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Embodied Carbon Assessment of Roofing (ECAR) Components

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Abstract

Roof is a unique building enclosure element due to its extreme environmental exposures and impact on whole building energy consumption. The roofing components affect the long-term environmental impact of the building. Embodied carbon of roofing component can be defined as the CO2 or GHG emission associated with extraction, manufacturing, transporting, installing, maintaining and disposing of roofing materials. Embodied carbon assessments of roofing (ECAR) draw on principles and methods from the field of life cycle assessment (LCA) to quantify the combined carbon emissions of each of these life cycle stages. The LCA assesses multiple environmental impacts across the full life cycle, whereas the ECAR focuses on a single impact category (e.g., global warming potential (GWP)) and applies a reduced scope (e.g., omitting the operational carbon). Furthermore, because of the roofing structure and assembly as well as the range of materials used whether in commercial or residential sectors, it is common to rely on collected data for the carbon emissions for each key component and processes using energy. This brief review states the current science related to the ECAR, points out the challenges and limitations of embodied carbon assessments and explains the data source of the ECAR research.

Keywords: Environmental exposures; Embodied carbon assessment; Global warming potential; Greenhouse gases; Roofing production; Generic carbon factors

Embodied Carbon Assessment

Embodied carbon assessment draws on techniques in the field of LCA. LCA of Roofing (LCAR) is a quantitative approach to describe and manage the environmental impacts of a roofing components across its entire life cycle through production, use, end-of-life treatment, recycling and final disposal. Thus, the LCAR indicates the multiple impact assessed from "cradle to grave" of roofing components. Meanwhile, the life cycle carbon assessments of roofing (LCCAR) determine the global warming potential (GWP) evaluated across full life cycle of roofing products. LCCAR focuses on GWP or carbon due in part to the emphasis on carbon emissions in environmental legislation. GWP is driven by emissions of greenhouse gases (GHGs) produced from human activities. The GWP of greenhouse gases is measured relative to CO_2, using the unit of carbon dioxide equivalent or CO2e. For example, each kilogram of methane released into the atmosphere due to roofing production is estimated to have the equivalent GWP of 25 kilograms of carbon dioxide. Hence carbon factors which account for multiple greenhouse gases are reported in units of carbon dioxide equivalent, CO2e (IPCC, 2015).

The embodied carbon assessment of roofing (ECAR) also focuses on GWP but only on a single impact category across partial life-cycle such as one component production processes. Therefore, the difference between LCCAR and ECAR is whether to assess the impact of GWP across the full life cycle (LCCAR) or only on a partial life cycle of the processes (ECAR). Figure 1 shows how ECAR fits into the broader field of LCAR and LCCAR.

There are three main methods to conduct ECAR:

a) Process analysis (PA);

b) Environmentally extended input-output analysis (EEIOA);

c) Hybrid of process analysis (HPA).

Process analysis (PA)

PA is a bottom-up method, which has been developed to understand the carbon emission/embodied carbon of individual products. The method involves defining a product system with a boundary and creating an inventory of all the inputs and outputs between that product system and the environment. These flows can be materials or energy, and once the inventory has been established, the embodied carbon of each item in the inventory is evaluated. Here the focus is only on material level of roofing assemblies.

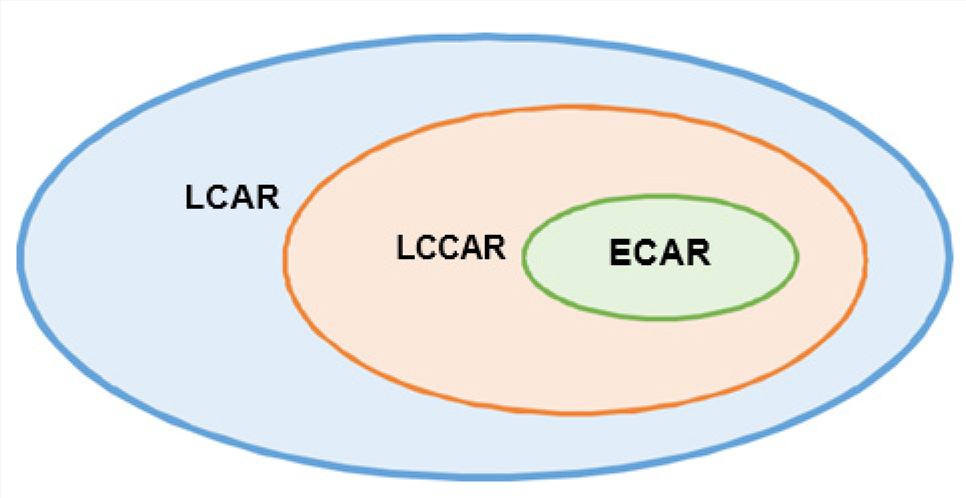

Figure 1: The interaction between LCAR, LCCAR, and ECAR.

Environmentally extended input-output analysis (EEIOA)

EEIOA is a top down approach, in that it uses macro-economic data (national or regional input-output tables) as the basis for assessing the environmental impact of a product. Input-output tables 'summarise economic transactions between sectors of an economy'. By assigning environmental impacts such as carbon emissions to the economic flows from each sector. Thus, it is possible to estimate the total impacts of an output from any given sector. EEIOA methods are most suitable for high level assessment such as when considering emissions at a sector or national level, thus it disregards the level of detail required to discriminate between the impacts of individual products or components. The reason for this is that economic input-output (IO) data is highly aggregated.

Hybrid of process analysis (HPA)

The hybrid assessment combines the data from EEIOA models with the data from process analysis (PA). However, recent research has called into question the accuracy of hybrid assessment methods, suggesting that the high levels of aggregation in EEIOA models may lead to significant overestimation of the outcomes (Yang et al., 2017).

Accordingly, of the three methods, process analysis (PA) is to be most commonly applied to conduct the Embodied carbon assessments of roofing. This may reflect the fact that this is the method adopted in LCAR standards and the data and tools to conduct process analysis of buildings are more widely available than for EEIOA or HPA (Moncaster and Song, 2012).

Challenges and Limitation of Embodied Carbon Assessment

Embodied carbon assessment is subject to theoretical, methodological and practical limitations:

Theoretical

a) Emissions associated with a particular material or product may occur at different times; often decades and possibly even centuries apart.

b) Emissions of all greenhouse gases must be converted into a common metric to allow comparison.

Methodological and practical

a) Production processes are complex and subject to many variations including sources of raw material, production volumes, batching and etc. Thus data are based on averages.

b) Many production processes result in two or more co-products and emissions from the process should then be assigned to each product in some meaningful way to avoid double counting.

c) Unless the assessment is conducted retrospectively, at the end of the building life cycle, assumptions must be made about future life cycle stages in order to account for all relevant emissions.

d) Data collection can be very resource intensive, meaning simplifications may be necessary such as the use of secondary and proxy data or estimates; the exclusion from the study of certain parts of the building, or stages in the building life cycle; and the use of cut-off criteria to exclude those materials or processes deemed to contribute less than a specified threshold value.

e) The opportunity to reduce embodied carbon is greatest in the early stages of design when the precise nature and quantum of different material inputs are uncertain.

However, there are several data sources that should be carefully investigated as follows.

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ECAR Data Sources

An embodied carbon assessment of a roofing requires two sets of data:

I. **Inputs to and outputs from the roofing:** For process analysis, these take the form of physical quantities of materials and energy at each life cycle stage. For EEIOA method, these data are estimated based on economic transactions between sectors. However, when the focus is only on the material level, these data is better to be collected from manufacturers or tested in the lab.

II. **The corresponding carbon factors for each of the roofing processes:** Carbon factors provide an estimate of the total global warming potential (GWP) of all greenhouse gas emissions associated with the production, use and disposal of a given unit of material or the consumption of a unit of fuel or electricity to produce roofing components for commercial or residential purposes.

Carbon factors

For materials, carbon factors are typically reported in either mass or volumetric terms with units of kgCO2e per kg (or tonne) or per cubic meter (or other appropriate volumetric unit) of material (Hammond & Jones, 2011). For energy, carbon factors are reported either per mega. Joule or KWh of electricity, or per physical unit of fuel consumed (e.g., litres) (Department for Environment, Food and Rural Affairs, 2015). As for roofing embodied carbon assessments, one can use the secondary sources of carbon factor data since producing or obtaining primary data would be too resource intensive (G. J. Treloar et al., 2000). A variety of different sources of data exists including:

a) Literature derived carbon factors

These sources provide generic carbon factors for a range of materials that have been derived by literature review. The methods used to determine a single value from the range of values in the literature vary between the different datasets. The secondary data that they draw on include peer-reviewed, academic work as well as data from industry and trade associations or specific companies with regard to roofing components production, use, assembly, and waste managing/cycling.

b) Industry data

Data that comes from industry bodies or individual companies is released in the form of Environmental Product Declarations (EPD) – e.g., carbon factors provided by a product supplier or industry body. However, there are examples of non-EPD data from industry for a range of materials. The World Steel Association produces an extensive set of Life Cycle Inventory (LCI) data for steel which is freely available for non-commercial use (World Steel Association, 2011).

c) Government data

Government data are typically based on national inventories or statistics meaning they are representative of typical carbon emissions for materials or activities in a given country. Examples of the use of Government data in embodied carbon assessments of roofing included assessing emissions from electricity and fuel consumption at different stages of the life cycle (Darby, 2014). There are also examples of Government data sources for full LCA inventories of materials, such as the US Life Cycle Inventory Database (Azari-N & Kim, 2012). Moreover, when EEIO or hybrid assessments are conducted, the input-output data are generally derived from Government sources.

d) Factor from a commercial LCA database

Commercial LCA packages comprise a software interface for conducting assessments and one or more databases of life cycle inventory (LCI) and impact assessment data. LCI data are the basic flows of materials and energy into and out of a product system. The LCI assessment data are used to determine the potential environmental impact of each of these flows.

Accordingly, the data quality needs to be assessed such as the empirical reliability of the data, the robustness of data acquisition methods, and the level of data validation. The use of the data quality matrix involves scoring each data source against the predetermined data quality criteria on roofing materials in different sector whether commercial or residential.

Material quantities

In addition to carbon factor data, an embodied carbon assessment requires data on the quantities of material used to construct roofing components, and the fuels or electricity used in the assembly and demolition. When an assessment is conducted during the design stage of a roofing assembly (residential, commercial, or vegetation roofing), materials quantities are estimated from the design drawings and documents whilst energy used in construction and demolition must be estimated.

For instance, first it is necessary to obtain material quantities for the roofing assemblies. Then, fuel or electricity consumption needs to be accounted for in the carbon factors for the relevant life cycle stage for each material. Equation 1 is adapted from Richardson et al. (2014) calculating embodied carbon and/or energy for a roofing material. This equation represents embodied carbon of initial roofing construction, embodied carbon of subsequent refurbishment, and embodied carbon of demolition respectively. The ECR refers to embodied carbon of the roofing from cradle-to-grave:

$$ECR = \left(\sum RM_i CF_{RMi} + RE_C CF_{\mathrm{R}EC}\right) + \left(\sum RM_i CF_{RMi}\left[\left(\frac{L_R}{L_{RM}}\right) - 1\right]\right) + \left(E_D CF_{ED}\right)$$

Where:

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RM_i is the quantity of roofing material I;

CF_{RMi} is the carbon factor of material i per unit;

RE_C is the roofing construction energy requirement;

CF_{REC} is the carbon factor of the roofing construction energy;

L_R is the assumed service life of the roofing in years;

L_{RM} is the assumed service life of roofing components/materials in years;

E_D is the energy requirements for demolition;

CF_{ED} is the carbon factor of the demolition energy.

Using building information modelling (BIM)

The process of extracting material quantities from design documentation is known as a quantity takeoff (QTO). Traditionally this has been conducted for the purposes of cost estimation and was a manual process of visualisation and taking scaled measurements from two dimensional technical drawings. The development of BIM is seen as a further opportunity to improve the efficiency of QTO processes (Cheung et al., 2012; Sattineni & Bradford, 2011).

Potential advantages of adopting BIM processes have been discussed and reviewed by academics, practitioners and policy makers. Commonly cited benefits include capital and operational cost savings, efficiency improvements, and increased profitability in the design and delivery of roofing assemblies (McGraw Hill Construction, 2014). Factors that are important for effective implementation of BIM for embodied carbon assessment of roofing components are ease of use and real-time appraisal.

The ease of use directly affect the amount of time required to conduct an assessment. Real-time appraisal means that the effects of different design changes on the embodied carbon of the roofing assembly can be evaluated as the design is being developed. This also ensures an efficient workflow, since the causal link between design changes and negative or positive effects on the embodied carbon results can be more readily appreciated. Thus, embodied carbon impacts can be addressed before the design progresses and changes become more difficult.

Creating a link between the BIM data and the carbon factor data in order to prevent or minimise the amount of data re-entry and evaluating how suitable typical BIM models currently are for this application are both key areas that require further investigation.

The use of a BIM integrated approach to conducting embodied carbon assessments may improve their efficiency. Moreover, if assessments can be conducted in near real-time during the design, then BIM can facilitate more effective decision making to reduce embodied carbon. However, the use of BIM in this way does not address some of the limitations of current methods. These limitations cause uncertainty about the embodied carbon results for the roofing. They also lead to uncertainty about the reliability of comparative assessments of the embodied carbon effects of different design options [1-18].

Summary of Key Outcomes from Literature Review

The following key conclusions drawn from the literature:

a) Process based embodied carbon assessment methods provide valid and useful insights to quantify and reduce the impact of the built environment on climate change;

b) BIM is seen by some as a useful source of material quantity data for conducting embodied carbon assessments of roofing components;

c) Tools have been developed to exploit the data generation capabilities of BIM for the purpose embodied carbon assessments. But this approach is relatively new and how suitable BIM data are for this purpose and how best to link BIM data and carbon factor data requires further exploration;

d) However, an apparent lack of comparability of results between studies is viewed as problematic. This is generally acknowledged to be due to variations in methods and data used;

e) The availability of carbon factor data at the product level has been highlighted as a cause of variation;

f) Despite the perceived lack of comparability and the acknowledgement of uncertainty about the outcomes of embodied carbon assessments, formal uncertainty assessment was only applied in only several of studies;

g) The studies of embodied carbon of buildings where uncertainty assessments were conducted lack a comprehensive review of the relevant sources of uncertainty;

The methods applied are predominantly quantitative and where the scope of the uncertainty assessment has been restricted to selected parameters or scenarios, the justification for their selection is unclear.

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