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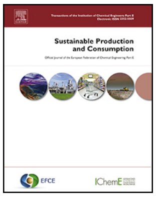

Understanding the global warming potential of circular design strategies: Life cycle assessment of a design-for-disassembly building

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ABSTRACT

Targets for carbon emissions and energy use are set within the built environment to drive change and reach net-zero by 2050. Meanwhile, circular design strategies, including design-for-disassembly (DfD), are promoted to address waste production, raw material usage and lack of reuse, however their environmental impacts are not always measured. Therefore, a process-based life cycle assessment of a DfD building has been performed to assess its environmental impacts across 18 impact categories. The results are compared against industry target values for global warming potential (GWP_{100}), energy use and material reuse to assess whether current targets are effective for assessing a broad range of sustainability principles. For the product and construction stages, the rank order of the main contributors to GWP_{100} is representative of 8 of the 18 impact categories. The superstructure and building services account for at least 75 % of the total impacts for product and construction stage across all impact categories. Compared against industry target values, the case study building has a GWP_{100} that is 26 % below baseline industry target values for the product and construction stage, operates using less energy than targets for education and office buildings, and has been designed to enable the reuse of 65 %, by mass, of the substructure and superstructure at end-of-life. Current target values focus on driving reductions in GWP_{100} while maintaining low operational energy use, but do not fully capture the benefits from increasing material reuse through circular and DfD strategies. Patterns within assessed impact categories need to be further investigated to develop target values capable of representing a range of impact categories and material circularity.

1. Introduction

The built environment is a critical sector for achieving the commitments set out in the Paris Agreement on climate change, because buildings and infrastructure are responsible for 40 % of global energy-related carbon dioxide equivalent (CO_2e) emissions (IEA and UNEP, 2019; UNEP and IEA, 2018). Recent increases in CO_2e emissions from the built environment are associated with an overall increase in developed floor area globally (IEA, 2020; IEA and UNEP, 2019). The growth in developed floor area also corresponds with a higher consumption of natural resources and increased waste production (UNEP, 2017). In recent years, many countries have established schemes to make net-zero carbon buildings a reality and combat the continued rise in global greenhouse gas (GHG) emissions (IEA and UNEP, 2019; WorldGBC, 2019a). Emissions must be reduced now while ensuring additional impacts will not occur in the future (Ellen MacArthur Foundation, 2021; LETI, 2020a). Otherwise, the impacts of climate change will simply be delayed until a later point.

Buildings produce environmental impacts throughout their lifespans. Historically, the operational use of buildings was viewed to be the largest producer of environmental impacts (Pomponi and Moncaster, 2016; Röck et al., 2020). However, in many industrialised countries the combination of energy efficiency improvements and a decarbonising electricity grid is reducing the environmental impacts of operational energy use (Kiss and Szalay, 2022; Röck et al., 2020). There has been an explosion of interest in reducing the "embodied carbon" of buildings – particularly the "upfront embodied carbon" associated with material production, transportation and onsite construction (Roberts et al., 2020; Röck et al., 2020). These emissions occur before a building is occupied and are, therefore, critical for achieving GHG reduction targets (LETI, 2020a; Pomponi and Moncaster, 2016; Röck et al., 2020). Several schemes with operational energy targets and upfront embodied carbon targets have been developed (Frischknecht et al.,

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2019a, 2019b; GLA, 2022; LETI, 2020b; RIBA, 2021). However, while the focus of these schemes give clarity, their focus on single indicators (energy, carbon) and particular life cycle stages (upfront, operational) does not ensure buildings will have generally low environmental impact over their whole life cycle.

Buildings are commonly constructed to fulfil a specific need and are either demolished or extensively renovated when they become redundant (Huuhka and Lahdensivu, 2016). This traditional view of buildings as single-use commodities follows the take-use-dispose precedent of a linear economy (Ellen MacArthur Foundation, 2017). A linear economy results in an inefficient use of materials and a significant production of waste (Ellen MacArthur Foundation, 2017; López Ruiz et al., 2020), which has negative societal, environmental and economic implications (Ellen MacArthur Foundation, 2021). To address the inefficient use of materials and minimise the environmental impacts of buildings, reduction strategies have been proposed for various aspects of a building's design, construction, use and disposal (Leoto and Lizarralde, 2019; Pomponi and Moncaster, 2016). Impact reduction strategies need to be assessed over the full life cycle of a building to ensure impacts are not simply shifted from one life cycle stage to another (Lavagna et al., 2018; Pomponi and Moncaster, 2017). To properly address climate change, optimal impact reduction strategies will address impacts occurring now while also mitigating future impacts.

The circular economy (CE) aims to ensure sustainable growth by moving away from the 'take-use-dispose' mentality and retaining materials in the value chain (Eberhardt et al., 2019; Ellen MacArthur Foundation, 2013; Reike et al., 2018). The successful implementation of a CE will mitigate disposal and waste processing impacts at end-of-life while subsequently minimising the reliance on virgin materials for future products (Ellen MacArthur Foundation, 2017; Ghisellini et al., 2018; Joensuu et al., 2020). The implementation of a CE within the built environment is not common practice, but it has seen growing interest in recent years (Hossain and Ng, 2018; Joensuu et al., 2020; Munaro et al., 2020). However, as discussed in Section 2.2, there is no consensus on how life cycle assessments (LCAs) of CE strategies should be conducted and whether these strategies meet carbon and energy targets (Eberhardt et al., 2020b; Gulck et al., 2022).

Design-for-disassembly (DfD) is one method that aims to break the 'take-use-dispose' system in the built environment by enabling greater reuse and recycling of components at the end of a building's lifespan (Joensuu et al., 2022). However, DfD focuses on the end-of-life of buildings, which is subject to a great degree of uncertainty due to the long lifespan of most buildings (Resch et al., 2021; Silvestre et al., 2014). Additionally, few empirical studies exist that demonstrate the success of DfD strategies in real-world applications (Akinade et al., 2017).

In summary, there are two limitations in existing research, which this paper seeks to address. (1) Prominent environmental targets in industry currently have a narrow scope, focusing particularly "upfront embodied carbon" and operational energy use, without consideration of the wider range of environmental impact categories nor future life cycle stages. This creates the risk of environmental "burden shifting" across categories or life cycle stages. (2) There is no consensus over how to conduct LCA of CE strategies (such as DfD) and report impacts for materials and components designed for use across multiple life spans. Therefore, an LCA of a DfD building has been conducted to comprehensively assess its environmental impacts and compare relevant results to current industry targets. The LCA is used to explore how DfD strategies can be compared against current industry targets and whether such targets should be expanded in the future to encompass a broader realm of sustainability principles.

2. Literature review

A combination of academic studies, industry documentation and international standards were used to inform the present study. Section 2.1 discusses how DfD can be used within the built environment to establish a CE. Section 2.2 summarises standards applicable to LCA and discusses how LCA has been conducted so far for DfD buildings. Section 2.3 presents industry documentation and academic studies relevant to the development of environmental targets for the built environment.

2.1. Design-for-disassembly as a route to a circular economy

DfD views buildings as 'banks of materials' that are designed to ease material recovery and reuse (Densley Tingley and Davison, 2011; Geldermans, 2016; Munaro et al., 2022). Therefore, DfD has the potential to reduce the environmental impacts and waste production from building demolition (Akinade et al., 2017; Geldermans, 2016). Some evidence suggests that, when implemented effectively, DfD can reduce environmental impacts and shift away from virgin material use, through closed loop recycling and reuse of materials at end-of-life (Akanbi et al., 2019; Densley Tingley et al., 2017). However, most studies analyse the environmental impacts for DfD strategies from a theoretical perspective (Akanbi et al., 2019; Eckelman et al., 2018) and there is a lack of evidence for the successful implementation of DfD strategies in real-world cases (Akinade et al., 2017). Uncertainty surrounding the benefits of DfD – particularly the future reuse of materials – are among the barriers inhibiting the uptake of DfD practices in the built environment (Akinade et al., 2020; Densley Tingley et al., 2017; Dunant et al., 2017; Munaro et al., 2022; Rahla et al., 2019; Rios et al., 2015). Improved communication throughout the supply chain is one method to address these barriers and increase the likelihood that reused materials will be considered, and used, for new projects (Dunant et al., 2017). With the publication of International Organization of Standardization (ISO) 20,887:2020 (BSI, 2020a), the implementation of DfD in industry should hopefully see a transition from novelty to more mainstream use.

DfD aims to extend the service life of individual materials (Joensuu et al., 2022). Rahla et al. (2019) view that a building can be "circular" when end-of-life has been incorporated into the design and materials are considered to be temporarily stored in the building. Based on the definition from Rahla et al. (2019) and work by Eberhardt et al. (2020a), design strategies that can enable a CE include assembly/disassembly, modularity, and prefabrication, among others. Therefore, DfD is aligned with key CE design strategies and can serve as a viable means of creating a CE within the built environment.

Modularity, prefabrication, and the ability to assemble and disassemble a building are all interlinked aspects that facilitate DfD within the built environment. All three influence how a building is designed and how it should be constructed (Akinade et al., 2017; Silva et al., 2020). Modularity can enable full components to be recovered and reused after their initial life, therefore retaining materials in the value chain and supporting the transition to a CE (Akinade et al., 2017; Benachio et al., 2020; Kyrö et al., 2019). Prefabrication and modularity can take many forms; modular building elements can be prefabricated to be assembled on-site and modular volumetric units can be prefabricated and transported to site to form the building (Jaillon and Poon, 2014; Silva et al., 2020). The ability to assemble and disassemble a building is greatly influenced by the types of connections and materials used (Akanbi et al., 2018; Akinade et al., 2017). The types of connections used for prefabricated and modular elements should be considered in the design process to enable ease of deconstruction and allow for reuse at end of life (Akanbi et al., 2018; Akinade et al., 2017; Silva et al., 2020). Eberhardt et al. (2020a) and Eckelman et al. (2018) demonstrate how the combination of these aforementioned design strategies can implement DfD and CE practices within the built environment. When implemented successfully, these aforementioned strategies can lead to net-reductions in environmental impacts when the materials and components are retained within the value chain for at least one reuse (Eberhardt et al., 2020a; Eckelman et al., 2018; Ellen MacArthur Foundation, 2017).

2.2. Life cycle assessment for design-for-disassembly buildings

Life cycle assessment (LCA) has become the predominant means of assessing the environmental impact of a product or system. However, determining the environmental impacts of a building is one of the most complex applications of LCA (Hollberg and Ruth, 2016). The use of LCA in the built environment is standardised by European Standard (EN) 15978 (BSI, 2012) and EN 15804 (BSI, 2020b) for assessments at building level and product level, respectively. Table 1 outlines the environmental impacts throughout a building's life cycle and the associated terminology. The environmental impacts associated with the Product Stage [A1-A3] and Construction Stage [A4-A5] are commonly referred to as the "upfront embodied" impacts (LETI, 2020a; WorldGBC, 2019b). "Embodied" is used to differentiate the environmental impacts associated with the manufacturing of materials from the impacts associated with the operational use of the building (i.e. operational energy use [B6] and operational water use [B7]) (Pomponi and Moncaster, 2018; Röck et al., 2020). "Upfront" is used to differentiate the impacts that occur during the initial construction [A1-A5] from the impacts that occur during the repair, maintenance and use of the building [B1-B5].

Assessing the environmental impacts of DfD buildings faces challenges when considering elements that have been designed for use in multiple life cycles. The allocation of environmental impacts between the initial and subsequent life cycles has been the focus of past research but consensus has yet to be reached (Allacker et al., 2014; Eberhardt et al., 2020b). As illustrated by De Wolf et al. (2020), the environmental impacts of materials used within multiple life cycles are dependent on the allocation method used to assign impacts to different life cycles. Eberhardt et al. (2020b) highlight that a mass balance is not maintained when using the 50/50 nor circular footprint formula (CFF) allocation methods. Unlike the 100–0 (cut-off) approach, allocation via 0–100, 50/50, CFF, linear degressive (LD) approaches do not reflect the timing of when emissions occur as they share the environmental impacts across multiple life cycles (Eberhardt et al., 2020b). Densley Tingley and Davison (2012), Bertin et al. (2022) and Eckelman et al. (2018) propose that environmental impacts of DfD materials should be distributed across multiple lifespans to incentivise DfD. The main challenge with dividing a known environmental impact across multiple life cycles results from the uncertainties surrounding the long lifespan of building elements and the inability to guarantee an element will be reused after its initial life under the sole pretense that it is designed to enable reuse (Eberhardt et al., 2020b; Gulck et al., 2022). To counter this, EN 15978 (BSI, 2012) requires a 100–0 (cut-off) approach that assigns burdens wholly to the first life cycle of a product.

The use of DfD strategies can influence the environmental impacts of a building at all stages of the building's life cycle. Bertin et al. (2022) and Eckelman et al. (2018) indicate that designing a building to enable its reuse can lead to increases in initial impacts due to greater energy and resource consumption when compared to conventional building practices. Therefore, if not reused DfD buildings can lead to increases in environmental impacts resulting from higher A1-A5 impacts when compared to traditional buildings (Bertin et al., 2022; Eckelman et al., 2018). The assessment of repair, maintenance and refurbishment of DfD buildings is not well studied within academia. However, from a fundamental perspective the strategies used to enable ease of deconstruction are likely to reduce the impacts associated with repair and maintenance due to types of connections and common use of prefabrication and standardised components within DfD buildings (Akinade et al., 2017).

Table 1
Environmental impacts of buildings.

Term	EN 15978 modules	Life cycle stages included
Product Stage	A1-A3	Raw material extraction, transportation in supply chain, and manufacturing of materials and products.
Construction	A4-A5	Activities and processes, including transportation, needed to construct the building
In Use	B1-B5	Repair, maintenance, and upkeep of the building throughout its life, including the embodied impacts of replacement and repair materials
Operational	B6-B7	Energy and water use needed to operate the building
End-of-Life	C1-C4	Deconstruction/demolition of the building, the waste processing, and disposal of all materials at end-of-life
Beyond the system boundary	D	Benefits and loads that occur outside the system boundary of the building's life cycle

The use of DfD strategies can limit end-of-life impacts when the "end-of-waste" state is reached (BSI, 2019; Gulck et al., 2022). The end-of-waste state delineates the environmental impacts that are attributed to the life cycle of the building being assessed and the impacts and benefits that are reported in Module D (Table 1) (BSI, 2012; Delem and Wastiels, 2019; Silvestre et al., 2014). According to EN 15978 (BSI, 2012), the end-of-waste state is reached when the recovered material: is used for a specific purpose; has an economic value; fulfils technical requirements and meets applicable standards and legislation, and; will not result in "adverse environmental or human health impacts" (BSI, 2012). Once disassembled, the elements designed for reuse would have an economic value and all the impacts and benefits of resulting from their use in a subsequent life would be reported in Module D (BSI, 2019; Gulck et al., 2022). Both Joensuu et al. (2022) and Silvestre et al. (2014) discuss how the benefits from DfD solutions can be captured within Module D. The approach ensures separation and hence transparent reporting of the impacts that occur within the initial life cycle and recognises the uncertainties surrounding the actual reuse of these materials in the future (BSI, 2012; Delem and Wastiels, 2019; Silvestre et al., 2014). Unfortunately, the complexity and uncertainty surrounding Module D remains a hindrance when conveying LCA information to non-specialist audiences.

2.3. Industry target values

Target values have emerged in recent years to set focus on specific aspects of sustainability within the built environment, namely carbon emissions and energy use. 'Carbon' has become shorthand for all GHGs, where each GHG is measured as an equivalent amount of carbon dioxide over a defined time horizon [$kgCO_2e$]. Frischknecht et al. (2019a, 2019b) summarise the advancements of target values across Europe. Target values for the United Kingdom (UK) were not included within that overview (Frischknecht et al., 2019a, 2019b), so an overview of recent developments in UK target values is provided here.

Target values are developed using either 'top-down' or 'bottom-up' approaches (Hollberg et al., 2019). As defined by Hollberg et al. (2019), top-down values are derived from a specific political agenda, i.e. reaching net-zero carbon by 2050, and bottom-up values are determined from theoretical values that represent the preferable technical performance. Target values for specific building typologies and building elements provide designers with a credible metric for use in evaluating their design decisions (Russell-Smith et al., 2015). When targets are set at multiple intervals, they can direct industry towards a goal, i.e., net-zero carbon emissions (Hollberg et al., 2021; Roberts et al., 2020). The combination of bottom-up and top-down approaches was highlighted by Trigaux et al. (2021) to provide achievable goals in the interim while driving change to meet national policy, i.e. national carbon reduction targets for 2050.

In recent years, there have been a number of industry developed target values and roadmaps published (UKGBC, 2019; WorldGBC, 2019a). Considerations for embodied carbon are included within the net-zero carbon schemes for the UK, Germany, France, Canada, Sweden and Australia (WorldGBC, 2019a). Within the UK, there are three main sets of carbon target values for buildings that have been derived using a combination of top-down and bottom-up approaches. Table 2 provides a summary of the target values that are published by: the Royal

Table 2
Summary of United Kingdom industry developed target values for 2030.

	RIBA 2030 Climate Challenge	LETI	GLA
Year	2030	2030	Aspirational[a]
Building type	Non-domestic (schools)	Commercial office/school	Schools, universities
Carbon target value [$kgCO_2e/m^2$]	<540	350	<675 (<500 for A1-A5)
Operational energy [kWh/m^2/year]	<60	55 (office) 65 (school)	N/A
Potable water [m^3/pupil/year]	<0.5	N/A	N/A
% reused	N/A	50 %	N/A
% reusable	N/A	80 %	N/A
Building element scope			
Substructure	x	x	x
Superstructure	x	x	x
Internal finishes	x	x	x
Furniture, fixtures & equipment	x (only fixed)		x
Services	x	x	x
External works			x
Life cycle stage scope			
A1-A5	x	x	x (includes individual target for A1-A5)
B1-B5	x		x
B6	x	x	
B7	x		
C1-C4	x		x
D			
Includes sequestration	Yes	Reported separately	Yes

[a] GLA provides a target for “aspirational” design practices that is not associated with a specific year.

Institute of British Architects (RIBA) (RIBA, 2021); the London Energy Transformation Initiative (LETI) (LETI, 2020b); and, the Greater London Authority (GLA) (GLA, 2020). The carbon target values are published in the form of interim targets for global warming potential evaluated over a 100-year timeframe (GWP_{100}) and are measured in terms of an equivalent mass of carbon dioxide emitted to atmosphere per square metre of building floor are [$kgCO_2e/m^2$].

As seen from Table 2, the RIBA targets encompass the largest scope for building life cycle stages (RIBA, 2021). The LETI targets were developed in response to the climate emergency declaration and hence, are focused on driving impact reductions now (LETI, 2020b). The LETI and RIBA targets have been aligned using a banded scoring system to account for the different scopes considered in each target (LETI, 2021). Additionally, LETI provides targets for the amounts of materials that are reused and suitable for reuse in a subsequent life (LETI, 2020a). These targets go beyond the more common carbon target values to consider aspects of raw material use and waste production that can otherwise be overlooked by carbon targets.

The targets set by RIBA go beyond other target values in Europe by assessing all life cycle stages, including separate targets for operational energy and water use (Frischknecht et al., 2019a, 2019b; RIBA, 2021). The scope of building elements considered in the UK target values matches, or exceeds, that of the target values for countries elsewhere in Europe (Frischknecht et al., 2019a, 2019b; LETI, 2020a; RIBA, 2021). The shortcoming of UK target values is the narrow focus on energy use and GWP_{100} impacts. Target value and benchmarking schemes in other areas of Europe include considerations for other environmental indicators, such as acidification, eutrophication and water use, among others (Frischknecht et al., 2019a, 2019b).

3. Methods

Details pertaining to the goal and scope used for the LCA are presented in Section 3.1 and the case study building is detailed in Section 3.2. Section 3.2 includes a description of the case study building, the functional equivalent required to contextualise the results, how the building demonstrates aspects of a CE, the life cycle inventory and additional considerations for end-of-life.

3.1. Life cycle assessment goal and scope

LCA has been used to evaluate the environmental impacts for constructing a DfD building in the UK. The case study is synonymous with a post-completion assessment for a building used in industry for validation and accountancy purposes within accreditation schemes. Therefore, the case study enables DfD design strategies to be compared against current industry target values.

The scope of the assessment is aligned with the Royal Institute of Chartered Surveyors (RICS) ‘*whole life carbon assessment for the built environment*’ (RICS, 2017) to enable comparison with the target values (since they are based on RICS). The life cycle stages, defined by EN 15978 (BSI, 2012), that form the system boundary for the study are highlighted in Fig. 1. RICS defines a 60-year reference study period to compare buildings, with different lifespans, under a predefined set of considerations (RICS, 2017). The study includes the substructure, superstructure, internal finishes, and building services, as defined by the RICS new rules of measurement (NRM) (RICS, 2012).

A process-based LCA has been undertaken to quantify the environmental impacts of the case study building due to the level of information available from the building owner/operator (Hauschild et al., 2014). The EN 15804 (BSI, 2020b) cut-off criteria have been followed to ensure an appropriate level of completeness for the assessment and avoid environmental discounting. These criteria require that no >5 % of the estimated total mass or energy is excluded from each reported life cycle stage (Fig. 1) (BSI, 2020b). The LCA has been conducted using openLCA with ecoinvent 3.6 (Wernet et al., 2016) and the ReCiPe 2016 Midpoint Hierarchist (National Institute for Public Health and the Environment, 2017) impact assessment method. A midpoint analysis was conducted to compare the results against target values (National Institute for Public Health and the Environment, 2017).

3.2. The case study building

The case study building, constructed in 2016 and located in Swansea, UK, was chosen for this study as it demonstrates a novel building fabric that exemplifies key circular design strategies, discussed in Section 3.2.2. Fig. 2 presents the building's floorplan and a photo of

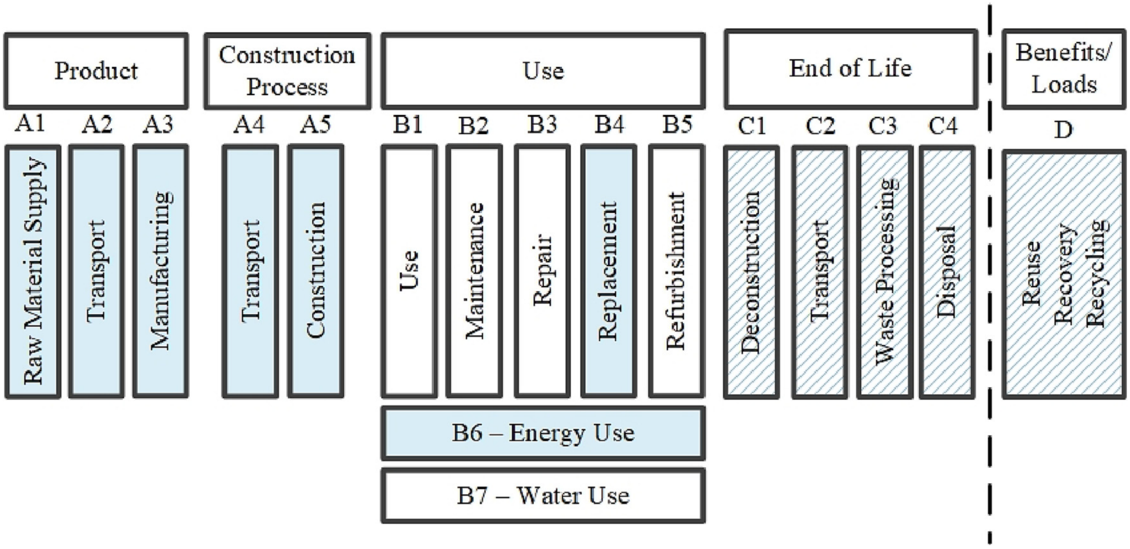

Fig. 1. Scope of study defined by EN 15978 life cycle stages. Solid – Required in scope; Hatched – discussed in Section 5.2 & 5.3.

the building post-completion. The functional equivalent defined for the study, applied aspects of circularity and life cycle inventory are outlined in Sections 3.2.1, 3.2.2, and 3.2.3, respectively.

The case study building does not have a traditional structural framing system due to the novel panel system used to enable the building to be disassembled at end-of-life. The panels interlock to form a rigid structural system without the use of defined columns and beams. Therefore, the building element breakdown of A1-A3 GWP_{100} is dependent on the allocation of the constituent materials in the panel system. Fig. 3 illustrates the allocation of panels to building element classifications, as defined by the RICS new rules of measurement (RICS, 2012) building element classifications, based on the location of the panels within the building. For the vertical panels: the steel framing elements have been allocated to frame (2.1); the finishing substrate and insulative materials have been allocated to external enclosing walls (2.5.1) and internal walls and partitions (2.7) based on the location of the panels. The allocation has been chosen to make the breakdown of building elements comparable to that of a traditional building. It is important to note that although the allocation of panels to individual building elements influences the breakdown of GWP_{100} by building element classification, the total impact for the building will remain the same. Therefore, since this study compares the case study building against industry target values that encompass the full building, the breakdown is less important than ensuring the completeness of the assessment.

3.2.1. Functional equivalent

Whereas LCA of most products is defined on the basis of a functional unit (ISO 14040 (BSI, 2020c), ISO 14044 (BSI, 2018)), the European standard for LCA of buildings (EN 15978 (BSI, 2012)) uses the term “functional equivalent”. This is defined as the “quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison” (BSI, 2012). Thus “functional unit” and “functional equivalence” are synonymous terms used for product and building scale LCA, respectively. The functional equivalent of the building is outlined in Table 3. The short service life and client requirements made a DfD building appealing for this specific use case, to minimise waste production and disturbances to the site at end-of-life. The study uses the net internal area to normalise the results per square metre [/m^2] (RICS, 2017).

3.2.2. Circularity in case study building design

The circular design strategies that are incorporated in the case study building's design include: short use; assembly/disassembly; modularity; adaptability/flexibility; material selection/substitution; and, optimised shapes/dimensions. The aforementioned design strategies

Fig. 2. Case study building A): View of north and west elevations. Courtesy of SPECIFIC; B) floorplan.

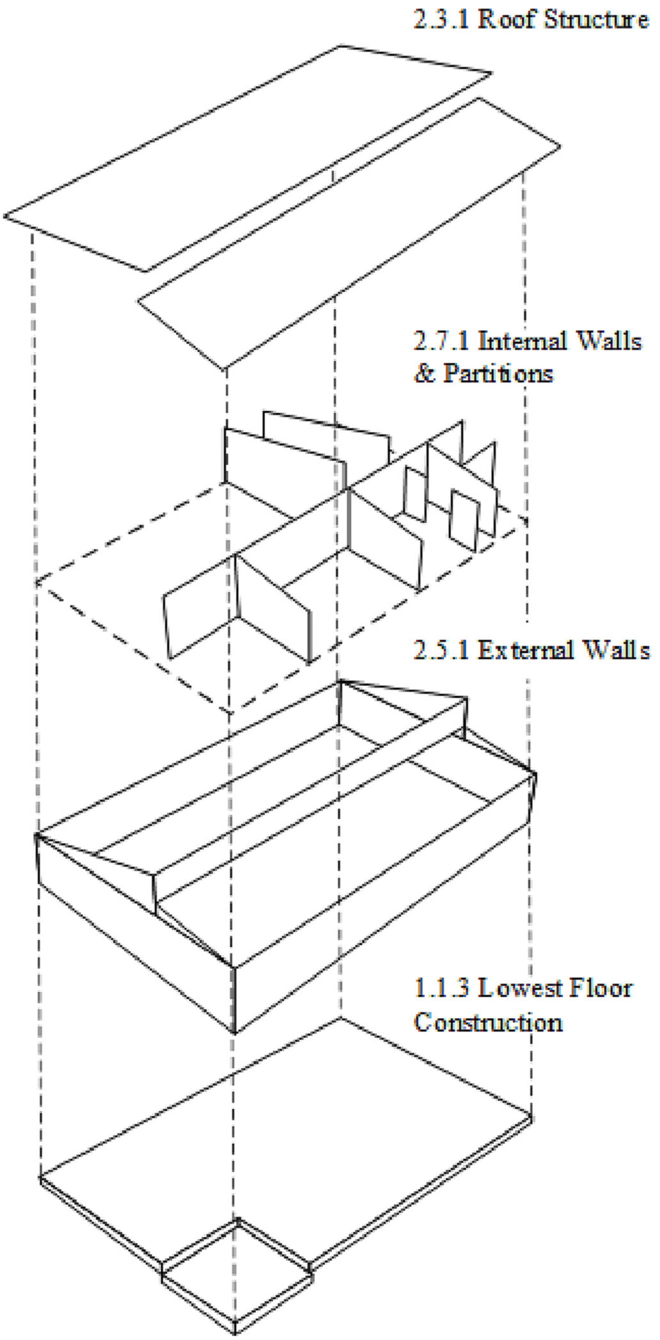

Fig. 3. Allocation of panelised building fabric to building element categories.

are included within the full list of CE design strategies discussed by Eberhardt et al. (2020a). "Short use" is required for the building due to the restrictions provided from the planning permission for the project. "Assembly/disassembly" and "modularity" has been achieved by the integrated panelised system that forms the building's roof structure, walls, and floor. The connection points in the integrated panelised system enable the building to be disassembled to panel level at end-of-life. When interlocked, the panels form a rigid frame that acts as the buildings structural system and provides insulative properties for the building. In theory, when disassembled the panels can be used to construct a new building in the same configuration, or the panels can be reconfigured to supply the frame and building envelope substrate for a new building of a different configuration. Therefore, realising the "assembly/disassembly" and "adaptability/flexibility" circular design strategies. The material selection and optimisation of the shapes and dimensions for the integrated panels are intrinsic to the "modularity" and "assembly/disassembly" circular design strategies for the building.

Table 3
Functional equivalent for case study building.

Aspect of functional equivalence	Case study building
Building type	Education with office space
Regulatory requirements	Welsh building regulations (Welsh Government, 2017)
Client requirements	- Minimise impact to site - Able to relocate building after initial life - Suitable to test energy technologies and control systems - Minimise use of specialised equipment for construction and deconstruction - use of local supply chains
Floor area	186 m^2 (net internal area)
Pattern of use	Teaching space: minimum 2-hour duration, up to 4 days per week Office space: continuous 08:00–17:00, 5 days per week
Required service life	10 Years (due to planning permission)

The integrated panelised system was designed to implement downstream reuse. Downstream reuse uses virgin materials in a configuration that enables disassembly and reuse after the initial life of the building (De Wolf et al., 2020). The integrated panel system is prefabricated elements with an expanded polystyrene insulative core sandwiched between magnesium oxide boards and a galvanised steel frame. The life cycle of the building's prefabricated panelised building fabric is illustrated in Fig. 4. If used as intended, the panelised system will eliminate waste at end-of-life and retain the materials within the value chain (Finch et al., 2021).

3.2.3. Life cycle inventory

The life cycle inventory (LCI) for the case study building was developed using as-built construction drawings, material specifications and a virtual tour of the building provided by the owner/operator. The complete LCI for the study is available in a supporting dataset (Roberts et al., 2021), and a summary LCI for the building materials used in the initial construction is presented in Table 4. The case study building employs on-site energy generation and on-site energy storage technologies to demonstrate the "active building" concept (Clarke, 2018). The present study focuses on the embodied impacts of the building, including the embodied impacts of the building's energy generation and storage technologies.

3.2.4. Considerations for end-of-life

For buildings that have been designed to enable their disassembly and subsequent reuse, the allocation of end-of-life impacts becomes relevant. There are three primary means for allocating end-of-life impacts between the initial and subsequent life cycles, i.e., 100–0, 0–100, and 50–50 (Allacker et al., 2014; De Wolf et al., 2020; Joensuu et al., 2022). The 100–0 approach allocates all end-of-life impacts to the initial life cycle as recommended by EN 15804 (BSI, 2020b; Joensuu et al., 2022). The 100–0 approach accounts for the environmental impacts that occur within the building elements life cycle at the time they occur. The 100–0 approach for allocating end-of-life impacts is followed in this study to be in compliance with EN 15804 and ensure environmental discounting does not take place. Due to the long-life of buildings and the inherent uncertainties surrounding end-of-life, the 100–0 approach best reflects the current reality faced by the industry since the reuse of elements cannot be guaranteed even when designed for reuse. Therefore, the 100–0 approach for circular strategies can be viewed as a pessimistic scenario that does not guarantee a subsequent life will take place.

Due to the DfD nature of the building, the identification of the end-of-waste state is crucial for properly accounting for the end-of-life impacts. The end-of-waste state is dependent on the material under

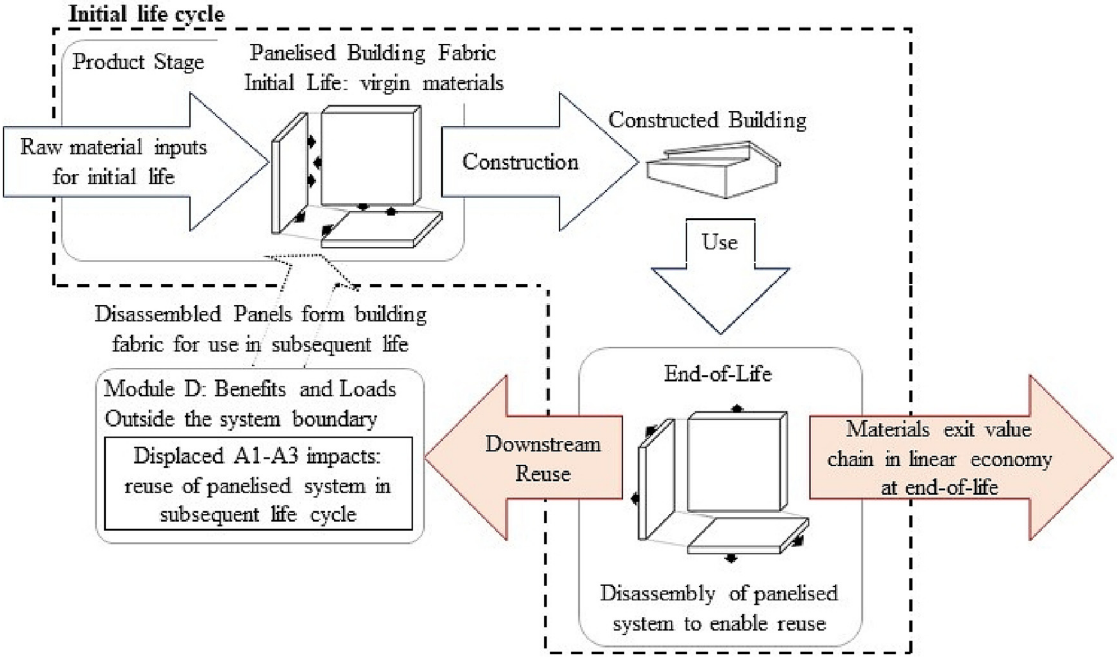

Fig. 4. Life cycle for panelised system designed for downstream reuse.

consideration. Aligned with EN 15978 (BSI, 2012), the panelised system will reach the end-of-waste state once the building has been disassembled to panel level. Therefore, once the building has been disassembled, the end-of-life impacts for the panelised system stop and the benefits from reusing the panels in a subsequent lifespan can be reported within Module D. Once the integrated panel system is disassembled, the associated materials will incur no waste processing [C3] nor disposal [C4] impacts due to the end-of-waste state being reached.

4. Results

The results for the study have been divided into two sections to correspond with the life cycle stages and timing of emissions considered for the building. Section 4.1 summarises the embodied environmental impacts which correspond with the life cycle stages A1-A5. Section 4.2 summarises the environmental impacts attributed to the operational energy use for the building, corresponding to life cycle stage B6.

4.1. Embodied Impacts [A1-A5]

4.1.1. Contribution analysis

The midpoint results for the case study building are presented in Table 5 for the upfront embodied, i.e. product and construction stage, impacts. The contribution analysis, presented in Table 5, illustrates the share of total A1-A5 impacts associated with the product stage [A1-A3] for the individual building element classifications, as well as the transportation to site [A4] and construction impacts [A5]. The

Table 4
Summary of building material life cycle inventory with building element classification. Units: kg – kilogram; m – metre; m^2 – square metre; m^3 – cubic metre; kWp – kilowatt peak; kWh – kilowatt hour.

Component	Quantity	Unit	1 - Substructure	2 – Superstructure	3 - Internal finishes	5 – Building services
Magnesium oxide board[a]	18,575	kg	X	X		
Adhesive[a]	7740	kg	X	X		
Expanded polystyrene insulation[a]	2875	kg	X	X		
Structural steel[a,b]	11,900	kg	X	X		
Rainscreen cladding – Steel	1480	kg		X		
Roof coverings – Steel	1380	kg		X		
Glass wool insulation	545	kg		X		
Double-glazed windows	27	m^2		X		
External doors – wood-aluminium	12	m^2		X		
Plywood	3	m^3	X	X		
Oriented strand board	4.4	m^3		X		
Sawnwood	0.5	m^3		X		
Paint	75	kg			X	
Flooring – carpet tiles	180	m^2			X	
Copper	78	kg				X
Stonewool insulation	6.6	kg				X
Ventilation ducts	305	m				X
Building integrated photovoltaics[c]	17	kWp				X
energy storage system[d]	120	kWh				X

[a] Component in integrated panel system.
[b] Includes screw pile foundations.
[c] Building integrated photovoltaic system includes copper indium gallium selenide laminate system affixed to south-facing roof and required ancillary technology.
[d] Energy storage system includes 12 × 10-kWh zinc bromide aqueous flow cell units and required ancillary technology.

contribution analysis is used to identify patterns among the assessed impact categories without adding additional sources of uncertainty that can result from normalisation and weighting of LCA results (Chau et al., 2015; Sleeswijk et al., 2007). There are two main patterns in the results. The first is that GWP_{100} has a similar breakdown to seven other impact categories: fine particulate matter formation; fossil resource scarcity; human non-carcinogenic toxicity; ionizing radiation; marine eutrophication; stratospheric ozone depletion; and, water consumption. For these impact categories, the superstructure accounts for over 50 % of the total A1-A5 impacts. The product stage for the building services is the second largest contributor followed by the product stage for the substructure. The product stage for the internal finishes and the construction stage [A4-A5] impacts collectively account for 1–8 % of the total A1-A5 impacts for these impact categories. A second pattern can be seen in a group of seven further impact categories: freshwater ecotoxicity; freshwater eutrophication; human carcinogenic toxicity; marine ecotoxicity; mineral resource scarcity; terrestrial acidification; and, terrestrial ecotoxicity. In this case, the product stage for the building services is the largest contributor to the total A1-A5 impacts, accounting for over 50 % of the total impact in each category included. Across all impact categories, the product stage [A1-A3] for the superstructure and building services together account for 75–97 % of the A1-A5 impacts.

112 background processes contribute >1 % to the total for a specific impact category, of which 66 background processes contribute >1 % to only one of the assessed impact categories. Summaries for the contribution analyses for individual impact categories can be found in the Supplemental Materials File. Three background processes contribute at least 2 % to the A1-A5 total for 6 separate impacts categories:

- Magnesium oxide production is responsible for: 9 % of the total GWP_{100}; 2 % of Fine Particulate Matter Formation; 3 % of Marine Ecotoxicity; 3 % of Freshwater Ecotoxicity; 5 % of Human Carcinogenic Toxicity; and 8 % of Human Non-Carcinogenic Toxicity
- Polystyrene production is responsible for: 8 % of the total GWP_{100}; 14 % of Fossil Resource Scarcity; 3 % of Terrestrial Acidification; 3 % of Fine Particulate Matter Formation; 6 % of Ozone Formation, Terrestrial Ecosystems; and 5 % of Ozone Formation, Human Health
- The inverter, used in the energy storage system, is responsible for: 2 % of Freshwater Eutrophication; 3 % of Human Non-Carcinogenic Toxicity; 2 % of Land Use; 3 % of Marine Eutrophication; 3 % of Freshwater Eutrophication; 3 % of Terrestrial Ecotoxicity.

The magnesium oxide production and polystyrene production are the two largest contributors to GWP_{100} for the A1-A5 impacts for the case study building. These two processes are associated with the production of the magnesium oxide boards and expanded polystyrene insulation used within the integrated panel system that forms the building's floor, roof and internal and external walls. These two materials account for 34 % of the mass for the building's substructure and superstructure. In fact, 10 of the 46 background processes, that contribute >1 % to at least two impacts categories, contribute at least 2 % to GWP_{100} and these 10 processes account for 38 % of the total A1-A5 GWP_{100} for the building. For the 46 processes that contribute >1 % to at least two impact categories, none contribute >1 % of the impacts associated with Mineral Resource Scarcity, Ionizing Radiation, nor Water Consumption.

4.1.2. Global warming potential analysis

As discussed in Section 4.1.1, the pattern in the contribution analysis for GWP_{100} is representative of 8 (out of 18) impact categories. Given this and the industry focus on reducing carbon emissions, an in-depth contribution analysis for GWP_{100} impacts is presented below.

The A1-A5 GWP_{100} is 736 $kgCO_2e/m^2$. The product stage [A1-A3] impacts account for 95 % of the A1-A5 GWP_{100} impacts, with A4 and A5 accounting for 2 % and 3 % of the total, respectively. Table 6 provides a breakdown of the A1-A3 GWP_{100} by building element. The breakdown of the A1-A3 GWP_{100} impacts corresponds to the building element classification presented in Fig. 3 and discussed in Section 3.2.3.

4.2. Operational energy use impacts [B6]

The GWP_{100} of the building's operational energy use [B6] was calculated by assuming that one year of consumption data is representative for all years in the reference study period. The total

Table 5
Summary of product and construction stage [A1-A5] impacts with contribution analysis.

Impact Category	A1-A5 Total	Unit	A1-A3 1-Substructure	A1-A3 2-Superstructure	A1-A3 3-Finishes	A1-A3 5-Services	A4	A5
Fine particulate matter formation	280	Kg fine particulate matter equivalent ($PM_{2.5}$ eq)	8%	55%	1%	37%	2%	4%
Fossil resource scarcity	40,270	kg oil eq	13%	61%	0%	21%	3%	3%
Freshwater ecotoxicity	47,080	Kg 1,4-dichlorobenzene (1,4-DCB)	3%	22%	0%	75%	0%	0%
Freshwater eutrophication	90	kg phosphorus equivalent (P eq)	6%	38%	0%	55%	0%	0%
Global warming (GWP_{100})	136,710	kg CO_2e	12%	62%	0%	20%	2%	3%
Human carcinogenic toxicity	480,640	kg 1,4-DCB	5%	33%	0%	62%	0%	0%
Human non-carcinogenic toxicity	32,700	kg 1,4-DCB	10%	79%	0%	11%	0%	0%
Ionizing radiation	9350	Kilobecquerel cobalt-60 equivalent (kBq Co-60 eq)	11%	53%	0%	31%	1%	4%
Land use	690	Land occupation crop equivalent (m^2a crop eq)	10%	68%	1%	9%	12%	1%
Marine ecotoxicity	53,690	kg 1,4-DCB	3%	23%	0%	74%	0%	0%
Marine eutrophication	5.5	kg nitrogen equivalent (N eq)	10%	55%	3%	31%	0%	1%
Mineral resource scarcity	330	kg copper equivalent (Cu eq)	3%	39%	0%	58%	0%	0%
Ozone formation, Human health	380	kg nitrogen oxides equivalent (NO_xe)	8%	52%	0%	23%	4%	13%
Ozone formation, Terrestrial ecosystems	390	kg NO_xe	8%	52%	0%	23%	3%	13%
Stratospheric ozone depletion	0.07	kg chlorofluorocarbon equivalent (CFC11 eq)	6%	57%	1%	28%	3%	4%
Terrestrial acidification	940	kg sulphur dioxide equivalent (SO_2e)	5%	40%	1%	51%	1%	2%
Terrestrial ecotoxicity	2,172,540	kg 1,4-DCB	2%	16%	0%	80%	2%	0%
Water consumption	608,180	m^3	9%	59%	0%	26%	0%	6%

Table 6
A1-A3 GWP_{100} impacts by building element classification.

Building element classification	Building element		A1-A3 GWP_{100} [$kgCO_2e/m^2$]	Percent of A1-A3 impacts
1 Substructure	1.1	1.1.1 Standard foundations	27	4 %
		1.1.3 Lowest floor construction	58	8 %
2 Superstructure	2.1 Frame		113	16 %
	2.3	2.3.1 Roof structure	90	13 %
		2.3.2 Roof coverings	25	3 %
	2.5	2.5.1 External walls	119	17 %
		2.5.3 Solar/rain screening	27	4 %
	2.6	2.6.1 External windows	43	6 %
		2.6.2 External doors	7	1 %
	2.7	2.7.1 Walls and partitions	33	5 %
3 Finishes	3.1 Wall finishes		2.3	<1 %
	3.2 Floor finishes		<1.0	<1 %
	3.3 Ceiling finishes		1.0	<1 %
5 Building services	5.1 Sanitary installations		<1.0	<1 %
	5.4	5.4.2 Cold water distribution	2.0	<1 %
		5.4.3 Hot water distribution	1.0	<1 %
	5.7	5.7.1 Ventilation ducts	11	2 %
	5.8	5.8.1 Electrical mains	9	1 %
		5.8.5 Local electricity generation	127	18 %

annual energy consumption of the building is 72 kilowatt hours per square metre per year [$kWh/m^2/year$], of which 53 $kWh/m^2/year$ is grid electricity. The use of grid electricity includes the direct consumption of grid electricity and the use of grid electricity to charge the building's batteries. The remainder of the building's energy consumption is satisfied by the BIPV either through direct consumption (35 $kWh/m^2/year$) or consumption via the batteries (14 $kWh/m^2/year$). The embodied GWP_{100} impacts of the batteries and BIPV are included within the A1-A5 GWP_{100} results while the impacts from using grid electricity to charge the battery are accounted for within the operational energy use impacts [B6]. Therefore, the use of electricity from the BIPV and battery systems is assigned an operational carbon intensity of 0 $kgCO_2e/kWh$. Attributing a carbon intensity to the use of the BIPV and batteries would double-count the GWP_{100} impacts attributed to these technologies. In addition, the building exported 26 $kWh/m^2/year$ to the grid over the course of the assessment year. The benefits from exporting electricity are not included within the scope of this study and will be the subject of future work to fully investigate system boundaries, marginal emissions factors and energy system operation schemes.

As indicated by Fig. 5, under a constant grid carbon intensity (GCI), the cumulative B6 GWP_{100} would exceed the A1-A5 GWP_{100} after 49 years of operation. A GCI of 0.283 $kgCO_2e/kWh$ (BEIS, 2018) has been used as the constant GCI for this study to correspond with the first year of building operation. The use of a constant GCI is suggested by EN 15978 to reduce uncertainty (BSI, 2012; RICS, 2017). However, a constant GCI does not capture the dynamic nature of the UK's changing GCI. In order to account for the decarbonisation of the UK grid, the projected GCI for the 'Gone Green' and 'Slow Progression' *Future Energy Scenarios* provided by National Grid (National Grid, 2016). As described by National Grid (National Grid, 2016), 'Gone Green' represents a high investment, high ambition scenario where "policy interventions and innovation are both ambitious and effective in reducing greenhouse gas emissions". Meanwhile, 'Slow Progression' represents a scenario where policy is set up to enable decarbonisation but there is a lack of economic investment to drive a reasonable transition to a low carbon world (National Grid, 2016). The GCI for both the 'Gone Green' and 'Slow Progression' scenarios are presented in Fig. 6. The associated B6 GWP_{100} impacts for a constant GCI, Gone Green and Slow Progression decarbonisation are presented in Fig. 5. In contrast to the constant GCI, the B6 GWP_{100} for a 60-year reference study period is <50 % of the A1–5 GWP_{100} when the Gone Green scenario is used to model grid decarbonisation.

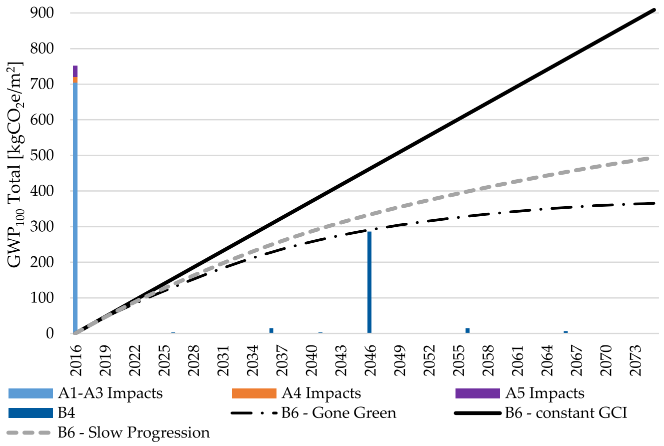

Fig. 5. Total global warming potential by life cycle stage for the 60-year reference study period.

5. Discussion

The discussion section has been subdivided into subsections to enable focused discussions for: comparing the case study building to current target values and the ability to capture aspects of material reuse and circularity in target values (Section 5.1); the intricacies surrounding modelling the end-of-life impacts for DfD buildings (Section 5.2); and the importance of Module D within the context of DfD and circular economy design strategies (Section 5.3). End-of-life and Module D are not well implemented within most LCAs for buildings and this is reflected within the scope for current target values introduced in Section 2.3 and further discussed in Section 5.1. The limitations for the presented work are outlined in Section 5.4.

5.1. Target values

5.1.1. Comparison to industry target values

The results from this study are compared to the benchmarks and targets produced by LETI (LETI, 2020b, 2020a) and GLA (GLA, 2022) in Table 7. The baseline values from LETI and GLA represent the scenario when no embodied carbon reduction strategies are implemented (GLA, 2022; LETI, 2020a). Since the case study building has educational and office facilities, it's energy use intensity (excluding on-site renewables) is compared against both target values published by LETI. It is important to note that the case study building was designed and built in 2016, prior to both sets of benchmarks being published.

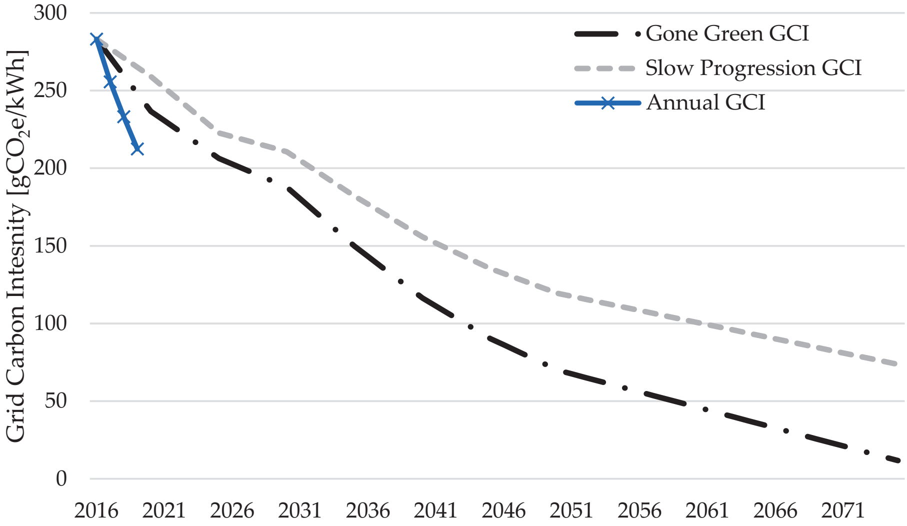

Fig. 6. Projected grid decarbonisation scenarios.

The considered target value schemes for the UK are aligned with the ambitions for those developed for other European countries as presented by Frischknecht et al. (2019b). The primary focus within the UK is reducing upfront [A1-A5] carbon emissions while maintaining low operational energy usage [B6]. However, efforts to increase material reuse and reusability by transitioning to a more circular built environment go beyond the scope for these A1-A5 and B6 target values. The targets from LETI for the amounts of reused materials and amounts of materials suitable for reuse at end-of-life, are not reflected in other target value schemes across Europe (Frischknecht et al., 2019a, 2019b; LETI, 2020a). These targets are further discussed in Section 5.1.2.

The scope of target value schemes should be expanded to encompass aspects of sustainability not currently represented by targets for carbon emissions nor operational energy use. As discussed in Section 4.1.1, the GWP_{100} impacts shared the same pattern in the contribution analysis as seven other impact categories. Unfortunately, 10 impact categories do not share this pattern and the use of current targets might overlook increases in these other impact categories. However, a balance needs to be found where enough impact categories are represented while not providing so many targets that building designers are unable to make decisions due to an overload of objectives. Therefore, the representativeness of different impact categories needs to be further investigated to identify target values that can be used to represent multiple impact categories.

5.1.2. Additional metrics to track sustainability

To assess whether the considered target values are suited to promote the implementation of circular design strategies, the system boundaries and scope need to be considered instead of just the target values themselves. The RIBA 2030 Climate Challenge targets encompass the full life cycle for a building and have a statement to “use circular design strategies” within the notes for the embodied carbon targets (RIBA, 2021). However, RIBA does not indicate what a circular design strategy is nor what assumptions or additional considerations need to be made when assessing these strategies.

In addition to the standard carbon targets set by LETI, the “reused” and “reusable” targets act as measures to track the percentages of materials, by mass, that are reused and designed to be reused, respectively (LETI, 2020a). An entirely circular built environment would use salvaged, or reused, materials for all aspects of new construction and ensure all building designs will enable the disassembly and subsequent reuse of materials at end-of-life (Eberhardt et al., 2020a; Rahla et al., 2019; Reike et al., 2018). Therefore, following the LETI targets, an entirely circular building would be constructed using 100 % reused materials and would be constructed to enable 100 % of these materials to be reused at end-of-life. As such, meeting the “reused” and “reusable” LETI targets provide a tangible metric, separate from the building's environmental impacts, that can be used to track increases in circularity of materials within the built environment.

For the case study building, the direct reuse of the panelised building fabric would divert approximately 29 t of materials from landfill and an additional 10 t of materials from recycling routes based on current industry practice. To put this into context, the mass for the building's substructure and superstructure is approximately 62 t. In total, 100 % of the building's substructure and 64 % of the building's superstructure, by mass, has been designed for reuse. If no materials are reused at end-of-life, 33 t of materials within the building's substructure and superstructure are suitable for recycling based current industry practice.

5.2. End-of-life

The end-of-life for buildings is subjected to high levels of uncertainty regarding when the building will be deconstructed and what will happen to the materials after their initial life (Bertin et al., 2019; Huuhka and Lahdensivu, 2016; Joensuu et al., 2022). Anderson et al. (2019) highlight that end-of-life is seldom reported in assessments for whole buildings that use traditional construction techniques. As such, it would be advantageous to gather detailed information when DfD buildings are disassembled in real-world cases to build more representative assumptions for the end-of-life impacts of DfD buildings. Until more

Table 7
Comparison of the case study building against industry benchmarks.

Metric	Case study building	LETI	GLA
Embodied carbon [A1-A5] [kgCO$_2$e/m^2]	736	Baseline: 1000 2020 target: <600	Baseline: <750 Aspirational: <500
Operational energy [kWh/m^2/year]	53 (grid electricity use)	55 (office) 65 (school)	N/A

representative information is available for the end-of-life of DfD buildings, it may be more appropriate to consider the amounts of materials that will be diverted from landfill if DfD practices are used to enable the reuse of building materials, as presented in Section 5.1.2.

The interlocking connections of the panelised building fabric will enable the building to be deconstructed in a reverse manner from which it was constructed. Therefore, the GWP_{100} for deconstruction [C1] will be approximately the same magnitude as that for the construction stage [A5]. Thus, following a 100–0 approach as suggested by ISO 15804 (BSI, 2020b), the GWP_{100} for deconstruction [C1] is estimated to be approximately 30 $kgCO_2e/m^2$ assuming today's technologies. Aligned with the delineation between end-of-life (Module C) and Module D discussed in Section 3.2.4, the panelised system and all elements designed to enable reuse will incur no environmental impacts associated with C2 – Transport, C3 – Waste Processing, nor C4 – Disposal.

5.3. Module D – benefits and loads beyond the system boundary

Within the context of the built environment, Module D quantifies the net environmental impact that may result from reuse and recycling of building materials, and energy recovery, among others (BSI, 2012). For the case study building there are anticipated Module D benefits that result from the panelised building fabric and the ability to export electricity back to the grid. Module D incurs significant levels of uncertainty due to: the inability to guarantee that the planned end-of-life scenario will actually occur; lack of guarantee that building elements will be suitable for reuse after deconstruction; and, the use of current technologies and GCIs to estimate benefits and loads that are likely to happen decades in the future (Delem and Wastiels, 2019; Rasmussen et al., 2019).

The reuse of the building's panelised building fabric will displace the raw material usage, and production impacts, associated with the production of new panels to fulfil the same purpose. The initial A1-A3 GWP_{100} of the panels is 440 $kgCO_2e/m^2$; this gives an indication of the Module D benefits that the panels will provide by avoiding production of the same set of panels from raw materials. However, by the time the panels are reused, the avoided production systems may have changed compared to today's technology, so the avoided GWP_{100} may differ from 440 $kgCO_2e/m^2$.

In addition, the building is equipped to export additional electricity to the grid due to the on-site energy generation and on-site energy storage systems. The building exported a total of 4836 kWh of electricity to the grid in 2016. Using a current GCI to calculate anticipated Module D benefits of exporting electricity will likely over-estimate these benefits over the full life span of the building in locations with decarbonising grids, such as the UK. A detailed investigation into the export of electricity from a building to the national grid system will be the subject of future work.

5.4. Limitations

The following limitations have been identified for the presented work:

I. The study uses one year of building operational energy use data to represent the annual use for the entire reference study period. Therefore, changes in user demand profiles over time are not accounted for.
II. The end-of-life impacts are estimated and subject to uncertainty. For example, the integrated panel system is designed to enable reuse of the building fabric and structural system. However, as this is the first building to employ this system at building-scale, the effectiveness and reusability of the integrated panel system will only be ascertained once the building has been deconstructed and the panels used for a new building.
III. The environmental impacts for the case study building are only compared against target values for buildings within the UK. This was deemed appropriate as the building is constructed within the UK. Similar buildings would have to be investigated in different geographies to assess how these buildings perform against their respective geography's target value schemes.
IV. LCA was not used to inform the design of the building, but rather after the construction of the building. Therefore, the LCA results presented are unlikely to represent the lowest possible impacts that can be achieved for a building equivalent to the case study building assessed.

These limitations do not diminish the presented findings, discussion nor the conclusions. However, the limitations should be considered when contextualising the presented work among other studies and when proposing future work as discussed in Section 6.

6. Conclusions

The presented work uses life cycle assessment (LCA) to quantify the environmental impacts of a novel design-for-disassembly (DfD) building, located in Swansea, UK. 8 of the 18 impact categories, including GWP_{100}, have the same rank order of product stage [A1-A3] and construction stage [A4-A5] impacts when the A1-A3 impacts are subdivided into the considered building elements. The A1-A3 impacts for the superstructure and building services contributed at least 75 % to the A1-A5 impacts across all impact categories. Current UK target values focus on driving reductions in carbon emissions across the life cycle of buildings, with an emphasis on upfront embodied [A1-A5] impacts. These target values are well suited to drive change but focus on one specific aspect of sustainability. Therefore, target values in the UK should be expanded to encompass more environmental indicators, providing a more holistic view of sustainability. Future studies should investigate patterns among the rank order for building elements and life cycle stages for large numbers of buildings to assess whether generalisations can be made regarding the representativeness between different impact categories. If generalised patterns can be identified across multiple impact categories, then additional sets of targets values should be developed to capture aspects of sustainability not currently represented by the targets for GWP_{100} and operational energy use.

The presented work highlights the importance of understanding the delineation between end-of-life and Module D for materials and components within a circular economy. The targets for the amounts of reused materials and reusable materials, presented by the London Energy Transformation Initiative (LETI), act as tangible metrics for tracking increases in circularity within the built environment without discounting, or allocating, environmental impacts for materials designed for multiple lifespans. Additionally, these simple targets are not plagued by the uncertainty and assumptions that typically hinder the confidence of end-of-life impacts in building LCAs and capture aspects of sustainability that are not easily translated within commonly assessed impact categories. These simple metrics should be used to track circularity within the built environment until more work is done to gain a better understanding of how end-of-life impacts for DfD buildings differ from those of traditional buildings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.03.001.

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