the building performance gap and consideration for the time value of carbon. It should not be expected that these uncertainties can be eliminated. Instead, they should be embraced, and designers are encouraged to evaluate upper and lower bounds to each variable and explore the sensitivity of the resulting CPP to each of these.

As a result, in practice the CPP is rarely likely to be a single figure. Given the sensitivity of the CPP to the influencing factors, the CPP is often better expressed as a range of years within which the true CPP is expected to occur.

Summary

Facades impact both the embodied and operational carbon emissions of a building. In many instances, a truly low carbon solution will require a trade-off between embodied and operational carbon to be established.

The CPP provides a useful metric for quantifying the balance between embodied and operational carbon. A CPP is associated with a given design decision (i.e., design option A versus design option B) and is a function of the materials involved, building energy use and energy emission factors.

The approach to calculating the CPP of a given design decision may be summarised as follows:

1. Calculate the difference in embodied carbon between design Option A and Option B (equation 1), where Option A is taken to have the lowest embodied carbon. Make due consideration for complex indirect embodied carbon changes;
2. Construct two building energy models (BEM) to calculate the operational energy use associated with design Option A and Option B;
3. Multiply the annual energy use by an appropriate emissions factors associated with the energy source (equation 3). Moreover, consideration for decarbonisation of the source should be accounted for with the use of the FES scenarios;
4. The difference in operational carbon between Option A and B should be determined on each successive year (equation 2);
5. A plot of net carbon emissions over time should be made (Figure 2 and equation 4) against which the CPP may be evaluated;
6. A sensitivity analysis should be undertaken to gain an appreciation for the influence of the building performance gap and decarbonsiation on the resulting CPP. Moreover, where the CPP extends beyond a few years, consideration should be given to the time value of carbon through the application of a weighting factor on future operational emissions (equations 2 and 7).

It should be noted that because the CPP only requires the assessment of the change (increment) in embodied carbon between design options. For this reason, it can readily be applied to smaller projects whose constraints may restrict the undertaking of a full LCA. This can allow for the meaningful appraisal of key decision decisions during the design process.

This decade is pivotal in the climate emergency. The impact of the design decisions we make today matter more than ever. This requires us to challenge what, how and why we build to satisfy the needs of the growing population today and in the future. Finding an optimal balance between intrinsic resources, fabrication processes, and operational use is key to successfully to reducing the contribution of façades to the climate crisis.

Worked example

The following worked example has been prepared to illustrate the approach to determining the Carbon Payback Period (CPP). The resulting CPP calculated herein is very specific and sensitive to the boundary conditions assumed. The example considers the following design decision for a medium rise residential project located in Glasgow, UK;

- Option A – Double glazed units (DGU) to windows;
- Option B – Triple glazed units (TGU) to windows.

The CPP answers the question "*How long do I need a TGU in service before its improvement on the building's operational carbon compensates for the additional embodied carbon when compared to a DGU*?".

The key boundary conditions and assumptions are:

- The building's heating energy demand are met with gas fuel energy and the building's auxiliary and lighting demand are met with electricity;
- Building is naturally ventilated;
- Building located in Glasgow, UK;
- The operational energy demand is based on typical mid-sized residential apartment.

Difference in embodied carbon

Step 1: Calculate the difference in embodied carbon between design Option A and Option B (equation 4).

For simplicity of this worked example, the difference in embodied carbon between the TGU and DGU is assumed to be just that which is related to the additional intermediate glass ply in the TGU, estimated as a 4mm thick annealed pane. For the simplification of this worked example, the embodied emissions associated with the additional edge spacer, sealant and assembly have been ignored. In practice, all additional materials must be included in the embodied carbon calculation.

This approach assumes that emissions related to transport and installation are equivalent to all practical purposes.

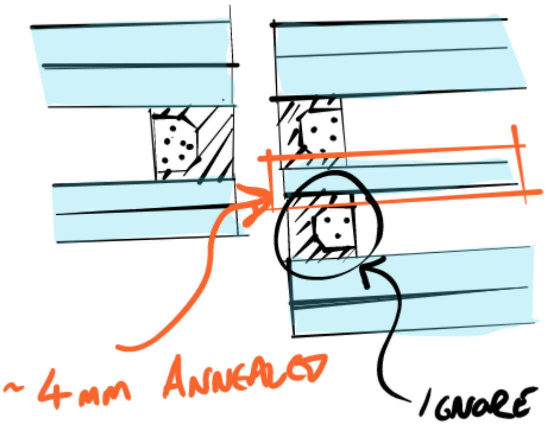


Figure 8: sketch illustrating the addition glass ply within the TGU

Data in the ICE V3 database provides an embodied carbon factor of 1.44 $kgCO_2e/kg$ for life cycle modules A1 to A3 of flat glass based on an average of 109 datapoints (26). Using this figure and an assumed glass density of 2,500 kg/m^3 the difference in embodied carbon between the Option A and B can be evaluated (equation *8*).

$$\Delta EC_{AB} = EC_{B,y} - EC_{A,y}$$

$$\Delta EC_{AB} = 0.004m \times 1m^2 \times 2{,}500kg/m^3 \times 1.44kgCO_2e/kg \qquad (8)$$

$$\Delta EC_{AB} = 14.4kgCO_2e/m^2$$

Determine operational energy use

Step 2: Construct two building energy models (BEM) to calculate the operational energy use associated with design Option A and Option B.

In this example the operational energy use was evaluated by constructing two BEM to represent the building studied, depicted in Figure 3.

- Model A: Incorporates DGUs with performance parameters; U-value = 1.4W/m^{2}K, g-value = 0.35, VLT = 0.70.
- Model B: Incorporates TGUs with performance parameters; U-value = 1.0W/m^{2}K, g-value = 0.30, VLT = 0.60.

All other boundary conditions and modelling assumptions were held consistent between the models, this includes but not limited to; typology, geometry, window-wall ratio, U-value of envelope, thermostat profiles, external climate files.

A summary of the energy use for each option is presented in Table 1.

Annual building energy use (kWh/m^2 / year)[1]						
	Heating	**Cooling[2]**	**Auxiliary**	**Lighting**	**Hot water**	**Total**
Option A (DGU)	95.3	0.0	25.4	140.3	101.7	362.8
Option B (TGU)	81.7	0.0	25.4	145.9	101.7	355.0

Note:
[1] The energy use output from the BEM is reported *per square meter of Gross Internal Area (GIA),* the figures presented above have been converted to *per square meter window area*.
[2] The example modelled assumes a naturally ventilated building with no mechanical cooling.

Table 1: Results from BEM

Convert operational energy use to operational carbon

Step 3: Multiply the annual energy use by an appropriate emissions factors associated with the energy source (equation 3). Consideration for decarbonisation of the source should be accounted for in the electricity supply.

This example assumes the building's heating and hot water energy demand are met with gas fuel energy and the building's auxiliary and lighting demand are met with electricity.

A constant 0.18 kgCO2e/kWh emissions factor for UK national gas has been adopted based on recent government data (6).

The emissions factor for the UK electricity supply has been taken from National Grid Future Energy Scenarios (FES) (20). The FES offer a range of scenarios illustrated in Figure 5, the emissions factors account for different rates of decarbonisation within the UK electricity supply. For the purpose of this assessment the 'steady progression' scenario has been assumed.

Year	Grid emissions factor (kgCO2e/kWh)
2020	0.1553
2021	0.1119
2022	0.0884
…	…
2050	0.0143

Table 2: FES 2021 power sector carbon intensity 'steady progression' scenario (20)

The annual operational carbon emissions on any given year are then evaluated by multiplying the emissions factor for a given mode by the respective energy use. For clarity the full calculations have not been presented, an example for Option A in the year 2022 has been shown in equation 9.

$$
\begin{aligned}
OC_{A,2022} &= \sum_i EU_{A,i} \cdot EF_{i,2022} \\
OC_{A,2022} &= \left(EU_{A,gas} \cdot EF_{gas,2022}\right) + \left(EU_{A,elec} \cdot EF_{elec,2022}\right) \\
OC_{A,2022} &= (197.1 \times 0.18) + (165.7 \times 0.0884) \\
OC_{A,2022} &= 50.1\ kgCO_2e/m^2
\end{aligned}
\tag{9}
$$

Difference in operational carbon

Step 4: The difference in operational carbon between Option A and B should be determined on each successive year (equation 10).

The difference in annual operational carbon emissions can be evaluated for any given year. An example for 2022 is presented in equation 10.

$$
\begin{aligned}
\Delta OC_{AB,2022} &= OC_{B,2022} - OC_{A,2022} \\
\Delta OC_{AB,2022} &= 48.2 - 50.1 = -1.9\ kgCO_2e/m^2
\end{aligned}
\tag{10}
$$

Carbon payback period

Step 5: A plot of net carbon emissions over time should be made against which the CPP may be evaluated.

Figure 9 plots the net carbon emissions from the design decision over time (equation 4). The plot indicates a CPP of approximately 7.5 years.

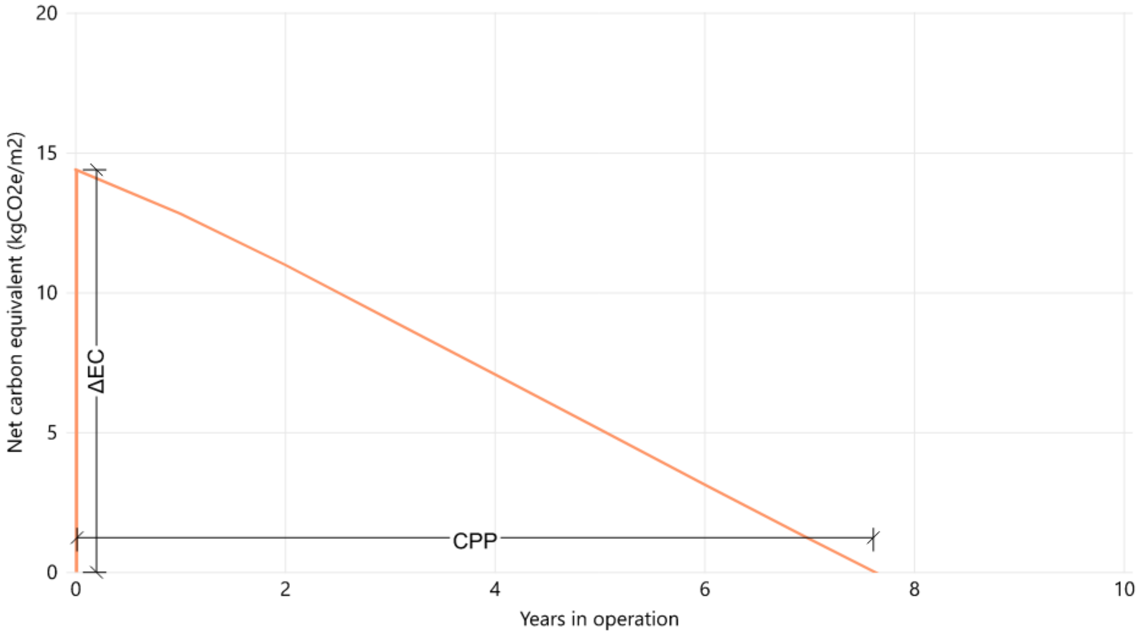


Figure 9: Net carbon emissions from the design decision over time

Consideration for the time value of carbon can be evaluated by reducing operational carbon emissions by the weighting factor detailed in equations *7* and 2. This factor acts to increases the CPP from 7.5 to 8.0 years, illustrated in Figure 10.

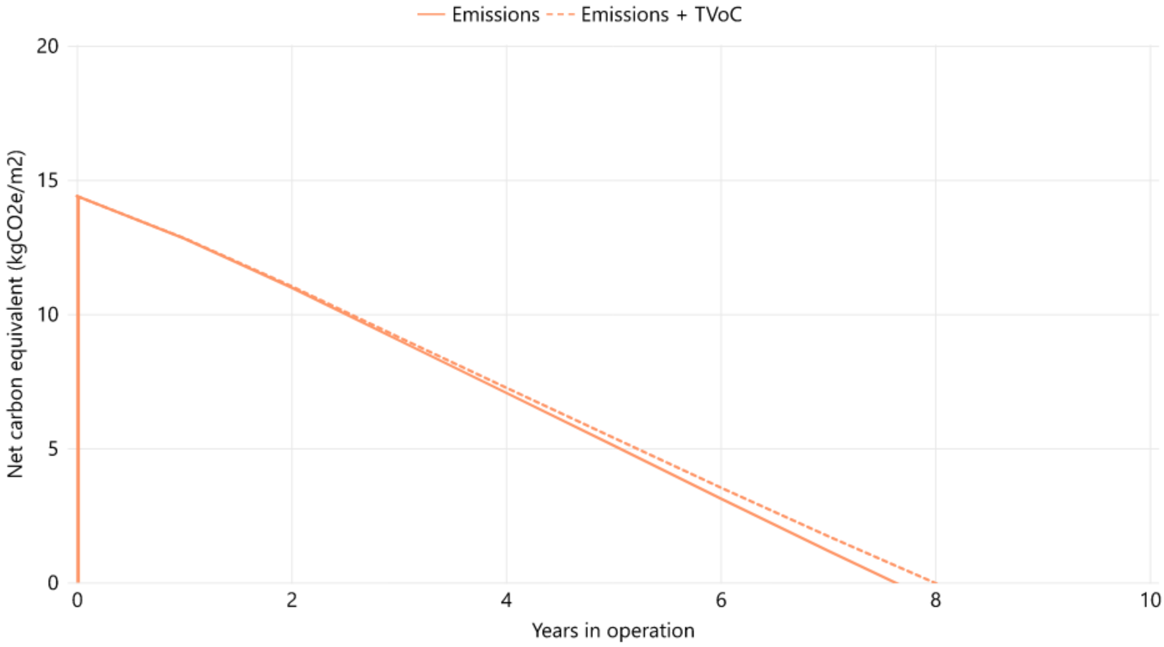


Figure 10: Net carbon emissions over time including time value of carbon (TVoC)

Sensitivity analysis

Step 6: The sensitivity of the resulting CCP to the influence of the building performance gap and decarbonisation.

Data at carbonbuzz.org (10) suggests actual energy consumption may typically be two times higher than predicted. Whilst the actual energy use is unknown, the sensitivity of the CPP to an estimated increase in energy use of 100% will be explored. This will provide a range of CPP within which the actual CPP is expected to fall. Figure 11 shows that the allowance for the building performance gap acts to reduce the CPP from 8.0 to 4.0 years and provides a ray (area highlighted in grey) within which the true emissions profile is expected to lie.

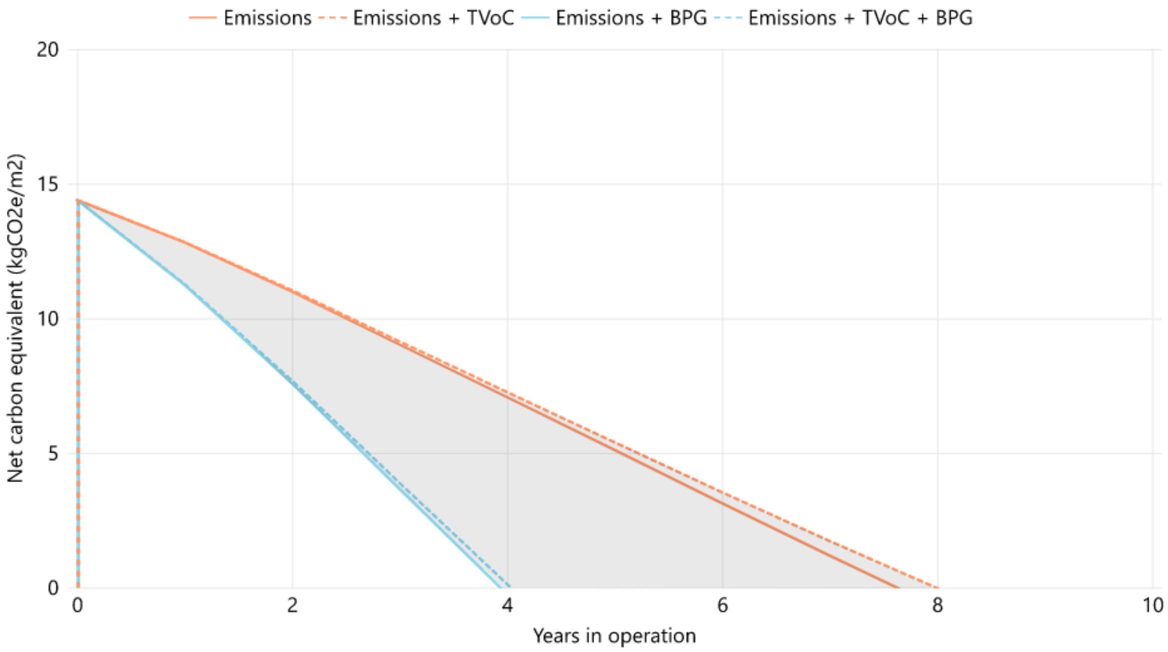


Figure 11: Net carbon emissions over time including time value of carbon (TVoC) and building performance gap (BPG)

Figure 12 expands on the sensitivity explored in Figure 11 by plotting the CPP for two scenarios which exclude the influence of decarbonisation and the building performance gap. These result in a maximum CPP close to 9.5 years. Readers should note that in this particular instance considered, including decarbonisation of the electricity grid act to decrease the carbon payback period, this is because the use of triple glazing acts to increase the lighting electricity demand. The reduced gas consumption is unaffected by the decarbonisation.

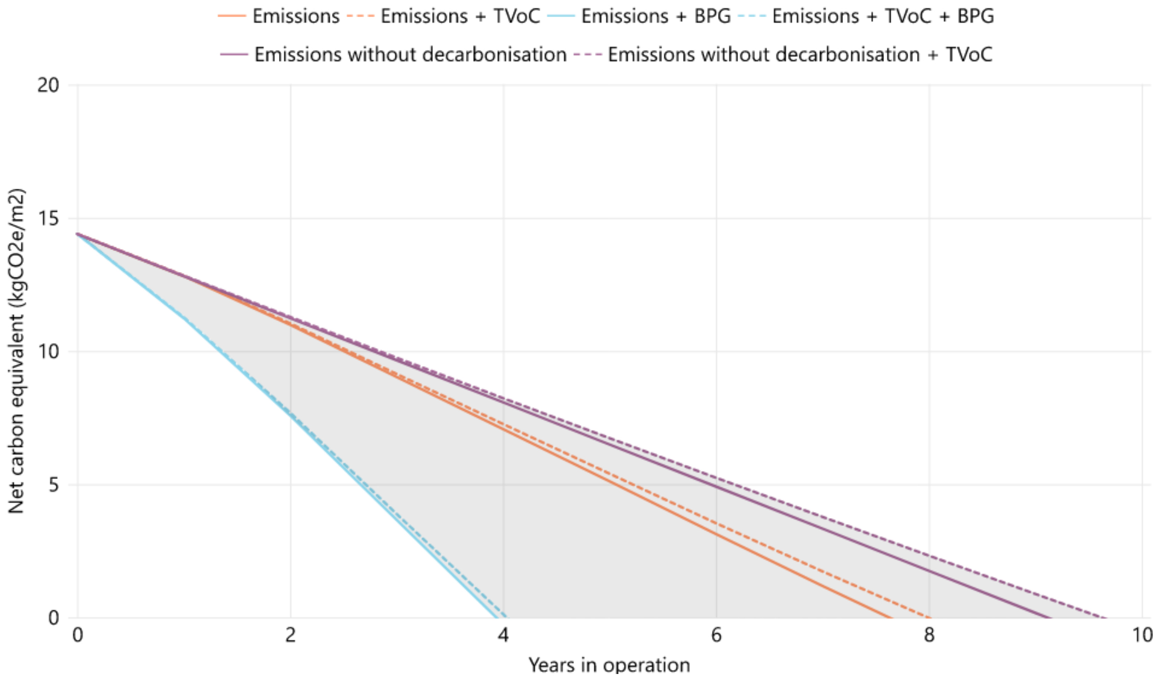


Figure 12: Net carbon emissions over time including time value of carbon (TVoC) and building performance gap (BPG)

Conclusion

The worked example presented derives a CPP of between 4.0 to 9.5 years for the design decision to adopt TGU over DGU windows on the specific residential project considered. The median expected service life of an insulated glazed unit is in the order of 25-30 years. Given the service life is significantly greater than the evaluated CPP it can be inferred that the design decision considered has a net carbon benefit. In other words, the reduced operational carbon emissions more than compensate for the additional embodied carbon emissions.

Exploring the sensitivity of the CPP to the variables considered has highlighted that, in this specific instance, whilst the CPP varies significantly, under all scenarios it remains well below the estimated service life of the glazing unit. This demonstrates that whilst there can be a lot of variability in the results, the interpretation of these still facilitate a useful conclusion to be drawn.

Design decisions related to façade engineering are multifaceted and minimising carbon emissions through the life of the façade is but one of these facets. In the selection of double or triple glazing other facets include; cost, local condensation risk, thermal comfort and more.

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