Building and Environment 275 (2025) 112823

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Embodied carbon in mechanical, electrical, and plumbing systems: A critical literature review

Matt Roberts [a,*], Claudiane Ouellet-Plamondon [b], Paul Raftery [a]

[a] Center for the Built Environment, University of California Berkeley, USA
[b] Ecole de technologie superieure, University du Quebec, Canada

ARTICLE INFO

Keywords:
Life cycle assessment (LCA)
Mechanical, electrical, plumbing (MEP) systems
Greenhouse gas (GHG) emissions
Net-zero carbon
Building decarbonization
Environmental impact

ABSTRACT

The environmental impacts of mechanical, electrical and plumbing (MEP) systems have been largely overlooked and are commonly excluded from building-scale life cycle assessments (LCAs). Understanding the impacts and reduction potential of these systems is crucial for decarbonizing retrofits and new buildings. Therefore, we have conducted a critical review of LCA studies on MEP systems in buildings, selected using a systematic method, to identify: 1) estimates for upfront embodied [A1-A5] and replacement [B4] carbon impacts; 2) LCA reporting fundamentals needed to ensure transparency and interpretability of results; 3) future research directions. Since 2016, 54 studies presented sufficient information to investigate presented methodologies and LCA results of MEP systems. The review reinforces the need to report environmental impacts by individual life cycle stages and building or system elements to interpret influencing factors and enable further utility of results. Two studies did not report the impact assessment method nor background dataset used for the assessment rendering their results incomparable with others and are excluded from analysis. Based on the median (and mean) of the reviewed studies, estimates for A1-A3 and A1-A5 of the MEP systems are 40 (49) and 49 (61) $kgCO_2e/m^2$, respectively. Additionally, based on reviewed studies, the systems will be replaced at least twice throughout a 60-year reference study period leading to approximately 100 $kgCO_2e/m^2$ for B4. These values almost certainly underestimate actual impacts due to the incomplete physical scopes spanned by the studies. Studies with more complete scopes generally reported higher values. The variability in scopes covered, reporting practices, and values reported, and the relatively small number of studies found, highlight the need for further investigation and improvement. Ten key research needs are identified, including the impact reduction potential of MEP systems and the influence of system layout and typology on the reported impacts. Additionally, future research should develop system specific benchmarks and reduction strategies while moving away from purely descriptive studies that report environmental impacts using single-point values.

1. Introduction

The timeline established by the Paris Agreement to achieve net-zero carbon emissions by 2050 strives to ensure global temperature rise remains below 2 ° Celsius [1]. This target places considerable attention on the built environment as it contributes 37% of global energy-related greenhouse gas (GHG) emissions [2]. To hold the built environment accountable and chart a path to a net-zero reality, the World Green Building Council (WorldGBC) established initial commitments to achieve net-zero carbon for the operations of new buildings by 2030 and all buildings by 2050 [3]. These initial commitments were quickly expanded to recognize the importance, both in terms of magnitude and timing of emissions, associated with the embodied carbon impacts of buildings [4]. Environmental impacts occur throughout all stages of a building's life. These impacts are commonly categorized into operational and embodied impacts [5,4]. The operational impacts of a building focus on the energy and water use that occur throughout the building's life. Whereas, embodied impacts are associated with the processes and activities related to raw material extraction, manufacturing, transportation, construction, repair, maintenance, refurbishment, deconstruction, waste processing and disposal. To provide a consistent framework and terminology, the environmental impacts of a building are categorized into a series of life cycle stages, as defined by EN 15804:2012+A2:2019 [6] and EN 15978:2011 [7].

---

[*] Corresponding author.
E-mail address: matt.roberts@berkeley.edu (M. Roberts).

https://doi.org/10.1016/j.buildenv.2025.112823
Received 28 October 2024; Received in revised form 24 February 2025; Accepted 4 March 2025

Fig. 1.1 illustrates the life cycle stages of a building and highlights how they are classified as operational and embodied impacts. Table 1 further defines the operational and embodied impact classifications. Module D is used to describe the environmental benefits and impacts outside the system boundary of the assessment which can include material reuse, material or energy recovery, recycling, export of energy.

Life cycle assessment (LCA) is an internationally recognized framework for determining the environmental impacts, including GHG emissions, across all stages of a product or system's life cycle [8–10]. LCA has been rapidly adopted as the predominant means of quantifying the environmental impacts of buildings and infrastructure. Yılmaz and Seyis [11] and Bahramian and Yetilmezsoy [12] highlight the growth of publications focused on using LCA within the built environment and the construction industry. Through a bibliometric analysis, Zeng and Chini [13] found an increasing focus on embodied carbon in published literature since 2014. The increased focus on embodied impacts of buildings signifies a growing recognition that the timing of emissions is crucial for meeting near-term climate targets. The upfront embodied carbon [A1-A5] impacts occur prior to the building being operated and cannot be mitigated once the building is complete. Therefore, understanding the magnitude and reduction potential of different building elements is crucial for identifying and implementing economically efficient impact reduction strategies.

The growing volume of literature on LCA and embodied carbon in buildings has been coupled with several reviews that aim to summarize, synthesize and critique past work to varying levels of success. Cabeza et al. [14] found early building-LCA studies focused on exemplary buildings that demonstrated novel low-energy or low-impact design principles instead of standard practice. Anand and Amor [15] highlighted the complexity of conducting a building-scale LCA and summarize research gaps that include: missing data for certain building elements; issue with comparability between studies; and lack of consistency regarding the system boundaries and functional units, among others. Pomponi and Moncaster [16] identified strategies for reducing the embodied carbon of buildings and highlighted that studies often overlook the embodied impacts that occur during the use phase [B1-B5] and end-of-life [C1-C4]. Thibodeau, Bataille, and Sié [17] and Vilches, Garcia-Martinez, and Sanchez-Montañes [18] reviewed studies that focused on building rehabilitation and refurbishment, respectively. Thibodeau, Bataille, and Sié [17] summarized how well studies adhere to reporting principles outlined in standards and guidance documents and found greater consistency in methodological choices in studies that followed guidance documents as opposed to standards. The studies reviewed by Vilches, Garcia-Martinez, and Sanchez-Montañes [18] focused on energy retrofits of the building fabric but did not consider how energy retrofits can extend the service life of the building nor the building systems. Other reviews have focused on LCAs of mass timber [19], the integration of building information modeling (BIM) and LCA [20], development of environmental benchmarks for buildings [21] and methods to visualize LCA results during the design process [22]. Even with the growth and prevalence of the research area, significant research gaps persist. Multiple reviews identify issues pertaining to consistency of methodological choices, functional units and system boundaries as well as lack of data for excluded scope.

Table 1
Scope of life cycle stages included in embodied and operational impact definitions.

Impact classifications	Life cycle stages included per EN 15978 [7]
Upfront embodied impacts	A1-A3, A4, A5
Recurring (in-use) embodied impacts	B1-B5
Operational impacts	B6, B7
Whole-life embodied impacts	A1-A3, A4, A5, B1-B5, C1-C4

Most building-scale LCAs have focused on the substructure, superstructure and enclosure [23,24]. Little attention has been placed on the mechanical, electrical, plumbing (MEP) services, interiors, and site impacts [24,25]. Additionally, the replacement, maintenance and end-of-life cycle stages are typically based on generalized assumptions and scenarios, if they are included at all [5,16,26]. In practice, the built environment is implementing strategies to reduce GHG emissions while simultaneously developing a better understanding of the true magnitude of environmental impacts for all building elements across all life cycle stages [27–29]. Through an analysis of 238 case studies, Röck et al. [28] found an overall increase in the magnitude of embodied impacts as we shift towards "new advanced" buildings (i.e. buildings that follow passive house principles and incorporate net-zero energy or net-zero emission strategies). These buildings typologies often employ more advanced building systems. To support the integration of these

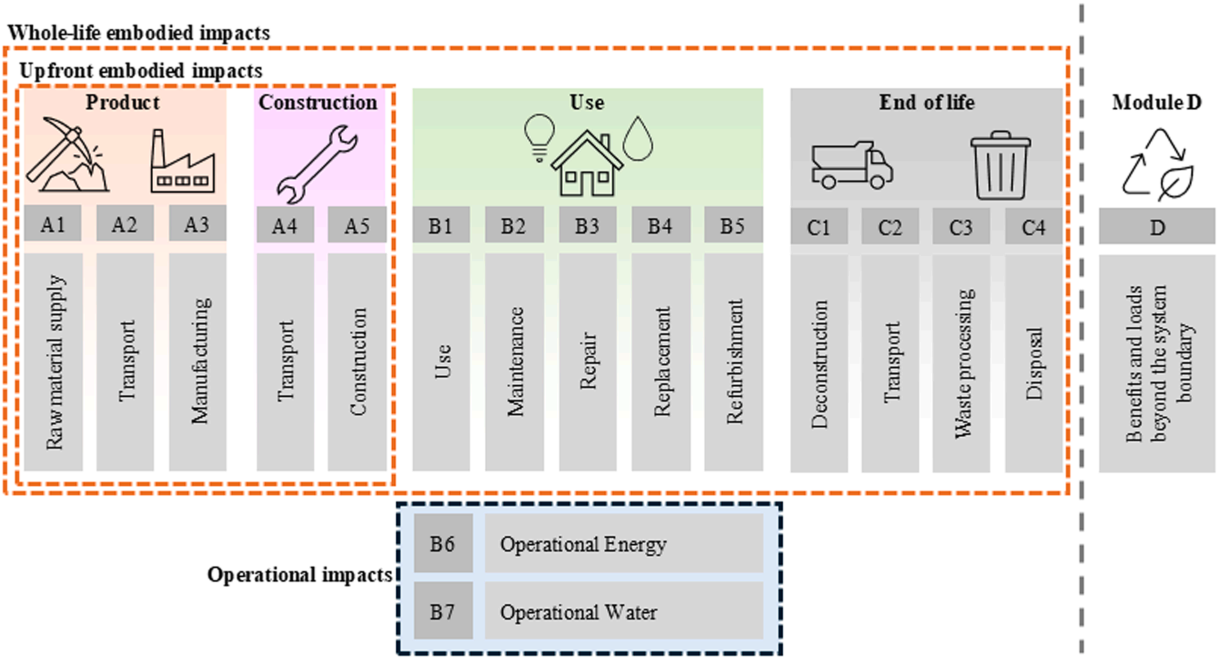

Fig. 1.1. Life cycle stages as defined by EN 15804:2012+A2:2019 [6].

technologies, research has been undertaken to understand the environmental impacts of: photovoltaic (PV) systems [30,31] including thin-film technologies [32]; energy storage systems [33] including lithium-ion batteries [34,35]; smart grids/technologies that incorporate PV, energy storage systems and buildings [36]; geothermal heating [37] and power generation [38,39]; and the use of phase change materials in buildings [40]. The novelty of these newer "clean" technologies can be argued to have overshadowed the lack of understanding surrounding the environmental impacts associated with the more traditional MEP systems in buildings.

To date, there has not been a review that critically analyses the inclusion of MEP systems within past LCA studies. Therefore, we have conducted a critical review of existing literature that includes the embodied impacts of MEP equipment in buildings. Litardo et al. [41] performed a systematic review of LCAs of air conditioning systems highlighting that the context surrounding energy generation mixes and climatic conditions must be considered when evaluating how impactful different air conditioning systems are. However, Litardo et al. [41] focuses on the systems themselves without considering how the associated impacts are reported and discussed within a building-scale LCA. Our study serves to improve the completeness of building-scale LCAs while highlighting good reporting practices for LCAs within the built environment to enable interpolation, interrogation and comparison within and between studies. It is important to note that articles focused solely on on-site or off-site energy generation and storage systems are not included as they have been the subject of previous reviews as introduced above. In summary, our study serves to:

1) Investigate recent LCA studies to determine a GHG estimate for MEP systems that can be used when project-specific information is not available;
2) Identify best-practices to improve reporting in LCA publications to enable for further comparability and interpolation between studies;
3) Formulate future research directions that should be investigated to advance the existing body of knowledge.

Our paper has been structured as follows: Section 2 outlines the methodology used to collect, screen and review the selected publications; Section 3 presents the main findings from the critical review with subsections on building characteristics, LCA methodological choices, and the reported impacts, respectively; Section 4 discusses the comparability and completeness of the reviewed publications, highlights exemplary studies for key considerations that should be included within all LCA publications and provides a lower bound estimate for the A1-A3, A1-A5 and B4 GWP impacts of MEP systems within a building; Section 5 outlines recommendations for future studies; Section 6 summarizes the main conclusions from this review. It is our intention that the main learnings from this review can be applied to LCA publications within the built environment regardless of the goal and scope of the assessment.

2. Method

We employed a combination of systematic and critical review principles, as described by Grant and Booth [42], to achieve our study goals. A purely descriptive literature review would not provide the analytical perspective necessary for achieving the goals set out for this review. We used a systematic approach to collect and sort through the pool of publications that pertain to the inclusion of MEP equipment within building-scale LCA. The systematic selection process ensures the quality and relevance of the reviewed literature to the research questions. The selected articles underwent a detailed critical review to enable discussions pertaining to methodological issues, reporting practices, and research gaps.

For this study, we sourced literature from Google Scholar using the advanced search function with Boolean operators. Initial literature searches were conducted in October 2023 using "building" and "life cycle assessment", returning ~135,000 results published since 2016. 2016 was used as the cut-off year for this study due to the emergence of industry initiatives and roadmaps as well as improved consistency and reliability of LCA methodological and reporting practices that has resulted from the publication of international standards (i.e.[6–9]). Additionally, as illustrated by Litardo et al. [41] more studies that focus on the life cycle assessment of air conditioning have been published since 2016 than from 2000–2016. To narrow the returned literature on the target research area a third keyword was added in independent searches. In total, 6 separate searches were conducted, returning a total of 46124 publications that were further screened to determine the relevant literature for this review. The independent searches were conducted to capture studies that focus on the environmental impacts of only one system, or a combination of systems included within the MEP designation. These search terms were devised to ensure that standard MEP systems and equipment, i.e. the mechanical, electrical and plumbing systems installed within a building to provide a functional and comfortable environment for the occupants and uses within the building as outlined in Table 2, would be captured within the returned literature. It is important to note that the categorization of systems and list of key components included in Table 2 are intended to reflect MEP systems in general and may not necessarily correlate nor reflect how these systems are reported or categorized in the reviewed studies. Additionally, search terms were devised to capture alternative or regional naming of systems (i.e. mechanical, mechanical ventilation, or heating ventilation and air conditioning (HVAC)). We conducted a second round of searches in September 2024 to capture articles published since the initial searches. Since the scope of this review is on the inclusion of MEP systems within building-scale assessments, it is plausible that system-level and component level assessments exist that may not be returned from the chosen search terms. However, we conducted preliminary searches to ensure appropriate coverage across system and building-scale assessments with the chosen keywords. Additionally, we conducted preliminary searches to ensure HVAC provided sufficient coverage across articles focusing on specifically on heating or air conditioning (AC) systems and to ensure MEP and HVAC provided sufficient coverage for articles focusing specifically on mechanical or mechanical ventilation systems.

Using Google Scholar's built-in algorithm to sort articles by relevance, we conducted a manual search via titles and keywords to identify articles with appropriate scope for inclusion in the review. Google Scholar's built-in algorithm searches the full text of the article, including the title, keywords, article text, abstract, authors, place of publication, and citations. Google Scholar results were searched until three consecutive pages of results did not return a relevant article for inclusion in this review. The identified articles underwent a preliminary systematic review to check titles, keywords and a visual inspection of figures and tables to ensure the chosen articles presented LCA results. In total, we reviewed 212 articles in more detail to ensure both alignment of the reviewed literature with the research questions and that an appropriate level of quality was present in the reviewed literature. The detailed review focused on identifying aspects of the articles that are necessary to interpret, understand, compare and replicate the LCA results presented, including: specification of systems and life cycle stages included in the system boundary, functional unit, and reference study period. For inclusion in the comparative figures and analysis presented in Section 3.3, the reviewed articles must report results for an attributional midpoint assessment and the reader must be able to interpret the product stage (cradle-to-gate) [A1-A3] global warming potential (GWP) impacts of the MEP system based on the presented results. Articles that did not specify the background dataset nor impact assessment method used to conduct the assessment were reviewed but excluded from the analysis presented due to the inherent uncertainties that arise from each of these and the inability to verify how LCA was conducted.

Fig. 2.1 provides a visual representation of the main steps used throughout the literature collection and screening process to select the

Table 2
Mechanical, electrical, and plumbing (MEP) systems included within scope of study.

System	System type	Key components
Mechanical (M)	Heating system[1]	-Boilers -Furnaces -Heat pumps -Radiators
	Ventilation system[1]	-Air handling units (AHUs) -Exhaust fans -Ductwork and diffusers -Fresh air intake systems
	Air conditioning systems[1]	-Chillers -Cooling towers -Split systems -Variable refrigerant flow (VRF) systems
	Fire protection (mechanical)[2]	-Smoke control systems -Fire dampers
Electrical (E)	Power supply and distribution	-Transformers -Switchgear -Circuit breakers and panels -Backup generators -Wires
	Lighting systems	-General lighting -Emergency and egress lighting -Perimeter and security lighting
	Low-voltage systems	-Fire alarms -Security and CCTV systems -Data and communication networks
Plumbing (P)	Water supply systems	-Pumps and pressure tanks -Water heaters and boilers -Domestic hot and cold water distribution
	Drainage and waste systems	-Sanitary drainage -Stormwater drainage -Grease traps and intercepts
	Fire protection systems (Plumbing)[2]	-Sprinkler systems -Standpipes and hose reels
	Specialty plumbing systems	-Gas supply systems -Water treatment and filtration -Greywater and rainwater harvesting
Hybrid & Controls[3]	Building management system (BMS)	-HVAC performance controls
	Control systems	-Building automation systems -Energy monitoring systems

Notes:
[1] included within heating, ventilation and air conditioning (HVAC) designation
[2] Fire protection may be reported based on their specific mechanical and plumbing characteristics or as a singular system grouping
[3] Hybrid and control systems can span across mechanical, electrical and plumbing designations. They are commonly the same physical system but with the ability to interact with specific mechanical, electrical or plumbing systems directly.

literature that has been reviewed as part of this study. Like other systematic literature reviews, such as Roberts et al. [10], we employed a systematic approach to select literature for review. However, instead of describing the reviewed literature to identify research trends or knowledge gaps, we critically review the inclusion of MEP systems within building-scale LCAs to identify areas of LCA reporting that can be targeted to improve transparency and interpretability of presented results while also identifying key research needs to support the of MEP systems within building-scale reporting and decarbonization efforts, A table is provided in the supplemental materials for this paper that summarizes key aspects of the reviewed studies as well as the environmental impacts that have been reported for each configuration of MEP system included within the presented results and discussion of our review. This table can be filtered to identify the papers that were included within the figures presented in Section 3 or to explore a specific reported aspect of the reviewed literature in more detail or to guide future work.

Following the systematic review process, 54 research articles underwent a detailed critical review for this study. This critical review does not intend to undermine nor diminish the outcomes and findings from the reviewed studies. Instead, our review highlights ways to improve the transparency, comparability and interpretability of published results while identifying areas that should be investigated to advance the field of knowledge. The following results and discussion sections have been formulated based on the critical review of the selected 54 research articles.

3. Results

The reviewed articles presented significant variability in the specificity and transparency for how the environmental impacts were quantified, discussed, and reported. Of the 54 papers reviewed, 37 papers provided sufficient information to interpret and compare the environmental impacts for the MEP systems included. Table 3 summarizes key methodological aspects of the studies included in the presented figures and analysis.

LCA results can be influenced by multiple factors including but not limited to the background dataset, impact assessment method and software used to conduct the assessment. 2 studies do not explicitly report the background dataset nor the impact assessment method, therefore hindering interpretation and comparability of the presented results. As such, these studies have been excluded from the figures and discussion presented in this review. From the 37 papers with sufficient information, 60 configurations of MEP systems are reported and discussed. The papers reviewed assessed buildings spanning 18 countries with the USA represented in 5 studies, Norway in 4 studies and China, Finland and Sweden each represented in 3 studies. Only 2 papers include case studies from multiple countries [56,78]. Fig. 3.1 illustrates the geographic distribution of the studies that have been reviewed as part of this study. It is important to note that no reviewed study represents a case study in the southern hemisphere highlighting a key geographic gap in the understanding of the environmental impacts of MEP systems.

Only two of the reviewed publications [79,80] followed a consequential methodology. Famiglietti et al. [79] employed a consequential methodology to assess a condensing boiler, gas absorption heat pump and electric heat pump across old, retrofitted and new buildings. Whereas Seuntjens et al. [80] assessed different ventilation strategies in a school building with a flexible floorplan. Consequential LCA assesses the marginal environmental impacts from changes in demand for goods and services [81]. All other reviewed studies follow an attributional methodology to describe the environmental impacts of the systems included within the scope of the respective assessments. It would be inappropriate to directly compare attributional to consequential LCA results due to the difference in modeled systems, background datasets and assessment goals [81]. Therefore, all results discussed within this paper are based on attributional LCAs. As such, the presented results may not be appropriate to use when inferring the change in environmental impacts due to changes in design decisions, system selection or other decisions that lead to change in demand.

3.1. Building characteristics

The reviewed MEP configurations correspond to 13 single-family residential, 10 multi-family residential, and 25 commercial buildings. Additionally, 12 buildings represent education, lab or public assembly typologies. 49 MEP configurations relate to new build projects and 8 relate to retrofit projects. Publications that assessed retrofit projects [44,47,52–54,77] included the full replacement of the reported MEP systems and therefore are compared directly against the installation of a new system in a new build project. Furthermore, 36 system configurations are based on real buildings with 22 using hypothetical or simulated building designs. Cai et al. [48] assessed a Library constructed in 2015 in

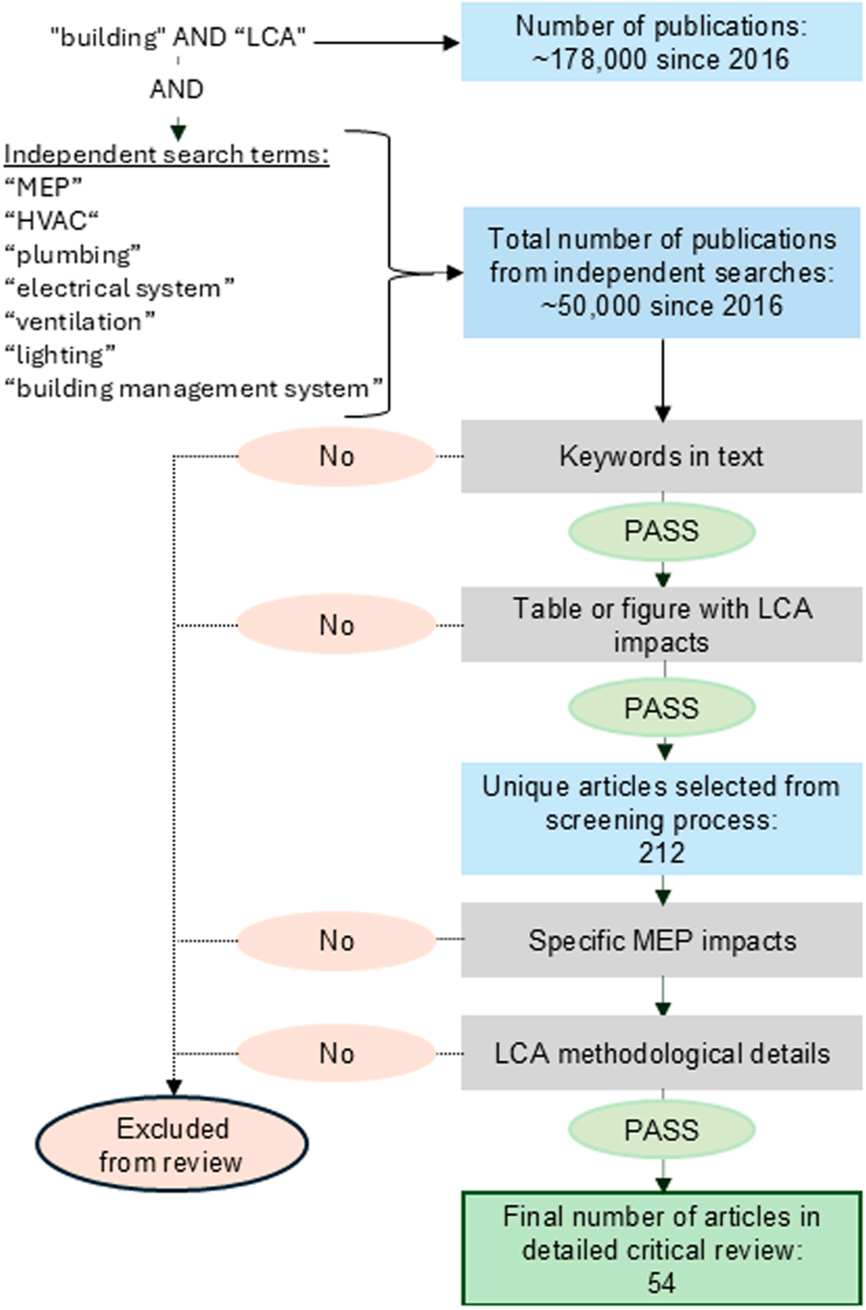

Fig. 2.1. Schematic diagram of screening process steps (shown in grey) used to select literature suitable for critical review.

Chicago, USA. Due to availability of data, Cai et al. [48] adopted the material estimates developed by Rodriguez et al. [25], who developed material quantity estimates (reported in kg/m^2) for hypothetical commercial buildings located in the Pacific Northwest based on input from an advisory committee. Rodriguez et al. [25] present 16 material quantity estimates that represent four ranges of building size each with two combinations of plumbing, HVAC and electrical systems for both the "standard" and "high-performance" designation. However, the material quantity estimates report total mass of materials per area (kg/m^2) and do not disclose the relative share of constituent material masses within the reported systems. Other reviewed studies used hypothetical or simulated buildings to assess: how building performance standards influences environmental impacts [71]; the influence of climate zone on energy consumption and operational carbon [59]; environmental impacts of different ventilation strategies [45]; and different insulation types with and without battery storage [70].

Several studies presented multiple scenarios to compare different options and investigate how these different variables influence the environmental impacts of the studied buildings. Goggins et al. [50] present 6 scenarios of a semi-detached house to study the impacts of four different building standards with the 2011 and NZEB standards having two different mechanical ventilation system specifications and airtightness levels. Kaspersen, Lohne, and Bohne [56] varied the number of floors for a hotel in Norway and a commercial office building in the USA to investigate if the number of floors influences the floor-area normalized GWP impacts of the mechanical ventilation, plumbing and elevator systems. Emami et al. [60] illustrate the difference in midpoint indicators that arise from the software used for the assessment by assessing two buildings with GaBi and SimaPro.

Table 3

Summary of critically reviewed studies that are included in presented figures and analyses. Studies that are bolded and marked with an * in the reference column are indicated as an exemplary study in Table 6.

Reference (* included in Table 6)	Country code[1]	System Code	MEP life cycle stages	RSP (years)	Background dataset	Impact assessment method	Software	Building type	LCI (Y/N)	Ref. Spec (Y/N)	Contribution analysis (Y/N)		Suppl. Material ID
											Physical	Temporal	
[43]	SE	MEP	A1-A3, B4	100	One Click LCA	EPD	One Click LCA	Res-S	N	N	Y	Y	1
[44]	SG	M	A1-A3, A4, C1-C4	20	Ecoinvent	CML	eBalance	Office	Y	Y	N	Y	3
[45]	CN	M	A1-A3	NA	CLCD, ELCD, ecoinvent,	NOS	eBalance	Education	Y	N	Y	NA	4
[46]	FR	M	A1-A3, A4, A5, B1, B2, B4, C1-C4	50	Ecoinvent	NOS	SimaPro, DyPLCA	Res-S	Y	Y	N	N	5
[47]*	**NO**	**M**	**A1-A3, A4, A5, B4-B5, C1-C4**	**60**	**One Click LCA**	**EPD**	**One Click LCA**	**Office**	**Y**	**N**	**Y**	**Y**	**6**
[48]	US	MEP	A1-A3, A4, B1	60	GREET	GREET	GREET	P.A.	Y	Y	N	Y	7
[49]*	**CH**	**MEP**	**A1-A5, B4, C1-C4**	**60**	**KBOB, ecoinvent**	**IPCC**	**SimaPro**	**Res-M**	**Y**	**N**	**Y**	**Y**	**8**
[50]*	**IE**	**M**	**A1-A3**	**60**	**ICE**	**ICE**	**NOS**	**Res-S**	**N**	**N**	**Y**	**NA**	**9**
[51]	CN	MEP	A1-A3	50	NBSC	ICE	NOS	Office	Y	N	Y	NA	10
[52]	NO	M	A1-A5	30	Ecoinvent	ReCiPe	SimaPro	Res-M	Y	N	N	NA	11
[25]	US	MEP	A1-A5, B4	60	EPD, ÖKOBAUDAT	NOS	NOS	Office	N	N	Y	Y	12
[53]	MX	M	A1-A5, C1-C4	25	NOS	TRACI	SimaPro	Education	Y	Y	N	Y	16
[54]*	**CA**	**M**	**A1-A3, A4, A5, B4-B5, C3-C4**	**60**	**One Click LCA**	**TRACI**	**One Click LCA**	**P.A.**	**Y**	**N**	**N**	**Y**	**17**
[55]	AT	MP	A1-A3, B4-B5, C3-C4	50	ÖKOBAUDAT	DGNB	LEGEP	Res-M	N	N	N	N	19
[56]	NO	MP	A1-A3	NA	EPD	ReCiPe	SimaPro	Res-M, Office	N	N	Y	NA	20
[57]*	**IN**	**M**	**A1-A3, A4, A5, B3, B4, C3**	**60**	**EPD, NOS, literature**	**NOS**	**NOS**	**Education**	**Y**	**Y**	**Y**	**Y**	**23**
[58]	NO	M	A1-A3, A5, B4, C1	60	EPD, ecoinvent	ReCiPe	SimaPro	Office	Y	N	Y	Y	24
[59]*	**US**	**M**	**A1-A5, B4**	**27–41**	**USLCI, ecoinvent**	**TRACI**	**SimaPro**	**Office**	**Y**	**N**	**Y**	**N**	**26**
[60]*	**FI**	**ME**	**A1-A3**	**NA**	**Ecoinvent**	**ReCiPe, TRACI**	**GaBi, SimaPro**	**Res-M, Res-S**	**Y**	**N**	**N**	**NA**	**27**
[61]	SE	M	A1-A3, A4-A5, B4, C1-C4	50	EPD, ILCD, ecoinvent	EPD	NOS	Office	Y	N	N	Y	29
[62]*	**US**	**MEP**	**A1-A3, B4**	**100**	**Ecoinvent, USLCI**	**TRACI**	**NOS**	**Office**	**Y**	**N**	**Y**	**Y**	**30**
[63]	FI	MP	A1-A5, B1-B5, C1-C4	50	One Click LCA	NOS	One Click LCA	Res-M	N	N	N	N	31
[64]	DK	MEP	A1-A3, A4, B4, C3, C4	80	Ecoinvent	DGNB	OpenLCA	Office	Y	N	N	N	32
[65]	CN	MEP	A1-A5	50	NOS	NOS	NOS	Res-M	Y	N	Y	NA	33
[66]*	**IT**	**ME**	**A1-A3**	**100**	**Ecoinvent**	**EPD**	**SimaPro**	**Res-M**	**Y**	**N**	**N**	**NA**	**34**
[67]*	**AT**	**MEP**	**A1-A3, A4, B4, C2, C4**	**50**	**Ecoinvent**	**IPCC, CED**	**SimaPro**	**Lab**	**Y**	**N**	**Y**	**Y**	**35**
[68]	ES	MP	A1-A3, A4, A5	10	CYPE	CYPE	CYPE	Res-S, Res-M	Y	N	N	Y	36
[69]*	**CH**	**M**	**A1-A3, B4, C3-C4**	**60**	**KBOB, ecoinvent**	**NOS**	**SimaPro**	**Office**	**Y**	**N**	**Y**	**Y**	**38**
[70]	IT	MP	A1-A3, B4, C1-C4	60	Ecoinvent	EN15804+A2	NOS	Res-S	Y	Y	N	Y	40
[71]	IE	ME	A1-A3,A4, B2,B4, C2-C4	60	Ecoinvent	CML	NOS	Res-S	Y	N	N	N	41
[72]	GB	MP	A1-A3	60	Ecoinvent	ReCiPe	OpenLCA	Education	Y	N	Y	NA	57
[73]	FI	MEP	A1-A3, B4,C3,C4	50	Finnish database	FMoE	Excel	Office	N	N	N	N	60
[74]	DE	M	A1-A3, B4,C3,C4	50	ÖKOBAUDAT	NOS	eLCA	Res-S, Res-M	Y	N	N	N	61
[75]*	**SE**	**MEP**	**A1-A3**	**NA**	**EPD, generic data**	**EPD**	**NOS**	**Education**	**N**	**N**	**Y**	**NA**	**64**
[76]	US	M	A1-A3	15	USLCI	IPCC	OpenLCA	Res-S	Y	Y	N	NA	70
[77]*	**ES**	**M**	**A1-A3,B4**	**50**	**Ecoinvent**	**ReCiPe**	**SimaPro**	**Office**	**Y**	**N**	**N**	**Y**	**85**

Notes: [1]Alpha-2 code based on ISO 3166. MEP LC stages: Reported life cycle stages for MEP systems; RSP: Reference study period; LCI: life cycle inventory; Ref. Spec: Refrigerant specified.
Acronyms: NA: Not applicable; NOS: not otherwise specified; P.A.: Public Assembly; Res-S: Single-family residential; Res-M: Multi-family residential; NBSC: National Bureau of Statistics of China.

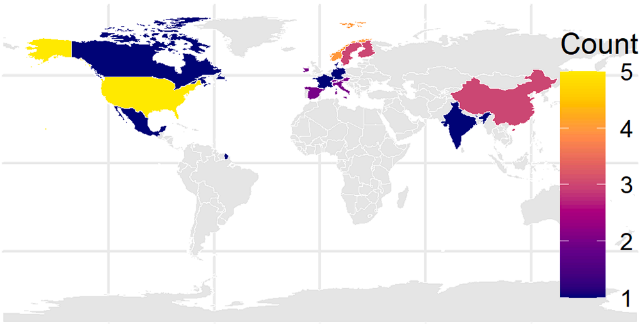

Fig. 3.1. Geographic distribution of reviewed studies.

3.2. LCA of MEP systems

There are various types of mechanical, electrical and plumbing systems, as introduced in Table 2, each with their own set of constituent components, materials and performance specifications that can influence the environmental impacts of the complete system and therefore the entire building. From the 37 papers included in this analysis, all included some scope of mechanical system, 2 include mechanical and electrical, 6 include mechanical and plumbing, and 11 included scope across mechanical, electrical and plumbing systems. However, 21 of the studies reviewed in detail do not describe the systems included within the study scope beyond their generic typology (i.e. HVAC, electrical, plumbing). Other studies report system characteristics to varying levels of specificity in tables [57,68,70,71] or use a combination of system schematics, in text descriptions and tables to convey the system characteristics [44,50]. A few studies did not directly provide system performance specifications but provided detailed material breakdowns of the constituent components included within the system boundary of the assessment [67,69]. Additionally, the reviewed studies were not consistent in disclosing whether the assessment scope included both equipment (chillers, air handling units, hot water tanks, etc.) and distribution systems (ventilation duct work, distribution pipes, electrical wiring, etc.) and whether fittings, ancillary accessories and valves were included.

The level of specificity in the reported MEP system GWP impacts ranged from single-point values representing all systems and life cycle stages included within the scope of the assessment [46,55,63,64,71,73,74] to studies that report disaggregated GWP impacts for the initial construction (i.e. A1-A3, A4, A5) [68] and studies that include disaggregated upfront, use and end-of-life impacts [47,54,57,61,67]. Additionally, 21 studies report fewer life cycle stages for the embodied impacts of the MEP systems than the other building elements included in the system boundaries of the respective studies. Fig. 3.2 visualizes the percent of times each life cycle stage was reported in the individual system configurations from the reviewed literature regardless of whether the impacts were reported as individual disaggregated impacts or a cumulative impact for multiple life cycle stages. Research and reporting practices have focused on the upfront product and construction stage impacts [A1-A5] and replacement impacts [B4] while other use stages and end-of-life impacts have been excluded from most studies.

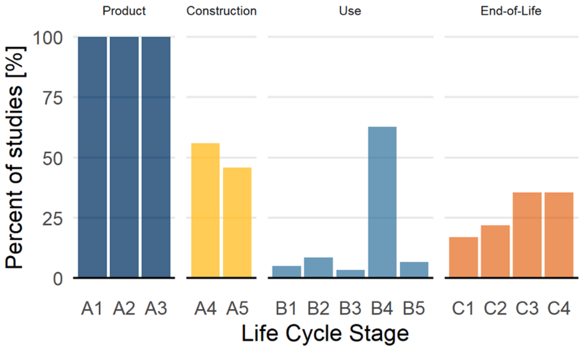

Fig. 3.2. Percent of studies that report life cycle stages, excluding operational stages [B6 & B7] and Module D.

Only 5 studies explicitly state the refrigerant type used within the mechanical system and the assumptions used to assess the GWP impacts associated with refrigerant leakage across the reference study period. Commonly used refrigerants are known to have high GWP impacts. Therefore, the transition to low-GWP refrigerants, low leakage detection and leak mitigation are seen to be crucial steps in decarbonizing the building stock. The leakage of refrigerants should be assessed and reported as a B1 stage impact as it is a fugitive emission. Since only 3 papers include B1 within their system boundary, this highlights critical gaps within how system boundaries are defined, the important building elements and life cycle stages that are included within the assessment scope, the assumptions used to model these emissions and the information gathered and reported to provide a transparent and reproducible assessment.

3.2.1. Impact assessment method and background data

Due to the focus of this review, global warming potential (GWP) was reported in every study reviewed. 20 papers only reported GWP impacts and 9 papers only report the material production [A1-A3] impacts for the systems included. Of these, 6 studies ([45,50,51,56,75,76]) report solely GWP for A1-A3 impacts, this represents the minimum acceptable scope for inclusion within this study. Beyond GWP, acidification was reported in 13 studies, ozone depletion was reported in 10 studies and photochemical ozone formation was reported in 10, making them the most common midpoint point indicators reported alongside GWP.

Heinonen et al. [82], Botejara-Antúnez et al. [83], Haddad et al. [84] and Decorte et al. [85] present detailed studies of a low energy apartment building, HVAC ductwork in healthcare buildings, a comparison of natural gas and solar heating hot water building systems in a multi-family residential building, and the importance of technical systems in a single-family home, respectively. These studies report environmental impacts using an endpoint analysis. Endpoint analyses simplify the interpretation of results as it summarizes the environmental impacts from 18 different midpoint categories into three categories representing the environmental impact to human health, ecosystems and resource depletion [82,84,86]. Additionally, as presented by Emami et al. [60] common LCA tools can lead to large differences in reported impacts for impact categories other than climate change (i.e. GWP). The primary focus of this article is how GWP, a midpoint indicator, is handled within MEP studies, as such the reported endpoint impacts are not included within the presented figures and analysis. However, these studies present considerable quality and transparency in the methodological considerations and LCI reporting. Therefore, these studies have been included within the discussions presented in Section 4.3.

6 studies use a version of ReCiPe [86] and 5 studies use a version of the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) developed by the US Environmental Protection Agency [87,88] to perform the impact assessment. Additionally, 6 use environmental product declarations (EPDs) to perform the assessment [43,47,61,66,75,89]. However, EPDs are descriptive by nature and are intended to guide comparisons within a defined product category rule (PCR) [90]. Additionally, comparability and transparency issues, along with the reporting of single-point deterministic values, in EPDs questions their viability to be aggregated together to perform building or system scale assessments [91,92]. More critically, 8 of the reviewed studies do not explicitly state what impact assessment method was used to determine the presented results. As stated previously, not stating the impact assessment method hinders the ability to compare and contrast studies as readers are unable to determine if differences in results are caused by underlying differences in impact assessment methods or another variable within the assessment. Specifying the impact

assessment method, including its associated version, should be considered standard practice for all LCA studies regardless of the goal and scope or subject matter of the study.

3.2.2. Reference study period

The reference study period (RSP), as defined by EN 15978 [7], represents a standardized time frame that enables buildings to be compared regardless of their actual lifespan. Fig. 3.3 summarizes the different RSPs used across the reviewed studies. The studies that did not specify a RSP (i.e. the N/A values in Fig. 3.3) only reported A1-A3 or A1-A5 impacts. For these studies, the RSP is not pertinent as the A1-A5 impacts are typically modeled and reported as a singular pulse impact reported within a 1-year time frame at the start of the study period. A 60-year RSP has been widely adopted as standard, and in certain contexts is required for reporting compliance, since it allows for the building to undergo refurbishment and maintenance cycles, recognizes decarbonization trajectories and represents a “reasonably predictable time period into the future” [5]. There is little to no correlation between geography and RSP for the reviewed studies. However, this is likely due to the lack of inclusion of MEP within building-scale LCA reporting practices and research. It is anticipated that the alignment of different RSPs with the reporting practices in different geographies could be visualized if analyzed for building-scale LCA studies more broadly.

3.2.3. Replacements and component service life

Several studies [47,49,57,58,62,64,67,70,71,76,77] report replacement period for the individual components and systems considered within the scope of the respective studies. Whereas others [25,54,59,66] report a single value for the replacement of all systems included within the study. As shown in Fig. 3.4, the disaggregated system or component level replacement periods are, on average, higher than the single-value assumptions for all systems included. The single-value replacement periods can be seen to be a more conservative estimate, leading to a higher replacement rate which in turn corresponds to higher replacement and use phase impacts. Whereas, the disaggregated replacement periods can indicate that these studies acquired a greater degree of information reflecting real-world service lives and replacement periods of the studied components and systems. Of the 21 studies that include replacements, 11 specify the replacement impacts associated with life cycle stage B4, 2 studies provide a cumulative value for all embodied impacts within the use phase (B1-B5) but do not include the impacts associated with the refrigerant leakage or other associated fugitive emissions. The observed replacement periods for the systems and components are closely aligned with the assumed service lives presented by RICS [5].

3.3. Summary of impacts for MEP systems

Several of the reviewed studies present the environmental impacts for a single MEP system configuration [43,44,48,51,65,66,69]. In total, 20 studies report environmental impacts for the individual systems and components considered within the assessment scope. Of which, Gardner et al. [62], Hoxha et al. [67], Jain et al. [57], Kiamili et al. [69], Petrovic et al. [43] convey the environmental impacts of the constituent components and systems at the different life cycle stages assessed. Whereas Goggins et al. [50], Zhang et al. [51] present detailed material or component specific breakdowns for the product stage [A1-A3] impacts associated with the systems assessed. Additionally, Eberhardt et al. [64], Ilgın et al. [73], Kovacic et al. [55], Liu et al. [44], Negishi et al. [46], Norouzi et al. [71], Pichlmeier and Lindner [74], Rinne et al. [63] present a total value for the GWP impacts of the included systems assessed over a defined set of life cycle stages without including a breakdown of impacts by life cycle stages nor system components. The disaggregation of environmental impacts by life cycle stages and the constituent components illustrates the level of rigor and detail achieved in the study while providing a greater degree of transparency to the reader that can be used to understand the factors contributing to the reported environmental impacts. Future studies should strive to report environmental impacts by individual building elements or system components and by individual life cycle stages to allow readers to understand the factors contributing to the reported environmental impacts.

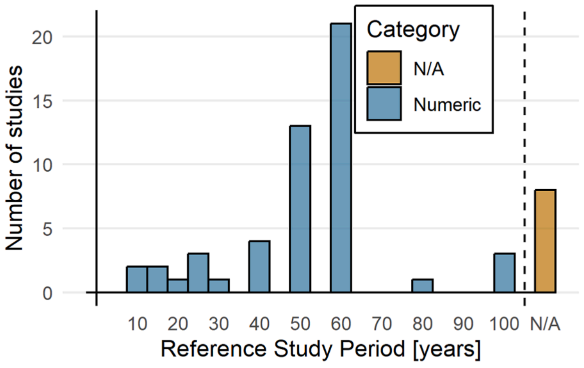

Fig. 3.3. Reference study periods of MEP systems used in reviewed studies.

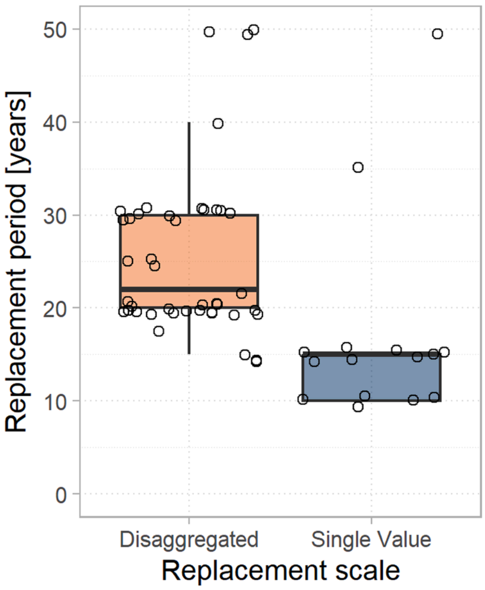

Fig. 3.4. Replacement periods of MEP systems used in reviewed studies.

Fig. 3.5 illustrates the GWP impacts as reported in the reviewed studies. The values included in Fig. 3.5 represent the total impact, normalized by the reported building area, for all systems reported within the study for the identified scope of life cycle stages. We extracted these values from Figures and Tables in the reviewed literature when the literature did not include it directly in text. The Supplementary Materials file notes the source of each extracted value. Beyond the alignment of life cycle stages for the A1-A3 and A1-A5 impacts, we have not aligned the reported values in terms of completeness of physical and temporal scope, system typology, geographic representation, nor methodological considerations. The “single values”, as shown in Figs. 3.5 and 3.6, correspond to publications that report a single value for the cumulative impact of a defined set of life cycle stages, systems and system components. These values have not been aligned by the temporal scope reported in each respective study nor do they represent the summation of GWP impacts for studies that report disaggregated GWP impacts by individual life cycle stages. Additionally, it should be noted that Figs. 3.5 and 3.6 exclude the A1-A5 GWP impacts reported by Cao et al. [65] which were a very high outlier at 1482 $kgCO_2e/m^2$. It is impractical to explore a correlation between normalized GWP and building area since the studies were completed to varying levels of completeness and

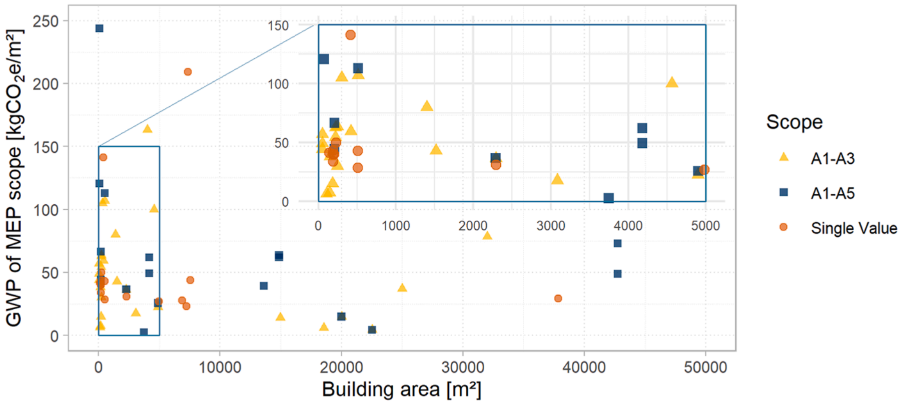

Fig. 3.5. Reported GWP impacts of MEP systems normalized by reported area compared to building area. Reported values correspond to varying physical scopes, system typologies and methodological considerations. Figure excludes impact from Cao et al. [65] which reported a very high outlier at 1482 $kgCO_2e\ /m^2$.

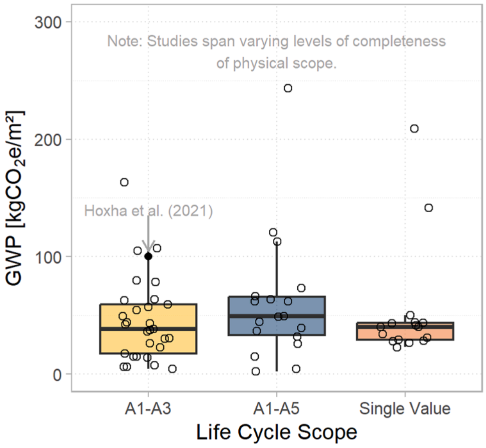

Fig. 3.6. MEP GWP impact, normalized by building area, by scope of life cycle stages. Reported values correspond to varying physical scopes, system typologies and methodological considerations. Figure excludes impact from Cao et al. [65] which reported a very high outlier at 1482 $kgCO_2e\ /m^2$.

include different background data sources, impact assessment methods and system typologies. However, with improved reporting practices for publication, future studies could be conducted to assess correlations between system typologies and various building characteristics, including but not limited to: building and system typology, height, number of floors, geography, and various massing and floorplan characteristics.

Two hypotheses can be inferred from Fig. 3.6: 1) studies that report a higher level of detail in their assessment (i.e. reporting A1-A3, A4 and A5 separately or A1-A3, A4-A5 instead of A1-A5) correspond to a greater degree of completeness and specificity within the physical scope, translating to a higher reported impact; 2) studies that solely report a total value for some defined scope of life cycle stages rely on assumptions and simplifications that lead to underrepresented environmental impacts. Hoxha et al. [67], indicated by the solid dot in A1-A3 for Fig. 3.6, presented a highly detailed life cycle inventory, demonstrating a great degree of physical completeness within the assessment scope. This greater degree of physical completeness correlates to a reported impact that is two-times larger than the mean of the reviewed literature. Additionally, it is important to note that is unlikely that the sample presented reflects a random sample. Given these major limitations, the inferences that we can draw from this data regarding the actual impact of these systems is similarly limited. The data contains outliers and the underlying population itself may not be normally distributed. For these reasons, we recommend referring to the median of the sample to summarize the data presented in Section 4.3, recognizing that this is almost certainly an underestimate of the impacts given the incomplete physical and temporal scope for many of the included studies.

4. Discussion

4.1. *Completeness and comparability*

In LCA, completeness refers to how well the object of the assessment, including all features within the system boundary, are represented within the assessment, i.e., how “complete” the assessment is. Table 4 summarizes the main dimensions of completeness considered within this review. Each dimension of completeness influences the degree to which LCA results can be interpreted and compared. Ultimately, the degree of completeness assesses how well a study represents the object of the assessment within the system boundary to achieve the goal of the assessment.

The completeness of the impact assessment phase, including the assessment of appropriate impact categories and the characterization factors used to perform the assessment, is highlighted by Dong et al. [93] as a key aspect of completeness. We have not directly considered the completeness of the impact assessment phase since we have focused this review on how GWP is assessed and reported for MEP systems. However, the completeness of the impact assessment phase can be interpreted from summary of impact categories and background datasets included within Section 3.2.1.

The reviewed studies presented varying degrees of completeness both in terms of their respective physical and temporal scopes. The degree to which you can say a study’s system boundary is “complete” is based off how the underlying assumptions, methodological considerations and life cycle inventory (LCI) are presented and discussed. Studies that present greater degrees of transparency in what is assessed and how the assessment is conducted enable readers to interpret the presented results to a greater degree and infer how complete the presented system

Table 4
Dimensions of completeness in LCA.

Dimension	Relates to:
Physical	The scope of materials, processes, components and products included within the system boundary to appropriately represent the object of the assessment, i.e. life cycle inventory.
Temporal	The life cycle stages included within the system boundary to appropriately represent the activities that take place across the life cycle of the object of the assessment.
Methodological	The assumptions, simplifications and decisions used to perform the assessment, including the selection of the impact assessment method, background dataset, software and reported impact categories.

boundary is. Some studies disclosed system elements that were excluded from the defined system boundary [48,56,58,71,73,89] while others indirectly disclosed what is included and excluded by how their life cycle inventories (LCIs) are presented [46,52–54,57,61,67,72,76,77]. Unfortunately, many studies provide vague descriptions of the systems included within the assessments and do not provide the level of granularity needed to replicate the presented results. The apparent inconsistencies in reporting and disclosure practices inhibit both the readers ability to assess the completeness of a study while also inhibiting comparisons against other studies. Improved transparency in reporting practices would support reproducibility of results while contributing to efforts to promote open-science within the LCA community.

In practice, the use of different background datasets, impact assessment methods and software introduce additional sources of variation and uncertainty that inhibit fair comparisons between studies. As stated in ISO 14040 [8], the functional unit of the study “ensures comparability of LCA results”. The functional unit defines the functions and performance characteristics of the entity being assessed to provide a quantitative reference. However, due to the multi-functionality of buildings, there isn’t a uniformly defined approach for establishing the functional unit, with the functional unit being influenced by the goal and scope of the study. In practice, many studies use a defined unit to encompass the range of scenarios and functions present within a building and normalize impacts by some unit of area. This unit of normalization can introduce another source of variability when it is not stated whether the area refers to: gross area; net internal area; net conditioned area; or some other form of area calculation. As such, the type of area that the unit of normalization corresponds to needs to be stated alongside the functional or declared unit. The results reported in this review (Figs. 3.5 and 3.6 and Table 7) have not been aligned by the different area measurements used in the respective reviewed publications.

The observed variability in how the studies report environmental impacts and how they describe systems is influenced by the goal and scope of the assessment. However, regardless of the goal and scope of the assessment, common reporting practices should be followed to enable the interrogation, comparison and reproducibility of the results. 8 studies, representing 16 system or building configurations, report the GWP as a total value for all life cycle stages included. These studies do not allow for further interrogation and interpretation beyond the single-point value presented. Therefore, this minimal reporting approach prevents readers from understanding which systems, components, life cycle stages, assessment assumptions or other considerations are the driving forces behind the reported impacts. Furthermore, as introduced in Section 3.3, 20 studies provide a contribution analysis by system or component within the reported GWP impacts. Studies such as Jain & Rawal [57] and Hoxha et al. [67] report GWP impacts disaggregated by life cycle stage and system or component. This granular reporting method enables readers to interpret whether the environmental impacts are being driven by high initial material impacts [A1-A3], multiple replacement periods or high replacement material impacts [B4], high end-of-life impacts [C1-C4], some combination of these factors or another driving factors. Both Jain & Rawal [57] and Hoxha et al. [67] report approximately 100 $kgCO_2e/m^2$ for the A1-A3 impacts, whereas Hoxha et al. [67] reports replacement [B4] impacts that are approximately five times higher than the repair [B3] and replacement [B4] impacts from Jain & Rawal [57]. Although the scope of life cycle stages is not directly aligned for these two studies, this more granular form of reporting enables greater levels of interpretation and comparison that would not be feasible if the studies report a single value for all life cycle stages and all system elements. Therefore, studies should include contribution analyses for the building elements or system components and life cycle stages to provide greater clarity regarding what factors could be influencing the reported environmental impacts.

4.2. Exemplary LCA studies for MEP systems

There is no universally agreed format for the presentation of LCA results within the built environment. Standards, including EN 15978 and EN 15804, describe what should be included within LCA reporting and have improved the consistency and transparency of information presented within environmental product declarations (EPDs). However, this does not translate to academic publications where publication requirements and the research objectives can influence the format and specificity in which the results are presented. This in turn can limit the readers ability to interpret the results from different publications and inhibit comparability across different journals and studies. Due to the time constraints of climate change, researchers, practitioners and LCA assessors should strive to publish a sufficient level of detail to enable reproducibility, transparency and interpretability of results. Table 5 outlines key aspects of LCA that should be clearly stated within all published LCA studies. Table 5 can act as a checklist for future publications to ensure appropriate aspects of LCAs are included to enable interpretability and transparency of published work regardless of the study’s goal or research objectives. Tables 5 and 6 have been organized based on the four main stages of an LCA as described by ISO 14040 (i.e. goal and scope definition, inventory analysis, impact assessment, interpretation) [8]. The checklist included in Table 5 has been developed based on our critical review and cross-referenced with other studies [94,24] and author experience. Additionally, Table 6 summarizes exemplary studies that can be referred to for how to incorporate critical aspects of LCAs into future publications. The studies referenced in Table 6 demonstrate admirable ways of presenting the associated aspect to ensure a high-level of rigor, transparency, reproducibility and interpretation of the presented results. For example, Opher et al. [54] and Hoxha et al. [67] present life cycle inventories with a high level of detail to sufficiently reproduce the results if needed. Whereas Jain & Rawal [57] provide clear sections outlining the limitations, exclusions or simplifications and the assumptions used throughout their study. As indicated in Fig. 3.6, Hoxha et al. [67] transparently demonstrated one of the highest levels of physical completeness within the reported scope based on using a detailed supplemental materials file outline each component and associated process used to conduct the presented LCA. The studies in Table 6 can be used to guide the development of future publications to ensure they provide an appropriate level of specificity and information necessary to communicate how the LCA was conducted, what was included in the assessment and how the results can be interpreted and used by the reader.

4.3. A reasonable lower bound estimate for GWP of MEP systems

Guidance documents, standards and industry initiatives, such as CIBSE TM65 [96], the forthcoming ASHRAE 240P, and MEP2040 are making great strides in closing gaps in the system boundaries used in building-scale LCA while improving data availability and understanding surrounding the environmental impacts associated with MEP systems.

Table 5
Key aspects of LCAs that should be included within all published LCA studies.

Stage of LCA	Must be stated within LCA studies:
Goal and scope definition	-Functional Unit -Temporal system boundary (life cycle stages) -Physical system boundary (system elements) -Reference study period
Inventory analysis	-Background dataset -Data sources for life cycle inventory -Exclusions and simplifications
Impact assessment	-Impact assessment method -Software -Impact categories assessed
Interpretation	-readable impact results *(ideally disaggregated by life cycle stage and building element)*

Table 6

Exemplary papers for critical aspects of LCAs that can be used to guide development of future publications

Stage of LCA	Critical aspects of LCAs	Exemplary papers
Goal and scope definition	Functional unit description	[66,77]
	Description of the object of assessment (i.e. building / system description)	[50,77,85]
Inventory analysis	Materials used to develop life cycle inventory (LCI)	[54,67,82]
	Specificity of LCI	[54,66,67, 77];
	Assumptions used	[57,62]
	Exclusions and simplifications	[57,60,66,77, 82]
	Limitations	[57,77]
Impact assessment	Refer to Table 5 for key aspects of the impact assessment phase that should be stated within all published LCAs	
Interpretation	Presentation of LCA results	[47,49,57,62, 67]
	Disaggregation of system impacts	[62,69,75,95]
	Presentation of multiple scenarios	[57,59,60]

Until the quality and frequency of MEP assessments advances to a sufficient level, it is important to consider an estimate of what the carbon impacts of MEP systems could be rather than simply ignoring them all together. For instance, LETI estimates the relative share of cradle-to-gate emissions [A1-A3] associated with MEP systems to be 15% for office buildings and 4% for medium-scale residential buildings [97]. Based on the building element share and the business-as-usual estimates, presented by LETI [97,98], the A1-A3 impacts for MEP systems can be estimated to be ~145 $kgCO_2e/m^2$ for office buildings and ~30 $kgCO_2e/m^2$ for medium-scale residential buildings. However, it is important to note that the rules-of-thumb and estimates set forth by LETI are based on buildings and practice within the UK. Therefore, the system typologies and specifications are specific to the UK context and may differ to other regions which can influence the environmental impacts of these systems.

From the results of the reviewed studies, estimates can be made for the A1-A3, A1-A5 and B4 GWP impacts. It is important to reiterate that these estimates are based on studies that rely on different background datasets, impact assessment methods, software, modeling assumptions, and assessment scopes with different system typologies, performance specifications, levels of completeness and system boundaries. Each of these factors represent sources of variability when the results are compared across studies and this adds another source of uncertainty in addition to the underlying uncertainty from each study. As such, these estimates have been formulated based off data with a high degree of variability and should thus be considered to be highly uncertain. In fact, only one reviewed study [57] included some form of uncertainty analysis for the presented results. As discussed by Marsh, Allen and Hattam [92] the use of single-point deterministic values can lead to large errors when making comparisons between LCAs as they do not articulate the uncertainty associated with each of the compared results. Therefore, these estimates should be considered highly uncertain and future research should seek to develop system specific estimates, including impact reduction strategies and uncertainty factors, for different MEP systems. Perhaps most importantly, due to the incomplete scopes accounted for in the reviewed literature, the environmental impacts are likely underestimated. The true median value is likely to be higher than that reported in this study. As such, the median value reported should be considered by the reader as a lower bound estimate, or minimum value, to assume in absence of other information.

4.3.1. Upfront embodied carbon estimates [A1-A3] & [A1-A5]

The estimates for upfront embodied carbon, including both the product stage [A1-A3] and cradle-to-completion [A1-A5] life cycle stages of MEP, are summarized in Table 7. These estimates are based on the reported impacts from the reviewed studies which have not been altered from how they are reported within their respective studies. It should be noted that based on the authors judgment these values should be treated as lower bound estimates and we hope that future studies will improve upon them to provide more rigorous and trusted estimates for the upfront GWP impacts of different system typologies by following the guidance set out in Section 4.2 and 5. We recommend referring to the median value as reported in Table 7, due to the limitations of the reviewed data outlined in Section 3.3. The 95% confidence intervals for the median A1-A3 and A1-A5 GWP impacts are 26–57 and 32–66, respectively. However, these estimates and the associated confidence intervals would likely increase if the studies included a more complete physical scope. Due to the limited number of detailed LCA studies available, the variability in reporting practices and methodological considerations, it is not yet possible to provide statistical values for specific mechanical, electrical or plumbing systems.

Table 7

Estimates for GWP impacts of MEP systems for defined life cycle stages based on reviewed studies, reported in $kgCO_2e/m^2$.

	A1-A3	A1-A5
Mean	49	61
Median	40	49
25th percentile	16	33
75th percentile	63	66
Standard Deviation	41	55

4.3.2. Replacement carbon estimates [B4]

The reference study period in conjunction with the service life of materials and systems influences the number of replacement cycles considered within studies. Knowing the reference study period and the service life of components or systems helps understand whether the replacement impacts are being driven by a long reference study period, the number of replacement cycles, the magnitude of an individual replacement cycle or a combination of these and other factors. The median replacement period in the studies is 22 years for those that report service lives for individual systems and components and 15 years for studies that report a single replacement period for all systems included within the system boundary. Therefore, based on the disaggregated replacement periods, it is assumed that all components will be replaced at least 2 times over a 60-year reference study period. Following standard LCA practices and based on the presented results from the reviewed studies, a reasonable estimate for the replacement [B4] GWP impacts for MEP systems would be approximately 122 $kgCO_2e/m^2$ based on the mean of the reported values and 98 $kgCO_2e/m^2$ based on the median of the reported values. Until more granular data is available, estimates for life cycle stages B1-B3, B5 and C1-C4 can be calculated based on scenarios and rules-of-thumb such as those presented by RICS [5] or CIBSE TM65 and its respective regional addenda.

5. Recommendations for future studies

Although our review has focused on studies that either focus exclusively on, or include MEP systems, many of the recommendations for future work apply to the use of LCA within the built environment regardless of the scope of the assessment. The review illustrates high levels of variability in how academic publications report LCA results and methodological considerations. This variability can inhibit and even prevent interpretation and transparency of the presented results. As such, we have listed out key LCA methodological considerations that need to be included in all publications regardless of publication outlet and goal and scope of assessment. In addition, minimum requirements for modeling and methodological considerations and reporting guidelines should be established to improve the baseline quality of published LCA studies and improve utility of these published studies. As discussed in Section 4.3, all LCAs should report the background dataset, impact assessment method, software, reference study period used to conduct the assessment. In addition, the scope of building elements and life cycle stages should be clearly defined. Furthermore, any simplifications, assumptions or exclusions that may influence the interpretation of the results should be clearly communicated. Researchers should disaggregate the environmental impacts associated with the product stage [A1-A3] by building element to enable readers to adequately interpret and interrogate the reported findings. Reporting environmental impacts as a single value representing the total impact of the building for a defined scope of building elements and life cycle stages over a defined reference study period greatly limits a readers ability to understand the factors influencing the reported impacts. As we strive to reduce the environmental impacts of the built environment, it is pertinent to understand and communicate whether the environmental impacts are being driven by specific building elements, specific life cycle stages, the overall reference study period used for the study, the replacement periods of different elements or a combination of these or other factors. Greater degrees of disaggregation and transparency of LCA results will improve the utility of published assessments. For studies that report the impacts of MEP systems, it is recommended to report the environmental impacts for the distribution components (piping, ductwork, fittings, etc.) separately from the impacts associated with the equipment. Additionally, uncertainty metrics should be incorporated into studies to move away from the use of single-point deterministic results [92]. Monte Carlo simulation is a common approach for conducting an uncertainty analysis. However, as highlighted by Marsh, Allen and Hattam [92], Monte Carlo simulation requires dependent sampling of both the characterization factors and unit processes to properly reflect uncertainty of recurring unit processes within each run of the Monte Carlo. Wherever possible, it is recommended to avoid independent sampling within uncertainty analyses of LCA results due to the creation of mass imbalances, improbable product compositions and inaccurate representation of the uncertainty associated with individual products [99].

Most studies reviewed for this study were descriptive by nature. Understanding the magnitude of environmental impacts is important, however due to the time constraints on reducing impacts to combat climate change, the impact reduction potential is equally, if not more, important. As such, studies need to move beyond being purely descriptive to include hotspot or contribution analyses with associated discussions regarding the factors influencing the reported impacts or explorations of impact reduction potential for key elements. Understanding the impact reduction potential of different systems and components can be used to formulate impact reduction strategies that can be implemented from the onset of the design process and can be used to guide policy development to target areas with the largest impact reduction potential. In addition, understanding the strategies that did not effectively reduce impacts under specific circumstances for case studies are also important for further developing impact reduction strategies. Furthermore, more research is needed to address previously overlooked building elements and life cycle stages to further close the gaps within common system boundaries and move towards a more holistic view of what the environmental impacts are for a building when accounting for all building elements and life cycle stages. Similar to Roberts et al. [10], Anand and Amor [15] and others, we are advocating for the development of target values and impact reduction strategies specific to the MEP industry and measures to improve the accessibility of LCA and LCA related information in the design process. The developed impact reduction strategies should be aligned with and build off those identified by Pomponi and Moncaster [16], LETI [98] and CIBSE TM65 [96].

In terms of future research that is needed to advance the body of knowledge surrounding the environmental impacts of MEP systems, we are only at the surface. More research is needed to:

1) develop system and geographic specific estimates for different system typologies and performance specifications;
2) iterate estimates that can be used when no information is known about the system typology and specifications;
3) investigate sources of uncertainty associated with different levels of specificity regarding MEP system typologies and performance specifications;
4) identify impact reduction strategies for different system typologies and associated impact reduction potential;
5) investigate the relationship between performance specifications and environmental impacts within system typologies;
6) investigate how system layout efficiency and material selection can influence environmental impacts;
7) investigate multi-element environmental impact optimization to assess how the performance and associated environmental impacts of different building systems are liked with the environmental performance of other building elements;
8) investigate reusability, end-of-life treatment and use phase impacts to improve the understanding surrounding life cycle stages beyond A1-A5;
9) understand the magnitude and reduction potential associated with refrigerant leakage and fugitive emissions from different MEP systems;
10) explore combining midpoint with endpoint reporting of results to avoid burden shifting to other environmental impact categories that can result from the sole focus on GWP.

The aforementioned list of research topics is not exhaustive but should serve as a starting point for researchers wanting to make contributions within this research area. The gaps and recommendations from the reviewed literature are largely aligned with [15,41] and others who have identified the need to improve data availability, data quality, transition away from single-point deterministic and purely descriptive assessments, improve reporting and communication of results and methodological decisions and improve the completeness of assessments. Recent efforts by Bergsdal et al. [100] have developed an inventory for ventilation components, the geographic and regional technological representativeness of this component life cycle inventory should be explored to determine how and when it can be used in absence of more manufacturer specific information. Future work could replicate the inventory by Bergsdal et al. [100] to develop similar supplemental life cycle inventories for other mechanical, electrical and plumbing components and validate the impacts obtained through these datasets by comparing against detailed process-based assessments.

6. Conclusions

We conducted a systematic critical review of academic publications that focus on LCAs of MEP systems to summarize publications on this topic to date, and to investigate the ability to interrogate and compare published results. Our review found that many studies do not include critical information that can influence LCA results and therefore inhibit the ability to interpret and compare the reported impacts. Current reporting practices in publications range from single-point values representing the total impacts associated with a defined scope of system elements over a defined scope of life cycle stage stages to studies that report detailed breakdowns of environmental impact by individual system component and life cycle stage. Studies that reported more granular results typically demonstrated higher degrees of completeness in their reported scope and used more primary data to develop their life cycle inventories used within the assessments. Higher levels of granularity in the reported results also correlate to greater transparency in the results. Therefore, enabling the published results to be interrogated and interpreted beyond the stated goals of the studies and provide readers with more context regarding the characteristics and assumptions influencing the reported results. We identified key aspects that need to be included in future publications to facilitate comparisons between studies. Additionally, exemplary studies have been identified that can be used as reference and inspiration in future works for conveying the level of detail required for a high quality LCA study. Last, we include the full set of references and the information extracted from them in the supplementary material so that others may re-use and further explore this work directly.

Building-scale LCAs typically employ multiple simplifying assumptions to enable assessments to be conducted in a timely manner. Several of these assumptions can be grouped into temporal and physical considerations. Assumptions regarding the physical scope of building elements and the system boundary are often driven by availability of information and which members of the design team are involved in conducting the assessment. Whereas, temporal assumptions are often reliant on commonly accepted rules-of-thumb. MEP systems are commonly excluded from assessments because practitioners assumed they did not contribute much to the overall environmental impacts of the building. However, as demonstrated through our review, MEP systems can have a considerable embodied impact, especially when system replacement is accounted for, and efforts should be made to incorporate these impacts in future building-scale assessments. Beyond the areas of future research outlined in Section 5, it is recommended that practitioners engage in industry initiatives such as MEP2040, request environmental product declarations (EPDs), take measures to quantify and consider the environmental impacts of the MEP systems they are specifying. Industry practitioners can use TM65, with its associated local addenda, published by CIBSE [96], to provide a conservative estimate for the embodied carbon impacts of the specified MEP systems. Additionally, TM65 provides guidance on the types of data to collect from manufacturers to support the inclusion of MEP within building-scale LCAs [96]. Furthermore, industry practitioners can employ impact reduction strategies in their design development that are aligned with CIBSE TM65 [96], LETI [98] and others. These strategies include: the specification and design of systems with low GWP refrigerants and low leakage rates; specification of components with long lifespans; low material weight; selection of low carbon materials; design of systems to enable disassembly and reuse; selection of materials that can be reused or recycled; and the design of systems that enable ease of maintenance and replacement. All efforts should support data transparency, communication and collaboration that enables MEP systems to be integrated into building-scale LCAs.

This review by no means closes the gaps surrounding the assessment, reporting and understanding of the environmental impacts of MEP systems within buildings, instead it should be viewed as a summary of current literature, and a guide that future studies can use to formulate research questions and structure how to report and discuss environmental impacts to ensure they contribute to the net-zero carbon transition for the built environment. The number of articles that did not meet the criteria to be included within this review highlights the need to further research and improve the body of knowledge surrounding the environmental impacts of MEP systems. From the reviewed studies, we have provided estimates for the product [A1-A3], upfront embodied [A1-A5] and replacement [B4] carbon impacts. However, these estimates are based on studies with varying system boundaries, background datasets, impact assessment methods and inconsistencies in the level of specificity and completeness achieved in the scope of the assessment. As such, these estimates should be further refined and iterated to reflect a consistent level of completeness in the physical and temporal scope considered within the assessments. Additionally, future studies should explore if specific considerations or adjustments need to be made to enable fair comparisons between studies that have been conducted using different background datasets, impact assessment methods and software. Ultimately, this review demonstrates that MEP systems can have a significant impact within a building's carbon footprint and therefore research and effort is needed to improve data availability and guidelines for what system components should be included within building-scale assessments, how these system components should be assessed and what can be said regarding their environmental impacts if no specifications or performance criteria are known about the systems during early stage design.

CRediT authorship contribution statement

Matt Roberts: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Claudiane Ouellet-Plamondon:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Paul Raftery:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matt Roberts reports financial support was provided by ClimateWorks Foundation. The Center for the Built Environment (CBE) at the University of California, Berkeley, with which two authors are affiliated, is advised and funded in part by many approximately 50 partners that represent a diversity of organizations from the building industry, including manufacturers, building owners, facility managers, contractors, architects, engineers, government agencies, and utilities. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The Center for the Built Environment at the University of California, Berkeley and the ClimateWorks Foundation supported this research.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2025.112823.

Data availability

Data available in Supplemental Materials

References

[1] WorldGBC, From Thousands to Billions: Coordinated Action Towards 100% Net Zero Carbon Buildings by 2050, World Green Building Council, London; Toronto, 2017.

[2] United Nations Environment Programme, 2022 Global Status Report for Buildings and Construction, United Nations Environment Programme, 2022.

[3] WorldGBC, WorldGBC Net Zero Carbon Buildings Commitment, World Green Building Council, London, 2019. January.

[4] WorldGBC, Bringing embodied carbon upfront, World Green Building Council, London; Toronto, 2019.

[5] RICS, Whole Life Carbon Assessment for the Built Environment, 2nd Edition, Royal Institution of Chartered Surveyors, London, 2023.

[6] BSI, BS EN 15804: 2012+ A2: 2019: Sustainability of Construction Works. Environmental Product Declarations. Core Rules for the Product Category of Construction Products (+A2:2019) (Incorporating Corrigenda February 2014 and July 2020), BSI London, UK, 2019.

[7] BSI, BS-EN 15978:2011 Sustainability of Construction Works - Assessment of environmental performance of buildings - calculation method, British Standards Institution, 2012.

[8] BSI, BS EN ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework, British Standards Institution, 2006, https://doi.org/10.1016/j.ecolind.2011.01.007. ISO 14040:2006.

[9] BSI, BS EN ISO 14044:2006+A1:2018 Environmental Management - Life Cycle Assessment - Requirements and Guidelines, British Standards Institution, 2018. ISO 14044:2006.

[10] M. Roberts, S. Allen, D. Coley, Life cycle assessment in the building design process – a systematic literature review, Build. Environ. 185 (November) (2020) 107274, https://doi.org/10.1016/j.buildenv.2020.107274.

[11] Y. Yılmaz, S. Seyis, Mapping the scientific research of the life cycle assessment in the construction industry: A scientometric analysis, Build. Environ. 204 (October) (2021) 108086, https://doi.org/10.1016/j.buildenv.2021.108086.

[12] M. Bahramian, K. Yetilmezsoy, Life cycle assessment of the building industry: an overview of two decades of research (1995–2018), Energy Build. 219 (July) (2020) 109917, https://doi.org/10.1016/j.enbuild.2020.109917.

[13] R. Zeng, A. Chini, A review of research on embodied energy of buildings using bibliometric analysis, Energy Build. 155 (November) (2017) 172–184, https://doi.org/10.1016/J.ENBUILD.2017.09.025.

[14] L.F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, Life cycle assessment (LCA) and Life cycle energy analysis (LCEA) of Buildings and the building sector: a review, Renew. Sustain. Energy Rev. 29 (January) (2014) 394–416, https://doi.org/10.1016/J.RSER.2013.08.037.

[15] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of Buildings: a critical review, Renew. Sustain. Energy Rev. 67 (January) (2017) 408–416, https://doi.org/10.1016/J.RSER.2016.09.058.

[16] F. Pomponi, A. Moncaster, Embodied carbon mitigation and reduction in the built environment – What does the evidence say? J. Environ. Manage. 181 (October) (2016) 687–700, https://doi.org/10.1016/J.JENVMAN.2016.08.036.

[17] C. Thibodeau, A. Bataille, M. Sié, Building rehabilitation life cycle assessment methodology–State of the art, Renew. Sustain. Energy Rev. 103 (April) (2019) 408–422, https://doi.org/10.1016/j.rser.2018.12.037.

[18] A. Vilches, A. Garcia-Martinez, B. Sanchez-Montañes, Life cycle Assessment (LCA) of building refurbishment: a literature review, Energy Build. 135 (January) (2017) 286–301, https://doi.org/10.1016/j.enbuild.2016.11.042.

[19] Z. Duan, Q. Huang, Q. Zhang, Life cycle assessment of mass timber construction: a review, Build. Environ. 221 (August) (2022) 109320, https://doi.org/10.1016/j.buildenv.2022.109320.

[20] B. Soust-Verdaguer, C. Llatas, A. García-Martínez, Critical review of Bim-based LCA method to buildings, Energy Build. 136 (2017) 110–120, https://doi.org/10.1016/j.enbuild.2016.12.009.

[21] D. Trigaux, K. Allacker, W. Debacker, Environmental Benchmarks for buildings: A critical literature review, Int. J. Life Cycle Assessm. 26 (1) (2021) 1–21, https://doi.org/10.1007/s11367-020-01840-7.

[22] A. Hollberg, B. Kiss, M. Röck, B. Soust-Verdaguer, A. Houlihan Wiberg, S. Lasvaux, A. Galimshina, G. Habert, Review of visualising LCA results in the design process of buildings, Build. Environ. 190 (August 2020) (2021), https://doi.org/10.1016/j.buildenv.2020.107530.

[23] B. Benke, M. Roberts, Y. Shen, S. Carlisle, M. Chafart, K. Simonen, The California Carbon Report: An Analysis of the Embodied and Operational Carbon Impacts of 30 Buildings, Carbon Leadership Forum, University of Washington, Seattle, WA, 2024.

[24] M. Nehasilova, J. Potting, E. Soulti, Subtask 4: case studies and recommendations for the reduction of embodied energy and embodied greenhouse gas emissions from buildings, in: H. Birgisdóttir, A. Houlihan-Wiberg, T. Malmqvist, A. Moncaster, F.N. Rasmussen (Eds.), Annex 57, Institute for Building Environment and Energy Conservation, Tokyo, 2016.

[25] B.X. Rodriguez, M. Huang, H.W. Lee, K. Simonen, J. Ditto, Mechanical, electrical, plumbing and tenant improvements over the building lifetime: estimating material quantities and embodied carbon for climate change mitigation, Energy Build. 226 (November) (2020) 110324, https://doi.org/10.1016/j.enbuild.2020.110324.

[26] H. Birgisdóttir, A. Houlihan-Wiberg, T. Malmqvist, A. Moncaster, F. Nygaard Rasmussen, M. Nehasilova, J. Potting, E. Soulti, Evaluation of Embodied Energy and CO 2eq for Building Construction (Annex 57) Subtask 4: Case Studies and Recommendations for the Reduction of Embodied Energy and Embodied Greenhouse Gas Emissions from Buildings, 2016.

[27] R. Frischknecht, M. Balouktsi, T. Lützkendorf, A. Aumann, H. Birgisdottir, E. Grosse Ruse, A. Hollberg, et al., Environmental Benchmarks for buildings: needs, challenges and solutions—71st LCA Forum, Swiss Federal Institute of Technology, Zürich, 18 June 2019, Int. J. Life Cycle Assessm. 24 (2019) 2272–2280, https://doi.org/10.1007/s11367-019-01690-y.

[28] M. Röck, M. Ruschi Mendes Saade, M. Balouktsi, F.N. Rasmussen, H. Birgisdottir, R. Frischknecht, G. Habert, T. Lützkendorf, A. Passer, Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation, Appl. Energy 258 (June 2019) (2020) 114107, https://doi.org/10.1016/j.apenergy.2019.114107.

[29] D. Satola, M. Balouktsi, T. Lützkendorf, A. Houlihan Wiberg, A. Gustavsen, How to define (Net) zero greenhouse gas emissions buildings: the results of an international survey as part of IEA EBC Annex 72, Build. Environ. 192 (October 2020) (2021) 107619, https://doi.org/10.1016/j.buildenv.2021.107619.

[30] S. Gerbinet, S. Belboom, A. Léonard, Life cycle analysis (LCA) of photovoltaic panels: a review, Renew. Sustain. Energy Rev. 38 (October) (2014) 747–753, https://doi.org/10.1016/j.rser.2014.07.043.

[31] N.A. Ludin, N.I. Mustafa, M.M. Hanafiah, M.A. Ibrahim, M.A.M. Teridi, S. Sepeai, A. Zaharim, K. Sopian, Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: a review, Renew. Sustain. Energy Rev. 96 (November) (2018) 11–28, https://doi.org/10.1016/j.rser.2018.07.048.

[32] M.D. Chatzisideris, N. Espinosa, A. Laurent, F.C. Krebs, Ecodesign Perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies, Sol. Energy Mater. Sol. Cell. 156 (November) (2016) 2–10, https://doi.org/10.1016/j.solmat.2016.05.048.

[33] M.M. Rahman, A.O. Oni, E. Gemechu, A. Kumar, Assessment of energy storage technologies: a review, Energy Convers. Manage. 223 (November) (2020) 113295, https://doi.org/10.1016/j.enconman.2020.113295.

[34] N. Nitta, F. Wu, J.T. Lee, G. Yushin, Li-ion battery materials: present and future, Mater. Today 18 (5) (2015) 252–264, https://doi.org/10.1016/j.mattod.2014.10.040.

[35] M.A. Pellow, H. Ambrose, D. Mulvaney, R. Betita, S. Shaw, Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: end-of-life options and other issues, Sustain. Mater. Technolog. 23 (X) (2020) e00120, https://doi.org/10.1016/j.susmat.2019.e00120.

[36] C. Lamnatou, D. Chemisana, C. Cristofari, Smart grids and Smart technologies in relation to photovoltaics, storage systems, buildings and the environment, Renew. Energy 185 (February) (2022) 1376–1391, https://doi.org/10.1016/j.renene.2021.11.019.

[37] A.S. Pratiwi, E. Trutnevyte, Review of life cycle assessments of geothermal heating systems, in: Proceedings World Geotermal Congress 2020. Universite de Geneve, 2020.

[38] Eberle, A., G.A. Heath, A.C. Carpenter Petri, and S.R. Nicholson. 2017. "Systematic review of life cycle greenhouse gas emissions from geothermal electricity." NREL/TP–6A20-68474, 1398245. 10.2172/1398245.

[39] C. Tomasini-Montenegro, E. Santoyo-Castelazo, H. Gujba, R.J. Romero, E. Santoyo, Life cycle assessment of geothermal power generation technologies: an updated review, Appl. Therm. Eng. 114 (March) (2017) 1119–1136, https://doi.org/10.1016/j.applthermaleng.2016.10.074.

[40] A. Kylili, P.A. Fokaides, Life cycle assessment (LCA) of phase change materials (PCMs) for building applications: a review, J. Build. Eng. 6 (June) (2016) 133–143, https://doi.org/10.1016/j.jobe.2016.02.008.

[41] J. Litardo, D. Gomez, A. Boero, R. Hidalgo-Leon, G. Soriano, A.D. Ramirez, Air-conditioning life cycle assessment research: A review of the methodology, environmental impacts, and areas of future improvement, Energy Build. 296 (October) (2023) 113415, https://doi.org/10.1016/j.enbuild.2023.113415.

[42] M.J. Grant, A. Booth, A typology of reviews: an analysis of 14 review types and associated methodologies, Health Inform. Libr. J. 26 (2) (2009) 91–108, https://doi.org/10.1111/j.1471-1842.2009.00848.x.

[43] B. Petrovic, J. Are Myhren, X. Zhang, M. Wallhagen, O. Eriksson, Life cycle assessment of a wooden single-Family house in Sweden, Appl. Energy 251 (October) (2019) 113253, https://doi.org/10.1016/j.apenergy.2019.05.056.

[44] S. Liu, U.W. Schulz, M.H. Sapar, S. Qian, Evaluation of the environmental performance of the chilled ceiling system using life cycle assessment (LCA): A case study in Singapore, Build. Environ. 102 (June) (2016) 207–216, https://doi.org/10.1016/j.buildenv.2016.03.005.

[45] M.L. Fong, Z. Lin, K.F. Fong, V. Hanby, R. Greenough, Life cycle assessment for three ventilation methods, Build. Environ. 116 (May) (2017) 73–88, https://doi.org/10.1016/j.buildenv.2017.02.006.

[46] K. Negishi, A. Lebert, D. Almeida, J. Chevalier, L. Tiruta-Barna, Evaluating climate change pathways through a building's lifecycle based on dynamic life cycle assessment, Build. Environ. 164 (October) (2019) 106377, https://doi.org/10.1016/j.buildenv.2019.106377.

[47] M. Rabani, H. Bayera Madessa, M. Ljungström, L. Aamodt, S. Løvvold, N. Nord, Life cycle analysis of GHG emissions from the building retrofitting: the case of a Norwegian office building, Build. Environ. 204 (October) (2021) 108159, https://doi.org/10.1016/j.buildenv.2021.108159.

[48] H. Cai, X. Wang, J.-H. Kim, A. Gowda, M. Wang, J. Mlade, S. Farbman, L. Leung, Whole-building life-cycle analysis with a new GREET tool: embodied greenhouse gas emissions and payback period of a LEED-certified library, Build. Environ. 209 (February) (2022) 108664, https://doi.org/10.1016/j.buildenv.2021.108664.

[49] H. Kröhnert, R. Itten, M. Stucki, Comparing flexible and conventional monolithic building design: life cycle environmental impact and potential for material circulation, Build. Environ. 222 (August) (2022) 109409, https://doi.org/10.1016/j.buildenv.2022.109409.

[50] J. Goggins, P. Moran, A. Armstrong, M. Hajdukiewicz, Lifecycle environmental and economic performance of nearly zero energy buildings (NZEB) in Ireland, Energy Build. 116 (March) (2016) 622–637, https://doi.org/10.1016/j.enbuild.2016.01.016.

[51] X. Zhang, F. Wang, Assessment of embodied carbon emissions for building construction in China: comparative case studies using alternative methods, Energy Build. 130 (October) (2016) 330–340, https://doi.org/10.1016/j.enbuild.2016.08.080.

[52] B. Wrålsen, R. O'Born, C. Skaar, Life cycle assessment of an ambitious renovation of a Norwegian apartment building to nZEB standard, Energy Build. 177 (October) (2018) 197–206, https://doi.org/10.1016/j.enbuild.2018.07.036.

[53] K. Solano–Olivares, R.J. Romero, E. Santoyo, I. Herrera, Y.R. Galindo–Luna, A. Rodríguez–Martínez, E. Santoyo-Castelazo, J. Cerezo, Life cycle assessment of a solar absorption air-conditioning system, J. Clean. Product. 240 (December) (2019) 118206, https://doi.org/10.1016/j.jclepro.2019.118206.

[54] T. Opher, M. Duhamel, I. Daniel Posen, D.K. Panesar, R. Brugmann, A. Roy, R. Zizzo, L. Sequeira, A. Anvari, H.L. MacLean, Life cycle GHG assessment of a building restoration: case study of a heritage Industrial building in Toronto, Canada, J. Clean. Product. 279 (January) (2021) 123819, https://doi.org/10.1016/j.jclepro.2020.123819.

[55] I. Kovacic, J. Reisinger, M. Honic, Life cycle assessment of embodied and operational energy for a passive housing block in Austria, Renew. Sustain. Energy Rev. 82 (February) (2018) 1774–1786, https://doi.org/10.1016/j.rser.2017.07.058.

[56] B. Kaspersen, J. Lohne, R.A. Bohne, Exploring the CO2-impact for building height; A study on technical building installations, Energy Procedia 96 (September) (2016) 5–16, https://doi.org/10.1016/j.egypro.2016.09.089.

[57] M. Jain, R. Rawal, Emissions from a net-zero building in India: life cycle assessment, Build. Citi. 3 (1) (2022) 398, https://doi.org/10.5334/bc.194.

[58] A.A. Borg, The environmental impact of ventilation systems in a Norwegian office building from a life cycle perspective, PhD thesis, Norwegian University of Science; Technology (NTNU), 2016.

[59] H. Zhang, J. Cai, J.E. Braun, A whole building life-cycle assessment methodology and its application for carbon footprint analysis of U.S. Commercial buildings, J. Build. Perform. Simulat. 16 (1) (2023) 38–56, https://doi.org/10.1080/19401493.2022.2107071.

[60] N. Emami, J. Heinonen, B. Marteinsson, A. Säynäjoki, J.-M. Junnonen, J. Laine, S. Junnila, A life cycle assessment of two residential buildings using two different LCA database-software combinations: recognizing uniformities and inconsistencies, Buildings 9 (1) (2019) 20, https://doi.org/10.3390/buildings9010020.

[61] P. Ylmén, D. Peñaloza, K. Mjörnell, Life cycle assessment of an office building based on site-specific data, Energies 12 (13) (2019) 2588, https://doi.org/10.3390/en12132588.

[62] H.M. Gardner, V. Hasik, A. Banawi, M. Olinzock, M.M. Bilec, Whole building life cycle assessment of a living building, J. Architect. Eng. 26 (4) (2020) 04020039, https://doi.org/10.1061/(ASCE)AE.1943-5568.0000436.

[63] R. Rinne, H. Emre Ilgın, M. Karjalainen, Comparative study on life-cycle assessment and carbon footprint of hybrid, concrete and timber apartment buildings in Finland, Int. J. Environ. Res. Public Health 19 (2) (2022) 774, https://doi.org/10.3390/ijerph19020774.

[64] L.C.M. Eberhardt, H. Birgisdóttir, M. Birkved, Life cycle assessment of a Danish office building designed for disassembly, Buildi. Res. Inform. 47 (6) (2019) 666–680, https://doi.org/10.1080/09613218.2018.1517458.

[65] J. Cao, Y. Zhu, J. Zhang, H. Wang, H. Zhu, The sustainability study and exploration in the building commercial complex system based on life cycle assessment (LCA)–Emergy–Carbon emission analysis, Processes 11 (7) (2023) 1989, https://doi.org/10.3390/pr11071989.

[66] M. Paleari, M. Lavagna, A. Campioli, The assessment of the relevance of building components and life phases for the environmental profile of nearly zero-energy buildings: life cycle assessment of a multifamily building in Italy, Int. J. Life Cycle Assessm. 21 (12) (2016) 1667–1690, https://doi.org/10.1007/s11367-016-1133-6.

[67] E. Hoxha, D. Maierhofer, M.R.M Saade, A. Passer, Influence of technical and electrical equipment in life cycle assessments of buildings: case of a laboratory and research building, Int. J. Life Cycle Assessm. 26 (5) (2021) 852–863, https://doi.org/10.1007/s11367-021-01919-9.

[68] R. Serrano, Antonio, S.P. Álvarez, Life cycle assessment in building: a case study on the energy and emissions impact related to the choice of housing typologies and construction process in Spain, Sustainability 8 (3) (2016) 287, https://doi.org/10.3390/su8030287.

[69] C. Kiamili, A. Hollberg, G. Habert, Detailed assessment of embodied carbon of HVAC systems for a new office building based on BIM, Sustainability 12 (8) (2020) 3372, https://doi.org/10.3390/su12083372.

[70] M.A. Cusenza, F. Guarino, S. Longo, M. Cellura, "An integrated energy simulation and life cycle assessment to measure the operational and embodied energy of a Mediterranean net zero energy building, Energy Build. 254 (January) (2022) 111558, https://doi.org/10.1016/j.enbuild.2021.111558.

[71] M. Norouzi, S. Colclough, L. Jiménez, J. Gavaldà, D. Boer, Low-energy buildings in combination with grid decarbonization, life cycle assessment of passive house buildings in Northern Ireland, Energy Build. 261 (April) (2022) 111936, https://doi.org/10.1016/j.enbuild.2022.111936.

[72] M. Roberts, S. Allen, J. Clarke, J. Searle, D. Coley, Understanding the global warming potential of circular design strategies: life cycle assessment of a design-for-disassembly building, Sustain. Product. Consumpt. 37 (May) (2023) 331–343, https://doi.org/10.1016/j.spc.2023.03.001.

[73] H.E. Ilgın, A. Saviharju, M. Karjalainen, T. Hirvilammi, Life cycle assessment of an office building in Finland using a custom assessment tool, Buildings 14 (7) (2024) 1944, https://doi.org/10.3390/buildings14071944.

[74] F. Pichlmeier, S. Lindner, Reuse potential of building services in building relocation, IOP Conferen. Ser.: Earth Environ. Sci. 1363 (1) (2024) 012050, https://doi.org/10.1088/1755-1315/1363/1/012050.

[75] K. Salwathura, F. Shabani, Evaluating Environmental Impacts: Embodied Carbon Assessment of Ventilation, Electrical, and Plumbing Systems in Swedish School architecture, Master Thesis in {Energy-efficient} and {Environmental Buildings}, Lund University, Lund, Sweden, 2024.

[76] M.F.D. Morales, M. Kouhirostamkolaei, R.J. Ries, Retrospective dynamic life cycle assessment of residential heating and cooling systems in four locations in the United States, Energy Build. 295 (September) (2023) 113272, https://doi.org/10.1016/j.enbuild.2023.113272.

[77] H. Pieskä, A. Ploskić, Q. Wang, Life-cycle assessment of a radiant high-temperature cooling system in the Mediterranean climate, Build. Environ. 245 (November) (2023) 110847, https://doi.org/10.1016/j.buildenv.2023.110847.

[78] V. Tavares, F. Freire, Life cycle assessment of a prefabricated house for seven locations in different climates, J. Build. Eng. 53 (August) (2022) 104504, https://doi.org/10.1016/j.jobe.2022.104504.

[79] J. Famiglietti, T. Toppi, D. Bonalumi, M. Motta, Heat pumps for space heating and domestic hot water production in residential buildings, an environmental comparison in a present and future scenario, Energy Convers. Manage. 276 (January) (2023) 116527, https://doi.org/10.1016/j.enconman.2022.116527.

[80] O. Seuntjens, M. Buyle, Z. Kabbara, B. Bert, A. Amaryllis, Ventilation's role in adaptable school buildings: comparing traditional and adaptable strategies through life cycle assessment, Build. Environ. 250 (February) (2024) 111150, https://doi.org/10.1016/j.buildenv.2023.111150.

[81] T. Schaubroeck, S. Schaubroeck, R. Heijungs, A. Zamagni, M. Brandão, E. Benetto, Attributional & consequential life cycle assessment: definitions, conceptual characteristics and modelling restrictions, Sustain. (Switzerl.) (13) (2021) 13, https://doi.org/10.3390/su13137386.

[82] J. Heinonen, A. Säynäjoki, J.-M. Junnonen, A. Pöyry, S. Junnila, Pre-use phase LCA of a multi-story residential building: can greenhouse gas emissions Be used as a more general environmental performance indicator? Build. Environ. 95 (January) (2016) 116–125, https://doi.org/10.1016/j.buildenv.2015.09.006.

[83] M. Botejara-Antúnez, J.G. Domínguez, J. García-Sanz-Calcedo, Life cycle analysis methodology for heating, ventilation and air conditioning ductwork in healthcare buildings, Indoor Built Environ. 32 (6) (2023) 1213–1230, https://doi.org/10.1177/1420326X231155146.

[84] A.N. Haddad, A.B. Silva, A.W.A. Hammad, M.K. Najjar, E.G. Vazquez, V.W. Y. Tam, An integrated approach of building information modelling and life cycle assessment (BIM-LCA) for gas and solar water heating systems, Int. J. Construct. Manage. 23 (14) (2023) 2452–2468, https://doi.org/10.1080/15623599.2022.2068179.

[85] Y. Decorte, N. Van Den Bossche, M. Steeman, Importance of technical installations in whole-building LCA: single-family case study in Flanders, Build. Environ. 250 (February) (2024) 111209, https://doi.org/10.1016/j.buildenv.2024.111209.

[86] National Institute for Public Health and the Environment, ReCiPe 2016 V1.1. RIVM Report 2016-0104, 2017.

[87] J. Bare, TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0, Clean Technolog. Environ. Policy 13 (5) (2011) 687–696, https://doi.org/10.1007/s10098-010-0338-9.

[88] J.C. Bare, G. Norris, D. Pennington, T. McKone, Traci: the tool for the reduction and assessment of chemical and other environmental impacts, J. Ind. Ecol. 6 (3-4) (2002) 49–78, https://doi.org/10.1162/108819802766269539.

[89] M. Roberts, P. Raftery, Material selection and system layout to lower embodied carbon of pipe in an office building, *ASHRAE Transact.* CH-24-C001 (2024).

[90] M.D.C. Gelowitz, J.J. McArthur, Comparison of type III environmental product declarations for construction products: material sourcing and harmonization evaluation, J. Clean. Product. 157 (2017) 125–133, https://doi.org/10.1016/j.jclepro.2017.04.133.

[91] H. AzariJafari, G. Guest, R. Kirchain, J. Gregory, B. Amor, Towards comparable environmental product declarations of construction materials: insights from a probabilistic comparative LCA approach, Build. Environ. 190 (December 2020) (2021) 107542, https://doi.org/10.1016/j.buildenv.2020.107542.

[92] E. Marsh, S. Allen, L. Hattam, Tackling uncertainty in life cycle assessments for the built environment: a review, Build. Environ. (2023), https://doi.org/10.1016/j.buildenv.2022.109941.

[93] Y. Dong, P. Liu, M. Uzzal Hossain, Y. Fang, Y. He, H. Li, An index of completeness (IoC) of Life cycle Assessment: implementation in the building sector, J. Clean. Product. 283 (February) (2021) 124672, https://doi.org/10.1016/j.jclepro.2020.124672.

[94] A. Laurent, B.P. Weidema, J. Bare, X. Liao, D. Maia De Souza, M. Pizzol, S. Sala, H. Schreiber, N. Thonemann, F. Verones, Methodological review and detailed guidance for the life cycle interpretation phase, J. Ind. Ecol. 24 (5) (2020) 986–1003, https://doi.org/10.1111/jiec.13012.

[95] G. Vignali, Environmental Assessment of Domestic Boilers: A Comparison of Condensing and Traditional Technology Using Life Cycle Assessment Methodology, J. Clean. Product. 142 (2017) 2493–2508, https://doi.org/10.1016/j.jclepro.2016.11.025. January.

[96] CIBSE, TM65 Embodied Carbon in Building Services: A Calculation Methodology, The Chartered Institution of Building Services Engineers, 2021.

[97] LETI, LETI Climate Emergency Design Guide: How New Buildings can Meet UK Climate Change Targets, London Energy Transformation Initiative, London, 2020.

[98] LETI, LETI Embodied Carbon Primer: Supplementary Guidance to the Climate Emergency Design Guide, London Energy Transformation Initiative, London, 2020.

[99] E. Marsh, L. Hattam, S. Allen, Stochastic error propagation with independent probability distributions in LCA does not preserve mass balances and leads to unusable product compositions—a first quantification, Int. J. Life Cycle Assessm. (2024), https://doi.org/10.1007/s11367-024-02380-0. October.

[100] H. Bergsdal, J. Tønnesen, A. Borg, C. Solli, Life cycle inventory library for embodied emissions in ventilation components, Build. Environ. 262 (August) (2024) 111854, https://doi.org/10.1016/j.buildenv.2024.111854.