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A systematic literature review of GHG emission declarations, limit values, and roadmaps for the decarbonisation of buildings

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ABSTRACT

The main objective of this paper is to systematically review the status and development of national greenhouse gas (GHG) emission declarations, GHG emission limit values, and decarbonisation roadmaps for buildings in literature. The systematic literature review (SLR) is carried out according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) checklist and uses the search database Scopus to identify relevant literature between 2016 and 2025. The following keywords were used: 'whole life carbon', 'building', 'ghg emission' and 'limit value'. The search was supplemented with publications identified through snowballing. In all, 560 publications were identified, and 51 publications were included as full text reads in the SLR. The results are presented according to a bibliometric analysis, semantic mapping, and content analysis. The results show that the forerunners in implementing national GHG emission requirements for buildings include Denmark, France, Iceland, The Netherlands, Norway, and Sweden. There is also a plethora of methods, tools, and databases being used with varying system boundaries for building typologies, building parts, and life cycle modules, which hinders direct comparison of national limit values. The information gleaned from the SLR is used to outline steps towards establishing policy frameworks and national GHG emission requirements for buildings. Insights from early adopters provide valuable experience for other countries to develop their own policy frameworks and GHG emission requirements for buildings.

1. Introduction

The latest Intergovernmental Panel on Climate Change's (IPCC) report highlights that buildings contribute 31 % and 21 % to global energy demand and global greenhouse gas (GHG) emissions, respectively [1,2]. It is therefore of paramount importance to reduce climate impacts arising from buildings. This urgency is accentuated by the international Paris agreement, and Conference of the Parties (COP) goals towards 2030 and 2050 [3]. In 2024, the European Energy Performance of Buildings Directive (EPBD) was revised to ensure that all member states require new public buildings to be zero emission from 2028, and all new buildings to be zero emission by 2030 [4]. Member states are also required to establish national databases and decarbonisation roadmaps with limit values for whole life carbon (WLC) global warming potential (GWP) by 2027 for different building typologies and climatic zones [4]. According to ISO 21678, a limit value is defined as the lowest value of acceptable performance [5]. WLC refers to total GHG emissions throughout the entire life cycle of a building. GWP is defined as the cumulative radiative forcing of direct and indirect GHG emissions over a 100-year time horizon [1,2].

Traditionally, the focus has been on direct operational emissions [6], however, recent years have seen the focus shift towards embodied emissions and achieving carbon neutrality [7–9]. This is challenging, as accounting for embodied emissions involves cross-sectoral emissions, from the process industry, energy, buildings, and transport. The construction industry is often represented by complex supply chains whereby indirect emissions (scope 3) are down prioritised. Governments and organisations typically focus on cutting direct emissions (scope 1), and indirect emissions from energy use (scope 2) [10]. In addition, buildings have emissions that span decades, whilst most national climate goals are focused on the next 5–25 years from 2030 to 2050.

Life cycle assessment (LCA) is a common methodology used to assess the environmental impacts from buildings [11–13]. prEN 15,978 classifies the life cycle of a building according to the product stage (A1 – extraction and upstream production, A2 – transport to factory, and A3 - manufacturing), the construction process (A4 - transport to site, and A5 - construction), the use stage (B1 - use, B2 - maintenance, B3 - repair, B4 - replacement, B5 - refurbishment, B6 - operational energy use, B7 -

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operational water use, and B8 – building related users' activities), the end-of-life (EOL) stage (C1 -deconstruction, C2 - transport to waste processing or disposal, C3 - waste processing, and C4 - disposal), and life cycle module D for benefits and loads beyond the system boundary in the form of exported utilities, reuse, recycling, and recovery [14]. These life cycle modules are often referred to as Cradle-to-Gate (A1-A3), Cradle-to-Grave (A1-C4), or Cradle-to-Cradle (A1-C4) which closes the loop in a circular economy.

Despite these harmonised methods, there is still a large scope for interpretation. In the International Energy Agency's Energy in Buildings and Communities programme (IEA EBC) Annex 72, the Be2226 office building in Austria was assessed by 22 institutions, and the GHG emission results varied from 10 to 71 $kgCO_2e/m^2/yr$ depending on the national assessment method used [15]. Similarly, a timber-framed building in Canada compared 16 different national methodologies and found a large variation in results depending on the choice of method for biogenic carbon [16]. These comparison case studies show that there is a large variation in LCA results due to varying national approaches in methodology, background data, scope of assessment, and reference study period (RSP).

Since, there has been a multitude of methods and strategies to reduce emissions from buildings, including net zero energy buildings (nZEB) [17], zero emission buildings (ZEB) [18], zero emission neighbourhoods (ZEN) [19], zero carbon buildings (ZCB) [20,21], near zero and resilient buildings (NZERB) [22], positive energy buildings (PEB) [23], and positive energy districts (PED) [24,25]. The International Energy Agency (IEA) refers to zero carbon ready, as a highly energy efficient building that uses renewable energy or energy that will be decarbonised by 2050, meaning that the building will be carbon neutral by 2050 without further changes [26]. Architecture 2030 refer to zero net carbon (ZNC) [27], whilst the World Green Building Council (WGBC) refer to net-zero operational and embodied carbon [28]. Here, embodied carbon refers to indirect GHG emissions. According to Habert et al. climate neutral building stocks should include existing and new buildings, as well as production (embodied emissions) and consumption-based (operational emissions) targets [29].

In terms of scientific literature, one comprehensive literature review has mapped the use of LCA in the building industry over the past two decades and found that despite LCA gaining in popularity to quantify environmental impacts from buildings, there is a high variation in scope, definition, methodology, functional unit, and data [30]. More often than not, building LCAs focus on GWP, often including life cycle modules A1 - A5 and B6, and use a functional unit of $kgCO_2e$ or $kgCO_2e/yr$ with a 50-year building lifetime [30]. Dominant tools and databases for LCA were SimaPro and EcoInvent [30]. The USA had the most amount of publications followed by China, Italy, the UK, Germany, Spain, Canada, and Australia [30]. Future research seems to be focusing on hybrid LCA, and lifting focus from buildings to the neighbourhood scale [30]. This is supported by Dong et al. who carried out a systematic review of LCAs of buildings, comparing seven mid-point and three end-point categories, and found large variations in LCA results due to a myriad of parameters, including: structure, materials, location, energy system, demolition practices, LCA modelling, definition of system boundaries, treatment of biogenic carbon, and selection of background data [31].

Another literature review mapped the integration of LCA in the building design process, and noted the level of detail across project phases increases as more information on the project becomes available [32]. Others have partially evaluated the status of GHG emission declarations, limit values, and roadmaps towards the decarbonation of buildings. For example, Balouktsi et al. has mapped the regulatory needs for harmonised carbon values in the Nordic countries, and compares methods and policies between Denmark, Estonia, Finland, Iceland, Norway, and Sweden [33]. At the EU level, a series of technical reports has mapped the needs for embodied carbon benchmarks in Europe and provides a framework and baseline for benchmarking [34–36].

However, a comprehensive systematic literature review of national GHG emission declarations, limit values, roadmaps, methods, and system boundaries has not previously been carried out. Trigaux et al. critically reviewed 23 existing benchmarking systems to identify main approaches and methods, and suggested reference values for future benchmarking systems should range between 15 and 35 $kgCO_{2e}/m^2/yr$ for WLC impacts from buildings [37]. Reference values are defined as the state of the art, or business as usual. Mata et al. also reviewed existing literature on roadmaps and targets for positive or zero and low energy and carbon buildings in 2020 and found that there is a bias towards more developed regions [38]. However, Mata et al.'s mapping is not a systematic review, and focuses primarily on zero energy building initiatives [38]. Existing literature is characterised by fragmented overviews of a rapidly developing field.

This article builds upon the existing body of knowledge by providing an up-to-date comprehensive systematic literature review (SLR) that assesses the geographical status of GHG emission declarations, limit values, and roadmaps towards the decarbonation of buildings. The research questions (RQ) this paper aims to address are:

1. Which countries are developing and setting GHG emission declarations, limit values, and roadmaps for the decarbonisation of buildings?
2. Which methods, tools, and databases are commonly used?
3. What is the scope of assessment in terms of building typologies, building parts, and life cycle modules?
4. How can this information be used to guide others in adopting policy frameworks for GHG emission requirements in buildings?

The scope of the SLR is limited to GHG emissions and does not consider other environmental indicators. The aim of this paper is to compare the different national approaches and makes no effort to harmonise them. This article is aimed at policy makers, and professionals from the construction industry that have a role in the design and implementation of buildings. The article uses insights gained from the SLR to provide recommendations for the decarbonisation of buildings. This article begins by presenting the theory and calculations for the SLR, followed by a presentation of the results in terms of the bibliometric analysis, semantic mapping, and content analysis. Subsequently, the results are discussed in terms of the steps identified through literature to facilitate for the decarbonisation of buildings. Lastly, further work is presented, and the conclusions are drawn.

2. Theory and calculation

The method used in this paper consists of a SLR following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) checklist [39] which is supplemented with literature from snowballing to ensure that important literature was not omitted. Owens discusses the merits of systematic reviews as a method for reviewing large amounts of information and emphasises the need for systematic reviews to be explicit, rigorous, and reproducible, and the need to disclose limitations, such as risk of bias [40].

Scopus was chosen as a search database since it is a scientific abstract and citation database containing a comprehensive overview of multidisciplinary peer-reviewed literature from a wide range of sources. Web of Science and Google Scholar were also considered, but they returned immoderate results and were therefore excluded. One limitation of this study is that it only uses Scopus in the database search. However, this limitation has been mitigated by quality assuring information gathered against government sources [41–45]. The search words used as selection criteria in the article title, abstract, and keyword search fields include: 'whole' AND 'life' AND 'carbon' OR 'building' OR 'ghg' AND 'emission' OR 'limit' AND 'value'.

The Boolean operators 'and' and 'or' were used to ensure the search results returned relevant literature. The initial search was carried out in January 2025 and resulted in 457 publications. A further 103 publications were identified through snowballing literature. This was achieved by using the reference lists of the search results in Scopus to identify additional papers. The publications were then screened according to the following exclusion criteria:

- Articles published before 2016
- Articles not in English
- Duplicates from snowballing
- Articles that were not Open Access
- Other media than scientific articles, conference papers, and technical reports
- Literature reviews
- Not relevant to the RQ after screening the title, keywords, abstract, and full text

Articles published before 2016 were excluded since the Paris agreement came into force in 2015. Other media that was excluded included websites, presentations, and pamphlets. After applying the exclusion criteria, the results were narrowed down to 51 publications, consisting of 29 scientific articles, 12 conference papers, and 10 technical reports. The search results were exported from Scopus to Zotero for referencing, to Microsoft Excel to keep an overview of the PRISMA selection, and to NVivo 14 for coding literature [46]. See Fig. 1 for an overview of the PRISMA flow diagram of the SLR search identification and screening procedure.

The author has independently reviewed the remaining 51 publications, and the literature was thereafter analysed in terms of (1) bibliometric analysis, (2) semantic mapping, and (3) content analysis.

The bibliometric analysis involves analysing the literature in terms of type and year of publication, and geographical distribution. The geographical distribution is identified through the lead author's institute affiliation. The results from the bibliometric analysis form the basis for country-by-country mapping in the content analysis. Some of the literature involved multiple country case studies, therefore the countries identified in the content analysis have been expanded to include these as well.

The semantic mapping involves mapping keywords identified over time in the form of a network diagram generated in VosViewer, and an analysis of word frequency in NVivo 14.

The content analysis involves identifying key themes by attaching codes to the literature in NVivo 14. The key words identified through the semantic mapping were used as a starting point for coding (see Table 1). However, the thematic codes were refined underway with the RQs in mind. Examples of key themes from the coding process include benchmark values, standardised method, tools and databases, reference units, life cycle modules, building typologies, building parts, declarations, and roadmaps. Here, the coding categories cover:

- **benchmark values** include all kinds of values relating to benchmarking GHG emissions

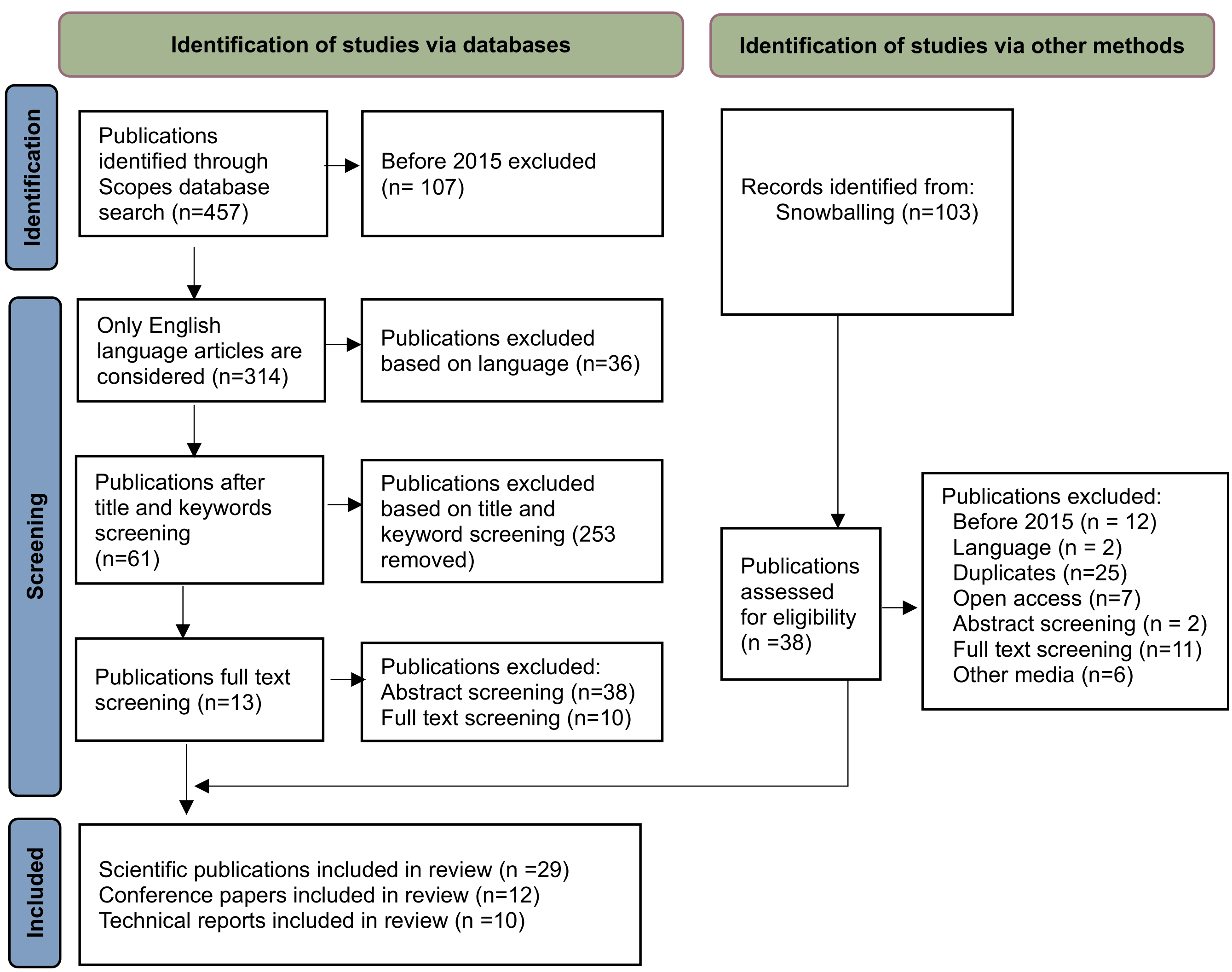

Fig. 1. PRISMA flow diagram of the SLR search.

Table 1
Table showing the most frequent words used in the SLR.

No.	Word	Count	Weighted Percentage (%)	Similar Words
1	builds	13 795	2.38	build, build', building, building', buildings, buildings', buildings', builds
2	energy'	4 839	0.83	energi, energie, energies, energy, energy'
3	emission'	4 196	0.72	emiss, emission, emission', emission', emissions, emissions', emissions'
	using	4 177	0.72	#use, use, use', used, useful, usefully, usefulness, uses, using
5	carbon'	4 025	0.69	'carbon, carbon, 'carbon, carbon', carbonate, carbonates, carbonating, carbonation, carbone
6	life'	3 504	0.60	life, life', life''
7	constructive	3 120	0.54	construct, constructed, constructing, construction, construction', constructions, constructions', constructive
8	impacts'	3 067	0.53	impact, impact', impacted, impactful, impacting, impacts, impacts'
9	embodied'	2 809	0.48	embodi, embodie, embodied, embodied', embody, embodying
10	value'	2 684	0.46	value, value', valued, values, values'
11	materials'	2 626	0.45	materi, material, materiality, materialization, materially, materials, materials'
12	study	2 573	0.44	studie, studied, studies, studies', study, studying
	cycling	2 554	0.44	cycl, cycle, cycle', cycles, cycling
	data	2 550	0.44	data, data'
15	'new	2 400	0.41	'new, new, new'
16	lca'	2 325	0.40	lca, lca'
17	assessments	2 096	0.36	assess, assessed, assesses, assessing, assessment, assessment', assessments
	environmentally	2 094	0.36	environmental, environmentally
19	benchmarks	2 025	0.35	benchmark, benchmark', benchmarked, benchmarker, benchmarking, benchmarking', benchmarks, benchmarks'
20	targets	1 917	0.33	target, targeted, targeting, targets

- **standardised method** relates to international, European, or national methods for GHG emission calculations of buildings
- **tools and databases** include any LCI/LCIA tool or database mentioned in the literature
- **reference units** refer to the unit of GHG emission quantification in the literature
- **life cycle modules** refer to the life cycle modules as defined in prEN 15,978
- **building typologies** include any type of building included in the literature
- **building parts** include any type of building part included in the literature
- **declarations** refer to national requirements for GHG emission declarations
- **roadmaps** refer to trajectories, emission reduction pathways, decarbonisation strategies, or action plans mentioned in the literature for GHG emissions from buildings

The content analysis also involves an in-depth analysis, country-by-country, of building sustainability schemes, national GHG emission declarations, GHG emission limit values, bottom-up and top-down values, national building GHG databases, and national roadmaps for the decarbonisation of buildings. This was followed by an in-depth analysis of the methodologies used including details on reference units, definition of area, reference study period (RSP), as well as the availability of LCA tools, life cycle inventory (LCI) databases, and environmental product declaration (EPD) databases. An overview of national system boundaries was then identified in terms of building typologies, building parts, and life cycle modules. The most recent information was used in situations where conflicting information across multiple sources was found. The information gleaned from the SLR was then used to draw inferences and outline steps towards establishing policy frameworks and national GHG emission requirements for buildings.

3. Results

The results from the SLR are presented in terms of the bibliometric analysis (Figs. 2–4), semantic mapping (Fig. 5 and Table 1), and content analysis (Fig. 6 and Tables 2–6). Fig. 2 shows the number and type of publications per year analysed in the SLR. The results indicate a slight decrease in the number of publications during the peak of the COVID-19 pandemic from 2020 to 2022. Fig. 3 shows a map of the geographical distribution of the literature analysed in the SLR. Here, Switzerland has the most publications (7), followed by Belgium and Denmark (5 each), New Zealand, Sweden, and the United States of America (USA) (4 each).

Fig. 4 shows the European geographical distribution of the literature analysed in the SLR. The results show Switzerland has the most publications (7), followed by Belgium and Denmark (5 each), Sweden (4), the Czech Republic and France (3 each), Austria, Italy, Norway, Spain, and the United Kingdom (UK) (2 each), and Germany, Hungary and Poland (1 each).

Fig. 5 shows a network diagram of keywords from the SLR over time. Earlier publications (purple) focus on energy efficient buildings, sustainable buildings, and construction management. More recent literature (turquoise) focuses on LCA, buildings, benchmarks, embodied carbon, WLC, and embodied GHG emissions, whilst emerging literature (lime green) focuses on carbon footprints, environmental footprints, building decarbonisation, and budget allocations. Table 1 shows the top 20 most frequent words identified from a query search in NVivo 14. Keywords from the initial Scopus database search are highlighted in blue. Out of the original keyword search, 'whole', 'GHG', and 'limit' were not ranked in the most frequent words. Notably, 'energy' (4839) continues to rank higher than 'materials' (2 626) despite the shift from operational to embodied emissions, and that 'benchmarks' (2025) ranked slightly higher than 'targets' (1 917).

For the content analysis, key themes were identified through coding the literature. After refinement, the following key themes emerged for the decarbonisation of buildings: benchmark values, standardised method, tools and databases, reference units, life cycle modules, building typologies, building parts, declarations, and roadmaps. Fig. 6 shows a histogram of the number of publications from the SLR that directly mention these key themes.

Table 2 shows which countries from the SLR have building sustainability schemes, national GHG emission declaration requirements, limit values, and decarbonisation roadmaps. Green boxes indicate implemented measures, whilst yellow boxes indicate voluntary measures, planned measures, or published research. Out of the reviewed articles, Denmark, France, Iceland, The Netherlands, Norway and Sweden have requirements for GHG emission declarations, whilst Belgium, Estonia, and Finland have plans for GHG emission declaration requirements in the future. Of these countries, Denmark, The Netherlands, and Sweden have limit values, with Belgium, the Czech Republic, Estonia, Finland, Germany, Iceland, Norway, and Switzerland currently developing limit

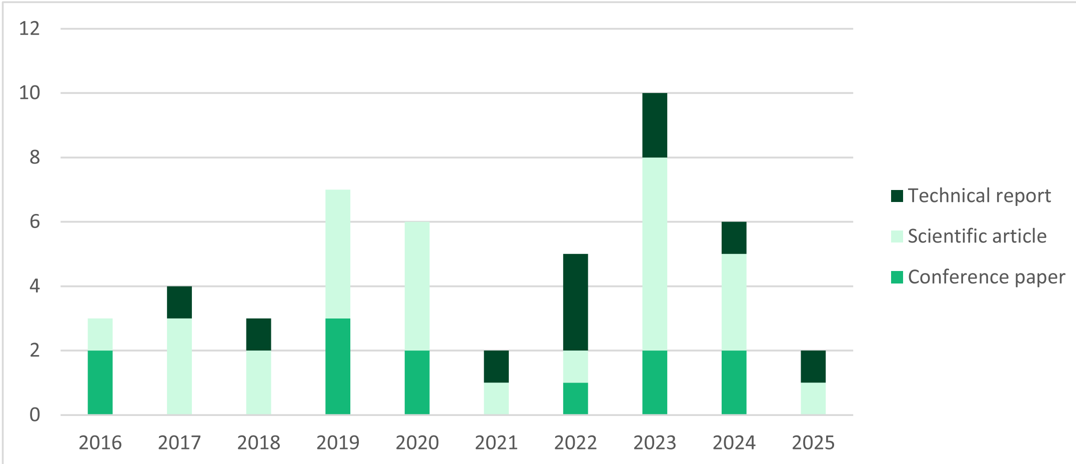

Fig. 2. Diagram showing the number and type of publications per year analysed in the SLR.

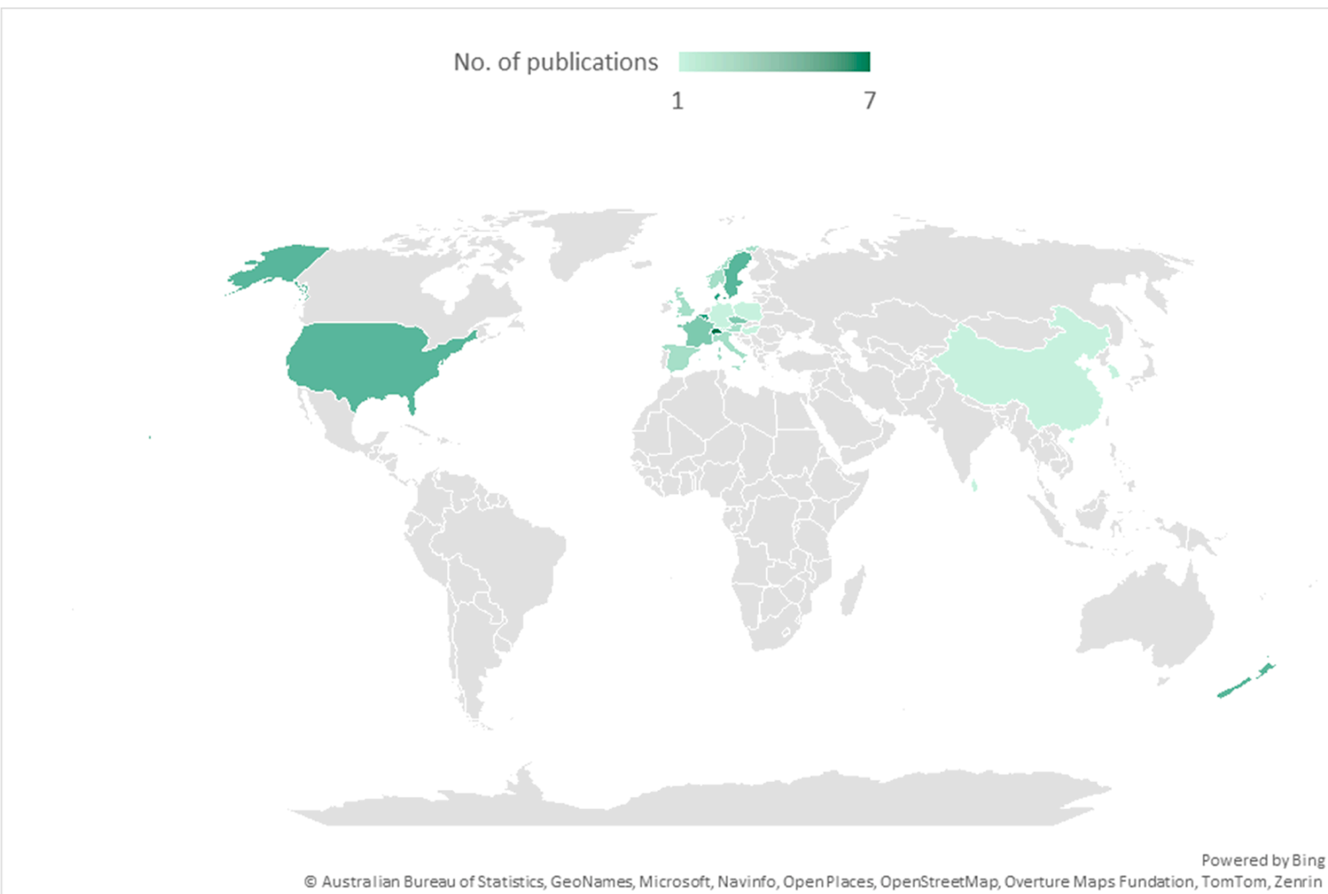

Fig. 3. Map showing the global geographical distribution of publications analysed in the SLR.

values. Most of these countries are taking a bottom-up approach to developing limit values based on a statistical meta-analysis of building case studies or archetypes. Whilst Austria, the Czech Republic, Denmark, France, New Zealand, Switzerland, and the UK are investigating top-down values based on planetary boundaries. Denmark, France, Iceland, and Sweden have national building databases for reporting GHG emissions. Denmark, France, and Sweden have national roadmaps or action plans for the decarbonisation of buildings, whilst the Czech Republic and Iceland have plans on developing roadmaps. Table 2 also includes information on the number of case studies or archetypes included in the bottom-up assessments, ranging from 1 archetype in New Zealand to over 20 000 cases in France. Some countries have multiple studies on bottom-up benchmarking, therefore multiple numbers of cases are given.

Table 3 builds upon the information given in Table 2 by providing details on the methods, tools, and databases mentioned in the SLR. When it comes to methods, nearly all countries follow the European Standard EN 15978. However, the USA follows the international standard ISO 14044, whilst China, the Netherlands, Norway, and Switzerland have national methods. The Czech Republic, Finland, Spain,

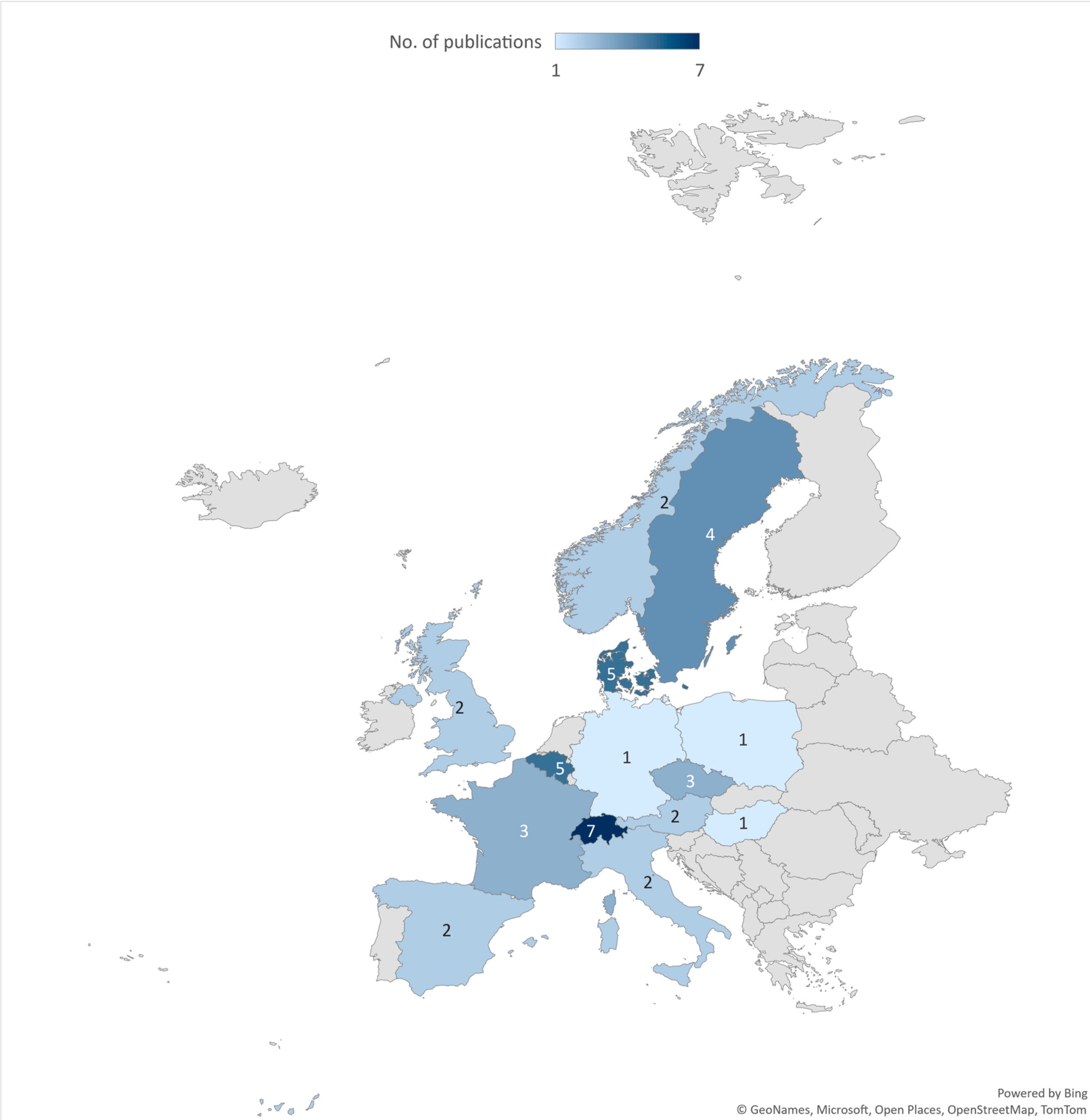

Fig. 4. Map showing the European geographical distribution of publications analysed.

and Sweden have supplementary methods. Nearly all the countries use $kgCO_2e/m^2/yr$ as a reference unit, whilst The Netherlands also uses €, the Czech Republic also uses tCO_2e/yr, Switzerland also uses $kgCO_2e/capita/yr$, and the USA, Spain, and Sweden use $kgCO_2e/m^2$.

The definition of area varies considerably from gross floor area, net floor area, gross internal floor area, internal floor area, heated floor area, heated net floor area, heated internal floor area, net internal floor area, usable floor area, and useful floor area. Germany, The Netherlands, and Norway mention national standards for the definition of area.

For the RSP, 17 countries use a RSP of 50 years, followed by 7 countries using 60 years, and one country each using either 40, 75, 80, 90, or 100 years. A broad range of LCA tools, LCI databases, and EPD databases (highlighted in green) are reported across the countries. Table 3 gives some indication on the readiness level for countries to implement GHG emission declarations, limit values, and decarbonisation roadmaps.

Table 4 gives an overview of the building typologies included in the SLR by country, whereby SFH stands for single-family house and MFH stands for multi-family house. Boxes marked green are mandatory reporting requirements, whilst boxes in yellow are based on system boundaries used in research for that country. Denmark, France, The Netherlands, Norway, and Sweden have mandatory reporting for a range of typologies, whereby Norway does not distinguish between new or refurbishment, and Sweden has plans on including refurbishment in the future. Residential buildings, followed by offices, and educational buildings are the most frequently reported building typologies.

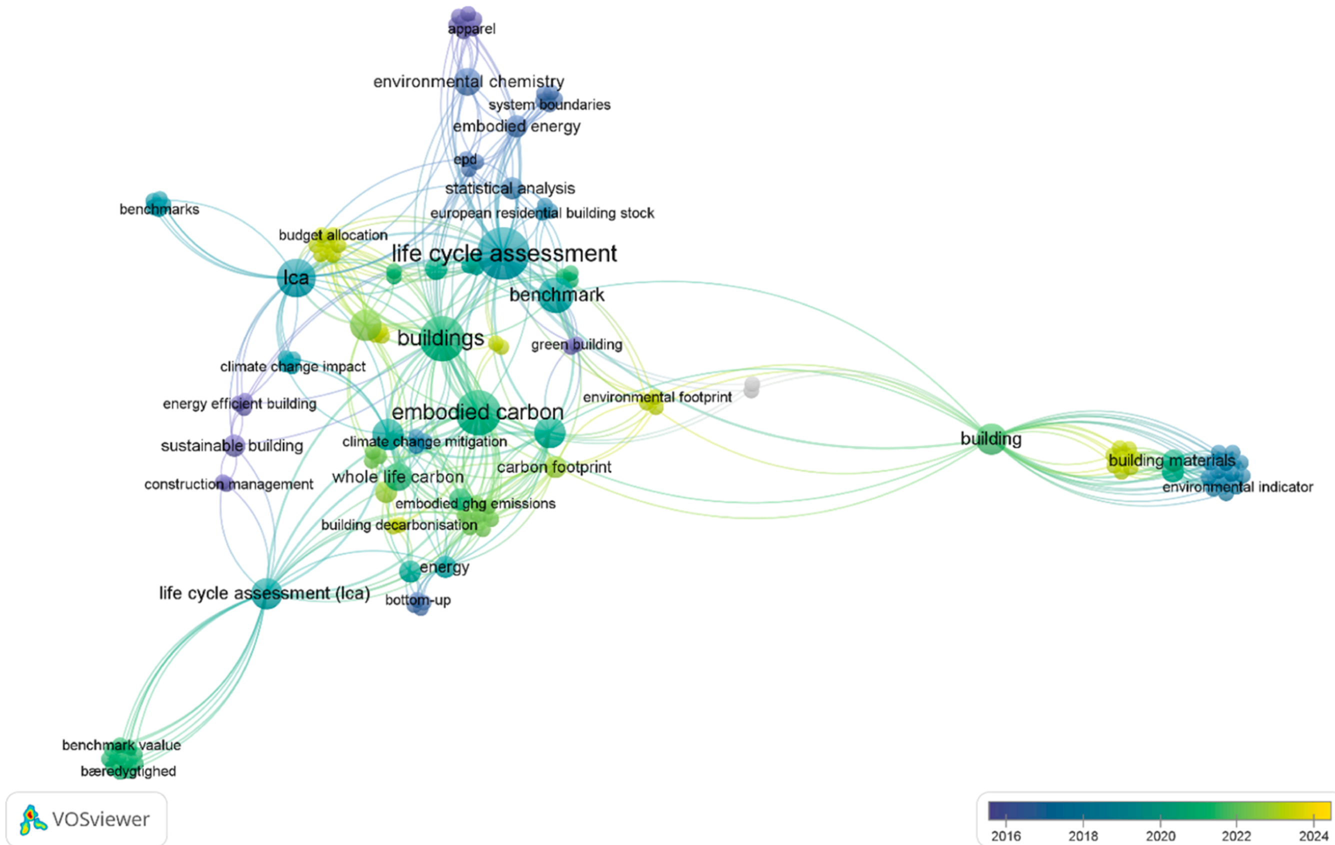

Fig. 5. Network diagram of keywords over time from the SLR.

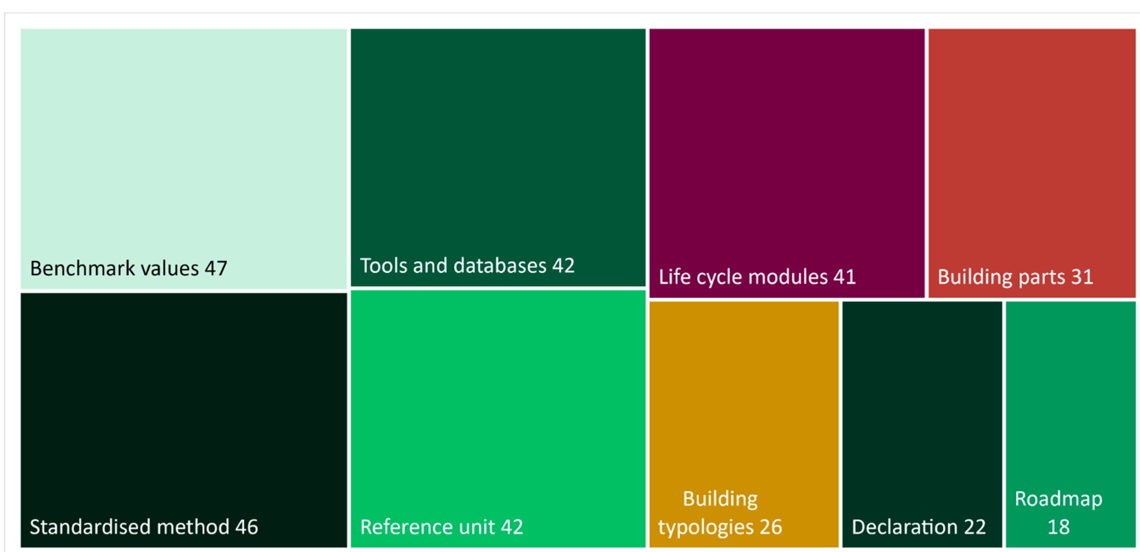

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Fig. 6. Histogram showing the number of publications from the SLR that mention key themes.

Table 5 gives an overview of the building parts included in the SLR by country, whereby boxes marked green are mandatory reporting requirements, and boxes in yellow are based on system boundaries used in research for that country. It should be noted that none of the publications reviewed consider loose furniture. Of the publications, several building classification systems were mentioned, including Level(s) for the EU [4], the Norwegian Standard NS 3451 Table of building parts for Norway [47,48], Baukostenplan Hochbau" (BKPeH), SIA 380/1 for Switzerland [49], and the ÚRS price system (CS ÚRS), the RTS pricing system, the national classification JSKO (in Czech Jednotné Klasifikaci Stavebních Objekt), the national version of the European classification of building construction CZ-CC (Classification of Types of Constructions), and the CZ-CPA building products (Classification of Product by Activities) in the Czech Republic [50,51]. Sweden is the only country that has indicated they will expand the scope of building parts covered [52]. The most frequently mentioned building parts consist primarily of

Table 2
Table showing which countries have building sustainability schemes, national GHG emission declarations, GHG limit values, and decarbonisation roadmaps according to the SLR.

Geographical coverage	Building sustainability schemes	National GHG emission declaration	National GHG limit values	Bottom-up values	Top-down values	National building LCA database	Decarbonisation roadmaps	References
Australia	Greenstar							[50]
Austria	DGNB			<50 cases				[34,51,52]
Belgium	BREEAM, Totem	Voluntary	Single score under development	35 archetypes 117 cases 105 cases				[33,50,51,53,54]
Czech Republic	SBToolCZ		Selected public buildings	50 cases			2030: planned	[49–51,53,55,56]
Denmark	DGNB-DK	2023	2021: Voluntary CO_2 class 2023: 12 kgCO_2e/m^2/yr 2025: 10.5 kgCO_2e/m^2/yr	60 cases 72 cases		BBR database	2024: published 2027: 9 kgCO_2e/m^2/yr 2029: 7.5 kgCO_2e/m^2/yr	[32,33,50,51,53,57–60]
Estonia	BREEAM	2025	2027: planned					[32,60]
Finland		2026	2026: planned	4 000+ cases 59 cases		Planned 'C' value in Energy performance certificates, OneClick LCA Carbon Heroes Benchmarks		[32,33,53,60]
France		2022		40 cases 486 cases 20 000+ cases		RE2020 building LCA database, Base de Données Nationale des Bâtiments (BDNB)	National Low-Carbon Strategy (SNBC) 2025, 2028, 2031	[33,50,51,53,58,61,62]
Germany	DGNB, BNB		Under development	350+ cases <50 cases				[50,51,53,63–65]
Hungary				6000+ archetypes				[50,51,66]
Iceland		2025	Under development			Húsnæðis- og mannvirkjastofnun (HMS) LCA portal	2028, 2030: planned	[32,60]
Netherlands		2017	2018: single score MPG <1	10 archetypes 47 cases				[33,50,51,53]
New Zealand				1 archetype				[50,51,67–70]
Norway	BREEAM-NOR, FutureBuilt, FME ZEB, FME ZEN, Klimasats	2023	2026: planned	133 cases 186 cases				[32,46,47,50,60]
Poland	BREEAM			11 cases				[71]
Republic of Korea	G-SEED			23 cases				[72]
Spain	VERDE, BREEAM			7 cases		Suggested: EU building stock observatory		[50,51,73,74]
Sweden	Miljöbyggnad, BREEAM-SE, NollCO2	2022	2025: varies per building typology	68 cases		Boverket	2027: 15-25% reduction	[32,50,51,60,75–77]
Switzerland	Minergie-ECO label		SIA 2040: 1 tCO_2e/capita/yr	31 cases <50 cases				[48,50–53,63,78]
EU	EU taxonomy	2027: EPBD	EPBD requirement	769 cases			EPBD requirement	[32–35,60,63,77,79,80]
UK	BREEAM			<50 cases				[63,81,82]
USA	LEED			1007 cases				[63,83–86]

the main building: foundations, basement, load-bearing structure, external and internal walls, floors and roof, whilst about half of the countries identify stairs, balconies and technical systems in the form of either electrical, heating ventilation and air-conditioning (HVAC), renewable energy systems (RES), water, sewage, fixed furniture, and external works. Only four countries consider groundworks.

Table 6 gives an overview of the life cycle modules included in the SLR by country. Green boxes are reporting requirements, whilst yellow boxes are system boundaries used in research for those countries. All countries include life cycle modules A1-A3 (cradle-to-gate) as a minimum, with most countries including life cycle modules A4-A5, B4, B6, and C1-C4. The least frequently reported life cycle modules are B1 and B8.

4. Discussion

This article provides a SLR of the status and development of national GHG emission declarations, limit values, and decarbonisation roadmaps for buildings in literature. It provides details on the methods, tools, and databases commonly used, as well as the scope of system boundaries in terms of building typologies, building parts, and life cycle modules. This information is used in the discussion to outline steps to guide others in adopting policy frameworks and facilitate for the decarbonisation of buildings.

Table 3
Table showing the main methods, tools and databases identified through the SLR.

	Method	Reference unit	Definition of area	RSP	LCA tools	LCI databases	EPD databases	References
Australia		$kgCO_2e/m^2/yr$	Internal floor area	50				[50]
Austria	EN 15978	$kgCO_2e/m^2/yr$	Net floor area	50	CAALA, eLCA, LEGEP, oekobilanz-bau.be, SBS online tool	Baubook	ÖkobauDat, ECO platform	[34,51,52]
Belgium	EN 15978	$kgCO_2e/m^2/yr$	Heated floor area	60	Tool to Optimize the Total Environmental impact of Materials (TOTEM)	MMGs - Environmental Profile of Building Elements		[33,50,51,53,54]
Canada		$kgCO_2e/m^2/yr$	Gross internal floor area	60				[50]
China	GB/T 51366-2019 China's Standard for Building Carbon Emission Calculation	$kgCO_2e/m^2/yr$		50	LCA tool eFootprint, building LCA tool BELES, Tsinghua University's IBLAT	CLCD database		[87]
Czech Republic	EN 15978, Level(s), SBToolCZ method	tCO_2e/yr $kgCO_2e/m^2/yr$	Net floor area	50	OneClick LCA, SBToolCZ	Envimat, ecoinvent, SBToolCZ database	CENIA database	[49–51,53,55,56]
Denmark	EN 15978	$kgCO_2e/m^2/yr$	Gross floor area, Heated floor area	50	LCAbyg	Okobaudat	ÖkobauDat, ECO platform	[32,33,50,51,53,57–60]
Estonia	EN 15978	$kgCO_2e/m^2/yr$	Heated floor area	50		CO2data.fi	CO2data.fi	[32,60]
Finland	EN 15978, carbon footprint and handprint	$kgCO_2e/m^2/yr$	Heated net floor area	50	OneClick LCA	CO2data.fi	RTS EPD, EPD-Norge, Environdec, ÖkobauDat, IBU and ICE	[32,33,53,60]
France	EN 15978	$kgCO_2e/m^2/yr$	Gross floor area	50, 100	ClimaWin, OneClick LCA, ELODIE, novaEQUER, ThermACV, Béa, ArchiWIZARD, Vizcab and COCON	INIES, EcoInvent	INIES EPD, PEP Ecopassport	[33,50,51,53,58,61,62]
Germany	EN 15978	$kgCO_2e/m^2/yr$	Net floor area (DIN 277)	50	CAALA, eLCA, LEGEP, oekobilanz-bau.de, SBS online tool, Generis, ökobilanz-bau.de		ÖkobauDat, ECO platform	[50,51,53,63–65]
Hungary	EN 15978	$kgCO_2e/m^2/yr$	Heated internal floor area	50	OpenLCA	EcoInvent	EPDs	[50,51,66]
Iceland	EN 15978	$kgCO_2e/m^2/yr$		50			EPD-Norge, environdec, ECO platform	[32,60]
New Zealand	EN 15978	$kgCO_2e/m^2/yr$	Gross floor area	90 60	LCAQuick	BRANZ CO2NSTRUCT	EPDs	[50,51,67–70]
Netherlands	Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken	€ $kgCO_2e/m^2/yr$	Gross floor area Net internal area (NEN 2580)	50 75	GPR Gebouw / Bouwbesluit, MPGCalc, MPRI MPG-software and One Click LCA	Nationale Milieudatabase (NMD)		[33,50,51,53]
Norway	NS 3720	$kgCO_2e/m^2/yr$	Gross floor area (NS 3940)	50	ZEB tool, Reduzer, OneClick LCA, Holte SmartKalk Miljø, ISY Calcus, LCAbyg Norway		EPD-Norge, ECO platform	[32,46,47,50,60]
Poland	EN 15978	$kgCO_2e/m^2/yr$	Usable floor area	60	OneClick LCA			[71]
Republic of Korea		$kgCO_2e/m^2/yr$	Gross floor area	40		Korean Life Cycle Impact Assessment Index based on a Damage-oriented Modeling (KOLID)		[72]
Spain	EN 15978, Level(s)	$kgCO_2e/m^2$	Useful floor area	50	IteC, OneClickLCA, Ecómetro, Cype, OpenLCA	EcoInvent	OERCO2 Andalusian building product database	[50,51,73,74]
Sri Lanka	EN 15978	$kgCO_2e/m^2/yr$	Gross floor area	80	Building Sustainability Assessment Tool (Building-SAT)		Digital Environmental Hub for Global Construction Products	[88]
Sweden	EN 15978, Boverket guideline	$kgCO_2e/m^2$	Gross floor area	N/A	Byggsektorns miljö-beräkningsverktyg	Boverkets klimatdatabas, ivl database	EPD-Norge, environdec, ECO platform	[32,50,51,60,75–77]

(continued on next page)

Table 3 (*continued*)

	Method	Reference unit	Definition of area	RSP	LCA tools	LCI databases	EPD databases	References
Switzerland	SIA 2023	$kgCO_2e$/capita/yr $kgCO_2e/m^2/yr$	Gross floor area	60	SIA 2040	Ökobilanz, EcoInvent, KBOB database		[48,50–53,63,78]
EU	EN 15978, Level(s)	$kgCO_2e/m^2/yr$	Useful floor area	50			Forthcoming CPR	[14–17,36,39,50,53,54]
UK	EN 15978			50-60	IES, eToolLCD and OneClick LCA	BRE Green Guide to Specification, Bath Inventory of Carbon and Energy, IMPACT database		[63,81,82]
USA	ISO 14044	$kgCO_2e/m^2$	Internal floor area	50-60	Tally, Athena			[63,83–86]

Table 4
Overview of building typologies included in the SLR. Green boxes indicate implemented measures, yellow boxes are voluntary, planned or published measures.

	Residential		Office	Educational	Retail and restaurants	Hospitals and health	Sports facilities	Cultural	Religious	Industrial	Holiday	Other	Refurbishment
	SFH	MFH											
Austria	yellow	yellow											
Belgium	yellow	yellow											
China				yellow									
Czech Republic	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
Denmark	green	green	green	green	green	green	green	green	green	green		green	
Estonia	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow				yellow	
Finland		yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow				yellow
France	green	green	green	green	green	green				green			
Hungary	yellow	yellow											
Iceland	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow		yellow	yellow
Netherlands	green	green	green	green	green								
New Zealand	yellow	yellow	yellow										
Norway		green	green	green	green	green	green	green	green	green		green	green
Poland			yellow										
Republic of Korea				yellow									
Spain	yellow	yellow	yellow										
Sri Lanka	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
Sweden	green	green	green	green	green	green	green	green	green			green	yellow
Switzerland	yellow	yellow	yellow	yellow	yellow								yellow
Turkey													
EU	yellow	yellow	yellow	yellow	yellow	yellow	yellow					yellow	
UK	yellow	yellow	yellow										
USA	yellow	yellow	yellow	yellow		yellow				yellow			
TOTAL	17	19	17	15	12	11	9	8	7	7	2	8	7

The SLR has its limitations and may be subject to convenience sampling. The access to publications is focused on those that have come furthest and has a bias towards more developed regions. One potential bias is illustrated by the geographical concentration of results in Europe. This concentration may be explained by the forthcoming requirements in the EPBD. However, it also highlights the importance of supporting other countries and regions in developing national GHG emission declarations, limit values, and decarbonisation roadmaps.

The SLR also indicates that the results are sensitive to the publication activities of individual researchers or research teams, whereby Switzerland, the Czech Republic, and Sweden have expansively covered this topic. However, the findings also indicate that the literature is underpinned by cross-border studies which has encouraged knowledge sharing, and the development of WLC methodologies for buildings. The content analysis in this SLR is a qualitative assessment, and subject to interpretation, since not all literature was clear in stating the status of policies, methodologies, or system boundaries. Measures were taken to compensate for this, by cross-referencing literature with government

Table 5
Overview of the building parts included in the SLR. Green boxes indicate implemented measures, yellow boxes are voluntary, planned or published measures.

	Groundworks	Foundations	Basement	Structure	External walls	Internal walls	Floors	Roof	Stairs	Balcony	Lifts	Electrical	HVAC	RES	Water	Sewage	Other systems	Fixed furniture	External works
Austria																			
China																			
Czech Republic																			
Denmark																			
Estonia																			
Finland																			
France																			
New Zealand																			
Norway		*																	
Sri Lanka																			
Sweden																			
Switzerland																			
EU																			
UK																			
USA																			
TOTAL	4	14	12	15	15	15	15	15	9	6	5	7	9	7	8	7	4	7	7

*Only includes pile foundations and direct foundations.

Table 6
Overview of life cycle modules included in the SLR. Green boxes indicate implemented measures, yellow boxes are voluntary, planned or published measures.

	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	C1	C2	C3	C4	D
Australia																
Austria																
Belgium																
Canada																
China																
Czech Rep.																
Denmark																
Estonia																
Finland																
France																
Germany																
Hungary																
Iceland																
Netherlands																
New Zealand																
Norway			*													
Poland																
Spain																
Sri Lanka																
Sweden																
Switzerland																
EU																
USA																
TOTAL	23	20	20	3	11	4	21	5	18	5	2	17	18	19	21	11

* Only includes waste.

sources [41–45].

In addition, the SLR does not consider the status of development at the regional level. For example, some states (i.e. California in the USA), organisations (i.e. RIBA in the UK), or cross-border construction companies (i.e. Rambøll) have adopted their own policies, methods, and system boundaries for the decarbonisation of buildings. Giesekam et al. discuss some of the challenges with aligning carbon reduction targets in the UK given a fragmented industry with many competing regional approaches [53].

From the key themes identified in the content analysis, it was possible to surmise ten steps towards the decarbonisation of buildings:

(a) Stakeholder engagement
(b) Environmental sustainability scheme
(c) Common standardised methodology
(d) LCA calculation tool
(e) LCI database and EPD data
(f) GHG emission declarations of buildings
(g) LCA database for buildings
(h) Reference values
(i) Target values
(j) Roadmap for decarbonisation

These steps are discussed and explained in more detail in the following sections. Thereafter, policy implications and further work are discussed.

4.1. Stakeholder engagement

One point made clear in the SLR, is that there needs to be a willingness to act, to achieve consensus and acceptance within the construction industry. Rock et al. highlight the importance of governmental, research, and private partnerships as a driver for benchmarking embodied carbon in buildings [34]. This can take different forms, such as workshops, webinars, open consultation meetings, roundtable discussions, or petitions from industry [50,54]. Bui et al. highlights some of the challenges for implementing ZCB in New Zealand, including a lack of financial incentives, knowledge, capacity, capability, legislation and cultural barriers [55,56].

Networks and fora for sharing knowledge and building competency within the industry were also identified as important steps towards decarbonisation [57,55]. The SLR also highlighted cross-border collaborations and sharing of knowledge and resources as important. This is demonstrated by the Nordic countries efforts to harmonise methodologies and system boundaries through the Nordic Sustainable Construction programme, and the sharing of databases and tools between Germany, Austria, Denmark, and Switzerland [57–60]. Belgium is also following a similar approach to The Netherlands in establishing a single aggregated environmental score [61]. Whilst INDICATE is a European research project focused on accelerating national building LCA data in the Czech Republic, Spain, and Ireland [50,62,63].

4.2. Environmental sustainability scheme

Environmental sustainability schemes and rating tools for buildings were identified as important to further the development of GHG emission calculations in buildings. Environmental sustainability schemes for buildings, such as BREEAM, LEED, DGNB, and FutureBuilt promote best practice and encourage GHG emission reporting and reduction strategies [34,64,65]. As voluntary schemes, they can be used to further GHG emission competency within the industry. Ganassali et al. outlines the development of LCA benchmarks in environmental certification schemes for buildings and finds internal and external benchmarks are used, whereby external benchmarks give context and facilitate for comparison [66].

4.3. Common standardised methodology

The results from the SLR show that ISO 14044 is mostly used in North America and Asia, whilst EN 15978 is used across Europe. The results show EN 15978 as the dominant method for GHG emission calculations of buildings, whereby even some non-European countries have adopted the standard. Findings show that EN 15978 is adopted by non-European countries to better structure GHG emission calculations for buildings and limit some of the parameters involved in a building LCA. It may be argued that an international standard for the LCA of buildings (akin to EN 15978) is required, to improve comparability, and facilitate for a wider uptake of GHG emission calculations of buildings internationally. Interestingly, Level(s) was only mentioned at the European level, whereby findings from the SLR show that European countries are more inclined to adopt aspects of Level(s) into their own national methodologies than use the Level(s) framework directly. Further work should investigate why this is the case.

Several publications highlight the need for a common standardised methodology that is comparative and robust [34,59,67]. A harmonised methodology will save time and costs for practitioners, remove trade barriers, and may lead to faster implementation of benchmarks [67]. A clear definition of system boundaries is required to narrow down the number of variables and improve comparability [37]. To follow is a discussion on the main variables mentioned in the literature, namely: reference unit, definition of area, RSP, building typologies, building parts, life cycle modules, and static and dynamic approaches.

4.3.1. Reference unit

Most of the countries from the SLR use $kgCO_2e/m^2/yr$ as a reference unit. Having a common reference unit for buildings makes it easier to understand and compare results. However, one known shortcoming of setting benchmarks per m^2 of building is that it may incentivise building with larger footprints since the material and emission intensity is less per square metre [59]. In Spain, Sweden, and the USA, the reference unit was not annualised per year to consider the timing of emissions and to place more focus on upfront emissions [62,65,68,69]. Another shortcoming of using $kgCO_2e/m^2/yr$ as a reference unit, is that it does not account for sufficiency of building area per user [70]. Switzerland was the only country to consider $kgCO_2e$/capita/yr [49,71,72]. Here, the focus was on top-down limit values based on per capita carbon budgets.

4.3.2. Definition of area

The results from the SLR show the two main definitions of area are gross floor area (GFA) and net floor area (NFA). GFA focuses on material use, whilst NFA is often chosen to align with operational energy calculations, since NFA focuses on internal heated areas. In Norway, heated (5–5.2 $kgCO_2e/m^2/yr$) and unheated basements (3.4–3.7 $kgCO_2e/m^2/yr$) are considered as separate building typologies to highlight this difference in the definition of areas [48]. Similarly, Zimmermann et al. discusses the implications of including secondary buildings (i.e. garages, sheds etc.) within the scope of assessment, and found that including a garage can increase total emissions by around 1.3 $kgCO_2e/m^2/yr$ due to additional materials used for the garage, whilst the GFA remains the same [64]. Gervasio et al. and Szalay explore the sensitivity of area in buildings and found that high-rise buildings have lower embodied impacts than medium-rise and low-rise buildings since the GHG emissions from foundations are shared across a larger building footprint [73,74].

4.3.3. Reference study period

The results from the SLR show a large span in RSP, ranging from 30 to 100 years [75]. However, most of the countries use a RSP of 50 years, as specified by the EU in Level(s) [76]. This is exemplified by Norway changing its RSP from 60 to 50 years to harmonise with the EU. A longer RSP is more likely to represent the true service life of a building, however it also diminishes the initial impacts from production and construction, and the use phase becomes more significant [64].

Zimmermann er al. compared a RSP of 50 and 80 years for Danish buildings and found that the duration of RSP influences the number of replacements in the use phase, and increases GHG emissions from replacement from 7 % for 50 years to 20 % in 80 years [64].

4.3.4. Building typologies

The results from the SLR show a large variation in the building typologies included. For that reason, it was decided to exclude subclassifications beyond SFH and MFH. It is also unclear from the literature how mixed-use buildings are addressed. Interestingly, the limit values in Denmark do not distinguish between building typologies [64]. Whilst Norway and Sweden highlight the differences in embodied emissions between building typologies [47,48,68,69]. In addition, different locations will have varying ground conditions for foundation works, varying climates for HVAC requirements, and varying transport distances [77]. Building typologies should be representative of the national building stock, and limit values should be developed according to the most populous and emission intensive building typologies. For that reason, refurbished buildings should also be included, as most of the building stock towards 2050 has already been built [59,78]. Refurbishment limit values should be set at the same level as new buildings to encourage the retention and upgrade of the existing building stock. It also brings into question the sufficiency of buildings and the number of building users or occupants, as illustrated by the embodied emissions of holiday homes.

4.3.5. Building parts

The results from the SLR show a large variation in the building parts included, and varying building part classification systems [48,50,71]. This is exemplified by the naming of HVAC in EU countries and mechanical, electrical, and plumbing (MEP) in the rest of the world. This highlights the need for international standardisation for the nomenclature and classification of building parts. The variation in building parts is also illustrated by how Norway's GHG emission declaration only includes part of the foundations [48] despite stabilisation measures (e.g. areas with seismic activity or challenging soil conditions) having higher embodied GHG emissions [59]. Building parts are largely influenced by maintenance intervals and service lifetimes [68]. One finding is that the physical system boundary for building parts is often connected to national standards for life cycle costing (LCC) and cost assessments [79]. Zelezna et al. raises the issue of varying building classification systems, and the compatibility with LCC methods and BIM classification systems [50]. The detailing level of building parts is also sensitive to the project phase, whereby an early design phase will have fewer details [50,80].

4.3.6. Life cycle modules

The results from the SLR show different life cycle modules being reported, however all studies include A1-A3 (cradle-to-gate) as a minimum. Norway was the only country to modify the life cycle system boundary in the GHG emission declaration for A5 so that the scope only considers construction waste [48]. In contrast, Sweden's strategy is to focus on upfront emissions (A1-A5) [57,69]. Across the literature, efforts are being made to expand the system boundary to cover the whole life cycle, whereby Sweden and Denmark have indicated an expansion of the life cycle modules covered in forthcoming regulations [57].

Level(s), is the only scheme to require whole life carbon reporting from cradle-to-grave. A stepwise approach may be appropriate for GHG emission reporting, whereby national requirements can focus on cradle-to-gate or upfront emissions and then expand the scope to include more life cycle modules, towards whole life carbon reporting (cradle-to-grave). The results from the SLR showed that no country has requirements for cradle-to-cradle reporting. This highlights an area for improvement, by bringing circular economy aspects into GHG emission requirements for buildings.

4.3.7. Static or dynamic

The guiding principle in LCA methodology is to base future scenarios on current technology and practices. As a result, nearly all the countries adopt static LCA, with some simplified dynamic approaches to simulate the decarbonisation of the electricity mix over the building RSP. Some of the publications explored dynamic LCA [81–84], whilst France was the only country to incorporate dynamic LCA methods into national policy frameworks [82].

4.4. LCA calculation tools

Many research institutes from the SLR have developed their own set of LCA tools that align with national methodologies or (e.g. LCAbyg or Reduzer) or have used existing LCA tools that are available internationally (e.g. OneClick LCA). Emphasis was given in the literature to automating calculations to speed up the time-consuming calculation process, or merging LCA calculations with other calculations or models such as cost, BIM, and energy [50,80]. Many emphasised the need for standardised values for scenarios regarding aspects such as average construction waste fractions, estimated service lifetimes of building parts, average transport distances, and maintenance intervals [68]. In Norway, guidance values for these parameters have been recently published in NS 3720:2018/G2: 2024 [85]. It is also important with open access to LCA calculation tools to facilitate for a broader uptake of GHG emission reporting.

4.5. LCI database and EPD data

Most of the countries in the SLR reported having access to EcoInvent or a national LCI database with generic emission factors for a range of building materials and components [34,57]. Having access to a LCI database is useful in the early design phase, when specific construction details have not yet been decided. Most of the countries also reported having access to an EPD database, or using EPD data from neighbouring countries, as exemplified by Denmark, Finland, and Austria using the German EPD database ÖkobauDat [59], and Iceland using EPDs from the Norwegian programme operator EPD-Norge [57]. Austria, Denmark, Germany, Iceland, Norway and Sweden all mentioned using ECO platform, a platform for standardising and sharing specific product data in the form of EPDs. Specific emission factors from EPDs are useful in the later project stages when specific manufacturers of building materials and components are known. EPD data can also be used to generate average values for the early design phase. Some LCA tools have LCI and EPD data built in, which streamlines the calculation process. In time, the EPD databases will be superseded by the EU construction products regulation (CPR) [86]. It is important for LCA practitioners to be prepared for this and have open access to either regional or national inventory data, whether in the form of an LCI database or EPD data from a programme operator.

4.6. GHG emission declarations of buildings

An important step towards decarbonisation and the setting of limit values for buildings is to first require GHG emission declarations of buildings in national building codes, as demonstrated by Sweden, Norway, and Iceland [33,48,57,69]. This may first be a voluntary step, to boost competency, and can be required by project owners, investors, or certification bodies, before national authorities require GHG emission declaration of buildings as a mandatory requirement in the national building code. Policy requiring GHG emission declarations should clearly define the method, system boundaries, and reporting requirements. Clear guidelines will provide predictability to construction actors, so that they can plan accordingly for future projects.

GHG emission declarations should also be integrated into the design process, so that practitioners can proactively reduce GHG emissions towards limit values rather than retrospectively reporting GHG emissions after the building has been built [32]. The GHG emission declaration should also clearly state which project phase it is valid for (e.g. building permit or certificate of completion). There is also a practical implication for when limit values are introduced, as to which limit values apply when the design, planning, and construction phases of a building can span multiple years. Denmark, France, the Netherlands, Sweden, and Norway require GHG emissions to be declared at building completion, whilst Iceland requires GHG emissions to be declared at both the building permit and final audit stages [59,57]. None of the countries from the SLR currently require quality control of the GHG emission calculations, however Denmark verifies around 10 % of calculations, Sweden allows for spot checks, and municipalities in Norway have the right to carry out spot checks [33].

4.7. LCA database for buildings

Rock et al. emphasise the need for available, accessible, and good quality data that is comparable and representative to create embodied carbon benchmarks [34]. This can be achieved by establishing an open access repository for GHG emission declarations of buildings. In the EU, the EPBD will impose mandatory reporting of life cycle GHG emissions of buildings, and member states are required to establish national databases to generate limit values and decarbonisation pathways. Schlegl et al. discuss the need for catalogues at the building, component, and material level to facilitate for the generation of bottom-up limit values, and how the level of detail should be connected to the planning phases to provide architects with guidance values [79]. Schlegl et al. recommend using standardised templates, a standardised interface, automated quality assurances, a building part classification system, and regular updates to maintain data integrity [79].

A digital, standardised reporting template will facilitate data management, regardless of which LCA calculation software has been used. Roberts et al. highlight that it should not be possible to identify specific projects in the repository [32]. This could be an automated process that does not require any additional effort on the practitioner's side. In addition, information should be disaggregated to improve data quality and transparency and better identify future GHG emission hot spots. Rock et al. also mention the possibilities of introducing machine learning to fill in data gaps [35].

4.8. Reference values

Reading through the literature has highlighted some of the challenges in defining values. Across the literature, values were referred to as: bottom-up reference values, business as usual, average, mean, or median values, non-binding guidance values, index values, baseline values, benchmark values, best practice values, state of the art, threshold values, top-down target values, limit values, absolute values, fixed values, relative values, environmental performance targets, sub-benchmarks, or indicative values, and in one case project-specific design goals. To avoid future confusion, practitioners should follow ISO 21678 which gives definitions and a framework for establishing benchmarks on sustainability in buildings [5].

Most countries identified in the SLR have generated bottom-up reference values as a starting point from either a meta-analysis of real LCA reports or from archetypes of buildings. Lützkendorf et al. outline various sources for reference values including statistics, surveys, theoretical calculation, legal and regulatory requirements, and national standards [59]. Szalay presents a parametric approach to generate bottom-up reference values from archetypes in cases where a database of climate declarations for buildings is not readily available [73]. Whilst Gervasio et al. structured a preliminary set of EU bottom-up reference values according to building typology and climatic zones, and found that buildings in colder climates (North Europe) have higher operational emissions than buildings in warmer climates (South Europe) [74]. These values act as a baseline or a snapshot of the current situation and are a good starting point for setting GHG emission requirements. The SLR highlights that bottom-up reference values represent what is technologically and economically feasible. The quality of reference values is highly dependent on the quality of data gathered. Many of the articles discussed the representativeness of data gathered as well as issues with data quality in terms of reliability, completeness, temporal correlation, consistency, and comparability. However, the SLR also pointed out that reference values do not necessarily align with the Paris Agreement targets [49].

4.9. Limit values

Top-down target values are good for establishing future GHG emission targets. Top-down target values are often allocated carbon budgets based on planetary boundaries. Priore et al. highlight the importance of including imported embodied emissions in top-down allocation of global carbon budgets, as well as the timing of emissions from buildings in relation to climate targets and reduction pathways [72]. Lützkendorf et al. outline various sources for target values including statistics, surveys, theoretical calculations, legal and regulatory requirements, national standards, as well as demonstrative projects, policy objectives, planetary boundaries and science-based targets [59]. Habert et al. outlines a framework for developing top-down carbon budgets for buildings, and presents top down carbon budgets for Switzerland, Denmark, Austria, and Czechia, noticing a 10-fold variation in national budgets dependent on choice of budget allocation and sharing principles [29].

4.10. Roadmap for decarbonisation

Findings across the SLR show that bottom-up reference values often exceed top-down planetary boundaries [87–89]. However, hybrid approaches involve combining bottom-up reference values as starting points with future top-down target values to create projected pathways towards reaching climate goals. These pathways can be used to define benchmark values at regular intervals (e.g. 2030, 2040, and 2050). In the literature, these pathways are referred to as trajectories, emission reduction pathways, decarbonisation strategies, and action plans [29,36,53,72]. Rasmussen et al. mapped benchmark values for 14 countries and found that WLC benchmark values range from 5 - 90 kgCO_2e/m^2/yr for residential and non-residential buildings [58]. Rock et al. assessed the embodied GHG emissions of 650 buildings and find that given a carbon budget of 300 kgCO_2e/capita/yr, a building service life of 50 years, and a living space of 30 m^2/person, the available carbon budget and target value for a building is around 10 kgCO_2e/m^2/yr [90,91]. Rock et al. also found that an increase in system completeness, in terms of building parts and life cycle modules, led to higher embodied GHG emissions, and that there is a need for increased standardisation and transparency in documentation requirements [90,91].

Lützkendorf et al. introduce the concept of a universal benchmark, namely net zero GHG emission [59]. Benchmark development is a constantly evolving, iterative process [74], and requires a clear roadmap for transitioning from limit to target values that is both realistic and achievable. It is recommended to periodically review limit values by expanding the scope of assessment and tightening trajectories with one- or two-year increments.

4.11. Policy implications

The findings from the SLR provide a policy framework for the decarbonisation of buildings. However, this framework will have implications for policy makers. For example, the policy framework may need to be supported by financial or regulatory incentives such as subsidies, prioritised processing of planning applications, green loans, or carbon taxes to encourage stakeholders to reduce WLC emissions from buildings. These incentives should also cohere with mandatory reporting, to increase transparency, bolster knowledge and competency, and facilitate for the development of WLC benchmark values and roadmap trajectories. However, these incentives and regulations are sensitive to the cost of compliance, administrative burdens, carbon pricing, and market readiness.

Policy makers should mandate for standardised LCA methodologies, since a standardised methodology and framework would reduce some of these time and cost burdens, as well as limit variability in reference units and system boundaries. Important lessons learnt from early adopters has influenced the revision of the EPBD and can influence international GHG policies, as well as speed up the adoption of EPBD requirements in the rest of Europe. The IEA EBC Annex 89 is a good forum for spreading lessons learnt from Europe to a wider audience internationally, as well as facilitate for international standardisation.

Similarly, the various net zero building initiatives can be used to align with and define the ambition levels of policy frameworks. For example, net zero energy buildings and zero carbon ready buildings can be used as a first step to reduce GHG emissions from operational energy use, before expanding the scope to include embodied GHG emissions in ZEBs and PEBs. The Norwegian research centre for Zero Emission Buildings (FME ZEB) present a stepwise approach for ZEBs whereby the lowest ambition level ZEB-O considers emissions from operational energy use, and the highest ambition level ZEB-COMPLETE considers WLC emissions from construction (C), operation (O), materials (M), maintenance replacement, and repair (PLE), operational transport (T), and end-of-life (E). The scope can be further expanded to the neighbourhood and district level by considering ZENs or PEDs, as suggested in the revised EPBD. The results from this SLR may also be useful for future revision of important standards, such as the EPBD.

4.12. Further work

The SLR has shown a broad range of responses to the implementation of GHG emission declarations, benchmark values, and decarbonisation road maps for buildings, whereby no one size fits all. This is illustrated by some countries implementing multiple steps at once, whilst other countries have a graded approach, by first establishing practices for declaring GHG emissions before introducing limit values. Some countries focus on upfront emissions (A1–A5), whilst others aim to cover WLC. The results from the SLR show there are numerous countries without national GHG emission declarations, limit values, or decarbonisation roadmaps. Further work is thus required to establish declarations, limit values, and roadmaps. Within Europe and the EEA, this includes Bulgaria, Croatia, Cyprus, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Portugal, Romania, Slovakia, Slovenia, Turkey, and Lichtenstein. These countries will need to quickly adopt a roadmap with limit values for WLC GWP by 2027, before requirements for ZEBs in the EPBD come into force in 2028–2030 [4]. To facilitate this adoption, requirements and limit values introduced into the EU taxonomy can function as a voluntary testbed for later EU requirements in the EPBD.

Benchmarking and decarbonisation roadmaps are rapidly developing as more knowledge is made available. The key research gaps identified through the SLR, highlight that further work is required on standardising and harmonising definitions, system boundaries, and methods to improve transparency and comparability. This will make it easier for policy makers to establish reference values, limit values and develop road maps for decarbonisation.

Further work may also include combining bottom-up and top-down approaches in a hybrid approach to assure more robust limit values and that climate targets are set within planetary boundaries. Standardised reporting of GHG emissions from buildings will also make it easier for stakeholders to identify GHG emission hotspots and implement targeted measures to reduce emissions. Further work should also investigate the incorporation of circular economy measures such as component reuse or upcycling into GHG emission methodology.

The results also highlight the rapid development of policy frameworks for the decarbonisation of buildings, whereby multiple countries have forthcoming GHG emission limit values and decarbonisation roadmaps. It would be interesting to repeat this study in 2027 to see how many of the EU countries are prepared for ZEBs in 2028 – 2030, and to see if the learnings from forerunner countries in the EU have spread to other continents.

Other aspects identified through the SLR for further work include developing a universal understanding and definition of what we mean by climate neutral, and net zero GHG emissions. Further work is also required on the identification of mitigation strategies to achieve limit values and guide policy-making decisions on optimal decarbonisation.

5. Conclusions

This article presents a SLR on national GHG emission declarations, limit values, and decarbonisation roadmaps for buildings. It details methods, tools, and databases used, and discusses system boundaries in terms of building typologies, building parts, and life cycle modules. The SLR highlights steps for policy adoption to aid building decarbonisation. Limitations include convenience sampling and a focus on publications from developed countries.

Key themes identified ten steps for decarbonisation: stakeholder engagement, sustainability schemes, standardised methodology, LCA tools, LCI databases, GHG declarations, LCA databases, reference values, target values, and roadmaps. A common methodology is essential for comparability. The SLR notes the importance of accessible data for GHG emission benchmarks and recommends mandatory GHG declarations in national building codes.

The findings indicate a need for hybrid approaches by combining bottom-up and top-down values for decarbonisation pathways. The SLR reveals varied responses in implementing GHG policies across countries, with a call for further work to establish GHG emission requirements in buildings. Insights from frontrunners are a valuable experience for other countries to develop their own policy frameworks and GHG emission requirements in buildings.

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CRediT authorship contribution statement

Marianne Kjendseth Wiik: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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