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Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice

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ABSTRACT

Lowering the embodied carbon dioxide equivalent (embodied CO_2e) of buildings is an essential response to national and global targets for carbon reduction. Globally, construction industry is developing tools, databases and practices for measuring embodied CO_2e in buildings and recommending routes to reduction. While the TC350 developed standardized methods for the assessment of sustainability aspects in construction works and Environmental Product Declarations, there is no consensus on how this should be carried out in practice. This paper evaluates the current construction industry practice through a review of both academic and professional literature, and through focus groups and interviews with industry experts in the field. Incentives in the available building codes, standards, and benchmarks are also analysed, as are the existing methodologies, tools and datasets. The multiple data sources are used to identify the barriers to the effective measurement and reduction of embodied CO_2e in practice. This paper recommends that Governments mandate for improved data quality and support the development of a transparent and simplified methodology.

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1. Introduction and study objectives

The building sector is responsible for 40% of global energy consumption and 30% of anthropogenic greenhouse gas (GHG) emissions [1]. The life cycle energy cost and GHG impacts of individual buildings can be divided into the operational and embodied impacts. Recent innovations and regulation have helped to reduce operational impacts, but a lack of comparable methodologies, data, and regulation still hinder the reduction of the embodied impacts [2–5]. In 2011 and 2012 the European Standards Committee moved towards addressing the first of these issues in publishing the TC350 standards [5] to define the stages which should be included for the whole life cycle impact assessment of buildings. Since the publication, both industry practice and academia are moving towards more similar methodologies. Academic publications in this area have also increased rapidly over the last few years, as shown by Pomponi and Moncaster [6]. However, the authors also demonstrate that in most Life Cycle Assessments (LCA) at the building scale, still only 20–40% of the life cycle stages are included, often the production stages.

While the academic literature tends to focus on published academic case studies and approaches, the calculation of embodied carbon dioxide equivalent (embodied CO_2e) of buildings is also becoming more common within industry consultancy. However, there is very little published information on how these industry calculations are being carried out. This paper aims to address this gap, by reviewing current industry practice in embodied CO_2e calculations, and the drivers or barriers in different countries and contexts. This information is derived through qualitative methods and across a range of countries.

Section 2 explains the methodology and sources of data, which include multiple regulatory and industry documents as well as qualitative studies with industry experts. This is followed by a review of the academic literature in Section 3 and of relevant industry reports, available tools, and datasets in Section 4. An analysis of these documents and qualitative studies reveals the drivers for the calculation of embodied CO_2e in industry practice outlined in Section 5. The remaining uncertainties and barriers are discussed in Section 6. The conclusions and recommendations are given in Section 7. Embodied energy is the amount of energy consumed, while embodied CO_2e is the amount of GHG emitted, to produce a material, product or building. Note that while energy costs and GHG emissions are related they are not directly equivalent, and this paper will concentrate on the latter, using the term 'CO_2e' as short-

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hand to incorporate all GHG emissions. In practice, embodied CO_2e is also referred to as 'embodied carbon'.

2. Methodology

The methodology followed a four-stage sequential qualitative approach, combining documentary analysis, pilot study, focus groups and semi-structured interviews to develop a rich picture of current international industry practice. First a documentary analysis of the policy instruments, reports, tools and databases was used to examine the context instructing the current industry practice of measuring embodied CO_2e. These documents were identified through a web search and via the participants in the qualitative studies. They were analysed to identify commonalities and differences in industry practice in the way professionals assess embodied CO_2e in their projects, how these assessments compare with others, and what drives or enables practitioners to calculate the embodied CO_2e of buildings. An inventory of the most frequently used databases in case studies, a study of the existing regulation, and the evaluation of available benchmarks are part of this documentary analysis. The industry reports, software, datasets, and standards were evaluated to shape the context of embodied CO_2e calculation and reduction in practice.

Second, a pilot study of industry experts within the Implementing Whole Life Carbon in Buildings (IWLCiB [7]) project was used to define areas of concern and variation within practice. This was followed by six further larger scale focus groups. Table 1 illustrates the profession and company sector of the participants in the pilot study (part a) and the focus groups (part b). The participants were selected based on their expertise in embodied CO_2e of buildings. The pilot study identified variations in methods and data used and uncertainties encountered in the assessment of embodied CO_2e in industry case studies. These issues were further explored through six focus groups held as part of an Embodied Carbon and Energy Symposium at the University of Cambridge in April 2016. The focus group discussions were audio-recorded and summarized in writing. The themes of the focus groups were: embodied CO_2e calculation; what can we do in practice?; risk and uncertainty; mitigation strategies; embodied CO_2e during use phase; demolition versus refurbishment. The initial pilot study and focus groups with industry experts were used to develop a preliminary understanding of the issues and to create interview questions.

The third step in the research examined the issues which were discussed within the focus groups in greater detail, through a series of semi-structured expert interviews (Table 2), in order to develop a wider understanding of perceptions and barriers towards the implementation of measurement in industry practice. The interviews were conducted with individuals who had expertise in this area, either industry practitioners in this field, or researchers collaborating closely with industry. Participants were identified through the snowballing technique [8] using established contacts of the authors, the 2016 Embodied Carbon and Energy Symposium, and the IWLCiB project. Both a general interview guide approach and a standardised semi-structured interview were combined to ensure the same areas of information were collected, analysed and compared [9]. The 15 core questions gathered data on drivers, barriers, calculation methods, and available tools, and were supplemented with additional questions depending on the interviewee's response. The interviews lasted between 30 and 90 min. A list of the interviewees, the interviewees' roles, their company's sectors, and main countries of expertise are given in Table 2.

Fig. 1 shows the roles of the participants to the pilot study, focus groups and interviews within the construction industry. All participants were offered anonymity. The focus groups and interviews were audio-recorded and transcribed.

Table 1
Participants to pilot study (a) and to focus groups at the embodied carbon and energy symposium (b).

Profession	Company Sector
a) Pilot Study	
Head of Research	Architecture & the Environment
Senior Consultant	Carbon Consultant
b) Focus Groups	
Senior Consultant	Construction
Researcher in Engineering	Engineering
Student in Environmental Design	Environmental Building Design
Architect	Architecture
Engineer	Engineering
Student in Engineering	Engineering
Sustainable design/LCA strategist	Engineering
Structural Engineer & Senior Consultant	Structural Engineering
Researcher in Engineering	Engineering
Monitoring officer and Assessor	NGO
Director	Architecture
Energy Consultant	Energy
Partner	Construction
Sustainability Officer	Construction
Researcher in Engineering	Engineering
Sustainability Consultant	Construction
Researcher in Engineering	Engineering
Partner	Management Consulting
Sustainability Analyst	Commercial Real Estate
Professor	Engineering
Professor	Engineering
Social Entrepreneur	Architecture
Principal Sustainability Consultant	Built Environment Consulting
Senior Project Consultant	Engineering
Environmental Manager	Developer
Researcher in Engineering	Engineering
Researcher in Engineering	Engineering
Director	LCA, Carbon Footprint
Student in Engineering	Engineering
Development Manager	Insurance
Structural Engineer	Structural Engineering
Researcher in Engineering	Engineering
Chartered Structural Engineer	Construction
Engineer	Structural Engineering
Researcher in Engineering	Engineering
Senior Consultant	Carbon Consulting
Lecturer in Engineering	Engineering
Student in Structures	Engineering
Lecturer	Environmental Sciences
Researcher in Engineering	Engineering
Engineer	Engineering
Architect	Architecture
Researcher in Engineering	Engineering
Sustainability Officer	Environmental Building Design
Senior Consultant	Architecture and Engineering
Senior Consultant	Carbon Consulting
Senior Engineer	Engineering
Senior Consultant	Environmental Building Design

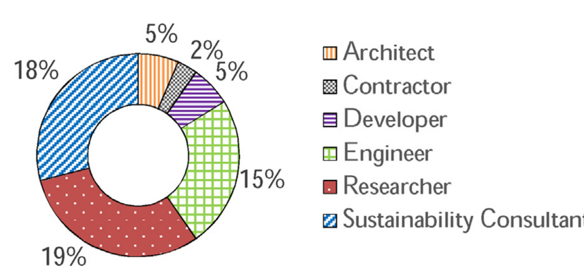

Fig. 1. The role of the participants of the pilot study, focus groups and interviews in the construction industry.

Table 2
List of interviewees (references [a] to [l] are used in the results of the paper).

Role	Company Sector	Country	
Head of Research	Architecture & the Environment	Czech Rep. (CZ)	[a]
Senior Consultant	Carbon Consultant	United Kingdom (UK)	[b]
Senior Project Consultant	Engineering	UK & United States (US)	[c]
Environmental Manager	Developer	UK	[d]
Coordinator in climate & materials	Contractor	Norway (NO)	[e]
Sustainable Business Developer	Project Developer & Contractor	Sweden (SE)	[f]
CEO Environmental Consultant	Environmental Consultancy	Australia (AU)	[g]
Associate Professor	Carbon Leadership Forum	US & Canada (CA)	[h]
Engineer Architect Researcher	Institute for Technological Research	Belgium (BE)	[i]
Engineering Sustainability Leader	Engineering & Contractor	UK & AU	[j]
Senior Structural Engineer, P.E.	Structures & Enclosure Design	US	[k]
Director of Sustainable Design	Structural, civil & traffic engineering	US, Panama (PA) & India (IN)	[l]

3. Academic literature

3.1. Published embodied energy and CO_2e results

There is a large body of academic literature available to practitioners for developing methodologies for calculating embodied CO_2e and providing benchmarks for different buildings types. An overview of general results on embodied energy (Fig. 2) and CO_2e (Fig. 3) shows the inconsistencies in data, methods and protocols used. For reference, a detailed explanation of the differences and similarities between causes of embodied CO_2e and of embodied energy are provided by Moncaster and Symons 2013 [10] in Section 3.

Cabeza et al. [11] reviewed LCA and Life Cycle Energy Analysis (LCEA) in the building sector, showing most studies look at exemplary low energy buildings rather than traditional buildings mostly found in our cities. Studies also focus on urban areas and are not equally distributed globally. Dixit et al. [12] revealed a significant variation between authors in their embodied energy results illustrating inconsistencies in the data used, coming from disparate sources and countries. This is one of several factors that lead to a wide range in values. The definitions of embodied life cycle stages also demonstrate the lack of agreement on which stages to include in assessments. Clark [13] looked at both academic and industry calculations for embodied CO_2e and obtained a wide range of results between 300 and 1650 kg_{CO2e}/m^2 from case studies of office buildings provided by various companies using different methodologies. Ding [14] reviewed previous literature on embodied energy in residential and commercial buildings with a wide variation between 3.6 and 19 GJ/m^2.

Cole and Kernan [15] were one of the first to compare the life-cycle energy use in office buildings for alternative wood, steel and concrete structural systems and found an initial embodied energy between 0.7–1.5 GJ/m^2. Eaton and Amato [16] included a pioneering study of the embodied CO_2e of steel, composite, reinforced and precast concrete office buildings, with results varying between 200 and 350 kg_{CO2e}/m^2 for the structure only and between 600 and 850 kg_{CO2e}/m^2 for the whole building. De Wolf et al. [17] gave results on the structural scale through surveying the material quantities and embodied CO_2e of 260 case studies obtained from industry. They showed that structural engineering companies mainly look at the production stage and expressed the need for more reliable and accessible datasets. Authors such as Sartori and Hestnes [2] have shown a slight increase in embodied energy for low-energy or zero (operational) energy buildings. Ramesh et al. [18] confirmed this increase in embodied energy with passive and active technologies, showing that low energy building cases performed better than zero (operational) energy buildings over their whole life. Inconsistencies are also found in different LCA software. Sinha et al. [19] compared the Swedish Environmental Load Profile tool and the commercial LCA tools GaBi and SimaPro. The results obtained from the three tools showed significant differences. They discussed in particular the lack of reliable and transparent data for the impacts related to materials and transport, and the need for data associated to the location of the project. Results for embodied energy of buildings and building structures are shown in Fig. 2 and results for embodied CO_2e are shown in Fig. 3.

3.2. Review of previous academic work on industry practice of embodied CO_2e assessment

The academic literature on the practice of embodied CO_2e measurement in industry is limited. However, several academic papers have surveyed practitioners directly to summarize the barriers to assessing embodied impacts of construction materials and buildings from a professionals' perspective. Anand and Amor [20] reviewed the use of LCA in the building industry needing research developments on comparison issues, system boundary selection procedure, standard data collection procedure, missing data, embodied energy indicator, deconstruction analysis, and implementation of dynamic LCA. Giesekam et al. [21] surveyed the views of the construction industry on low-carbon materials in the United Kingdom. Through interviews with practitioners, the study identifies the barriers to using low-carbon materials as economic, technical, practical, and cultural. Next to high costs, the conservative nature of clients, and the established practice, barriers for implementing low-carbon materials also included the lack of demonstration projects, information, knowledge, skills, and regulation. The survey participants identified assessment schemes and requirements from clients, architects, engineers or contractors as potential drivers. Ng et al. [22] interviewed senior industry practitioners in Hong Kong on the challenges of labelling CO_2e emissions of construction materials. Results showed that the large data demands, the reluctance in using alternative materials, and the limited environmental awareness were the main barriers. The interviewees recommended labels, international standards, integrated local data, and verification by an impartial and independent certification body as potential drivers. On the building scale, Fouché and Crawford [23] reviewed the Australian construction industry's approach to embodied CO_2e assessment. The study investigated which tools and databases are being used by Australian industry through a survey. The research identified the following barriers for Australian industry: the lack of local and accurate data, the inconsistent and time-consuming methodologies, the questionable boundaries, and the lack of benchmarks, though the National Standards Development Organisation (NSDO) proposed a method for assessing and declaring the comparative environmental impact of building products and systems. Davies et al. [24] used a case study of a new industrial warehouse project to highlight the view of contractors on the challenges of LCAs. The contractors identified the lack of data on the environmental impact of materials as one of the main challenges for capturing initial embodied energy, followed

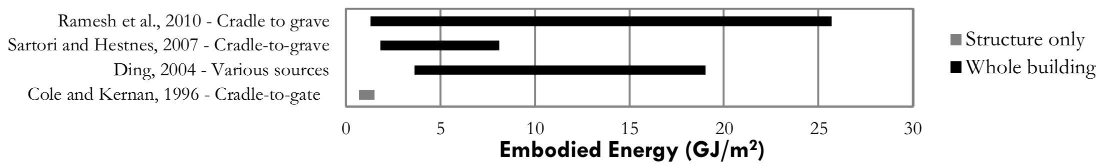

Fig. 2. Variation in the published embodied energy results.

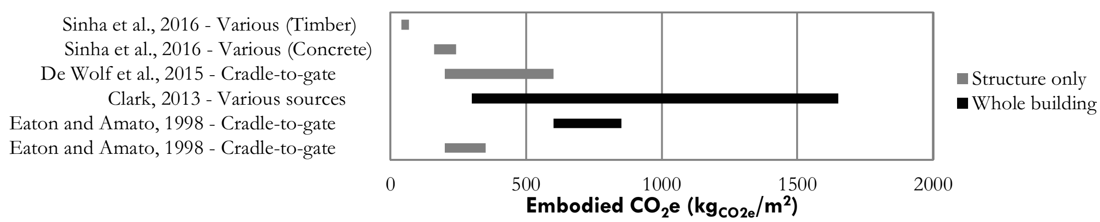

Fig. 3. Variation in the published embodied CO_2e results.

by the lack of an agreement on the terminology, the legibility, and which life cycle stages should be included. Conversely, contractors are driven by the competitive advantage to demonstrate improvements in embodied energy reduction, in order to be well positioned to influence industry standards and policy strategy.

Next to the above surveys with industry practitioners on their own views on embodied CO_2e measurement of construction materials and buildings, other papers have expressed the academic view on addressing challenges in the field of embodied CO_2e and making recommendations for industry and policy. Lützkendorf et al. [25] have given recommendations for designers and other stakeholders on incorporating embodied impacts in net-zero buildings. The cited challenges are the system boundaries concerning life cycle stages included, the inclusion of non-energy-related use of energy sources (feedstock energy), the lack of guidance to apply information from one country in another where data is not available, and the accessibility, reliability and availability of the right type of data in the appropriate format for design decision-making. The emerging Environmental Product Declaration (EPD) databases and use of Building Information Models (BIM) are opportunities to improve embodied CO_2e assessment in practice. A checklist of minimum requirements is proposed. Gavotsis and Moncaster [26] have made recommendations for industry and policy for an improved embodied energy and CO_2e accounting. The study of a low-energy school building showed a high level of uncertainty due to a lack of an industry-wide data collection method, to the uncertainties of use and end-of-life scenarios, and to a lack of published figures for EPDs of components. In the United States, Simonen [27] also points out the need for an EPD database with clear Product Category Rules (PCR) similar to the existing databases in the Netherlands, Sweden, France, Germany, Korea and Japan. Ariyaratne and Moncaster [28] showed that stand-alone calculation tools do not offer a satisfying embodied CO_2e assessment approach. Dixit et al. [29] also illustrated the need for a uniform protocol for embodied energy.

Other papers discuss methodologies. Moncaster and Symons [10] have given an overview of how calculations are carried out in the different life cycle stages according to the TC350 standards. The study identifies the need for the construction and manufacturing industries to develop improved and comprehensive data. Giordano et al. [3] analyse the mutual impact of operational and embodied impacts on residential buildings showing the lack of national and agreed embodied energy databases for building materials. Moncaster and Song [30] compare existing data and methodologies for calculating embodied impacts of buildings. Table 3 summarizes the main challenges encountered in academic literature for applying embodied CO_2e assessments in industry practice. The main issues are clearly a general lack of data and a need for a consistent methodology. Incentives are emerging EPD databases, integration in BIM, rating schemes, and policies.

4. Analysis of industry context

4.1. Industry documents

This section gives a contextual analysis of the documents, tools and databases available for calculating embodied CO_2e in industry practice. Industry papers have regularly illustrated carbon footprinting in specific case studies, rather than giving a general overview of where the industry is [31–33]. Other reports illustrate a methodology through the use of tools to calculate the greenhouse gas emissions of buildings [34]. Institutions are publishing various methodologies related to embodied CO_2e analysis, showing the growing interest of industry stakeholders (Table 4). In the key findings from the Embodied Carbon Week 2014 (UKGBC [35]), consistency in measurement and availability of comparable data were identified as key challenges. Consensus was reached that industry should take the lead and not wait for governmental regulations, especially in terms of the construction value chain in addressing embodied CO_2e. The Embodied Carbon Industry Task Force [36] therefore wrote recommendations in a proposal for a standardised measurement method and for zero carbon building regulations and allowable solutions. This collaborative effort of professionals in the United Kingdom proposes minimum reporting requirements for practitioners to follow, based on the life cycles stages defined in the European standards. The practitioners agreed to report to the database of the Waste Reduction Action Program (WRAP [37]). WRAP works with companies, researchers and the construction community to achieve a circular economy. Therefore, they created an embodied CO_2e database for buildings where practitioners and researchers can explore embodied CO_2e calculations for buildings at different project stages. It is an interactive database to which engineers and architects can add their completed calculations and help to develop a detailed comparative dataset in the aim to develop benchmarks at the building scale. The creation of a national database for emission factors is also recommended. Separately the Royal Institution of Chartered Surveyors (RICS [38]) published an information paper laying out the methodology to calculate the embodied CO_2e of materials and buildings. Applying this methodology to 53 case studies using the Atkins Carbon Critical Masterplanning tool presented results between 395 and 3250 kg_{CO2e}/m^2. Other similar initiatives have been taking place in other parts of the world.

Table 3
Challenges for embodied CO_2e calculation in industry practice from academic literature.

	Anand & Amor [20]	Ariyaratne & Mon-caster [28]	Clark [13]	Cole Kernan [15]	Davies et al. [24]	De Wolf et al. [17]	Ding [14]	Dixit et al. [12]	Eaton & Amato [16]	Gavotsis & Mon-caster [26]	Giesekam et al. [21]	Giordano et al. [3]	Lützkendorf et al. [25]	Moncaster and Song [30]	Moncaster & Symons [10]	Ng et al. [22]	Ramesh et al. [18]	Sartori and Hes-tnes [2]	Simonen [27]	Sinha et al. [19]
Poor availability of data	✓	✓	✓		✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
• Need for EPD databases																				
• Geographic variation																				
• Aged or incomplete data																				
• Accessibility & reliability																				
Life cycle stages & uncertainties	✓		✓	✓	✓			✓		✓			✓		✓	✓	✓	✓		
Building layers: structure vs. all			✓			✓		✓	✓										✓	✓
Lack of benchmarks	✓		✓			✓	✓	✓	✓									✓	✓	✓
Method consistency/transparency	✓	✓			✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Knowledge dissemination	✓	✓	✓			✓	✓			✓	✓					✓				✓

The Low Carbon Construction Innovation & Growth Team (LCCIGT [39]) produced a report analysing if the construction industry is fit for purpose for the transition to a low-carbon economy in terms of housing, non-domestic buildings and infrastructure. They identified barriers such as the need for clear leadership and co-operation, the complexity and confusing language, the absence of a transparent plan, the need for a reform of industry structure, the demand for skills, and the need for incentives and funding. The British Council for Offices (BCO [40]) explained whole-life carbon footprint measurements in offices for building owners, contractors or real estate companies. The benchmarks offered in the report range between 5500 and 8500 kg_{CO2e}/m^2 or between 80,000 and 12,000 kg_{CO2e}/person. The RICS Research report on redefining zero illustrates carbon profiling as a solution to whole life CO_2e emission measurement in buildings, including both operational and embodied CO_2e resulting in 85 $kg_{CO2e}/(m^2\ year)$ for a notional building case study [41]. The American Institute of Architects (AIA [42]) published a guide to help practitioners in the United States with the LCA of buildings. Various European countries including Norway, Sweden, Germany and the Netherlands have been involved in similar efforts.

4.2. Tools

Several Life Cycle Inventory (LCI) and LCA tools exist to calculate impacts of single projects or materials. Kieran Timberlake and PE International released the Tally tool [43], which extracts data from Revit models to calculate embodied impacts. In Canada and the United States, the Athena Institute has integrated Life Cycle Inventory (LCI) data into two building industry specific tools: the Athena Eco Calculator (free) and the Athena Impact Estimator [44]. In Belgium, the MMG [45] tool calculates the LCA of an entire building. In the Czech Republic, the SBtoolCZ [46] calculates the annualized embodied CO_2e per year per floor area, expressed in $kg_{CO2e}/(m^2\ year)$. The SOM Environmental Analysis tool estimates the embodied CO_2e of design projects [47]. The Atkins Carbon Critical Masterplanning tool calculates the embodied CO_2e of existing buildings [38]. The National Institute of Standards and Technology (NIST) in the United States developed Building for Environmental and Economic Sustainability (BEES [48]). The Environment Agency in the United Kingdom also developed a carbon calculator for materials, transportation, site energy and waste management [49]. PE International developed the commercial LCA software GaBi [50], and the Centre of Environmental Science of Leiden University (CML) developed SimaPro [51]. OpenLCA [52] is an open-source software that helps users perform LCAs of buildings. NovaEQUER [53] uses EcoInvent [54] data in a simplified LCA tool. Multiple other LCA tools exist including but not limited to the Carbon Calculations over the Life Cycle of Industrial Activities tool (CCaLC Tool) using EcoInvent data, Eco-Bat 2.1, Global Emissions Model for integrated Systems (GEMIS), LEGEP, LTE OGIP, Qantis suite, SankeyEditor, Bousted Model, and Umberto [55], some also developed a corresponding database.

However, most tools are not transparent, up to date, open-source and adapted to the needs of architects and engineers. Therefore, leading structural design and architecture firms, such as Thornton Tomasetti [56] and SOM [47], have started to develop their own in-house embodied CO_2e assessment tool. However, in order to compare with competitors, a uniform methodology is needed. Over 260 existing buildings were collected in the Database for Embodied Quantity Outputs (deQo), developed at MIT in collaboration with Arup and Thornton Tomasetti [57].

Table 4
Comparison and assessment of methodologies published by various institutions.

Institution	Report	Methodology	Boundaries	Benchmarks
UKGBC [35]	Embodied Carbon Week	Data & method improvements	Cradle to grave	Refer to WRAP
EC Industry Task Force [36]	Recommendations	Standards & regulation	Cradle to gate/site/grave	Reporting requirements
WRAP [37]	Embodied carbon database	Building data collection	Cradle to gate/site/grave	Scattered data
RICS [38]	Information paper	Based on EPDs & Atkins	Cradle to gate	395–3250 kg_{CO2e}/m^2
LCCIGT [39]	Low Carbon Construction	Engagement of industry	Cradle to site	None
BCO [40]	Whole-life Carbon in Offices	Explain all life cycle stages	Cradle to grave	5500–8500 kg_{CO2e}/m^2
RICS [41]	Carbon Profiling	Embodied & Operational	Cradle to grave	85 $kg_{CO2e}/(m^2$ year)
AIA [42]	Guide to building LCA	LCA on building scale	Cradle to gate/site/grave	Developing

Table 5
Non-exhaustive summary of the available ECCs globally (*I/O = Input/Output).

	EEC	ECC	LCA	Method	Boundaries	Region	Free
Industry data reports							
Inventory of Carbon and Energy (ICE)	√	√		Literature	Cradle to gate	UK	√
Structure and Carbon (Carbon working group)		√		Engineering	Cradle to gate	US	√
Hutchins UK Building Blackbook		√		Economic I/O LCA	Cradle to gate	UK	
WBCSD on cement		√		Manufacturing	Cradle to gate	World	√
NRMCA on concrete		√	√	Manufacturing	Cradle to gate	US	
World Steel		√	√	Manufacturing	Cradle to gate	World	
CORRIM on timber		√	√	Manufacturing	Cradle to gate	US	
Software and tools							
Carbon Calculator Environmental Agency		√		Economic I/O LCA	Cradle to gate	UK	√
BEES	√	√	√	Economic I/O LCA	Cradle to gate	US	√
Athena Sustainable Materials (North America)		√	√	Process LCA	Cradle to gate/grave	N. America	√
CCaLC Tool		√	√	Process LCA	Cradle to gate/grave	UK	√
GaBi		√	√	Process LCA	Cradle to grave	Germany	
GEMIS		√	√	Process LCA	Cradle to gate	Germany	
LEGEP Software GmbH		√	√	Process LCA	Cradle to gate	Germany	
LTE OGIP		√	√	Process LCA	Cradle to gate	Germany	
Sankey Editor	√		√	Economic I/O* LCA	Cradle to grave	Germany	
Umberto		√	√	Process LCA	Cradle to grave	Germany	
SimaPro & OpenLCA		√	√	Process LCA	Cradle to grave	Netherlands	
OpenLCA		√	√	Process LCA	Cradle to grave	Netherlands	√
EQUER and novaEQUER		√	√	Process LCA	Cradle to grave	France	
Qantis suite		√	√	Process LCA	Cradle to gate	France	
Eco-Bat 2.1		√	√	Process LCA	Cradle to grave	Switzerland	
Bousted Model	√		√	Process LCA	Cradle to grave	UK	
Databases							
European Life Cycle Database (ELCD)		√	√	EPD	Cradle to gate	Europe	√
US LCI		√	√	EPD	Cradle to gate	US	√
Quartz		√	√	Literature	Cradle to gate	US	√
IVL Swedish Environmental Research Institute		√	√	EPD	Cradle to gate	Sweden	√
EcoInvent		√	√	LCIA	Cradle to gate	Switzerland	
Oekobaudat.de (German National Database)		√	√	EPD	Cradle to gate	Germany	√
Milieudatabase.nl (Dutch National Database)		√	√	EPD	Cradle to gate	Netherlands	√
INIES (French National Database)		√	√	EPD	Cradle to gate	France	√
IVAM		√		EPD	Cradle to gate	Netherlands	
EPD database BBRI (Belgian National Database)		√	√	EPD	Cradle to gate	Belgium	
AusLCI, BPLCI, etc.		√	√	EPD	Cradle to gate	Australia	√
New Zealand building materials embodied energy	√			EPD	Cradle to gate	NZ	√

4.3. Data and databases

One of the key data requirements to assess embodied CO_2e of buildings is the emissions coefficient of the materials and components. As the major material use tends to be within the structure, the CO_2e and energy impacts of structural materials is an important concern. Various reports have analysed the environmental impact of concrete [58,59] and cement [60,61]. Other articles describe the embodied impacts of metals [62] and in particular steel [63,64]. Next to concrete and steel, impacts of other construction materials such as timber have been discussed [65,66]. However, there is a substantial variability in the results.

In the United Kingdom, the open-source Inventory of Carbon and Energy (ICE) database from the University of Bath summarizes Embodied Energy Coefficients (EEC) and Embodied Carbon Coefficients (ECC) for most common construction materials (Hammond and Jones [67]). The Hutchins UK Building Blackbook [68] also reports ECCs of materials. However, there is still a need for updated values per country or region, as both databases are specific for the United Kingdom and have not been updated since 2011. In the United States, Quartz [69] is collecting environmental impact data of common products and materials. The National Renewable Energy Laboratory (NREL) and its partners have also developed a general US energy and material flows database, based on an input-output economic model (US LCI [70]). The Carbon Working Group (Webster et al. [71]) discusses the ECC of common construction materials and its uncertainty, data quality and variability. EcoInvent [54] provides thousands of LCI datasets in Switzerland and globally.

The Netherlands (milieudatabase.nl [72]), Belgium (EPD Database [73]), France (INIES [74]) and Germany (oekobaudat.de [75]) offer open-access national databases of their construction materials. The Netherlands also has a licensed database (IVAM [76]). In Sweden, the IVL Swedish Environmental Research Insti-

Table 6
Example of DEFRA factors for transport after [87].

Transportation Mode	Factor	Unit
AirFreight: Short-haul international	2.31277	kg_{CO2e}/tkm
AirFreight: Long-haul international	1.27944	kg_{CO2e}/tkm
RailFreight: Diesel/Electric	0.02601	kg_{CO2e}/tkm
RoadFreight: Rigid – >3.5–7.5t	0.55731	kg_{CO2e}/tkm
RoadFreight: Rigid – >7.5–17t	0.36024	kg_{CO2e}/tkm
RoadFreight: Rigid – >17t	0.17398	kg_{CO2e}/tkm
ShipFreight: General cargo	0.013155	kg_{CO2e}/tkm

Table 7
Example of WRAP Net Waste Tool factors for construction after [88].

Construction Area Factor	50	kg_{CO2e}/m^2
Construction Cost Factor	1400	kg_{CO2e}/£100k spent

tute (IVL [77]) provides ECCs. In Australia, major trade associations of concrete, timber, windows, etc. also included their data in the open-access Building Product Life Cycle Inventory database (BPLCI [78]) between 2007 and 2011. Robati and al. [79] mention four other LCI databases available in Australia: eTool [80], BPIC [81], Crawford [82], and AusLCI [83]. The latter is the pre-eminent LCI database in the country. In New Zealand, Alcorn [84] at the Victoria University of Wellington has developed a building materials embodied energy database. The Joint Research Centre (JRC) from the European Commission offers the European reference Life Cycle Database (ELCD [85]) with LCI data from business associations in the European Union.

A non-exhaustive summary of industry data reports, available software and databases is given in Table 5, based on the response of the participants in the qualitative studies. Furthermore, many companies developed in-house databases, based on a combination of these databases. Reports and journal papers have highlighted the urgent need for a standardized database for the environmental impact of building materials in industry [86].

Next to the production stages, two further stages commonly included in the calculation are the impacts of transport to site, and of the construction work itself. There is very limited published information generally available for either stage, with both being highly context- and project- dependant. For the transport stage, the UK Department for Environment Food & Rural Affairs (DEFRA [87]) offers factors, expressed in kg_{CO2e}/(kg km), for different transportation modes such as air, rail, road, and sea (Table 6). For the construction stage, the WRAP Net Waste Tool [88] offers construction emissions factors expressed per floor area of the building (kg_{CO2e}/m^2) and per cost of the building (kg_{CO2e}/£), as illustrated in Table 7.

For the use stages (B) and the end-of-life stages (C), little data is available to practitioners, both highly dependent on the assessor's assumptions for the scenarios of the rest of the building's life cycle. An important question for the replacement of building components is their different lifespans [i]. The life expectancy of building components is described by the RICS NRM 3 (BCIS [89]) and in the CIBSE Guide [90]. Moreover, grid decarbonisation can be taken into account and influence the use stage and end-of-life stage results. In the United Kingdom, DEFRA [87] offers electricity conversion factors for the slow progression scenario. In optimist countries, a linear decarbonisation is assumed to zero in 2050 in line with the European Union targets [e]. For the end-of-life scenarios, the Wrap Net Waste tool [88] gives guidelines on waste percentages. For these scenario predictions, official national statistics of end-of-life treatment for different types of wastes for recorded years are combined with data describing these processes, for example sourced from EcoInvent, and analysed in SimaPro.

Finally, there is a lack of consensus on how to integrate the benefits and loads of reuse-, recycling and recovery potentials (module D) into the whole life cycle assessments. The JRC developed formulae to calculate net benefits. The 50-50 formula, used by the Product Environmental Footprinting (PEF) method [91], allocates 50% of, for example, recycling impacts to the previous system and 50% to the next [i].

5. Drivers and enablers

This section evaluates the drivers and enablers for calculating the embodied CO_2e through the available regulations, benchmarks, and other incentives worldwide.

5.1. Regulation

While there is little conformity in the data and methodologies used in practice, there has been considerable work over the last few years to develop norms, standards and guidelines. The International Organization for Standardization (ISO [4]) includes life cycle thinking in ISO 14001, describes LCA and the life cycle stages of buildings in ISO 14040 and ISO 14044, and explains EPDs for building construction in ISO 21930. Meanwhile the European Standards Technical Committee CEN TC350 (Sustainability of Construction Works) has defined the assessment of buildings in EN 15643, the calculation method for the assessment of environmental performance of buildings in EN 15978, and the PCRs for EPDs of construction products in EN 15804. These norms are also available in the national standards of European member states, including the British Standards.

The TC350 standards use LCA to define the 'cradle to grave' impact of buildings [10] and civil engineering works [92], as illustrated in Fig. 4. The product stage includes raw material supply (A1), transport of materials from extraction to manufacturing site (A2), and manufacturing itself (A3). The construction process stage is divided in the transport from gate to site (A4) and the construction-installation process (A5). The use stage includes the impacts arising from anticipated conditions of use of components (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5). The operational energy use (B6) and operational water use (B7) are excluded from the embodied CO_2e assessment, but are part of the whole life CO_2e calculations. The end-of-life stage comprises deconstruction and demolition (C1), transport to landfill, incineration or recycling facilities (C2), waste processing (C3) and disposal (C4). Beyond these life cycle stages, potential benefits and loads of reuse, recovery, or recycling (D) can be taken into account. According to EN 15978, the data should be as recent as possible and should be checked with the rules of EN 15804 [5]. The data should also be geographically coherent with the location of the production, which is rarely the case. For example, the ICE database [67], which was mainly developed for common construction materials in the United Kingdom, is used in other parts of the world. Data also need to correspond to the system boundaries set for the assessment. Ciroth et al. [93] developed the uncertainty factors for the pedigree or data quality matrix to assess the data quality for LCI. Generally, there is a shortage in sensitivity and uncertainty analyses in industry. The most performed data quality assessment in current practice, if any, is to cross-reference with other sources and validating with other projects previously calculated [b]. For a greater transparency, the type of source (EPDs, scientific papers, ICE database, etc.) should be listed for each part of the calculation.

Publicly Available Specifications (PAS2050 [94]) include life cycle GHG emissions of goods and services. The Institute for Environment and Sustainability in the European Commission's Joint Research Centre (JRC) created the International Reference Life

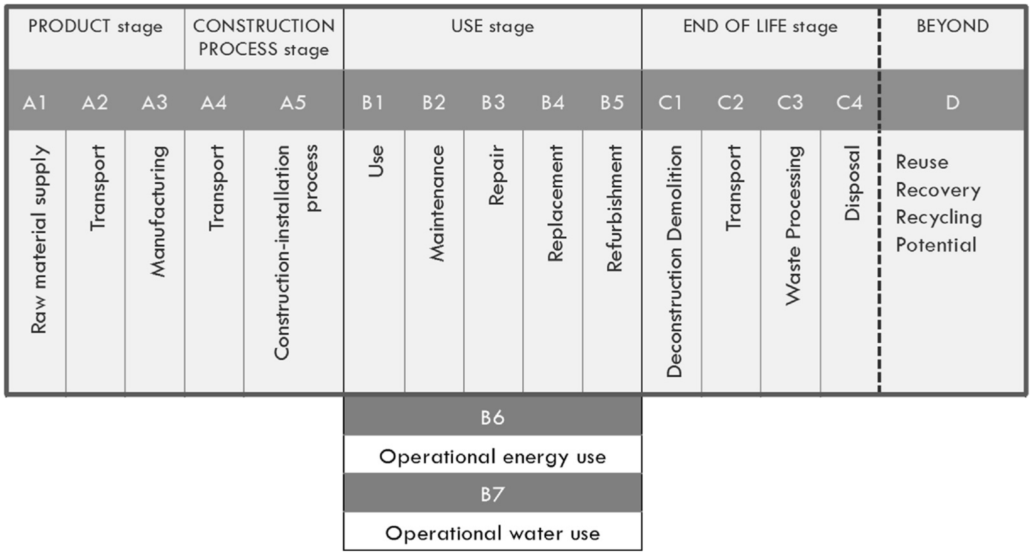

Fig. 4. Life cycles defined by EN 15978, adapted from [10].

Cycle Data System (ILCD [95]) Handbook to provide more detailed instructions on LCA, as well as the PEF method [91].

5.2. Benchmarks

Engineers and architects in the qualitative studies agreed that there was a problem of a lack of benchmarking for embodied CO_2e in buildings [c, i, h], though several countries started collecting data towards this goal. While studies at the structural and the building scale have attempted to give ranges of the embodied CO_2e of different building types (RICS [38], De Wolf et al. [17], WRAP [37]). However, the scarcity and scattering of the datapoints, as well as a lack of uncertainty analysis and transparency prevents the defintion of clear benchmarks. This appears to be a problem across all the nations represented:

> "Not any [benchmarks are available]. Individual publications on various building types were published but they all use different methodologies and different datasets, making it difficult to compare them to each other." *CEO, Environmental Consultancy in Australia [g]*

All interviewees when asked commented that there was a lack of national, reliable and comparable benchmarks. If any baselines are available, they are isolated case studies using different methods and databases. This prevents comparing their own results and identifying low, medium and high impacts. On a national basis some countries have started developing tools such as databases of EPDs and of buildings data (e.g. the voluntary WRAP [37] Embodied Carbon Database in the United Kingdom), but there is still a lack of global, reliable and comparable benchmarks of embodied CO_2e in buildings.

5.3. Incentives in different countries

No policies in any of the countries who participated yet provide formal incentives for calculating embodied CO_2e., other than the Netherlands who require the calculation, although not the reduction, within the Building Regulations. However, many companies do engage in embodied CO_2e assessment, and decide to do so in prospect of future regulations and rating advantages. These industry leaders commit to various carbon targets including the Science Based Targets [96], the Dow Jones Sustainability World Index [97], GRESB [98], CDP [99], RE100 [100], and Structural Engineering 2050 (SE 2050 [101]). In current practice, incentives mostly rely on corporate liability and the willingness of the client.

> "The business drivers behind why we calculate embodied carbon are that we as a business have recently signed up to a carbon target. The reason why we are measuring embodied carbon is because over the coming years we will inevitably need to report it and we want to be ahead of the game." *Environmental Manager, Real Estate Investment Trust in the United Kingdom [d]*

Rating schemes including the Building Research Establishment Environmental Assessment Methodology (BREEAM [102]) and Leadership in Energy and Environmental Design (LEED [103]) also incentivize practitioners to assess the embodied CO_2e of their projects. The new development of user-friendly tools in recent years gives an incentive to architects and engineers to look at the embodied CO_2e of their designs [k, l]. A list of incentives and enablers varying by country is given in Table 8. Rating schemes are recurrent incentives, whereas the national databases are enablers for embodied CO_2e assessments.

6. Barriers and omissions

6.1. Remaining uncertainties with embodied CO_2e calculations

In spite of the incentives described in the section above, the implementation of embodied CO_2e in practice still faces numerous barriers. Through the pilot study and the following focus groups, 14 remaining uncertainties were identified (Table 9). Giesekam et al. [21] define four barriers to low-carbon materials: institutional and habitual; economic; technical and performance related; and knowledge and perceptions. The uncertainties discussed in the following sections are all related to at least one of these barriers, which succinctly summarize reasons for omissions or inconsistencies in embodied CO_2e calculation in industry.

Whilst a review on the state-of-the art of uncertainty analysis in embodied CO_2e assessments would need a paper on its own, it is crucial to highlight that uncertainty plays a role in at least two stages in the assessments. First, different sources are used with boundaries and assumptions that are not often declared, thus preventing a transparent comparison of the results which in turn further increase the uncertainty around numbers. Second, such sources are used to produce assessments which result in unique, very definite numbers with no information whatsoever on their

Table 8
Incentives in different countries according to interviewees.

Country	Drivers	Enablers
Australia	Green Star	BPLCI
Belgium	BREEAM; MMG tool	Law on EPDs for manufacturers
China/India	RE100	
Europe	RE100; EN 15978 and EN 15804	
France	HQE	INIES database
Germany	DGNB German Sustainable Building Council	oekobaudat.de
Japan	CASBEE	
Norway	BREEAM; CEEQUAL	Fremtidens byer
Sweden	Business opportunity, design criterion, costs savings	IVL
Switzerland	Minergie	EcoInvent
The Czech Republic	LEED; BREEAM; Green Light for Savings	SBToolZ
The Netherlands		milieudatabase.nl; IVAM
United Kingdom	BREEAM; sciencebasedtargets.org	ICE database
United States	LEED v4 WBLCA credit; RE100; Self-promotion	US LCI, Quartz
World	Dow Jones Sustainability World Index; GRESB; CDP	

Table 9
Remaining uncertainties divided in four categories after [21].

	Institutional Habitual	Economic	Technical Performance	Knowledge Perceptions
1. Life cycle stages included	√			
2. Life span considered	√			
3. Normalization: floor area definition (kg_{CO2e}/m^2)	√			
4. Building layers: sub/superstructure, façade, finishes, services, etc.	√			
5. Reliability of sources for ECCs				√
6. Material quantity collection: BIM, contractor, bill of quantities, etc.				√
7. Transport: (multiple) modes/distances per component vs. factor		√	√	
8. Construction: per financial cost, floor area, days, or building type		√	√	√
9. Use stages included			√	
10. Decarbonisation of the grid taken into account	√			√
11. Comparison with operational energy and water use	√			√
12. End-of-life: simplified factors or detailed calculation for C1 to C4			√	
13. Accuracy of beyond life cycle stage predictions, stage D included			√	
14. Data quality assessment		√	√	

uncertainty and probability distribution, as explained by Pomponi and Moncaster [6]. Furthermore, in each stage, the uncertainty can be caused by or related to three main elements; this was initially framed by Lloyd and Ries [104] and represents seminal work in uncertainty analysis in LCAs. These are:

- Parameter uncertainty (i.e. the uncertainty refers to the values of a parameter such as the embodied CO_2e of processes and/or assemblies);
- Scenario uncertainty (i.e. the uncertainty refers to the likelihood of different scenarios, such as the energy mix of the United Kingdom in 20 years' time);
- Model uncertainty (i.e. the uncertainty refers to the specific model being used, such as the model developed by the Intergovernmental Panel on Climate Change (IPCC [105]) to calculate the Global Warming Potential related to GHGs over 20, 50, and 100 years' horizons).

6.2. Life cycle stages and life span of buildings

Practitioners (identified by letters as described in Table 2) believe that the production phases A1-A3 and the use phases B1-B5 are the major contributors to the embodied CO_2e of buildings [c, h]. For production, the structure is the highest contributor [k, l]. For the use phase, building components that need frequent replacement, maintenance or refurbishment contribute more [b]. These perceptions are supported by the academic literature, although the impact of later life cycle stages is generally found to be of greater importance than recognised by more industry respondents. Fig. 5 illustrates which life cycle stages the interviewees include in their assessments. The production stage is always included where assessment is carried out, and most account for transport and construction. However, poor availability of material quantities and EPDs, assumptions on transportation modes and distances as well as a lack of data on construction emissions lead to a high level of uncertainties [b, c, i]. Use and end-of-life are often omitted due to a lack of data and time, uncertainty over the future of the building after construction, and potentially a lack of understanding of the impact. This confirms findings in academic literature [6]. The benefits and loads beyond the life cycle stages are rarely calculated.

The design life of a building is often taken by structural engineers as 50 years, based on the structural design codes of the American Concrete Institute (ACI [106]), the American Institute of Steel Construction (AISC [107]), the Eurocodes [108] and the Australian/New Zealand Standard (AU/NZS [109]). The common lifetime for an LCA is 60 years. However, the life span of buildings is dependent on the typology of the building and the nature of the study. The life span given by interviewees was mainly 50 or 60 years by default due to the structural code (50 years [b, c, f, g, h, i]), though some interviewees emphasized how life span is determined by occupancy type, client's view (30–60 years [b, j]), lease length (15–30 years [b, d]), rating schemes (20–60 years) [g] and the sensitivity analysis (30–120 years [i]).

> "The life span is defined for each project. The standard economic life span is defined as 50 years for a building." *Sustainable Business Developer, Development/Construction Company in Sweden [f]*

6.3. Normalization

Table 10 illustrates the interviewees' responses on the different normalization strategies. Most cases would normalize by floor

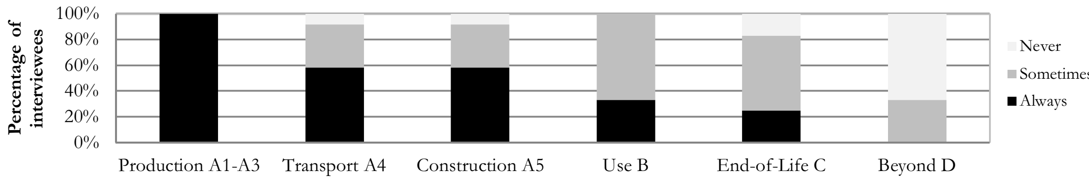

Fig. 5. Interview results on included life cycle stages.

Table 10
Interview results on normalization strategies (always – sometimes – never).

	[a]	[b]	[c]	[d]	[e]	[f]	[g]	[h]	[i]	[j]	[k]	[l]
NIA	always	sometimes										
GIA		sometimes	always			sometimes		always			always	
Heated Floor Area					always	sometimes						
Per Year	always			sometimes	always					always		
Compare Designs						always	always					always
Per Occupant								sometimes				
Monetization Factor									always	always		

area, but the definition of floor area varies from Net Internal Area (NIA) to Gross Internal Area (GIA) and Heated Floor Area (HFA). Practitioners would also normalize per year in order to compare embodied to operational impacts. A few practitioners mentioned that normalizing is not accurate yet, due to various boundary conditions and assumptions that are different from one case study to another. Therefore, they compare the analysed building project to an alternative design in order to measure how they can lower the embodied CO_2e [f, g, l]. Others mentioned normalizing per occupant or based on financial costing [43].

6.4. Assumptions for scenario predictions and grid decarbonisation

For the use stage (B), the end-of-life stages (C) and beyond the life cycle stages (D), scenario predictions and assumptions are needed to evaluate the whole life cycle impact of buildings. What is included in the use stage (B) for embodied CO_2e calculation varies widely. Most industry partners include figures for operational CO_2e from an external source in order to have an overview of the whole life CO_2e of the building.

> "Until now the common practice is to include replacements of products and operational energy use." *Advisor and Coordinator for climate and materials, international Contractor in Norway [e]*

The B1 stage is rarely included, as products seldom emit greenhouse gases over their lives. Maintenance (B2) is generally split into planned and reactive maintenance [b]. The planned maintenance is calculated through a frequency per component. The reactive maintenance is not included, as it lacks a defined frequency. Repair (B3) is assumed to mean partial replacement of a building component. For the replacement stage (B4), the impacts calculated for the production stage are multiplied with a factor depending on the expected service life of the corresponding building components, if shorter than the building's lifespan. It also includes the transport of the new component, potential material losses, and the waste management of the removed component, though most practitioners only include the production of the replaced components. Refurbishment (B5) is treated similarly to replacement and is applied to components replaced due to internal refurbishment at a notional lifetime, often 25 years, rather than due to the end of its service life.

For the end-of-life (C) scenario predictions, the demolition emissions are often neglected. If practitioners calculate the end-of-life CO_2e, they tend to focus on the transport in terms of disposal of all components. Depending on countries, a certain percentage is recycled, another percentage landfilled, and another incinerated. Life cycle stage D is rarely included as this exceeds the whole life embodied CO_2 cradle-to-grave boundaries. When it is included, the benefits and loads are often described qualitatively and separately. It is particularly important for materials such as metals (recycling) and timber (carbon sequestration). Some practitioners argue stage D should not be included if industry is driven by lowering CO_2e emissions quickly, so that benefits of scenarios in the far future are of lesser value [e, h, i].

Grid decarbonisation is occasionally taken into account in practice. Often, the future scenarios for energy mixes are taken as they are at the moment of the calculation. Table 11 illustrates the interview results.

7. Conclusions and recommendations

7.1. Key findings

This paper has considered how embodied CO_2e is calculated in practice, through the academic and professional literature on the state of the art in the construction industry, and through qualitative studies with practitioners. As demonstrated, there is currently a lack of implementation of the considerable body of academic work within industry practice. A comprehensive overview of a simplified, applicable embodied CO_2e assessment approach with reliable datasets is yet to be defined for wide use in the construction industry. Many individual case studies exist in academic literature and industry reports. However, the freedom of boundary conditions and assumptions of the assessor still leads to a wide variability in the results, and these are not yet in a form, which could produce useful and reliable benchmarks.

The academic literature showed that current results for the embodied CO_2e in buildings vary as studies tend to focus on low energy case studies, buildings in urban areas, selected countries, program types (office, residential, etc.), materials (wood, steel, concrete, etc.), building layers (structure, etc.), and selected life cycle stages (production, etc.). The use of different LCA software and LCI databases also leads to comparison issues. Research on industry practice in embodied CO_2e reveals the main challenges include boundary conditions, the lack of local and accurate data, and the lack of demonstration projects and benchmarks. This paper reviewed the available reports, software, tools, and databases to calculate the environmental impact of building materials and buildings, illustrating the different methods, boundary conditions and regions. Solutions offered in literature and in the qualitative stud-

Table 11
Interview results on taking grid decarbonisation into account.

	[a]	[b]	[c]	[d]	[e]	[f]	[g]	[h]	[i]	[j]	[k]	[l]
Yes		√		√	√				√			
No	√		√					√		√	√	√
When asked						√						
For 25 yrs							√					

ies are the standardisation of data, the dissemination of knowledge and skills, and the implementation of embodied CO_2e in labels. The drivers and enablers for calculating the embodied CO_2e of buildings include building codes such as ISO 14040/44 and EN 15978/804, as well as voluntary rating schemes such as LEED and BREEAM. Other incentives include the competitive advantages in industry and climate change commitments such as the Science Based Targets and SE 2050. Several national databases for EPDs of materials exist, and various commercial software have tried to collect this data worldwide, but more efforts in data collection are still required.

The remaining challenges identified during the qualitative studies are the included life cycle stages, the considered life span, the normalization, the included building layers, the lack of reliable sources for ECCs, the need for material quantity collection, the uncertainty for transport and construction emissions, the use stages included, the decarbonisation of the grid, the comparison with operational impacts, the scenario predictions of end-of-life stages and beyond, and the data quality assessment. The life cycle stage that is most taken into account in practice is the material production stage (A1–A3). Transport (A4) and construction (A5) are also factored into some cradle-to-site calculations. Replacement (B4) is the most straightforward aspect of the embodied use stage. The impacts from anticipated conditions of use (B1), maintenance (B2), repair (B3) or refurbishment (B5) are often omitted in industry practice. End-of-life (C) scenario predictions are still unclear, also due to a lack of data and baseline case studies. Rarely, practitioners look beyond the life cycle of buildings at the benefits and loads of the reuse, recovery and recycling potentials (D). Due to the lack of data and methods for the post-production life cycle stages, practitioners are routinely missing a significant part of the whole life cycle, even when they (partially) calculate embodied CO_2e and energy.

To calculate the embodied CO_2e in buildings, the lack of reliable benchmarks and the lack of consistency in the approaches are two of the main barriers encountered in the academic literature, in the documentary analysis, and in the interviews. In order to include embodied CO_2e in regulations or rating schemes, a baseline for benchmarking is needed globally. However, due to a lack of transparency in the methodologies as well as a lack of available, reliable, and accessible databases, the results of building assessments are not comparable to one another. As demonstrated in this paper, a clear opportunity exists for leading construction companies to collaborate on developing comparable embodied CO_2e benchmarks and uniform calculation methods.

7.2. Study limitations

This paper is based on an analysis of a non-exhaustive number of documents and tools and a limited number of interviews, mostly in Europe, North America and Australia. Further work should include the view of the construction sectors in Asia, Africa and South America. In addition, interviews were held with those already interested in this area. Nonetheless, as demonstrated by the growing industry activity in this field, there is a developing awareness of the importance of calculating embodied CO_2e in buildings.

It should be noted that embodied CO_2e is only one indicator of LCA. Evaluating the environmental impact of buildings requires a full LCA of buildings, in order to account for other important factors including toxicity and depletion of resources. With reliable calculation methods and data, embodied CO_2e should be included as one of these LCA indicators.

7.3. Recommendations

The remaining uncertainties in embodied CO_2e are divided into two aspects: databases and methodologies. Though the method for calculating the whole life embodied CO_2e of buildings is described in norms mutually agreed upon, implementation in practice differs. Furthermore, the available databases for factors (ECCs, transport factors, construction factors, waste factors, etc.) are still unreliable and sparse. There is a demand for reliable product LCIs to be provided by the manufacturing industry. Regulation for mandatory EPD databases would help in improving the accuracy of embodied CO_2e assessments. Furthermore, there is a need for more transparency and data quality assessment. Sensitivity analyses and working on the uncertainty issues could potentially solve the lack of uniform embodied CO_2e calculations. Finally, the Green Building Council of each country could disseminate a uniform embodied CO_2e calculation methodology.

7.4. Future work

Future work in this project includes a comparative analysis of case studies in collaboration with industry partners. The results of this comparative analysis will be published in a future paper. Based on this analysis, a uniform method for embodied CO_2e assessment with mutually agreed upon databases will be developed and integrated into the broader LCA of buildings. This will lead to the definition of clear and accurate benchmarks on embodied CO_2e in buildings much needed across industry.

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