CENTRE FOR WINDOW AND CLADDING TECHNOLOGY

How to calculate the embodied carbon of facades: Worked example

Issue 1 Rev 01, February 2023

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Rev 01 February 2023 Summary of changes

Table 6

Corrections to the factory waste module $A3_W$ embodied carbon factor ($ECF_{A3,w,i}$). This results in a change in the overall EC_{A13} value and therefore also changes subsequent calculations.

Appendix A

ECF of mid-iron float glass per unit thickness corrected to 2.96 $kgCO_2e/m^2/mm$ in accordance with C.3.1.1 of *How to calculate the embodied carbon of facades: A methodology.*

Introduction

The following worked example has been presented to aid readers' understanding of the minimum scope calculation described in the *How to calculate embodied carbon of facades: A methodology* (1). It must be used for this purpose only, and the results presented herein should not be used to inform design decisions or benchmarking on projects. Refer to the CWCT article *Life cycle modules explained* (2) for further detailed guidance on the definition of the life cycle modules presented in this document.

The following steps provide a worked example for the minimum of a facade embodied carbon calculation according to the methodology outlined in this document, which follows the equation (22) in the document presented below:

$$EC_{AC,min} = F \times \left[EC_{A15} + \sum_{i=1}^{n} \left[Q_i \left(ECF_{B4,i} + ECF_{C2,i} + ECF_{C34,i} \right) \right] + \left(A \times ECF_{C1} \right) \right]$$

Where:

$EC_{AC,min}$	= total embodied carbon for life cycle modules A to C minimum scope ($kgCO_2e$)
F	= carbon calculation scale-up factor (refer section 2.2.15 of the methodology)
EC_{A15}	= total embodied carbon for life cycle modules A1 – A5 ($kgCO_2e$)
Q_i	= quantity of i^{th} material (kg) within representative area assessed (A)
$ECF_{B4,i}$	= module B4 embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
$ECF_{C2,i}$	= transportation away from site at end of life (Module C2) embodied carbon for the i^{th} material.
$ECF_{C34,i}$	= waste processing and disposal (Module C3 and C4) embodied carbon for the i^{th} material.
ECF_{C1}	= demolition emissions factor (Module C1) of $1m^2$ of facade ($kgCO_2e/m^2$ FSA)
A	= representative area of facade assessed (m^2)
$\sum_{i=1}^{n}$	= the summation of components from 1 to total number of components in the facade system.

In accordance with section 2.3.3.of this methodology, the modules calculated in this example include A1-A5, B4 and C1-C4 to reflect the minimum scope of an assessment advised for a representative area of a facade system bay on a project.

> In practice it is often more practical to assess the embodied carbon of a representative area of each facade system (i.e. a standard bay width, or repeating arrangement). The total embodied carbon of the project can then be assessed by multiplying the results of each facade system by the surface area of the building the system is applicable to. **For this reason, the equations presented in this example are formulated in the context of assessing a single facade system over a representative area (A).**

Figure 1 presents an illustration of the definitions for the areas referenced in the formulas presented in this worked example.

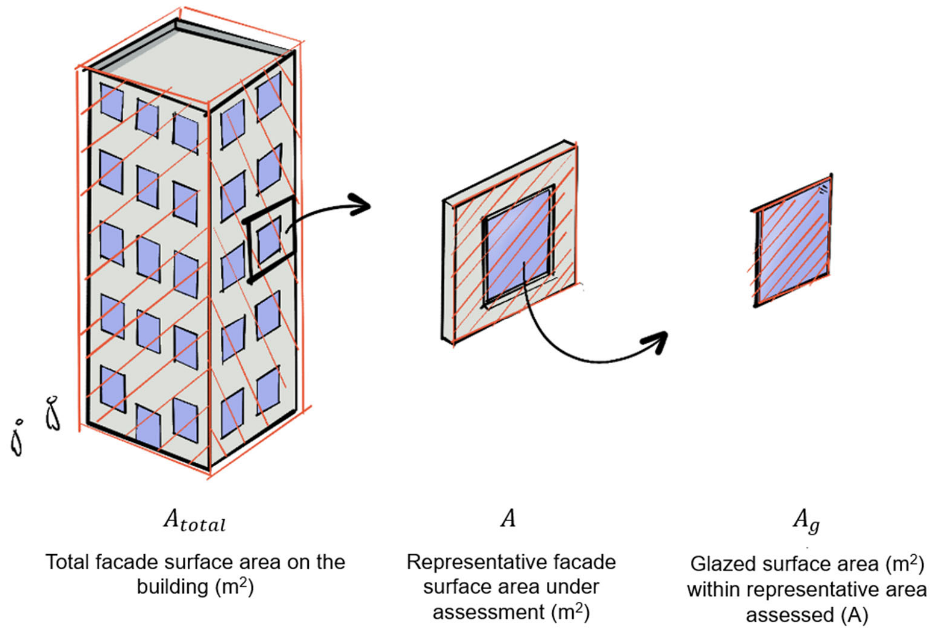

Figure 1 – Illustration of areas A_{total}, A, and A_g

Object of assessment

The ‘object of assessment’ is the vertical building envelope of a new-build 20-storey residential tower block in London, UK assessed over a Reference Study Period of 60 years.

The building envelope consists of a single façade system (FS-01) characterised as an aluminium unitised curtain walling with aluminium feature fins. The curtain wall system includes a range of integrated glazed windows/doors and large format terracotta rainscreen tiles (Figure 2). Notably, the balcony is excluded from the scope of assessment.

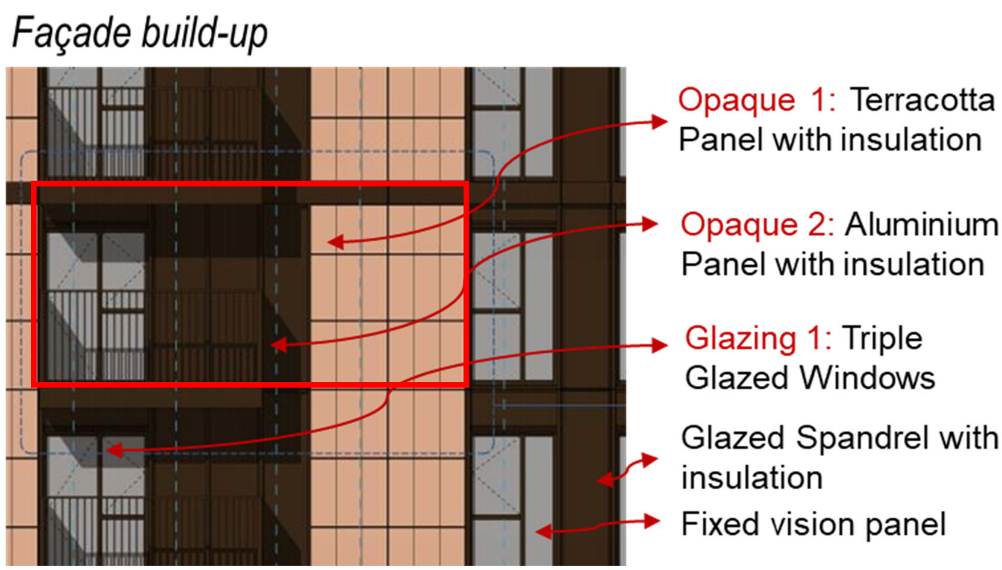

Figure 2 – Representative facade bay area (FSA) of FS-01 considered within the red box

The functional equivalent of the façade system is characterised by the following performance parameters:

- Reference study period (RSP) of the facade system = 60 years
- Floor-to-floor height = 3.5m
- Opaque wall U-value = 0.18 W/m^{2}K
- Glazing U-value (including frame) = 1.3 W/m^{2}K
- Y-value: 0.15 W/m^{2}K
- Peak characteristic wind load used in the design = 1.2 kPa

Key assumptions

This calculation is for one typical facade system bay for FS-01 of the project building located in London, UK as highlighted in Figure 2. The facade system will be assembled off-site. The components are assumed to be manufactured and pre-assembled in Cologne, Germany prior to being shipped to site for installation onto the building in London, UK.

Additional assumptions are summarised below, while others are described at different steps in this calculation example:

- Stage of assessment: final design for construction (RIBA Stage 5), specialist contractor drawings produced for fabrication and construction
- Representative area (AKA: bay area) (A): 18.45 m^2 FSA
- Facade Surface Area (FSA) = 5200 m^2
- Gross Internal Area (GIA) = 9454 m^2
- Facade Form Factor (FFF): 0.55
- Total project cost: £45 million
- Facade cost: 15% of total project cost
- Reference study period (RSP): 60 years

This example uses an off-site assembled facade which will require calculation of off-site emissions and associated embodied carbon coefficients. The following additional off-site emissions factors will be included:

- Transportation to off-site factory ($ECF_{A2,F}$)
- Off-site assembly emissions ($ECF_{A3,ASS}$)
- Off-site wastage rates ($ECF_{A3,W}$)

Refer to section 1.7 of the methodology for further examples of when the application of off-site emission coefficients would be appropriate to apply for various project scenarios.

EC_{A13} for the glass is calculated using the method described in Appendix C of the methodology.

Calculation steps

The following steps outline the process of undertaking the embodied carbon assessment.

Step 1: Define all the facade components to be included within the representative area of the facade system.

Step 2: Conduct a detailed quantity take-off of the components identified in the representative area. Then determine A1-A3 ECFs for each component.

Step 3: Calculate the total embodied carbon to manufacture the facade (EC_{A13}).

Step 4: Calculate the total embodied carbon required to transport the factory assembled facade to the site for installation (EC_{A4}).

Step 5: Calculate the total embodied carbon required to install the factory assembled facade onto the project building on site (EC_{A5}).

Step 6: Calculate the total embodied carbon required to deconstruct/demolish the facade (EC_{C1}).

Step 7: Calculate the total embodied carbon required to transport deconstructed/demolished materials to the waste processing or disposal site (EC_{C2}).

Step 8: Calculate the total embodied carbon required for waste processing and disposal of the facade ($EC_{C34,i}$).

Step 9: Calculate applicable factory assembly emissions to include in addition to the total product stage embodied carbon for the A1-A3 calculation.

Step 10: Calculate the total embodied carbon for any facade components that will be required to be replaced during the reference study period (EC_{B4}).

Step 11: Sum all embodied carbon totals for each module calculated and apply applicable carbon calculation scale-up factor to determine the total embodied carbon for the facade.

Step 1: Define all the facade components to be included within the representative area (A) of the facade system from the construction and fabrication documentation or building models.

Be sure to also make note of the type of materials, finishes, material density, known manufacturer and sources, etc. for each component. All of which will be useful to determine the correct component quantity mass and product stage embodied carbon factors (ECFs) to apply in this calculation in the next steps.

Facade components within the representative area:

- Unitised curtain wall frames
- Terracotta rainscreen cladding
- Window and door framing
- Curtain wall feature fins
- Triple glazed units (two glass types: G5 and G5A)
- Mineral wool thermal insulation
- Aluminium external spandrel panel
- Steel internal spandrel panel
- Steel curtain wall brackets
- Aluminium curtain wall brackets
- Aluminium rainscreen subframe
- Stainless steel rainscreen brackets
- Fire stops and cavity barriers

Step 2: Conduct a detailed quantity take-off of the components identified in the facade bay using the most accurate source of information available to determine each component's mass. Then determine A1-A3 ECFs for each component using the most accurate source of data to represent what will be manufactured (e.g. manufacture EPDs or open-source databases)

Note: This example represents an assessment undertaken at RIBA Workstage 5 where all the materials and therefore components are known to a detailed level. For this reason, the 'full approach' defined in section 1.6.3 of the methodology has been used and the material factor discussed in section 1.6.2 for the 'simplified approach' has not been included.

Quantities for all facade components can be more accurately taken from fabrication drawings, and EPDs can be obtained from the confirmed supply chain.

Select A1-A3 ECFs that best reflect the specification of the project components. All data sources are to be reported in final results. For further guidance on selecting ECFs refer to section 2.2.2.1 of the methodology.

The quantity of material or component within the representative area (Q_i) and respective ECF_{A13} are presented in the table below.

Facade Components	Q_i (kg)	$ECF_{A13,i}$ ($kgCO_2e/kg$)	Additional notes
Unitised curtain wall frames	200	8.15	Includes PPC aluminium extrusions, thermal breaks, gaskets within in manufacturer EPD
Terracotta rainscreen cladding	350	1.36	
Window and door framing	85	7.98	Includes PPC aluminium extrusions, thermal breaks, gaskets within manufacturer EPD
Curtain wall feature fins	20	8.59	PPC aluminium, cut and formed in the assembly factory
Triple glazed units – type G5	47	n/a[1]	Includes mid-iron double laminated glass, and a high-performance coating
Triple glazed units type G5A	219	n/a[1]	Includes mid-iron double laminated glass, and a high-performance coating
Mineral wool thermal insulation	90	1.72	
Aluminium external spandrel panel	100	8.59	PPC aluminium, cut and formed in the assembly factory
Steel internal spandrel panel	90	2.76	Galvanised steel, cut and formed in the assembly factory
Steel curtain wall brackets	15	2.76	
Aluminium curtain wall brackets	50	6.83	
Aluminium rainscreen subframe	5	6.83	
Stainless steel rainscreen brackets	15	4.41	
Fire stops and cavity barriers	15	5.34	

Table 1 – Material quantities and A1-A3 embodied carbon factors

[1] Refer to Appendix A for how to determine $ECF_{A13,G5}$ and $ECF_{A13,G5A}$ for each glass build-up where the glazing surface area (m^2) is required in lieu of the weight.

Step 3: Calculate the total embodied carbon to manufacture the facade (EC_{A13}) using the quantities and ECFs determined for each facade component in the previous step.

Methodology equation (2) requires:

$$EC_{A13,i} = Q_i \times ECF_{A13,i}$$

Where:

Q_i = quantity of i^{th} material (kg)

$ECF_{A13,i}$ = module A1 – A3 embodied carbon factor for i^{th} material ($kgCO_2e/kg$)

Multiply the quantity of each component by $ECF_{A13,i}$ to determine $EC_{A13,i}$.

Facade Components	Q_i (kg)	$ECF_{A13,i}$ ($kgCO_2e/kg$)	$EC_{A13,i}$ ($kgCO_2e$)
Unitised curtain wall frames	200	8.15	1630.00
Terracotta rainscreen cladding	350	1.36	476.00
Window and door framing	85	7.98	678.30
Curtain wall feature fins	20	8.59	171.80
Triple glazed units – type G5	47	n/a	103.04[1]
Triple glazed units type G5A	219	n/a	451.05[1]
Mineral wool thermal insulation	90	1.72	154.80
Aluminium external spandrel panel	100	8.59	859.00
Steel internal spandrel panel	90	2.76	248.40
Steel curtain wall brackets	15	2.76	41.40
Aluminium curtain wall brackets	50	6.83	341.50
Aluminium rainscreen subframe	5	6.83	34.15
Stainless steel rainscreen brackets	15	4.41	66.15
Fire stops and cavity barriers	15	5.34	80.10
TOTAL	**1301 kg**		**5336 $kgCO_2e$**

Table 2 – Embodied carbon from production/manufacturing

EC_{A13} = 5336 $kgCO_2e$ / 18.45 m^2 FSA = **289 $kgCO_2e/m^2$ FSA***

*Note: At this step, the A1-A3 emissions associated with off-site activities have yet to be included. This will be completed in Step 9 because emissions from module C must first be known.

[1] Refer to Appendix A for how to determine $EC_{A13,G5}$ and $EC_{A13,G5A}$ for each glass build-up where the glazing surface area (m^2) is required in lieu of the weight.

Step 4: Calculate the total embodied carbon required to transport the factory assembled facade to the site for installation (EC_{A4}).

Methodology equation (10) requires:

$$ECF_{A4,i} = \sum_{mode} \left[TD_{mode} \times \frac{TEF_{mode}}{1000} \right]$$

Where:

$ECF_{A4,i}$	= transportation to site, module A4 embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
TD_{mode}	= transport distance for given mode of transport (km)
TEF_{mode}	= transport emissions factor for given mode of transport ($gCO_2e/km.kg$)
1000	= conversion from grammes to kilogrammes

The total facade is being transported from one factory location in Cologne, Germany to London, UK. All materials are being transported from Cologne, Germany by road via a 50% laden diesel HGV (approx. 450km by road).

In the absence of specific transport distances, refer to default assumptions provided in Table 4 within the methodology for TD_{mode}. TEF_{mode} assumptions can be sourced from the Department for Business, Energy & Industrial Strategy (3).

- Road transport based on 50% laden diesel HGV (= 0.12145 $gCO_2e/kg.km$ in 2022)
- Sea transport based on an average container ship (= 0.01614 $gCO_2e/kg.km$ in 2022)

	Road	Ship
TD_{mode} =	450 km	50 km
TEF_{mode} =	0.12145 $gCO_2e/kg.km$	0.01614 $gCO_2e/kg.km$
$ECF_{A4,i}$ =	0.055 $kgCO_2e/kg$	0.001 $kgCO_2e/kg$

$\boldsymbol{ECF_{A4,i}}$ = 0.055 + 0.001 = **0.055 $kgCO_2e/kg$**

Multiply the quantity of each component by $ECF_{A4,i}$ to determine $EC_{A4,i}$.

Facade Components	Q_i (kg)	$ECF_{A4,i}$ ($kgCO_2e/kg$)	$EC_{A4,i}$ ($kgCO_2e$)
Unitised curtain wall frames	200	0.055	11.09
Terracotta rainscreen cladding	350	0.055	19.41
Window and door framing	85	0.055	4.71
Curtain wall feature fins	20	0.055	1.11
Triple glazed units – type G5	47	0.055	2.61
Triple glazed units type G5A	219	0.055	12.15
Mineral wool thermal insulation	90	0.055	4.99
Aluminium external spandrel panel	100	0.055	5.55
Steel internal spandrel panel	90	0.055	4.99
Steel curtain wall brackets	15	0.055	0.83
Aluminium curtain wall brackets	50	0.055	2.77
Aluminium rainscreen subframe	5	0.055	0.28
Stainless steel rainscreen brackets	15	0.055	0.83
Fire stops and cavity barriers	15	0.055	0.83
TOTAL	**1301 kg**		**72 $kgCO_2e$**

Table 3 – Embodied carbon due to transport from factor to site

$\boldsymbol{EC_{A4}}$ = 72 $kgCO_2e$ / 18.45 m^2 FSA = **4 $kgCO_2e/m^2$ FSA**

Step 5: Calculate the total embodied carbon required to install the factory assembled facade onto the project building on site (EC_{A5}).

In accordance with section 2.2.4.1 of the methodology, because the facade system is assembled off-site, it can be assumed that $\boldsymbol{ECF_{A5,w}}$ **for site wastage is 0 kgCO₂e/kg.** The majority of the waste occurring will be accounted for within factory wastage emissions to be calculated at Step 9.

Site activity emissions (EC_{A5a}) must still be calculated during this step. In this example, project specific data for fuel carbon factors and fuel consumption are unknown, so the RICS guidance (4) method will be used, which is the equation below.

Methodology equation (14) requires:

$$\boldsymbol{EC_{A5a} = FC_{\%} \times CAEF \times \frac{PC}{100,000}}$$

Where:

EC_{A5a}	= embodied carbon emissions from construction activities ($kgCO_2e$)
PC	= project cost (£).
$FC_{\%}$	= facade cost as a percentage of the project cost (%). Advise should be sought from the project Quantity Surveyor at an early stage.
$CAEF$	= whole building Construction Activities Emissions Factor of: 1400 $kgCO_2e$/£100,000 of Project Cost (BRE Meeting Construction 2025 Targets – SMARTWaste KPI p.3, footnote 9) (5)

The facade is assumed to be 15% of the project cost for this example.

$\boldsymbol{EC_{A5a}}$ = 0.15 x 1400 x (45,000,000 / 100,000) = 94,500 $kgCO_2e$

$\boldsymbol{EC_{A5a}}$ = 94,500 $kgCO_2e$ / 5200 m^2 total facade surface area = **18 $kgCO_2e/m^2$ FSA**

Step 6: Calculate the total embodied carbon required to deconstruct/demolish the facade (EC_{C1}).

Methodology equation (17) requires:

$$ECF_{C1} = FC_{\%} \times \frac{3.4}{FFF}$$

Where:

ECF_{C1}	= demolition emissions factor (Module C1) of $1m^2$ of facade ($kgCO_2e/m^2$ FSA)
FFF	= facade form factor (m^2 FSA /m^2 GIA)
$FC_{\%}$	= facade cost as a percentage of the project cost (%). Advice should be sought from the project Quantity Surveyor at an early stage.

The facade is assumed to be 15% of the project cost for this example.

***ECF**$_{C1}$* **=** 0.15 x (3.4 / 0.55) = **1 $kgCO_2e/m^2$ FSA**

Step 7: Calculate the total embodied carbon required to transport deconstructed/demolished materials to the waste processing or disposal site (EC_2).

Methodology equation (18) requires:

$$ECF_{C2,i} = \sum_{mode} \left[TD_{mode} \times \frac{TEF_{mode}}{1000} \right]$$

$ECF_{C2,i}$	= transportation to site, module C2 embodied carbon factor for ith material ($kgCO_2e/kg$)
TD_{mode}	= transport distance for given mode of transport (km)
TEF_{mode}	= transport emissions factor for given mode of transport ($gCO_2e/km.kg$)
1000	= conversion from grammes to kilogrammes

For this example, it is assumed that no materials are reused or recycled on site. All materials are transported to the average of the two closest waste processing sites to be prepared for reuse or recycling, or they are transported to the two closest landfill sites for disposal. Both types of site are 50 km away from the site by road.

In accordance with section 2.2.11 of the methodology, it has been assumed all materials are transported by an average diesel HGV with 50% load. Based on this assumption a TEF of 0.12145 $gCO_2e/kg.km$ has been used from the UK Department for Business, Energy & Industrial Strategy *'Greenhouse gas reporting: conversion factors'* guidance (3).

$\boldsymbol{ECF_{C2,i}}$ = 50 km x (0.12145 $gCO_2/km{\cdot}kg$ / 1000) = **0.006 $kgCO_2e/kg$**

Multiply the quantity of each component by $ECF_{C2,i}$ to determine $EC_{C2,i}$.

$$EC_{C2,i} = ECF_{C2,i} \times Q_i$$

Facade Components	Q_i (kg)	$ECF_{C2,i}$ ($kgCO_2e/kg$)	$EC_{C2,i}$ ($kgCO_2e$)
Unitised curtain wall frames	200	0.006	1.21
Terracotta rainscreen cladding	350	0.006	2.13
Window and door framing	85	0.006	0.52
Curtain wall feature fins	20	0.006	0.12
Triple glazed units – type G5	47	0.006	0.29
Triple glazed units type G5A	219	0.006	1.33
Mineral wool thermal insulation	90	0.006	0.55
Aluminium external spandrel panel	100	0.006	0.61
Steel internal spandrel panel	90	0.006	0.55
Steel curtain wall brackets	15	0.006	0.09
Aluminium curtain wall brackets	50	0.006	0.30
Aluminium rainscreen subframe	5	0.006	0.03
Stainless steel rainscreen brackets	15	0.006	0.09
Fire stops and cavity barriers	15	0.006	0.09
TOTAL	**1301 kg**		**8 $kgCO_2e$**

Table 4 – Embodied carbon from transport emissions due to deconstruction/demolition

$\boldsymbol{EC_{C2}}$ = 8 $kgCO_2e$ / 18.45 m^2 FSA = **0.4 $kgCO_2e/m^2$ FSA**

Step 8: Calculate the total embodied carbon required for waste processing and disposal of the facade ($EC_{C34,i}$).

For the purpose of this example, the end-of-life scenario for facade components that are not aluminium are assumed to be 'sent to landfill' as inorganic waste, while aluminium components are assumed to undergo waste processing for future recycling or reuse.

Refer to Table 10 in the methodology for default disposal process ECF assumptions for different types of waste. A default value has been assumed for the waste processing and disposal of the metallic components taken from Table 10 in the methodology for metallic waste planned for partial recycling (93%) and partial landfilling (7%). This information can also be sourced directly from a supplier or project specific EPD if available.

$$ECF_{C34,i} = 0.013 \text{ kgCO}_2\text{e/kg (inorganic waste)}$$

$$ECF_{C34,i} = 0.020 \text{ kgCO}_2\text{e/kg (metallic waste)}$$

Multiply the quantity of each component by $ECF_{C34,i}$ to determine $EC_{C34,i}$.

$$EC_{C34,i} = ECF_{C34,i} \times Q_i$$

Facade Components	Q_i (kg)	ECF $_{C34,i}$ ($kgCO_2e/kg$)	EC $_{C34,i}$ ($kgCO_2e$)
Unitised curtain wall frames	200	0.020	4.00
Terracotta rainscreen cladding	350	0.013	4.55
Window and door framing	85	0.020	1.70
Curtain wall feature fins	20	0.020	0.40
Triple glazed units – type G5	47	0.013	0.61
Triple glazed units type G5A	219	0.013	2.85
Mineral wool thermal insulation	90	0.013	1.17
Aluminium external spandrel panel	100	0.020	2.00
Steel internal spandrel panel	90	0.020	1.80
Steel curtain wall brackets	15	0.020	0.30
Aluminium curtain wall brackets	50	0.020	1.00
Aluminium rainscreen subframe	5	0.020	0.10
Stainless steel rainscreen brackets	15	0.020	0.30
Fire stops and cavity barriers	15	0.013	0.20
TOTAL	**1301 kg**		**21 $kgCO_2e$**

Table 5 – Embodied carbon from waste processing

EC_{C34} = 21 $kgCO_2e$ / 18.45 m^2 FSA = **1 $kgCO_2e/m^2$ FSA**

Step 9: Calculate applicable factory assembly emissions to include in the total product stage embodied carbon for A1-A3 calculation.

The facade studied in this example is a unitised curtain wall assembly, where each panel will be pre-assembled off-site at a factory located in Cologne, Germany prior to being shipped to site and installed on the building in London, UK. Therefore it is appropriate to consider the additional off-site transportation, assembly, and waste emissions for inclusion in product stage (EC_{A13}). Emissions that must be calculated include:

$ECF_{A2, F}$	Transportation to off-site factory
$ECF_{A3, FAB}$	Off-site fabrication emissions
$ECF_{A3, ASS}$	Off-site assembly emissions
$ECF_{A3, W}$	Off-site wastage rates

Terminology required for an understanding of factory assembly emissions and how it is interpreted for facade embodied carbon calculations can be found in section 1.7 of the methodology.

Methodology equation (20) requires the complete calculation of A1-A3 including factory emissions:

$$EC_{A13} = \sum_{i=1}^{n} \left[Q_i (ECF_{A13,i} + ECF_{A2,F,i} + ECF_{A3,FAB,i} + ECF_{A3,W,i}) \right] + (A \times ECF_{A3,ASS})$$

Where:

EC_{A13}	= total embodied carbon for life cycle modules A1 – A3 ($kgCO_2e$)
Q_i	= quantity of i^{th} material (kg) within representative area assessed (A)
A	= representative area of facade assessed (m^2)
$ECF_{A13,i}$	= module A1 – A3 embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
$ECF_{A3,W,i}$	= factory waste module $A3_W$ embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
$ECF_{A2,F,i}$	= transportation to factory module $A2_F$ embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
$ECF_{A3,ASS}$	= off-site assembly module emissions factor ($kgCO_2e/m^2$ FSA)
$ECF_{A3,FAB,i}$	= off-site fabrication emissions factor for the i^{th} component ($kgCO_2e/kg$)
$\sum_{i=1}^{n}$	= the summation of components from 1 to total number of components, n, in the facade system.

$ECF_{A13,i}$ has been determined in Step 3.

Transportation of materials to the factory emissions

Methodology equation (3) requires:

$$ECF_{A2,F,i} = \sum_{mode} \left[TD_{mode} \times \frac{TEF_{mode}}{1000} \right]$$

Where:

$ECF_{A2,F,i}$	= transportation to factory, embodied carbon factor for i^{th} component ($kgCO_2e/kg$)
TD_{mode}	= transport distance for each transport mode (km)
TEF_{mode}	= transport emission factor for each transport mode ($gCO_2e/km.kg$)
1000	= conversion from grammes to kilogrammes

For this example, it is assumed that the transportation distance for all materials nationally in the country of fabrication, Germany, assumed as 300 km by road. Moreover, it has been assumed the components are transported by an average laden diesel HGV with TEF taken from the UK Government '*GHG conversion factors 2022'* (3) (= 0.10614 gCO_2/ km·kg).

$$\boldsymbol{ECF_{A2,F}} = 300\text{ km} \times (0.10614\ gCO_2/km\cdot kg / 1000) = \mathbf{0.03\ kgCO_2e/kg}$$

Off-site fabrication emissions

Methodology equation (4) requires:

$$ECF_{A3,FAB,i} = FEI_i \times GCF$$

Where:

$ECF_{A3,FAB,i}$	= off-site fabrication emissions factor for the i^{th} component ($kgCO_2e/kg$)
FEI_i	= factory energy intensity (kWh/kg of i^{th} component)
GCF	= grid carbon factor ($kgCO_2e/kWh$)

The components that these emissions apply to include the metal internal and external spandrel panels, and aluminium feature fins, which are assumed in this example to be cut and formed in the factory prior to assembly onto the facade system.

As the factory energy intensity (FEI_i) is not known for this project example, the default assumption of 4 kWh/kg is assumed for fabrication. A grid carbon factor (GCF) is also assumed for Europe (refer to Table 2 within the methodology for default GCFs specific to project locations).

$$\boldsymbol{ECF_{A3,FAB,i}} = 4\text{ kWh/kg} \times 0.30\ kgCO_2e/kWh = \mathbf{1.20\ kgCO2e/kg}$$

Off-site assembly emissions

Methodology equation (6) requires:

$$\boldsymbol{ECF_{A3,ASS} = FEI \times GCF}$$

Where:

$ECF_{A3,ASS}$	= factory assembly emissions ($kgCO_2e/m^2$)
FEI	= factory energy intensity (kWh/m^2 of facade surface area)
GCF	= grid carbon factor ($kgCO_2e/kWh$)

As the factory energy intensity (FEI) is not known for this project example, the default assumption of 30 kWh/m^2 is assumed for assembly. A grid carbon factor (GCF) is also assumed for Europe (refer to Table 3 within the methodology for default GCFs specific to project locations).

$$ECF_{A3,ASS} = 30 \text{ kWh/m}^2 \times 0.30 \text{ kgCO}_2\text{e/kWh} = \mathbf{9\ kgCO_2e/m^2\ FSA}$$

Off-site wastage emissions

Methodology equation (8) requires:

$$ECF_{A3w,i} = WF_i \times (ECF_{A13,i} + ECF_{A2F,i} + ECF_{C2,i} + ECF_{C34,i})$$

Where:

$ECF_{A3w,i}$	= construction waste embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
WF_i	= waste factor for i^{th} material given by equation (9)
$ECF_{A13,i}$	= module A1 – A3 embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
$ECF_{A2F,i}$	= transportation to factory, embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
$ECF_{C2,i}$	= transportation to waste processing, embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
$ECF_{C34,i}$	= waste processing and disposal emissions ($kgCO_2e/kg$)

And methodology equation (9) requires:

$$WF_i = \frac{WR_i}{1 - WR_i}$$

Where:

WR_i	= waste rate (proportion of the total quantity of the i^{th} material brought to the factory that ends up as waste).

In the absence of data from the supplier or project EPDs, waste rates can be assumed as follows:

- Components requiring cutting to size in the factory: $WR_i = 15\%$
- Components not requiring cutting to size in the factory: $WR_i = 3\%$

WFi for components requiring cutting to size = 0.18

WFi for components not requiring cutting to size = 0.03

Waste factors determined for each component are included in the table below for inclusion in the calculation of wastage emissions ($ECF_{A3,w}$) for each component. It is assumed in this example that thermal insulation, metal external and internal spandrel panels, metal feature fins, fire stops and cavity barriers require cutting to size in the factory. All other components are assumed to not require cutting to size in the factory.

How to calculate the embodied carbon of facades: Worked example

Emissions associated with off-site assembly emissions, $EC_{A3,ASS}$, are evaluated separately from the quantity of materials and therefore for sit outside the summation of ECFs included in the table below.

Facade Components	Q_i (kg)	WF_i	ECF $_{A13,i}$ ($kgCO_2e/kg$)	ECF $_{A2,F,i}$ ($kgCO_2e/kg$)	ECF $_{A3,FAB,i}$ ($kgCO_2e/kg$)	ECF $_{A3,w,i}$ ($kgCO_2e/kg$)	ECF $_{C2,i}$ ($kgCO_2e/kg$)	ECF $_{C34,i}$ ($kgCO_2e/kg$)	EC $_{A13,i}$ ($kgCO_2e$)
Unitised curtain wall frames	200	0.03	8.15	0.03	n/a	0.25	0.006	0.020	1687.14
Terracotta rainscreen cladding	350	0.03	1.36	0.03	n/a	0.04	0.006	0.013	502.42
Window and door framing	85	0.03	7.98	0.03	n/a	0.25	0.006	0.020	702.14
Curtain wall feature fins	20	0.18	8.59	0.03	1.20	1.53	0.006	0.020	226.96
Triple glazed units – type G5	47	n/a[1]	n/a[1]	0.03	n/a	n/a[1]	0.006	0.013	104.41[2]
Triple glazed units type G5A	219	n/a[1]	n/a[1]	0.03	n/a	n/a[1]	0.006	0.013	457.57[2]
Mineral wool thermal insulation	90	0.18	1.72	0.03	n/a	0.31	0.006	0.013	185.79
Aluminium external spandrel panel	100	0.18	8.59	0.03	1.20	1.53	0.006	0.020	1134.79
Steel internal spandrel panel	90	0.18	2.76	0.03	1.20	0.50	0.006	0.020	404.02
Steel curtain wall brackets	15	0.03	2.76	0.03	n/a	0.09	0.006	0.020	43.18
Aluminium curtain wall brackets	50	0.03	6.83	0.03	n/a	0.21	0.006	0.020	353.74
Aluminium rainscreen subframe	5	0.03	6.83	0.03	n/a	0.21	0.006	0.020	35.37
Stainless steel rainscreen brackets	15	0.03	4.41	0.03	n/a	0.14	0.006	0.020	68.70
Fire stops and cavity barriers	15	0.18	5.34	0.03	n/a	0.95	0.006	0.013	94.85
TOTALS	**1301 kg**								**6001kgCO2e**

Table 6 – Emissions resulting from factory assembly

$$ECF_{A3,ASS} = \mathbf{9\ kgCO_2e/m^2\ FSA}$$

$$EC_{A13} = (6001\ kgCO_2e / 18.45\ m^2\ FSA) + 9\ kgCO_2e/m^2\ FSA =$$

334 $kgCO_2e/m^2$ FSA (including off-site emissions)[1]

[1] Off-site emissions for assembly and fabrication of the glazing unit materials have not been considered here. Refer to Appendix A for calculation of $EC_{A13,G5}$ and $EC_{A13,G5A}$ for the glass build-ups, and Appendix C in the methodology for further guidance.

[2] ECF A13 for the glass calculated in Appendix A now also includes required off-site transportation emissions (ECF $_{A2,F,i}$)

Step 10: Calculate the total embodied carbon for any facade components that will be required to be replaced during the lifetime of the building (EC_{B4}).

Methodology equation (16) requires:

$$ECF_{B4,i} = \left\lceil \frac{RSP}{CL_i} - 1 \right\rceil \times (ECF_{A13,i} + ECF_{A2,F,i} + ECF_{A3w,i} + ECF_{A3,FAB,i} + ECF_{A4,i} + ECF_{A5w,i} + ECF_{C2,i} + ECF_{C34,i})$$

Where:

$ECF_{B4,i}$	= replacement emissions for i^{th} material ($kgCO_2e/kg$)
RSP	= asset reference study period (years)
CL_i	= component lifespan (years) for i^{th} material
$ECF_{A13,i}$	= embodied carbon factor for modules A1 – A3 for the i^{th} replacement material ($kgCO_2e/kg$)
$ECF_{A2,F,i}$	= transportation to factory module $A2_F$ embodied carbon factor for i^{th} material ($kgCO_2e/kg$)
$ECF_{A3w,i}$	= embodied carbon factor for module A3w for the i^{th} replacement material ($kgCO_2e/kg$)
$ECF_{A3,FAB,i}$	= off-site fabrication emissions factor for the i^{th} component ($kgCO_2e/kg$)
$ECF_{A4,i}$	= embodied carbon factor for module A4 for the i^{th} replacement material ($kgCO_2e/kg$)
$ECF_{A5w,i}$	= embodied carbon factor for module A5w for the i^{th} replacement material ($kgCO_2e/kg$)
$ECF_{C2,i}$	= embodied carbon factor for module C2 for the i^{th} replaced material ($kgCO_2e/kg$)
$ECF_{C34,i}$	= embodied carbon factor for modules C3 – C4 for the i^{th} replaced material ($kgCO_2e/kg$)

For this project example, we will assume that the **glazing units will be replaced once** during the lifetime of the building, where RSP is 60 years for the building, and the component lifespan of the glazing units is 30 years.

$ECF_{A5w,i}$ for site wastage is assumed as 0 $kgCO_2e/kg$ in this example. $ECF_{A3w,i}$ and $ECF_{A3,FAB,i}$ are not applicable to the glazing (n/a) in this example as described in the Step 9.

Additionally, $ECF_{A13,i}$ emissions required in the calculation of B4 emissions for the glazing units are taken from the calculation using the glazing methodology in Appendix A in which the total is provided in units $kgCO_2e$. Therefore, due to the difference in units (ECF = $kgCO_2e/kg$,vs EC = $kgCO_2e$) $EC_{A13,G5}$ and $EC_{A13,G5A}$ are initially excluded (n/a) then included in the total sum at the end.

Refer to the previous steps for additional ECFs required in this equation that have already been calculated.

$ECF_{B4,i}$ for glass types G5 and G5A:

$ECF_{B4,i}$ = [(60 / 30) – 1] x (n/a* + 0.03 + n/a + n/a + 0.06 + 0 + 0.006 + 0.013) = **0.109 $kgCO_2e/kg$**

**see equation below where $ECF_{A13,i}$ will be included in the final sum*

Multiply each quantity (kg) of the glazing by $ECF_{B4,i}$ to determine EC_{B4} for each glass type. Then add this value to $EC_{A13,G5}$ and $EC_{A13,G5A}$ for each glass type to determine the final total for each.

G5: 47 kg x 0.109 $kgCO_2e/kg$ = 5.123 $kgCO_2e$ + 103.04 $kgCO_2e$ = **108 $kgCO_2e$**

G5A: 219 kg x 0.109 $kgCO_2e/kg$ = 23.87 $kgCO_2e$ + 451.05 $kgCO_2e$ = **475 $kgCO_2e$**

EC_{B4} = (108 + 475 $kgCO_2e$) / 18.45 m^2 FSA = **32 $kgCO_2e/m^2$ FSA**

Step 11: Sum all embodied carbon totals for each module calculated and apply applicable carbon calculation scale-up factor to determine the total embodied carbon for the facade.

The carbon calculation scale-up factor (F) is applied in this example to address any uncertainties that may remain in the assessment. The factor applied here is not based on any studies. It is rather used solely to represent an example of a potential factor that could be applied during the later stages of a project when an appointed facade contractor has produced the design for construction. This factor is likely to be higher during earlier stage assessments before the design has been refined. For more details on the carbon calculation scale-up factor, refer to section 2.2.15 of the methodology.

EC_{A13} Product	= 334 $kgCO_2e/m^2$ FSA*
EC_{A4} Transport to site	= 4 $kgCO_2e/m^2$ FSA (Step 4)
EC_{A5} Construction/installation	= 18 $kgCO_2e/m^2$ FSA (Step 5)
EC_{B4} Replacement	= 32 $kgCO_2e/m^2$ FSA (Step 10)
EC_{C1} Deconstruction/demolition	= 1 $kgCO_2e/m^2$ FSA (Step 6)
EC_{C2} Waste transport	= 0.4 $kgCO_2e/m^2$ FSA (Step 7)
EC_{C34} Waste processing/disposal	= 1 $kgCO_2e/m^2$ FSA (Step 8)
F Carbon calculation scale-up factor	= 1.05

*Includes factory assembly emissions (Step 3 and 9)

$EC_{AC,min}$ = 390 $kgCO_2e/m^2$ FSA

$\boldsymbol{EC_{AC,min} \times F}$ = 390 $kgCO_2e/m^2$ FSA x 1.05 = **410 $kgCO_2e/m^2$ FSA**

A breakdown of the embodied carbon per life cycle stage is presented in Figure 3. The embodied carbon can be further analysed by product stage and at a component level to better understand how embodied carbon can be reduced in coordination with whole life cycle carbon assessment for the entire project building. For example, embodied carbon in A1-A3 as the largest contributor can be assessed in greater detail to understand where and how embodied carbon can be mitigated in the design.

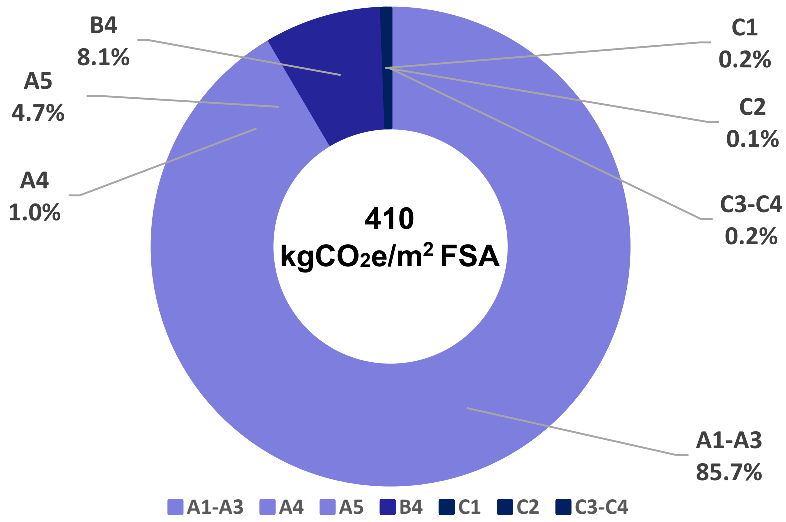

Figure 3 – Embodied carbon of FS-01 per life cycle stage

Presenting results

The results including assumptions are to be presented as described in section 2.4 of the methodology. The reporting template included in Appendix A of the methodology is recommended to be used to summarise results. An example of this is included on the following page.

When reporting the results of the assessment, it is recommended that they are reported no more precisely than to the nearest integer value.

Accuracy

It is always important to highlight the uncertainties, even if only qualitatively, associated with the assessment. Highlighting the uncertainties will help communicate the level of accuracy with which the results should be interpreted.

Key areas of uncertainty in the worked example:

- **EPD cut-off criteria:** In accordance with BS EN 15804 section 6.3.6 it should be recognised that the results reported within EPDs shall be within 5% of the actual result of the product reported.
- **Material quantities:** The material quantities have been assessed by a review of construction-level drawings. The assessment is limited to the materials and quantity presented in the information.
- **Carbon factors:** The selection of carbon factors used in the assessment has been undertaken based identifying the most representative factors for the products under assessment with consideration for the level of certainty of the supply chain known at the time of assessment.
- **Assumptions:** Key assumptions used in the assessment have been presented. The extent to which these may change as the design development presents a source of uncertainty in the results.

How to calculate the embodied carbon of facades: Worked example

Project Title	*Project X*	**Date:**	*01/09/2022*	**Assessment Approach:**	*Full*
Project Type	*Residential*	**Project Location**	*London, UK*	**Prepared by:**	*Name*
Project Stage	*RIBA Stage 5*	**Project Cost**	*£45 million*	**Reviewed by:**	*Name*
GIA	*9454 m^2*	**FSA**	*5200 m^2*	**Facade Form Factor**	*0.55*

Facade System	**Description**	**Facade Surface Area (m^2 FSA)**	**Embodied Carbon ($kgCO_2e/m^2$ FSA)**															**EC_{AC} ($kgCO_2e/m^2$ FSA)**	**F x EC_{AC} ($kgCO_2e/m^2$ FSA)[3]**
			PRODUCT[1]	**Stored biogenic carbon**	**CONSTRUCTION**		**USE**							**END OF LIFE**			**BEYOND**		
			A1-A3		**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3/C4[2]**	**D**		
FS-01	*Unitised curtain wall*	*5200*	*334*	*0*	*4*	*18*	*MNA*	*MNA*	*MNA*	*32*	*MNA*	*MNA*	*MNA*	*1*	*0.4*	*1*	*MNA*	***390***	***410***

Embodied carbon per GIA[3]	EC_{AC} = *225 $kgCO_2e/m^2$ GIA*
	Stored biogenic carbon = n/a
	EC_D = *n/a $kgCO_2e/m^2$ GIA*
Total embodied carbon[3]	EC_{AC} = *2130 tCO_2e*
	Stored biogenic carbon = n/a tCO_2e
	EC_D = *n/a tCO_2e*

Note:

[1] Product stage emissions excluding stored biogenic carbon (refer to Appendix D of the methodology).

[2] Module C4 includes carbon emissions or transfers of stored biogenic carbon (refer to Appendix D of the methodology).

[3] Designers to make clear where a material uplift factor (section 1.6.2 of the methodology) and/or carbon calculation scale-up factor (section 2.2.15 of the methodology) have been applied.

References

1. **Centre for Window and Cladding Technology.** *How to calculate embodied carbon for facades: A methodology.* Bath, UK : Centre for Window and Cladding Technology, 2022.

2. —. *Life cycle modules explained.* Bath, UK : Centre for Window and Cladding Technology, 2022.

3. **UK Government.** Government conversion factors for company reporting of greenhouse gas emissions. [Online] Department for Buisness, Energy & Industrial Strategy, June 2022. https:www.gov.uk/government/collections/government-conversion-factors-for-company-reporting.

4. **RICS.** *Whole life carbon assessment for the built environment.* s.l. : RICS, 2017.

5. **BRE.** *Meeting Construction 2025 Targets: The positive impact of BRE Group products and services.* s.l. : Building Reseach Establishment, 2015.

Appendix A. Glass build-up worked example

In this appendix, the calculation of the embodied carbon of the glazing included in the typical bay is carried out in accordance with *Appendix C – Glazing embodied carbon methodology*, part of the main document *How to calculate embodied carbon of facades: A methodology (1)*.

The typical facade bay taken as the object of the assessment includes two glass types, whose location and detailed build-ups are illustrated in the images below. All glass was confirmed to be mid-iron.

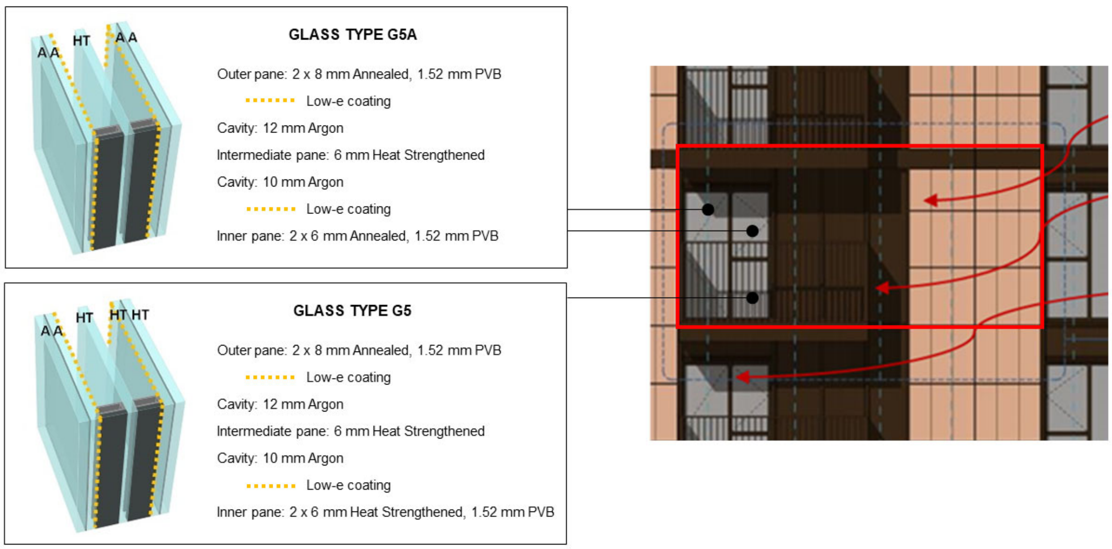

Figure 4 – Glass build-ups

The following steps outline the process of determining the A1-A3 embodied carbon associated with each glass type:

Step 1: calculate the embodied carbon factor ($ECF_{A13,i}$) associated with each pane of the IGU

Step 2: calculate the total embodied carbon factor ($ECF_{A13,IGU}$) of the IGU

Step 3: calculate the embodied carbon of the glass type by multiplying $ECF_{A13,IGU}$ by the reference area

Refer to the methodology Appendix C for reference equations applied and ECF values.

Embodied carbon of glass type G5A

Outer (laminated) pane

$$ECF_{A13,out} = EC_{A13,M,1} + EC_{A13,M,2} + ECF_{LAM} + z \times ECF_{INT}$$

$$= 23.68 + 24.59 + 0.5 + 4 \times 2.74 = 59.73 \text{ (kgCO}_2\text{e/m}^2\text{)}$$

Where the embodied carbon associated with each monolithic glass pane was calculated as follows:

$ECF_{A13,M1} = t \times ECF_{FL,t} = 8 \times 2.96 = 23.68$ (kgCO$_2$e/m^2)

$ECF_{A13,M,2} = t \times ECF_{FL,t} + ECF_C = 8 \times 2.96 + 0.91 = 24.59$ (kgCO$_2$e/m^2)

How to calculate the embodied carbon of facades: Worked example

Intermediate pane

$$ECF_{A13,int} = t \times ECF_{FL,t} + ECF_{P,f} + t \times ECF_{P,v} = 6 \times 2.96 + 2.79 + 6 \times 0.47 = 23.37$$ (kgCO2e/m2)

Inner (laminated) pane

$$ECF_{A13,in} = EC_{A13,M,4} + EC_{A13,M,5} + ECF_{LAM} + z \times ECF_{INT}$$

$$= 18.67 + 17.76 + 0.5 + 4 \times 2.74 = 47.89$$ (kgCO2e/m2)

Where the embodied carbon associated with each monolithic glass pane was calculated as follows:

$ECF_{A13,M,4} = t \times ECF_{FL,t} + ECF_C = 6 \times 2.96 + 0.91 = 18.67$ (kgCO2e/m2)

$ECF_{A13,M,5} = t \times ECF_{FL,t} = 6 \times 2.96 = 17.76$ (kgCO2e/m2)

Triple glazed unit as a whole

$$ECF_{A13,IGU} = ECF_{A13,out} + ECF_{A13,int} + ECF_{A13,in} + ECF_{Assembly}$$

$$= 59.73 + 23.37 + 47.89 + 24 = 155.0$$ (kgCO2e/m2)

Embodied carbon of the glass type

$$\boldsymbol{EC_{A13,G5A}} = ECF_{A13,IGU} \times A_{G5A} = 155.0 \times 2.91 = \mathbf{451}$$ **(kgCO2e)**

Embodied carbon of glass type G5

Outer (laminated) pane

$$ECF_{A13,L,out} = EC_{A13,M,1} + EC_{A13,M,2} + ECF_{LAM} + z \times ECF_{INT}$$

$$= 23.68 + 24.59 + 0.5 + 4 \times 2.74 = 59.73$$ (kgCO2e/m2)

Where the embodied carbon associated with each monolithic glass pane was calculated as follows:

$ECF_{A13,M1} = t \times ECF_{FL,t} = 8 \times 2.96 = 23.68$ (kgCO2e/m2)

$ECF_{A13,M,2} = t \times ECF_{FL,t} + ECF_C = 8 \times 2.96 + 0.91 = 24.59$ (kgCO2e/m2)

Intermediate pane

$$ECF_{A13,M,int} = t \times ECF_{FL,t} + ECF_{P,f} + t \times ECF_{P,v} = 6 \times 2.96 + 2.79 + 6 \times 0.47 = 23.37$$ (kgCO2e/m2)

Inner (laminated) pane

$$ECF_{A13,L,in} = EC_{A13,M,4} + EC_{A13,M,5} + ECF_{LAM} + z \times ECF_{INT}$$

$$= 24.28 + 23.37 + 0.5 + 4 \times 2.74 = 59.11$$ (kgCO2e/m2)

Where the embodied carbon associated with each monolithic glass pane was calculated as follows:

$ECF_{A13,M,4} = t \times ECF_{FL,t} + ECF_C + ECF_{P,f} + t \times ECF_{P,v} = 6 \times 2.96 + 0.91 + 2.79 + 6 \times 0.47 = 24.28$ (kgCO2e/m2)

$ECF_{A13,M,5} = t \times ECF_{FL,t} + ECF_{P,f} + t \times ECF_{P,v} = 6 \times 2.96 + 2.79 + 6 \times 0.47 = 23.37$ ($kgCO_2e/m^2$)

Triple glazed unit as a whole

$$ECF_{A13,IGU} = ECF_{A13,out} + ECF_{A13,int} + ECF_{A13,in} + ECF_{Assembly}$$

$$= 59.73 + 23.37 + 59.11 + 24 = 166.2 \quad (kgCO_2e/m^2)$$

Embodied carbon of the glass type

$$\boldsymbol{EC_{A13,G5}} = ECF_{A13,IGU} \times A_{G5} = 166.2 \times 0.62 = \mathbf{103} \quad \mathbf{(kgCO_2e)}$$

Total embodied carbon of glazing

The total carbon emissions associated with all glazing on the project can finally be calculated by adding up the contributions due to each glass type

$$\boldsymbol{EC_{A13,Glass}} = EC_{A13,G5A} + EC_{A13,G5} = 451 + 103 = \mathbf{554} \quad \mathbf{(kgCO_2e)}$$