CO_2 2.Low carbon

Carbon footprint benchmarking data for buildings

David Collings summarises the results of a study into the carbon footprint of buildings, allowing structural engineers to benchmark their current designs.

Introduction

In this article, the carbon footprint of a range of current buildings is given to benchmark current design practice and to compare this with published theoretical studies. The embodied and capital carbon of the whole building (structure, cladding, finishes, services and associated works) is presented relative to cost, height and area. The data shows the trends for different building usages, and highlights the positive correlation between carbon and cost, height and area.

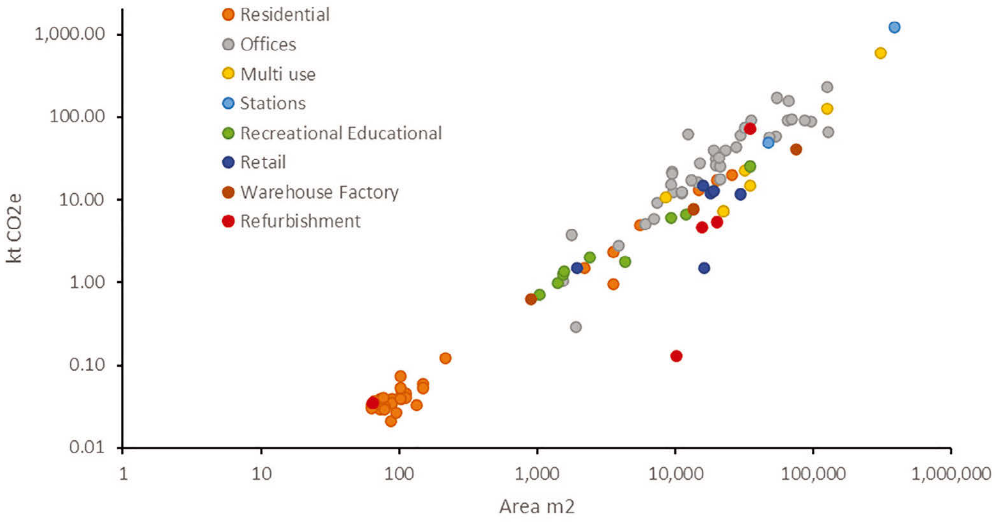
Refurbishment projects consistently show a lower ratio of carbon to both building area and cost, indicating that these are a way of helping us towards the 'net zero' requirement to limit future global warming.

Definitions

The term 'carbon' is used in this article as shorthand for the carbon dioxide equivalent of all greenhouse gases measured in tonnes (tCO_2e). This paper uses the BS EN 15978[1] lifecycle stages (A1, A2, etc.), which are described in the IStructE guide *How to calculate embodied carbon*[2].

This article uses the term 'capital carbon'[3,4], which is often adopted within the construction sector as it accords with the concept of capital cost. It refers to the combined embodied carbon at the product stage and the construction-stage emissions associated with the creation of the building (modules A1 to A5 of the lifecycle). The operational and whole-life carbon (modules B, C and D) are not included in the carbon data given in this article.

The 'carbon emissions intensity'[3] (CEI) is the capital carbon divided by the project capital cost. The UK government terminology of 'net zero' means that carbon from homes, transport, farming and industry will be avoided completely or offset by sequestration. The government has committed to reach this by 2050.



↓FIGURE 1: Capital carbon content, structure only ($1000tCO_2e$) of building with area (GFA) of building (m^2), and with building type, data plotted on Log-Log scale

Literature review

Ekundayo *et al*.[5] outlined the various methods available for estimating the embodied capital carbon of a building floor slab. They noted a range of 90–150 kilograms per square meter ($kgCO_2e/m^2$), including finishes but excluding supporting beams, columns and any bracing structure or foundations.

Collings[6] noted the capital carbon content (structure only) of various types of composite slabs, beams and supporting columns to be 190–740$kgCO_2e/m^2$, depending on the structural configuration of the supporting beams and the column spacing, with longer-span structures having the greater carbon content.

Nadoushani and Akbarnezhad[7] estimated the capital carbon (structure only) of the lateral load-resisting system, giving frame capital carbon values of 145–170$kgCO_2e/m^2$ at three storeys and 205–235 $kgCO_2e/m^2$ at 15 storeys, indicating an increase of approx. 5$kgCO_2e/m^2$ per storey.

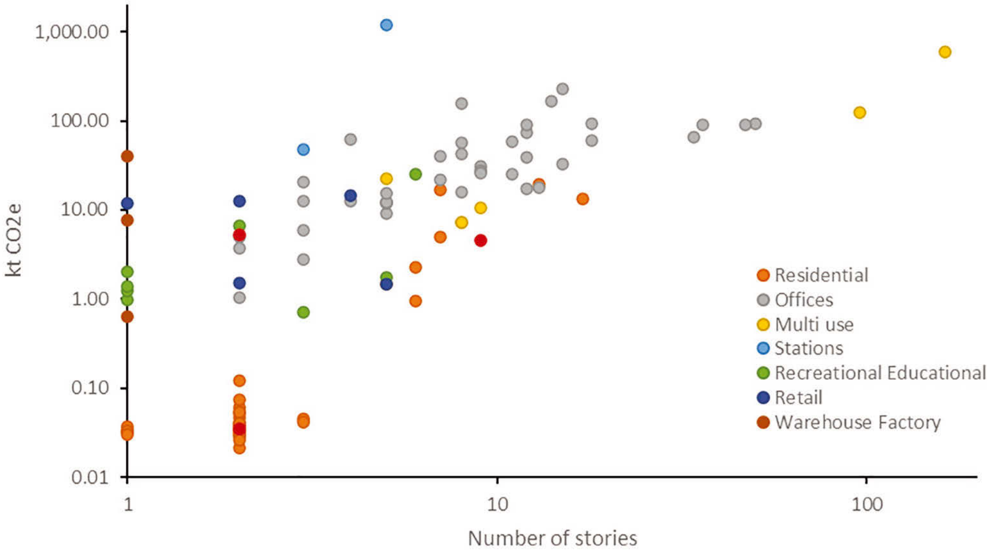
Kaethner and Burridge[8] carried out a literature review of building carbon footprints and noted a 100–600$kgCO_2e/m^2$ range for the capital carbon in the structure alone and 350–800$kgCO_2e/m^2$ for the whole building. Their own estimates of embodied carbon to practical completion were lower at 125–350$kgCO_2e/m^2$. They also noted that the building superstructure typically accounted for 40–47% of the capital carbon, with substructures accounting for 11–17%, and cladding finishes and construction-related carbon making up the rest.

Most recently, Arnold *et al*.[9] noted capital carbon (structure only) in the range of 200–400$kgCO_2e/m^2$ for 60% of the projects they studied, but with outliers of <100 and >1000$kgCO_2e/m^2$.

The theoretical studies have been carried out by different researchers with differing assumptions and some caution is required in their use; there is significant variation in results. However, capital carbon estimates of approx. 200–600$kgCO_2e/m^2$ for the structure and 400–800$kgCO_2e/m^2$ for the entire building seem reasonable for simple and standard buildings.

Knight and Addis[10] published the embodied carbon for a station structure which equated to almost 2770$kgCO_2e/m^2$. This is significantly above the other estimates, although they noted that over 80% of this carbon was in below-ground structure.

↘FIGURE 2: Capital carbon content, structure only (1000tCO$_2$e) with number of storeys and building type, data plotted on Log-Log scale



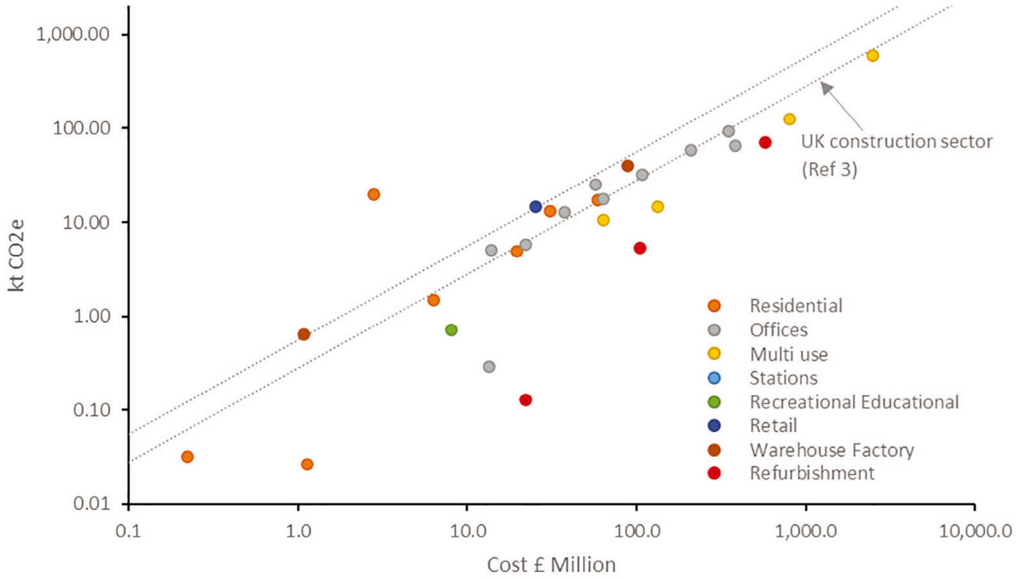
Databases of buildings

Some of the buildings in this article are taken from the author's database of buildings. This has been kept for research, teaching and to use in verification of design. Parts of the database have been used in books[6] and papers[11].

WRAP/RICS[12] also have an online database of the embodied carbon for buildings, which includes all aspects of the building, not just the structure. The database consists of approx. 161 anonymous datasets ranging from single-storey housing to multi-storey offices, most from the UK. The building data used is grouped into new-build and refurbishment. Within the new-build the data is further subdivided into residential, offices, retail, mixed use, warehouses and factories, stations, and education and leisure.

There is some inconsistency in the way data was added to the database by the multiple providers. Hence, the data in the database is not always reliable, not all data fields are input. There are several instances of multiple entries for the same building and some filtering was needed to ensure consistency in the data used. The data was not used when the building size was not given, or the A1–A5 data was not separated. Where multiple entries for the same building were given, an average value was used.

The total number of buildings considered in this article from the author's database and the WRAP/RICS database is 103.



↑FIGURE 3: Capital carbon content, structure only (1000tCO$_2$e) with capital cost (£M) and building type, data plotted on Log-Log scale

Database results

In this section, the raw data is plotted to show trends and highlight potential data anomalies. **Figure 1** plots the capital carbon data against gross floor area (GFA). There is a significant range of carbon values, but with an expected trend for increased carbon with increased area. The size of the buildings varies considerably from 65 to 390 000m^2. The largest 10 buildings account for over half of the total aggregated GFA and embodied carbon in the database.

From **Fig. 1** it is seen that there are a few data points above and below the general trend. The buildings above trend indicate those that should be optimised. The office dataset is of structures with relatively large areas and has the largest number of data points in the database. A few of the office data points are above trend, with one below trend.

Many of the residential projects are relatively small compared with other datasets and are grouped apart from the larger structures of the other building types. The refurbishment projects tend to be below the general data trend, as has been noted in other carbon data[4].

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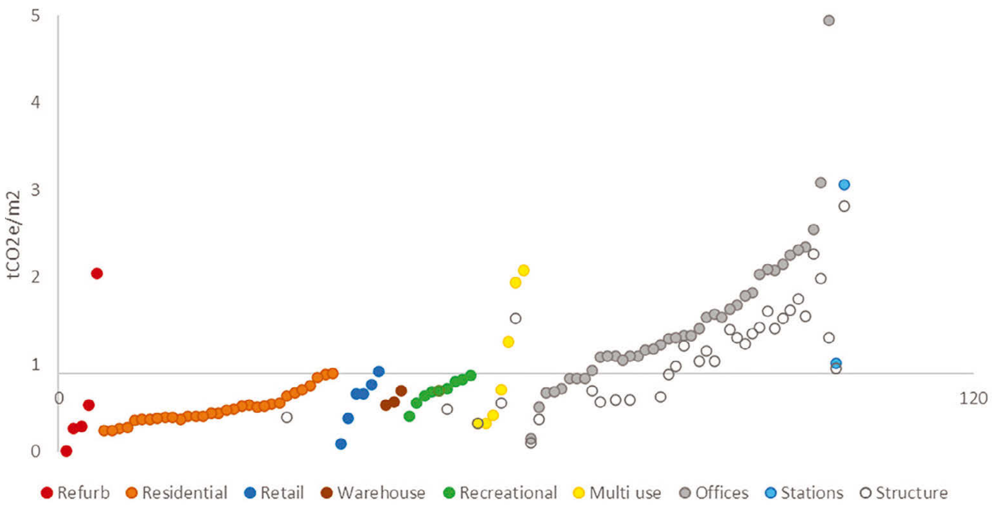
> **REFURBISHMENT PROJECTS CONSISTENTLY SHOW A LOWER RATIO OF CARBON TO BOTH BUILDING AREA AND COST, INDICATING THAT THESE ARE A WAY OF HELPING US TOWARDS THE ‘NET ZERO’ REQUIREMENT**

Figure 2 plots the capital carbon data with number of storeys above ground. There is a general trend for increased carbon with increased height, but it is not as pronounced as for the building area. There is a significant range of carbon values, with the highest value not being associated with the tallest structure. The residential buildings tend to be below the general trend, with offices and stations tending to be above the general trend. The station data point above the general data is the structure noted in the previous studies with significant substructure content.

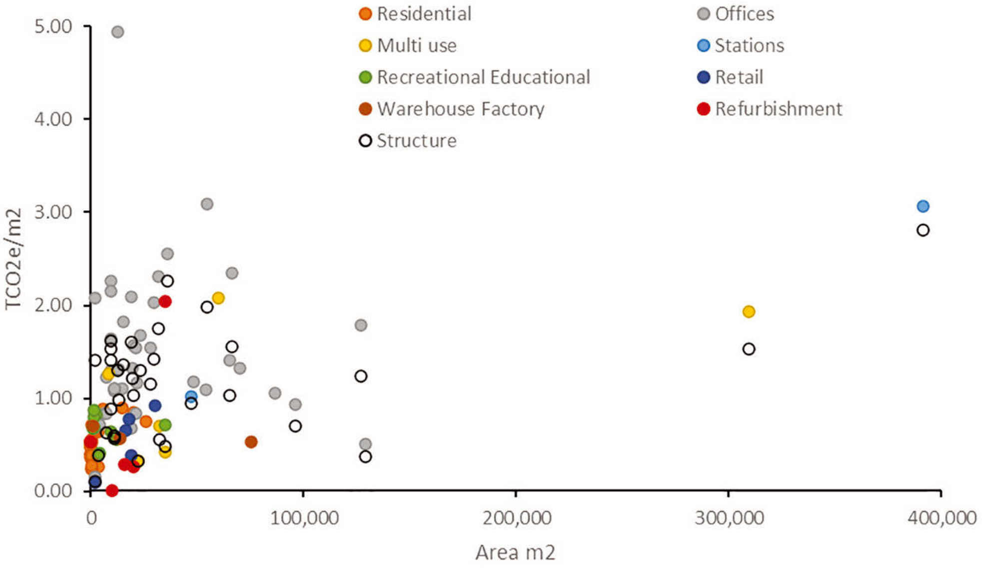
The costs are available for 28 buildings in the database; these have been normalised to the end of 2019. **Figure 3** shows the capital carbon content with cost for the available data. There is a clear positive correlation of increased cost with higher carbon



↑FIGURE 4: Normalised capital carbon content of building (tCO_2e/m^2) for various building types compared with average value. Whole-building data points coloured, structure-only in white (where known)

contents. The refurbishment projects again tend to be below the general trend. The same office data point that was below trend in the area data is below trend in the cost data. From this and other carbon database analysis[4], the author considers the buildings with capital cost data tend to be those that have more reliable capital carbon or can be noted as being off trend.

The Green Construction Board[3] noted that the CEI of the construction sector was between 0.28 and 0.56ktCO$_2$e/£M **(Fig. 3)**. The carbon–cost data for buildings is broadly following this trend. There is a wide range of CEI between 0.05 and 0.76ktCO$_2$e/£M for the data. Projects above the construction sector range are those that have a high CEI (high amount of carbon per pound spent) and would have benefited from optimisation or value engineering. The projects below the construction sector range are those that have a lower CEI and are potential models for future buildings; these are primarily refurbishment projects.



↓FIGURE 5: Normalised capital carbon content of building (tCO_2e/m^2) with building area for various building types. Whole-building data points coloured, structure-only in white (where known)

Normalised data

The basic data as plotted in **Figs. 1–3** can give broad trends and indicate anomalous data. Normalising the data can give a different perspective and assist with benchmarking of new buildings. The average normalised whole-building capital carbon for the buildings in the database is 895kgCO$_2$e/m^2, slightly higher than the range of 400–800kgCO$_2$e/m^2 seen in the literature review.

Figure 4 outlines data in each type in ascending order and shows the variation in this data. The offices, stations and some multi-use structures tend to be above the average, with the remaining building types below average, at approx. 500kgCO$_2$e/m^2, within the theoretical range. The range of whole-building capital carbon is from 13kgCO$_2$e/m^2 for refurbishment to 4940kgCO$_2$e/m^2 for an office building.

Some outlying data points can be seen in **Fig. 4**. One of the refurbishment points is significantly above the trend; this data point is associated with a station refurbishment and significant below-ground works. The highest data point is an office building; from the carbon database it is noted that much of the embodied carbon is associated with external works for the building. The office data point with the lowest value of carbon is that noted as being off trend in both the area and cost data of **Figs. 1 and 3**.

The data on the embodied carbon of the structural components (substructure and superstructure) is available for approx. one third of the data points used. The normalised available structure data is shown in white on **Fig. 4**. The data provided is heavily skewed towards office buildings, with little structure data provided for other types of building.

Figure 5 shows the variation in normalised data with building GFA. The lowest-area buildings are associated with the greatest variation in carbon footprint. The data indicates an increase in carbon for the two largest buildings; however, these are associated with large substructures on the station and a tall building in the mixed-use category – neither is representative of a typical building.

Figure 6 shows the variation in normalised data with building height. The data confirms that there is an increase in carbon with height, but that other factors have a larger influence as the biggest range per square metre in carbon values is at lower-storey heights. The theoretical structure-only capital carbon data for buildings with height, given by Nadoushani and Akbarnezhad[7], is also shown on the figure and appears to give a lower bound to the data. It is also noted that the carbon content of the 10–20-storey buildings rises more steeply than this limit. Further research on the effects of increased height and carbon footprints is required.

Figure 7 shows the variation in normalised capital carbon data with the building capital cost. The data indicates an increase in carbon with increasing cost and a plateauing of normalised carbon for the higher-cost buildings.

Summary and conclusions

In this article, the capital carbon data of building projects of various types, size, height and cost was used. The data in the database was of variable quality, and many datasets were not used due to

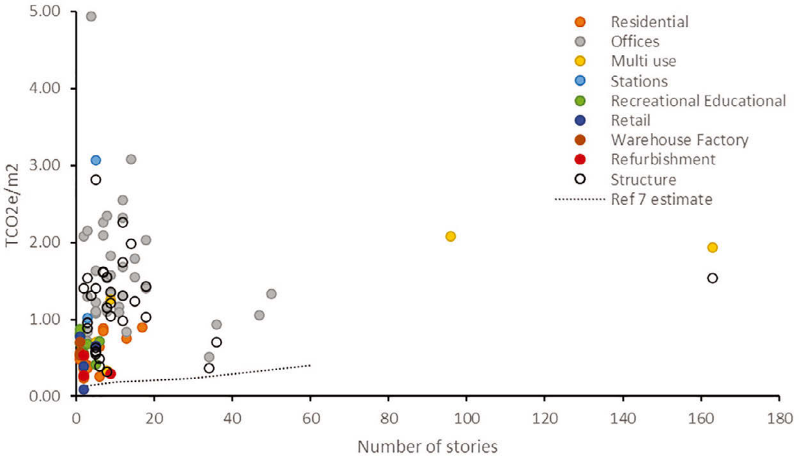


FIGURE 6: Normalised capital carbon content of building (tCO$_2$e/m^2) with number of storeys for various building types

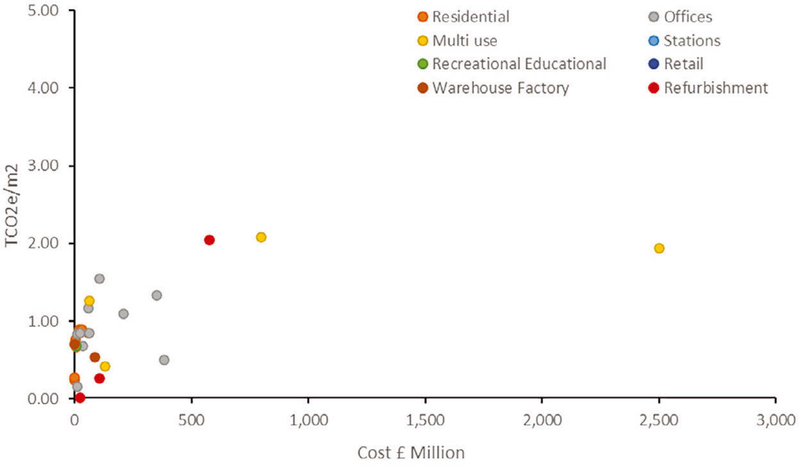


FIGURE 7: Normalised capital carbon content of building (tCO$_2$e/m^2) with capital cost (£M)

issues of reliability. Only one third of the datasets contained usable information on the structural embodied carbon; only one quarter had associated cost data. The author would urge those inputting data into a database to ensure all the subsections within the database are completed.

There is a clear positive correlation between carbon content and building area **(Fig. 1)**; hence, reducing or optimising the area of a building will reduce carbon. The largest variation in the carbon data occurs on smaller buildings **(Fig. 5)**.

There is some correlation of carbon content with building height **(Figs. 2 and 6)**, but this is not as strong as the carbon–area correlation. Further research on the relationship with height is recommended.

There is a positive correlation between carbon content and cost **(Fig. 3)**; however, this has significant variation. The higher normalised carbon tends to be associated with larger buildings **(Fig. 7)**. To achieve net zero, the relationship between embodied carbon of buildings and cost must be changed and the CEI reduced, to give a lower amount of carbon per unit of cost.

The data in **Figs. 1–7** can be used to benchmark current designs against past practice. In order to progress towards net zero, our future buildings should be trending below the current data.

The carbon for the smaller refurbishment, residential, recreation and educational, warehouse and factory, and retail projects tended to be similar to published theoretical studies. The larger multi-use offices and station buildings tended to have higher values than those reported in previous studies; more consideration of capital carbon should be taken for large buildings in these categories.

Refurbishment projects consistently show lower carbon and have low CEI, indicating that more refurbishment rather than new-build is a way of helping the government achieve its net-zero commitment.

HAVE YOUR SAY

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