Towards net zero: sectoral ambitions and global trends in building decarbonisation

BUILDINGS & CITIES

SYNTHESIS

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ABSTRACT

Limiting global warming in line with the Paris Agreement requires rapid and ambitious decarbonisation of the global building and real estate (BRE) sector. This study presents the first global systematic review and structured alignment assessment of BRE decarbonisation efforts from 212 publications over the past two decades, evaluating them against six relevant alignment factors: temperature-based targets, main indicators, life-cycle scope, decarbonisation goals, target years and assessment scales. Using a multi-criteria scoring and weighting framework, the analysis reveals the evolution and prevalent shortcomings in research. Only four studies are Paris-aligned, while most efforts remain fragmented, narrowly scoped, low in ambition, or disconnected from explicit temperature limits and mid-century net zero goals. Although ambition has increased since 2015, inconsistent terminology, incomplete life-cycle scopes, small assessment scales and delayed policy uptake persist. Significant geographical disparities are evident, with Europe and Oceania leading in whole-life-cycle approaches, while Africa, South America and much of Asia remain underrepresented, despite rapid projected growth in building stocks. The findings demonstrate that current BRE decarbonisation trajectories are largely incompatible with Paris-aligned pathways. Three priority research areas are identified: harmonised definitions and ambition levels, robust data infrastructures, and scalable sector-wide frameworks to enable Paris-compatible decarbonisation within planetary boundaries.

POLICY RELEVANCE

The systemic misalignments and research-to-policy adoption challenges identified in this research provide policymakers with insights to set Paris-aligned emissions-reduction targets and pathways for national BRE sectors, establish sector-wide governance and support effective contributions from key stakeholders. First, international harmonisation of definitions and standards for whole-life-cycle assessment, data collection and reporting

KEYWORDS:
decarbonisation pathway; climate mitigation; climate policy; greenhouse gas (GHG) reduction pathways; Paris Agreement; Nationally Determined Contributions (NDCs); real estate; construction; built environment; whole life-cycle

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is required. Second, given that operational-emissions-only, building-level approaches are insufficient to achieve Paris-compatible outcomes, it is necessary to include embodied emissions, mandate whole-life-cycle, sector-wide assessments of the national building stock, and implement legally binding limit values, carbon budgets or decarbonisation trajectories into Nationally Determined Contributions. Third, since projected high-growth regions in Africa, South America and Asia are currently underrepresented in the literature, international policy support should focus on establishing the data infrastructures and technical expertise in these areas to ensure global climate goals are not undermined by regional data and capability gaps.

GLOSSARY

	MEANING	DEFINITION
BRE	Building and real estate	The sum of all activities, supply chains, processes and stakeholders in the whole life-cycle (WLC) of buildings, property and real estate only, not including civil infrastructure
DEs	Decarbonisation efforts	An overarching term referring to the goals, initiatives, strategies and actions (*e.g.* carbon budget, limit values, pledges, pathways) aimed at reducing carbon dioxide (CO_2) and/or other greenhouse gas (GHG) emissions
GHGs	Greenhouse gases	The Intergovernmental Panel on Climate Change (IPCC) describes GHGs as the gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's surface, by the atmosphere itself and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary GHGs in the atmosphere. Human-made GHGs include sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs) and perfluorocarbons (PFCs) (IPCC 2023)
SLR	Systematic literature review	A methodical comprehensive review of the existing literature
WLC	Whole life-cycle	All processes related to the planning, design, construction, operation, maintenance, refurbishment and deconstruction of buildings, including end-of-life processes

1. INTRODUCTION

To support achieving the goals of the Paris Agreement (United Nations 2015), adopted at COP21 in 2015, and to remain within climate stability thresholds (IPCC 2023), greenhouse gas (GHG) emissions must decrease rapidly to limit global warming well below 2°C, preferably below 1.5°C. Recent studies (Diffenbaugh & Barnes 2024; Dunstone *et al.* 2024; Gagnon 2022) have indicated a dangerous acceleration of warming towards the long-term 1.5°C barrier, with the global average temperature in 2024 temporarily exceeding the 1.5°C limit on a short-term basis (Goessling *et al.* 2025). To stay below 2°C in the long term, all anthropogenic emissions must first be reduced, then offset by anthropogenic sinks. Building on this, the scientific literature has proposed a wide range of decarbonisation efforts (DEs) through various strategies, including the establishment of national carbon budgets, development of sectoral (or cross-sectoral) decarbonisation pathways, establishment of (GHG or CO_2) emission benchmarks or target values, and development of prospective building stock models, *etc.* However, the extent to which these efforts are reflected in national policy and aligned with the full set of principles underlying the Paris Agreement goals remains largely underexplored. Moreover, limited attention has been given to the time lag between science-based decarbonisation pathways and their adoption in national policy (*e.g.* through legally binding mitigation road maps), obscuring how rapidly research informs policy action.

The building and real estate (BRE) sector plays a pivotal role, being responsible (in addition to infrastructure) for around 37% of global CO_2 emissions (UNEP 2024) and more than 21% of all anthropogenic GHG emissions (IPCC 2023). Some regions have already set sector-specific pathways, such as the European Union's Fit for 55 package and the revised Energy Performance of Buildings Directive (EPBD), that call for more than a 50% emission reduction by 2030 and climate neutrality by 2050 (Toth *et al.* 2022; European Union Council 2023; UNEP 2023). Such figures are already based on cross-sectoral considerations, including both direct (Scope 1) as well as indirect (Scopes 2 and 3) embodied and operational GHG emissions from energy production, industry, transport and waste management; each recognised as a distinct economic sector contributing to the whole life-cycle (WLC) emissions of buildings. From a macroeconomic perspective, traditional national statistics often categorise 'building sector' emissions primarily by direct operational sources, such as on-site fossil fuel combustion, thereby underestimating the impact of buildings when up- and downstream supply chains are excluded (Truger *et al.* 2022).

In line with this cross-sectoral perspective, recent European policy developments explicitly recognise the need to move beyond operational considerations. The revised EPBD calls for the mandatory calculation of life-cycle global warming potential of all new buildings from 2030 on, alongside the development of benchmarks and target values that can serve as the basis for legally binding requirements. Importantly, the delegated act of the EPBD also emphasises the role of mitigation road maps for national building stocks as a prerequisite to defining benchmarks of increasing ambition, consistent with top-down decarbonisation pathways. This policy shift mirrors the findings of this study, which show that moving to WLC scopes and considering sectoral-scale decarbonisation in benchmarking improves alignment with climate goals.

Despite advances, evidence shows that DEs remain off-track and fall short of the ambition required to curb current (increasing) emission trajectories. In exploring DEs in the sector, significant inconsistencies persist in terms of the applied temperature increase limits, indicators, life-cycle scope, ambition level, target years and scale of assessment (Gupta *et al.* 2024; Habert *et al.* 2020; Kuriakose *et al.* 2022; Steininger *et al.* 2020). These inconsistencies contribute to misalignments between the DEs and the Paris Agreement's goals (D'Agostino 2015; Habert *et al.* 2020; United Nations 2015).

While previous research has examined decarbonisation strategies, technologies and pathways in the BRE sector (Abam *et al.* 2023; Andrews & Jain 2022; Cheekatamarla & Nawaz 2022; Hu & Esram 2021; Mata *et al.* 2020), a comprehensive assessment of how these efforts align with goals of the Paris Agreement has yet to be undertaken, particularly with respect to differences before and after its adoption. Thus, this study systematically assesses and compares DEs in the BRE sector documented in the academic and grey literature since 2000 with the aim of identifying how these efforts have evolved globally over the last two decades. Using a systematic literature review (SLR) and a multi-criteria scoring and weighting framework, the research will evaluate the alignment of these efforts based on ambition, scope, scale and other key factors, identify regional and thematic disparities, and pinpoint priority research and policy gaps to support researchers, policymakers, standardisation bodies and other stakeholders involved in the decarbonisation of the BRE sector.

2. METHODS

2.1 OVERVIEW

This paper focuses on the collection, analysis and assessment of DEs in the BRE sector worldwide between 2000 and 2024. The collection and analysis of DEs is conducted through an SLR. A global approach provides insight into the current state of research and policy, revealing trends and gaps in different regions and countries. The alignment of the literature with the goals of the Paris Agreement is assessed using a multi-criteria scoring and weighting framework.

2.2 LITERATURE SEARCH

The paper aims to answer the following research question:

- How have the DEs within the BRE sector been developed globally in the last two decades?

Three sub-questions were defined, from which four search strings for the SLR were derived (Figure 1). The sub-questions were as follows:

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- When have DEs been published in research and policy for the BRE sector?
- How has the ambition of DEs changed over the years?
- How many DEs are aligned with the goals of the Paris Agreement?

The systematic screening process is illustrated in Figure 1 (for the full paper list, see the supplemental data online). The paper databases Scopus and Springer were chosen for their broad, complementary coverage of engineering, environmental sciences, policy and decarbonisation of the built environment. Backward and forward citation tracking along with the inclusion of relevant grey literature via snowballing were used to minimise database bias and ensure comprehensive coverage of key document types.

The search was conducted in June 2025, yielding 8616 relevant scientific articles. Then, 268 duplications were excluded using a Python script. A total of 5118 publications from research areas outside the SLR's scope were filtered out (*e.g.* chemistry, medicine, physics). Afterward, the titles of the papers were manually screened, excluding 2914 papers that did not focus on the BRE sector (*e.g.* those focused on transport, industrial processes or infrastructure). Then, 87 papers were further filtered out based on their abstracts as they focused on economic or societal problems rather than environmental impact assessment. Afterwards, 63 documents were excluded after full-text review because they addressed technical and viability issues, leaving 167 articles. Through expert recommendations (IEA 2023b) and citation-tracking, 47 documents (including grey literature) were added during the snowballing phase, resulting in a final sample of 212 documents for data extraction. It is recognised that including the grey literature introduces variability in the quality of cited research; however, this is an unavoidable inherent limitation of capturing policy-relevant DEs at the global level.

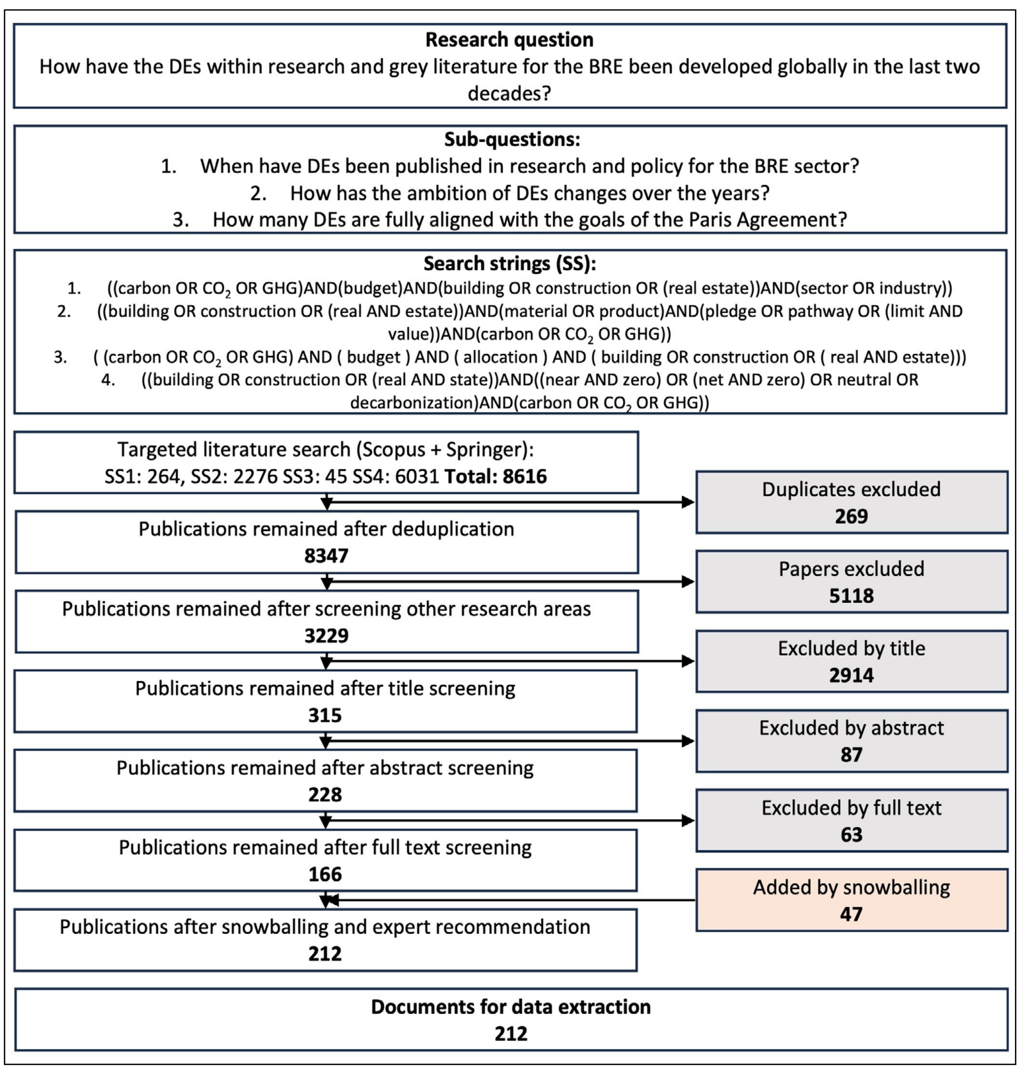

Figure 1: Systematic literature review (SLR) search and results.

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2.3 DATA EXTRACTION

To answer the research questions, six key factors towards decarbonisation were analysed in the data-extraction phase (Table 1). These were inspired by the typology and conceptual framework proposed by Lützkendorf & Frischknecht (2020), which systematically distinguishes net zero approaches in the built environment by terminology and indicators. The Paris Agreement aims to mitigate climate change to well under 2°C, preferably 1.5°C. In the literature, DEs have focused primarily on these two temperature limits. Some papers consider only CO_2 emissions, while others expand their main indicator to include additional GHG emissions. These variations are categorised under the 'main indicator' factor. The 'life-cycle scope' factor indicates whether the documents focus on operational or embodied aspects, or on both (WLC approach). Three factors related to the decarbonisation goals were considered: the type of goal (reflecting ambition), the target year and the assessment scale (a key factor in assessing alignment with top-down goals). These variations are considerable across the literature, providing crucial insights into the temporal and geographical evolution of research and policy.

FACTOR	CHARACTERISTIC	POINTS	FACTOR	CHARACTERISTIC	POINTS
Temperature limit	1.5°C	1.10	Decarbonisation goal	Net zero carbon	1.10
	2.0°C	1.00		Net zero emissions	1.05
	None	0.00		Carbon neutrality	1.00
Main indicator	GHG emissions	1.00		Decarbonisation	0.92
	CO_2 emissions only	0.50		Zero carbon	0.83
	Other, non-GHG	0.00		Zero emissions	0.75
Life-cycle scope	WLC	1.00		Near zero emissions	0.67
	Embodied only[a]	0.67		Low carbon	0.58
	Operational only	0.33		Low emissions	0.50
	Other	0.00		Net zero energy	0.42
Target year	2020–25	1.10		Zero energy	0.33
	2030	1.08		Near zero energy	0.25
	2035	1.06		2000 Watt Society	0.17
	2040	1.04		Low energy	0.08
	2045	1.02		None	0.00
	2050	1.00	Scale of assessment	Whole BRE	1.00
	2060	0.66		Building stock[b]	0.67
	2100	0.33		Individual building	0.33
	None	0.00		Other	0.00

Table 1: Overview of the analysed factors, characteristics and evaluation factors in points.

Note: [a]Although not further disaggregated, this can refer to up-front, use-phase or end-of-life embodied emissions (Caballero-Güereca *et al.* 2025).

[b]The building typologies considered in the building stocks vary (sometimes only residential or educational buildings are considered).

BRE = building and real estate;
GHG = greenhouse gas;
WLC = whole life-cycle.

The documents were analysed and their properties categorised into these factors. To answer the research questions, geographical and temporal factors are needed. To this end, metadata useful for the analysis (such as year, location and document type) were also extracted. The document search was limited to publications in English, and although international experts were consulted in the snowballing phase, a potential language bias should be noted.

2.4 MULTI-CRITERIA SCORING AND WEIGHTING FRAMEWORK

A simple multi-attribute rating technique was used, based on Siregar *et al.* (2017). This framework collects data on selected key factors and generates a rating classification based on each factor's characteristics. The chosen factors were characterised based on the SLR's findings, and their characteristics were assigned points (Table 1) according to their alignment with current decarbonisation needs, considering the typology of terms and definitions by Lützkendorf &

Frischknecht (2020). Full alignment is defined as the decarbonisation of the whole BRE sector to limit global warming to 2°C at the latest by 2050 by reaching net zero GHG emissions during the WLC of buildings, as stated by the IPCC (2023), United Nations (2015) and World GBC (2019). Consistent with patterns observed across the reviewed literature and summarised in both 'net zero carbon' and 'net zero emissions' are frequently treated as Paris-aligned concepts; however, 'net zero carbon' is more often defined with a broader GHG-emission scope. The characteristics given 1 point describe the minimum requirements for alignment; characteristics beyond these requirements (*e.g.* sooner target years or lower temperature limits) are awarded higher points. For studies that considered more than one characteristic per factor, the points corresponding to the highest-rated characteristic were assigned. For non-aligned characteristics, the awarded points were based on their completeness and ambition. Zero points were awarded if a factor was not mentioned. The scoring framework reflects degrees of Paris alignment rather than a binary classification, allowing approaches that address necessary but incomplete dimensions of decarbonisation (*e.g.* energy performance without WLC coverage) to be distinguished from fully aligned pathways. Target-year scores reflect the relative ambition of stated goals at the time of publication, rather than their feasibility at the time of this review. Earlier target years, therefore, indicate higher ambition, even if they are no longer achievable at the time of analysis.

The reviewed literature spans a wide range of analytical scales, including individual buildings, building stocks and sector-wide assessments. The scale of assessment was therefore included as an explicit evaluation criterion. Studies focusing on individual buildings were assessed based on their potential contribution to scalable decarbonisation pathways, rather than being interpreted as sector-level solutions. For this reason, the attributed points reflect the scale and their linked uncertainty of representing sector-wide alignment.

3. RESULTS AND DISCUSSION

In this section, the temporal distribution of the DEs is analysed based on the aforementioned factors and characteristics. The alignment of the documents with the goals of the Paris Agreement is then assessed using a multi-criteria scoring and weighting framework. Geographical data are aggregated by region according to the United Nations Department of Economic and Social Affairs (UNDESA) (United Nations 2024).

3.1 DOCUMENT TYPE

The literature shows a clear temporal pattern in the emergence of different document types, with scientific research leading the development of DEs. Figure 2 shows the temporal distribution of document types found in the literature (books, conference papers, reports, policies, scientific papers). It can be seen that the publication of scientific papers precedes that of reports, which in turn precedes that of policies. Zimmermann *et al.* (2005) was the first scientific article found through this SLR. It was among the first to define permissible limit values for energy demands and pollutant loads during the construction, maintenance and operation of buildings. The present paper, like others predating the Paris Agreement, does not use terms such as 'net' or 'near zero' emissions, but rather aims to lower energy demand and emissions, in line with the publication of the Kyoto Protocol and the principles of the 2000 Watt Society. Since the Paris Agreement was established in 2015, the number of scientific papers on the decarbonisation of the BRE sector has increased significantly. The data indicate that the increase in the academic literature precedes the growth in reports and policies, suggesting a diffusion of concepts from academia to institutional or regulatory publications.

Focusing on operational energy demand, Pless & Torcellini (2010) published a technical report for the US Department of Commerce that defined net zero energy buildings. On the policy side, in 2011, a road map to reduce India's energy demand was published as part of the United States Agency for International Development's (USAID) programme (Kapoor *et al.* 2011). It was not until 2019 that (British) reports and policies adopted the term 'net zero carbon buildings' (CCC 2019; UKGBC

2019), while scientific publications had been using it and similar terms since 2011 (Xing *et al.* 2011). This temporal sequencing suggests a lag of approximately five years in the adoption of ambitious science-based goals into policies.

Overall, the temporal distribution of the documents shows that the publication of scientific research is followed by that of reports by organisations, which in turn is followed by the implementation into policies. The data show that translating scientific knowledge into climate policy can be delayed by up to a decade due to political, social and economic factors, a pattern observed internationally (Boykoff 2007; Colvin & Jotzo 2021; Roper *et al.* 2016; Shue 2023), which has such delays increasing future mitigation costs and reducing climate target feasibility (Luderer *et al.* 2013, 2016). At the same time, the literature shows a worrying trend: as the feasibility of the 1.5°C limit declines, recent DEs shift toward 2°C-based framing rather than increasing ambition. This reinforces the urgency of addressing the growing gap between scientific publications and policy adoption. As emphasised by Kuittinen *et al.* (2024), closer collaboration between researchers and policymakers is essential to shorten this gap between scientific evidence and effective policy implementation.

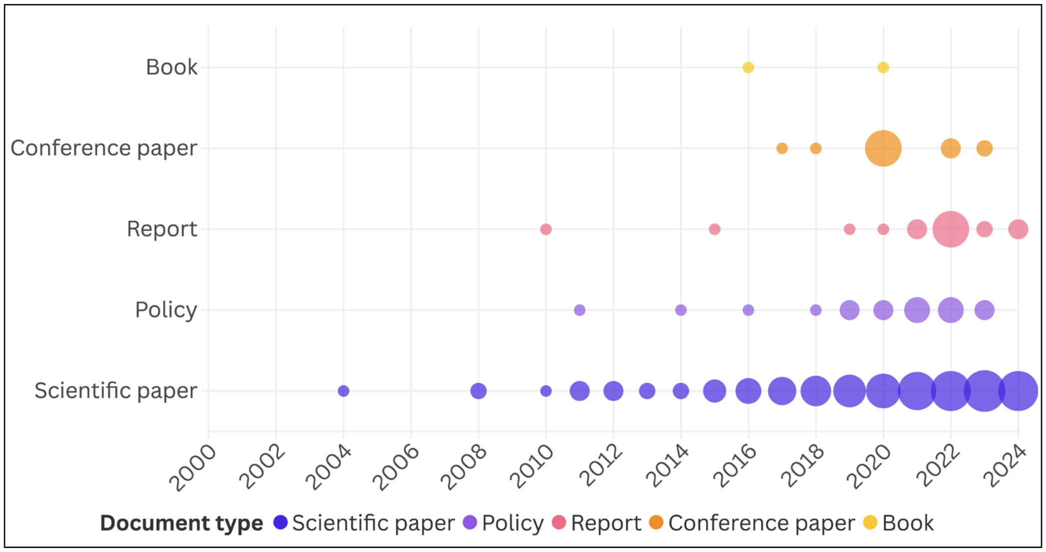

Figure 2: Temporal distribution of documents by document type.

Note: Dot size is proportional to document count; maximum = 23.

3.2 LOCATION OF THE ASSESSMENT

Across regions, the scope of DEs has gradually expanded from operational energy use towards WLC perspectives (especially since 2020), although operational-only approaches remain prevalent. Figure 3 illustrates the temporal and geographical distribution of DEs by scope.

The first publications in Europe from the UK and Switzerland focused on reducing operational emissions through 2000 Watt Society-compatible energy-saving scenarios (Peacock & Newborough 2008; Schulz *et al.* 2008; Zimmermann *et al.* 2005). Recently (since 2021), nearly all European studies have shifted their focus to a WLC approach.

The aforementioned report by Pless & Torcellini (2010) was among the earliest contributions originating from North America. While all identified North American studies published since 2022 adopt a WLC scope, the number of publications declines after 2017. This trend may be partly associated with shifts in US climate policy following its withdrawal from the Paris Agreement in 2017 (and again in 2025); however, broader socio-economic factors are outside the scope of this SLR.

For Asia, the data do not indicate a clear transition to a WLC scope. In several Asian countries, including China, DEs remain strongly operationally focused, often overlooking the embodied impacts of construction materials (Cui *et al.* 2019; Du *et al.* 2024; Hu *et al.* 2022; Huo *et al.* 2021; Kang *et al.* 2020; Li *et al.* 2022; Liu *et al.* 2019a, 2019b; Yang *et al.* 2021; Zou *et al.* 2023). While operational emissions account for a substantial share of China's total emissions (Liu *et al.* 2019b), excluding embodied emissions risks significantly underestimating the climate impacts of refurbishments and renovation (Röck *et al.* 2020).

In Oceania, the first publication picked up in the SLR search was by Ximenes & Grant (2013) on the embodied impacts of timber maximisation in two popular house designs in Sydney, Australia. They considered temporary carbon storage within buildings and different end-of-life parameters for landfill decomposition, which significantly influence GHG outcomes. Under these assumptions, they present timber use in construction, combined with timber landfilling, as a potential CO_2 sink, thereby potentially contributing to the decarbonisation of the BRE sector. Nonetheless, no carbon opportunity (*i.e.* unrealised carbon storage potential in forests) was considered in this paper (Maierhofer *et al.* 2024). Since 2018, there has been a shift toward WLC, as exemplified by Chandrakumar *et al.* (2019), who defined 1.5 and 2°C-compatible carbon budgets for New Zealand. Compared with other regions, Oceania was among the first to adopt a WLC approach.

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An unequal geographical distribution of publications is very evident. South America and Africa are underrepresented in the literature, with only one (Besser & Vogdt 2017) and two (Fan & Xia 2017; Ohene *et al.* 2023) studies identified, respectively. These publications predominantly adopt an operational focus and are largely authored by institutions based outside of the studied regions, a pattern also noted in previous research (Ala-Mantila *et al.* 2023; Furini 2019; Perissi *et al.* 2018). While countries in these regions may face other development and funding priorities (Mata *et al.* 2020), the projected growth of their building stocks makes early integration of DEs critical. Without such integration, future emissions from their BRE sectors risk overshooting climate goals (Caballero-Güereca *et al.* 2023).

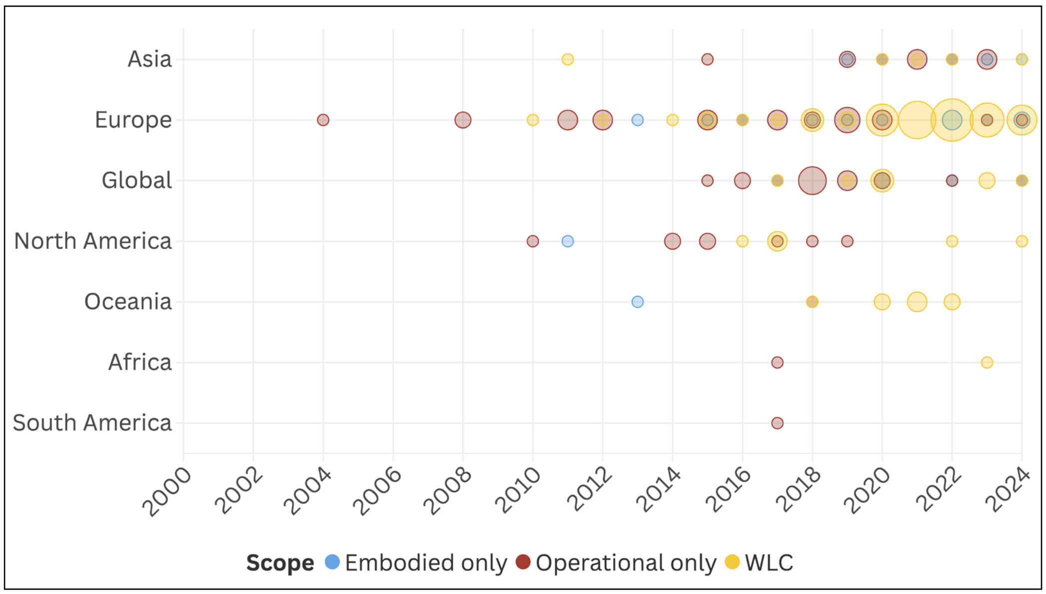

Figure 3: Temporal and geographical distribution of documents considering the life-cycle scope.

Note: Dot size is proportional to document count; maximum = 14.

3.3 DECARBONISATION TARGETS AND GOALS

Across the analysed timeframe, the terminology used to define decarbonisation goals has changed noticeably. Table 2 presents a typology of these goals, as defined in the literature, including terms no longer used in current standards. For example, some recent standards have updated their treatment of operational energy offsets in the net zero energy concept to better reflect climate science. Because exporting renewable energy produced *in situ* does not constitute a negative emission (*i.e.* no CO_2 is removed from the atmosphere), the latest draft of the European Standard for building life-cycle assessment, FprEN 15978 (CEN 2025), does not allow grid electricity demand to be offset by exported electricity; instead, grid demand and exports must be reported separately.

The terminology used to express decarbonisation goals has evolved over time, reflecting a gradual increase in ambition and a shift towards different offsetting approaches (*i.e.* net zero). Figure 4 illustrates the temporal evolution of terms used to express decarbonisation goals, revealing a stepwise increase in ambition over time. This trend reflects growing urgency to meet climate targets as action remains insufficient, leading to stricter policies, steeper decarbonisation pathways and swifter lifestyle changes to remain within shrinking carbon budgets (Global ABC 2024).

TERM	DEFINITION (AS USED IN THE LITERATURE)	REPRESENTATIVE DOCUMENTS
Low energy	Focuses on reducing operational energy demand in new buildings or retrofits	Blengini & Di Carlo (2010); European Commission (2019); Grove-Smith *et al.* (2018); Mata *et al.* (2020)
2000 Watt Society	Swiss concept aiming to limit per capita primary energy demand to 2000 W by 2050 and transitioning to a fully renewable energy supply	Aumann (2012); Heeren *et al.* (2012); Purtik *et al.* (2016); Scarinci *et al.* (2017); Schulz *et al.* (2008)
Near-zero energy[a]	Mostly used at the building level, it refers to the improving energy performance to minimise operational energy demand. Does not necessarily include renewable energy production	Attia *et al.* (2017); Besser & Vogdt (2017); D'Agostino (2015); D'Agostino *et al.* (2017); D'Agostino & Mazzarella (2019); Gauch *et al.* (2023); Kuramochi *et al.* (2018); Liu *et al.* (2019a, 2019b); Magrini *et al.* (2020); Mata *et al.* (2018); Oh *et al.* (2017); Patiño-Cambeiro *et al.* (2016); Reda & Fatima (2019); Santos-Herrero *et al.* (2018); Szalay *et al.* (2022)
Zero energy	Mostly used at the building level, it refers to the (currently outdated) concept of offsetting grid energy demand with on-site renewable energy generation and use across a time period (typically annually)	Belussi *et al.* (2019); Cao *et al.* (2016); Kylili & Fokaides (2015); Marszal *et al.* (2011); Mytafides *et al.* (2017); Saheb *et al.* (2018); Staniūnas *et al.* (2013)
Net zero energy	Used at building and building stock level, it refers to the balance between grid energy demand and renewable energy supply through renewable energy production and exports across a time period (typically annually)	Asdrubali *et al.* (2018); Feng *et al.* (2019); Harkouss *et al.* (2018); Kapoor *et al.* (2011); Kolokotsa *et al.* (2011); Korpal (2020); Liu *et al.* (2019b); Pless *et al.* (2014); Pless & Torcellini (2010); Sartori *et al.* (2012); Torcellini *et al.* (2015); Ürge-Vorsatz *et al.* (2020); Wells *et al.* (2018)
Low emissions	Reduction of CO_2 or GHG emissions (operational and/or embodied) at any scale	Langevin *et al.* (2019); Oshiro *et al.* (2020); Scherz *et al.* (2023)
Low carbon	Broad term referring to the reduction of operational and/or embodied GHG emissions ('carbon' is commonly used in the literature as a proxy for all GHGs) at any scale	Akbarnezhad & Xiao (2017); Alwan & Jones (2014); Chandrakumar *et al.* (2019, 2020); Cui *et al.* (2019); Du *et al.* (2024); European Commission (2019); Fajardy & MacDowell (2020); Freis *et al.* (2016); Galimshina *et al.* (2024); Government of Canada (2016); Hafner & Özdemir (2022); Häkkinen *et al.* (2015); Koo *et al.* (2015); Kuittinen & Häkkinen (2020); Lützkendorf & Balouktsi (2022); Mata *et al.* (2020); Mota & Heras (2018); Nishioka (2016); Pomponi & Moncaster (2016); Resch *et al.* (2022); Satola *et al.* (2021); Shahmohammadi *et al.* (2024); UKGBC (2014); Wang *et al.* (2018); Wright *et al.* (2014); Yang *et al.* (2021)
Near zero emissions	Operational and/or embodied emissions at any scale are decreased to the minimum unavoidable 'residuals', but no negative emissions or offsets are considered	Chaudry *et al.* (2015); Georges *et al.* (2015); Knobloch *et al.* (2019); Ruparathna *et al.* (2017)
Zero emissions/ zero carbon	Complete elimination of emissions without considering negative emissions. This term generally implies an incomplete scope (*e.g.* considering only operational direct emissions of buildings)	Chandrakumar *et al.* (2019, 2020); European Commission (2019); Kristjansdottir *et al.* (2018); Mata *et al.* (2020); Röck *et al.* (2020); Shahmohammadi *et al.* (2024); Stephan & Stephan (2020); Xing *et al.* (2011)
Decarbonisation	An overarching term describing the process to phase out the use of fossil fuels and eliminate the GHG emissions of a building stock or the BRE sector. Since it is a generic term, it is not linked to specific scopes or scales	Bataille *et al.* (2016); Broer *et al.* (2021); Camarasa *et al.* (2022); Hill *et al.* (2019); IGBC (2022b); Korpal (2020); Mota & Heras (2018); Ouria & de Almeida (2021); Shahmohammadi *et al.* (2024); Sulzer *et al.* (2020); Szalay *et al.* (2022); Toth *et al.* (2022); World GBC (2019); Xia-Bauer *et al.* (2024)

(Contd.)

TERM	DEFINITION (AS USED IN THE LITERATURE)	REPRESENTATIVE DOCUMENTS
Carbon neutrality	A broad term commonly used at the operational level to describe a fully renewable energy infrastructure and at the embodied level to describe the use of bio-based products in buildings/stocks or the BRE sector which (temporarily) store carbon during its life-cycle, releasing it at the end of life (also known as the –1/1 approach)	Braune *et al.* (2019); Ferreira *et al.* (2020); Hu *et al.* (2022); Huo *et al.* (2021); Roca-Puigròs *et al.* (2020); Wheeler (2017); Zou *et al.* (2023)
Net zero emissions	The WLC reduction of emissions to the residuals and followed by an offset through using negative emissions through a net balance accounting (*e.g.* credits from avoiding emissions beyond the system boundary), the purchase of CO_2 certificates or the use of negative-emission technologies (Lützkendorf & Frischknecht 2020). The balancing can be done across various time periods	Alaux *et al.* (2023); Allen *et al.* (2022); Balouktsi & Lützkendorf (2022); Bullen *et al.* (2021); Dai *et al.* (2024); Frischknecht *et al.* (2019, 2020); Fyson *et al.* (2023); Horup *et al.* (2024); Im & Kwon (2022); Lützkendorf & Balouktsi (2022); Lützkendorf & Frischknecht (2020); Maierhofer *et al.* (2024); Þórólfsdóttir *et al.* (2023); Priore *et al.* (2021, 2023); Robiou du Pont *et al.* (2025); Satola *et al.* (2021); Schmidt *et al.* (2020); Science Based Targets (2024); Shimoda *et al.* (2021); Stephan & Stephan (2020); Sugsaisakon & Kittipongvises (2024); World GBC (2019); Zhang *et al.* (2024)
Net zero carbon	This term is interchangeably used with net zero emissions. However, it also means that GHG emissions have first been lowered to a minimum during the WLC, and then the residual emissions are offset by negative-emission technologies. The balancing can be done across various time periods. The term is common in recent reports and policies, but not always explicitly defined to include embodied emissions. When termed as net zero 'whole life carbon', it includes both embodied and operational emissions. However, there is a lack of transparency in the granularity of materials and components considered, and completeness of life-cycle phases. In most of the literature found, it accounts not only for CO_2 emissions but also for other GHG emissions. Most of the grey literature added through snowballing aligns with this goal	Amaripadath *et al.* (2024); Balouktsi *et al.* (2024); BPIE (2023a); Broer *et al.* (2021); CCC (2019); Cerasoli & Porporato (2023); EAC (2022); Global ABC (2024); Habert *et al.* (2020); He & Prasad (2022); Hill *et al.* (2019); Horup *et al.* (2023); Hu (2022); IEA (2022, 2023a); IGBC (2022a, 2022b); IPA (2021); JH Sustainability *et al.* (2020); Kruit *et al.* (2020); Kuriakose *et al.* (2022); LETI (2020, 2023); Maierhofer *et al.* (2022); Marin *et al.* (2024); Mitchell-Larson *et al.* (2023); Nugent *et al.* (2023); O'Dwyer *et al.* (2023); Oghazi *et al.* (2023); O'Hegarty *et al.* (2022); Ohene *et al.* (2023); Passivhaus Trust (2019); Prasad *et al.* (2021); Priore *et al.* (2022, 2023); Scherz *et al.* (2020); Schrembi (2022); Shabha *et al.* (2023); Sharmina *et al.* (2023); Sinclair (2020); Steininger *et al.* (2020); Szalay *et al.* (2022); Tirelli & Besana (2023); Toth & Volt (2021); Toth *et al.* (2022); Tozan *et al.* (2024); UKGBC (2019, 2021a, 2021b, 2024); Ürge-Vorsatz *et al.* (2020); Velten *et al.* (2022); WSP (2021); Wu *et al.* (2022); Xia-Bauer *et al.* (2024)

Table 2: Typologies of the terms and definitions for goals used in the literature.

Note: [a]In the literature, terms to describe the energy type (primary, final, renewable, non-renewable, *etc.*) might be used, but for this paper, they were grouped in the same category.

BRE = building and real estate; GHG = greenhouse gas; WLC = whole life-cycle.

Energy-focused goals (*e.g.* low energy, 2000 Watt Society, near zero energy, net zero energy and zero energy) dominated the literature between 2010 and 2020, whereas more recent literature increasingly emphasises carbon neutrality. This shift towards net zero emission goals aligns with the academic literature (Roberts *et al.* 2020), and also with the grey literature (predominantly published in Europe), where reports and policies from 2019 onwards have had an overwhelming focus on reaching net zero carbon (CCC 2019; European Commission 2024; Global ABC 2024; Hill *et al.* 2019; IEA 2023a; IGBC 2022a; LETI 2020; O'Dwyer *et al.* 2023; Passivhaus Trust 2019; Toth *et al.* 2022; UKGBC 2019; World GBC 2019).

In the literature on DEs for the BRE sector, climate neutrality and carbon neutrality are often treated as synonymous. As they are not differentiated in the analysed literature, they are therefore considered here under a single term. Nonetheless, the recent literature has clarified important differences between these concepts, which are particularly relevant for methane (CH_4)-intensive sectors such as agriculture. Carbon neutrality is commonly associated with net zero CO_2 emissions, typically achieved by balancing emissions and removals (Chen *et al.* 2022; Wang *et al.* 2022). Climate neutrality, by contrast, has a broader scope, encompassing all GHG emissions and accounting for their differing global warming potentials (Borning *et al.* 2020). Whether mitigation efforts address only CO_2 or all GHG emissions has important policy implications, as carbon-neutral strategies may overlook non-CO_2 emissions that are critical for achieving Paris-aligned climate outcomes. For this reason, this distinction on the main indicator was explicitly included as an additional assessed key factor. Although the need for harmonised definitions and transparent system boundaries has been explicitly highlighted in IEA EBC Annex 72 (Frischknecht *et al.* 2023), the current scientific literature remains methodologically and terminologically ambiguous and unaligned with the principles of the Paris Agreement.

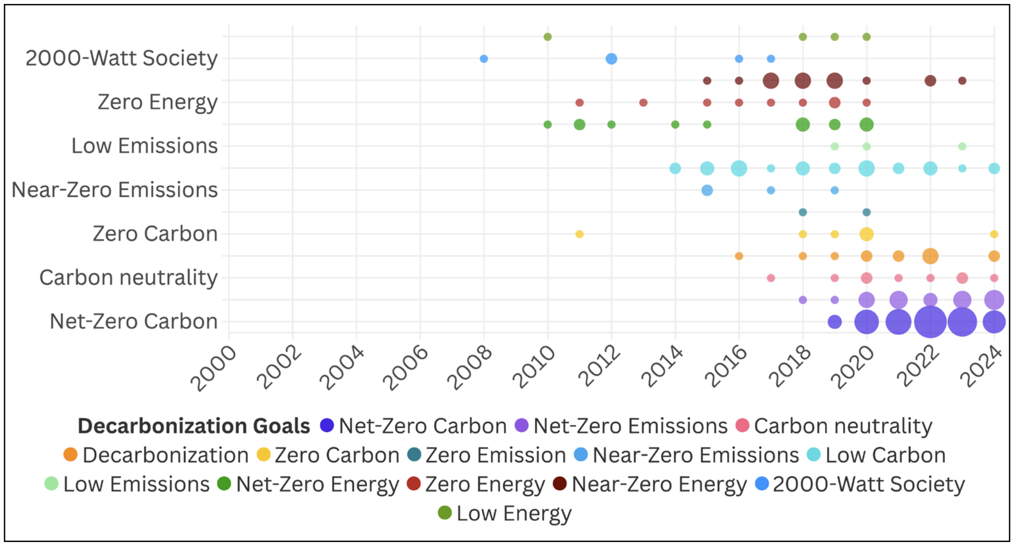

Figure 4: Temporal distribution of decarbonization targets and goals.

Note: Dot size is proportional to document count; maximum = 16.

3.4 SCALE OF THE ASSESSMENT

Across all scales, an increase in publications is observed after 2016, reflecting the influence of the Paris Agreement. Figure 5 presents the three assessment scales identified in the literature: individual buildings, building stocks and the BRE sector. A stepwise progression is evident, with building-level analyses appearing first, followed by building stock assessments and, more recently, sector-wide studies. While individual building studies cannot ensure sector-level compliance with the Paris Agreement, they can inform typology-specific, bottom-up approaches to benchmarking and building stock modelling to explore decarbonisation trajectories across different policy settings and frameworks (Alaux *et al.* 2025; Chan *et al.* 2024; Foliente & Seo 2012).

Specific examples of the early literature predominantly focusing on the individual building scale include Zimmermann *et al.* (2005), who defined energy demand benchmarks per floor area for residential and office typologies, and Peacock & Newborough (2008), who addressed heat-saving measures across UK residential buildings. These approaches enable comparability, but are inherently limited in their ability to assess system-wide alignment with climate targets.

From 2011 onward, building stock-based approaches emerged, allowing DEs to account for aggregate effects, geographical and temporal dynamics. For example, a strategy net zero energy road map for India applied a stock-level perspective across commercial and residential buildings. Heeren *et al.* (2012) modelled different structural changes, retrofit rates and thermal insulation factors to align the Swiss residential building stock with the 2000 Watt Society's goals. Since 2016, particularly after 2020, stock-level analyses have become more prevalent, reflecting a growing recognition of the need to capture cumulative impacts and the mid- to long-term effects of DEs.

In the case of sector-wide BRE analyses explicitly addressing material flows, technology scenarios and policy levers, Xing *et al.* (2011) adopted an operational approach in the UK to phase out fossil fuels, including scenarios for thermal insulation, lighting, heating and ventilation technologies. From 2015 onward, the publication of sectoral-level studies became mainstream, particularly in the UK (Chaudry *et al.* 2015; Hannon 2015; UKGBC 2014). These studies coincided with the UK's commitment to reducing its GHG emissions by 80% by 2050, announced in 2015, and illustrate how sector-level framing enables the integration of operational, embodied and policy dimensions that cannot be captured at smaller scales.

Figure 5: Assessment scale considered in the screened documents.

Note: Dot size is proportional to document count; maximum = 13.

3.5 ALIGNMENT WITH THE PARIS AGREEMENT GOALS

Across the analysed literature, significant methodological discrepancies are observed, even where identical terminology is used. These differences appear across key factors such as the temperature limit, the accounting of CO_2 or GHG emissions, the life-cycle scope considered, the scale of assessment, the target year and the set goal. As outlined in the methods section, not all characteristics are consistent with the principles of the Paris Agreement. These criteria are systematically assessed to assign an alignment rating to the DEs identified in the literature, reflecting their degree of alignment with the goals of the Paris Agreement. Although emission mitigation strategies in the BRE sector predated the Paris Agreement, the Agreement marked a turning point by clearly defining long-term temperature limits and net-zero objectives. Prior to 2015, most of the literature did not link DEs to explicit temperature thresholds or sector-specific net zero commitments.

Before the adoption of the Paris Agreement (United Nations 2015), explicit temperature limits for global warming were rarely mentioned, with only 5% of documents prior to 2015 mentioning a 1.5°C threshold. Between 2015 and 2017, this share increased rapidly, with approximately half of the studies adopting a 1.5°C limit. Since 2018, however, an increasing number of DEs have incorporated both 1.5 and 2°C in pathways for 2050 and beyond. This finding provides evidence that reflects the growing difficulty of limiting global warming to 1.5°C under current trajectories, as highlighted in the recent literature (Alaux *et al.* 2025; IEA 2023a; Kuramochi *et al.* 2018) and by Intergovernmental Panel on Climate Change (IPCC) climate scientists (Carrington 2024).

The indicator used to quantify global warming potential has also evolved unevenly. While early benchmarks already accounted for multiple GHG emissions from buildings (Zimmermann *et al.* 2005), a substantial share of recent DEs has focused exclusively on CO_2 emissions. Overall, around 25% of the assessed documents quantify CO_2 emissions only. Even though CO_2 emissions account for the greatest share of GHGs emitted by the BRE sector (Nejat *et al.* 2015), disregarding other GHGs increases the risk of overshooting temperature limits when defining DEs. Additionally, the lack of transparency and confusion about the BRE's contribution to global GHG emissions (21% according to IPCC 2023) and global CO_2 emissions (37% according to UNEP 2024) can lead to incompatible national pathways, increasing the risk of overshoot.

Based on the Paris Agreement goals, this study defines full alignment as (1) limiting global warming to at most 2°C, relative to preindustrial levels; (2) achieving net zero emissions in the entire BRE sector by 2050 at the latest; and (3) accounting for all GHG emissions over the WLC of buildings. Using these criteria, a non-binary multi-attribute rating framework was applied to assess the degree of alignment across the reviewed literature.

In the rating, high scores are consistently associated with ambitious temperature targets, WLC scopes, sector-level assessments and explicit net zero carbon goals. Figure 6 illustrates how the combinations of analytical factors considered in the literature relate to overall alignment scores.

In contrast, documents with limited scope, narrow scale or less ambitious targets have lower alignment levels. Figure 6 highlights the small subset of documents that fully meet all alignment criteria, underscoring the fragmented nature of current DEs. Notably, most of the analysed literature reflects only partial integration of Paris-compatible criteria, such as ambitious net zero goals with an incomplete scope, or aligned temperature limits with a single-building approach.

Only four documents fully align with the Paris Agreement's compatibility criteria defined in this study. Despite different scopes and formats (*i.e.* scientific papers versus policy-oriented reports), these documents share a combination of key characteristics in which they frame their DEs in alignment with the Paris Agreement by explicitly addressing a 1.5°C limit, WLC coverage of GHG emissions, sectoral-level perspectives and clearly defined net zero carbon end goals within mid-century timeframes. These four studies will be described below.

A central reference was the study by Lützkendorf & Frischknecht (2020), which defines and characterises the different balancing mechanisms of net zero. Their typology on terms and definitions informed the construction of the multi-criteria scoring framework applied in the present study. By explicitly defining net balance, offsetting and technical net zero pathways, their work enables the comparability across studies and avoids the ambiguity that characterises much of the earlier literature.

Another fully aligned paper was that of Steininger *et al.* (2020), which operationalises Paris-aligned climate goals through a top-down carbon budget allocation framework that translates global temperature limits into sectoral and national carbon constraints for the built environment. Their approach explicitly confronts the inconsistencies between sectoral pathways and carbon budgets, revealing systematic overshoots when sectoral ambitions are assessed in isolation. This contribution is particularly important because it highlights the uncertainties related to the scale of assessment and alignment with global targets, which were also considered in the rating framework of the present paper.

Where Steininger *et al.* (2020) provide a budgetary boundary, Allen *et al.* (2022) demonstrate feasibility and coherence through dynamic national pathway modelling. Allen *et al.* also consider a WLC perspective in a single system framework and test whether net zero WLC outcomes are achievable by 2050 under varying ambition levels. Their results show that deep operational decarbonisation alone is insufficient, since embodied residuals become prevalent, reinforcing the need for low-emission materials, biogenic carbon storage and end-of-life management. The present paper aligns with the balancing principles defined by Lützkendorf & Frischknecht (2020) and complements the global budgetary constraints as highlighted by Steininger *et al.* (2020).

The only policy document that fully aligns with the principles of the Paris Agreement is the Buildings Performance Institute Europe's (BPIE) life-cycle road map for Germany (BPIE 2023b). It translates prior scientific DEs into an actor-specific, time-bound implementation framework, bridging the gap between science and policy (albeit with a relevant delay, as mentioned previously). Unlike other national strategies that adopt terminologies without transparency, this road map explicitly embeds WLC, sector-wide coverage and step-wise milestones (2025–45). Its alignment is further strengthened by its assessment of its consistency with national carbon-budget discussions in Germany. Furthermore, it explicitly recognises the governance responsibilities across multiple stakeholder groups, exemplifying how Paris-aligned scientific principles can be translated into actionable DEs.

Although they do not directly reference one another, these four documents illustrate the progression of the Paris Agreement-aligned literature over time. Ideally, the broader literature should be able to follow a similar trajectory: from conceptual clarity in terminology and definitions (Lützkendorf & Frischknecht 2020), to budgetary consistency (Steininger *et al.* 2020), to feasibility assessments (Allen *et al.* 2022), and finally to policy adoption (BPIE 2023b). Their publication dates indicate a maturation phase in the literature following the Paris Agreement, alongside a growing recognition of embodied emissions within WLC scopes, the development of sectoral carbon budgets and increasing urgency to reach net zero GHG emissions. Earlier studies typically meet one or two of these criteria, but fail to integrate them simultaneously, resulting in lower alignment scores. Notably, a small subset of studies (Koo *et al.* 2015; Liu *et al.* 2019b; Pless & Torcellini 2010; Soares *et al.* 2017) mentions highly ambitious target years (*i.e.* 2020–25), yet remains operationally focused on or limited to individual buildings; despite their apparent ambition, such approaches do not meet Paris Agreement compatibility due to incomplete life-cycle scope and insufficient scaling, and an assessment of their feasibility lies outside the scope of this paper.

Despite these aligned examples, the majority of reviewed documents fall short of full Paris compatibility due to ambiguous treatment of temperature-based limits or emission indicators, incomplete life-cycle scopes, limited scales beyond individual buildings, unambitious target years, or outdated decarbonisation goals. While the results indicate meaningful progress since the adoption of the Paris Agreement, they also reveal persistent disparities, delays in policy uptake, and cross-country misalignments that remain highly relevant for implementation and may risk undermining collective progress toward the Agreement's goals. This is particularly important given the temporal gap between academic publications and their adoption into policy frameworks. The limited number of fully aligned studies underscores a critical gap: although the goals of the Agreement are conceptually defined, DEs in the BRE sector are rarely articulated in a comprehensive, coherent and policy-relevant way. Addressing this gap requires urgent alignment of research with the implementation of science-based principles into policy, while integrating sector-wide pathways and action plans within coherently defined carbon budgets. For a complete list of documents and their alignment rating, see the supplemental data online.

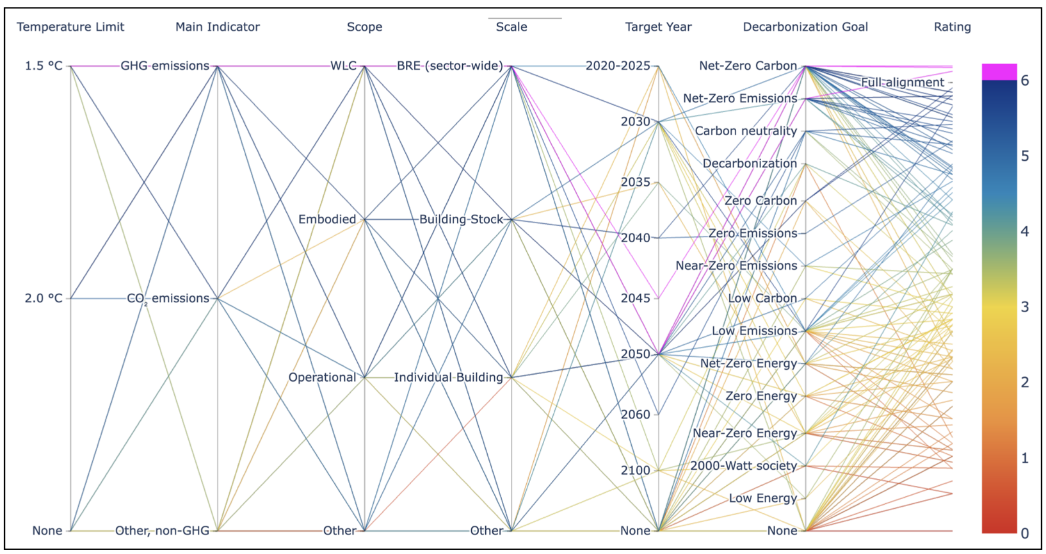

Figure 6: Parallel coordinates plot showing how combinations of key analytical factors in the reviewed literature relate to alignment with current decarbonisation needs.

Note: Each line represents a single document, coloured according to its overall rating.

4. CONCLUSIONS AND RECOMMENDATIONS

This study provides the first global systematic literature review (SLR) and structured alignment assessment of decarbonisation efforts (DEs) in the global building and real estate (BRE) sector against the principles of the Paris Agreement. By evaluating 212 publications using six analytical factors (temperature increase limit, main indicator, life-cycle scope, scale, target year and decarbonisation goal), the paper introduces a transparent multi-criteria rating technique to quantify degrees of alignment with the Paris Agreement. Its main contribution lies in quantitatively demonstrating, through a consistent and comparable assessment method, how existing research and policy DEs have evolved before and after the Agreement, and in highlighting prevalent trends and misalignments in recent literature worldwide.

The first research question—examining when DEs in the BRE sector have been published in research and policy—reveals a clear temporal lag between scientific output and policy adoption. Scientific publications precede policy documents by several years, in some regions by half a decade, indicating a delayed translation of decarbonisation knowledge into governance frameworks.

The second research question—addressing how the ambition of DEs in the BRE sector has evolved—shows a stepwise increase in ambition over time, particularly after 2015, with a shift from energy-efficiency targets toward net zero greenhouse gas (GHG) emission goals. However, this convergence in stated ambition is not matched by methodological consistency. Many DEs adopt ambitious targets while maintaining incomplete life-cycle scopes, limited spatial scales, inconsistent definitions or insufficiently specified pathways. Step-wise approaches, such as the Buildings Breakthrough initiative (Lützkendorf *et al.* 2025; UNEP 2023), may represent important intermediate milestones; however, by focusing on less ambitious goals and small scales (near zero emissions buildings by 2030) rather than achieving sector-wide net zero emissions by 2050, they do not in themselves ensure the achievements of the Paris Agreement's goals.

The third research question—assessing how many DEs in the BRE sector are fully aligned with the principles of the Paris Agreement—highlights the central finding of the study: only a very small fraction of documents meet all alignment criteria simultaneously. Most DEs fail to integrate whole life-cycle (WLC) emissions, sector-wide perspectives, explicit temperature limits and mid-century net zero targets within a coherent framework. Consequently, despite ongoing efforts, the current global body of research and policy is not yet on a trajectory to meet the goals of the Agreement, underscoring the need for stronger international coordination and harmonisation.

The results reveal marked geographical and scope disparities: Europe and Oceania lead the integration of whole-life carbon into DEs, while Africa, South America, North America and most of Asia remain underrepresented and predominantly focused on operational emissions. This imbalance is critical given the projected growth of built environments in these regions in the coming decades. To achieve the economy-wide goals of the Paris Agreement by 2050, it is imperative that developing countries within regions industrialise while staying within the Agreement's thresholds. Since all regions must advance their decarbonisation trajectories for their national BRE sectors, industrialised countries, which already possess established WLC methodologies, pathways, regulatory instruments and funding mechanisms, and are overrepresented in the literature, should support emerging economies through targeted research funding, capacity-building and institutional development to enable sector-wide alignment with global climate objectives. Considering current research on DEs to generate context-specific national research in developing countries could close the gap between research and policy, enabling these countries to include decarbonisation and development pathways for their national BRE sectors in their Nationally Determined Contributions.

Against this background of uneven progress and limited policy adoption, and based on the systematic patterns identified in the results, priority research directions and targeted policy recommendations are outlined to accelerate the development of Paris-aligned, WLC DEs for national BRE sectors worldwide.

A first priority for international research is the harmonisation of terminology, system boundaries and goal ambition in DEs for the BRE sector. Clear and consistent definitions of terms such as low, near, net and absolute zero; explicitly linked to decarbonisation goals, indicators, life-cycle scope, and balancing approaches are essential to improve comparability and coherence across research in DEs of the BRE sector. These concepts continue to be used interchangeably despite representing fundamentally different ambition levels, offsetting logics and boundary conditions. In particular, credible net zero claims require transparent disclosure of scope, system boundaries at the analysed scale, balancing approaches and the treatment of negative emissions, consistent with established definitions (Erlach *et al.* 2022; Ouellet-Plamondon *et al.* 2025).

A second priority for research is the development of robust, context-specific data infrastructure, indispensable to the development of viable prospective decarbonisation pathways for national BRE sectors. Such systems should support dynamic and prospective analyses of national decarbonisation capacities, as well as the long-term monitoring of decarbonisation trajectories. This challenge is particularly pronounced in the underrepresented regions in literature, where the generation and management of essential datasets, such as life-cycle-assessment data and building stock statistics, often depend on individual research initiatives (only sometimes funded) rather than established national data institutions (Amarasinghe & Hadiwattege 2022; Soust-Verdaguer *et al.* 2025; UNAM-iingen n.d.).

A third priority for research is ensuring methodological scalability across levels of assessment. Advancing Paris-aligned decarbonisation analysis in the BRE sector requires consistent frameworks that link individual building assessments with building stock modelling and sector-wide evaluations. Limiting analyses to the single-building scale constrains the ability to assess compatibility with economy-wide climate goals, such as those of the Paris Agreement. Future research should therefore develop scalable, cross-level approaches that integrate WLC perspectives (accounting for the BRE sector's Scopes 1–3 emissions) and enable coherent aggregation from building-level data to national sectoral pathways.

The findings indicate that the policy's decarbonisation ambition remains inconsistent across regions and is rarely fully aligned with the principles of the Paris Agreement. A first policy priority is therefore to raise international ambition and develop harmonised standards and common frameworks within the Agreement's thresholds. In particular, greater alignment is needed regarding system boundaries and scales, methodological transparency in indicators, and the scope used in net zero approaches. Aligning reporting requirements and policy instruments with such harmonised standards would reduce methodological ambiguity, improve cross-jurisdictional comparability and minimise persistent misinterpretations. While harmonisation may limit certain degrees of national flexibility, clearly defined common structures can still accommodate contextual differences, balancing global coherence with regional adaptability.

The continued dominance of operationally focused, small-scale approaches identified in the results highlights the need to embed whole-life carbon and sector-wide perspectives within national climate strategies. A second policy priority is therefore the integration of WLC-based decarbonisation frameworks into national planning instruments. Governments should translate science-based, top-down pathways into coherent bottom-up implementation mechanisms, including road maps, updated building codes with legally binding limit values, carbon budgets and decarbonisation trajectories integrated into Nationally Determined Contributions. The implementation of legally binding policies should be progressive and scalable, prioritising the emission sources that can be most effectively addressed, such as on-site use of fossil fuels in building operations (contributing to Scope 1 emissions of buildings), while establishing and integrating embodied emissions into accounting frameworks. At the national level, effective climate action within the BRE sector requires the coordinated formulation and integration of strategies across different stakeholders, sectors and levels of responsibility (Foliente *et al.* 2025; Graham *et al.* 2025).

Many regions with rapidly expanding building stocks, including parts of Africa, South America, North America and Asia, remain underrepresented in the literature and continue to rely predominantly on operational-only or building-scale DEs. A third policy priority is therefore the strategic allocation of research funding, capacity-building initiatives and institutional support toward these regions, where future construction activity could worsen global emissions trajectories if no action is taken. Strengthening local data infrastructures, modelling capacities and regulatory frameworks can enable the adoption of WLC, sector-wide approaches consistent with Paris-aligned pathways. At the same time, regions already approaching higher ambition levels should consolidate and extend existing measures while supporting the international diffusion of methodologies, data systems and policy instruments across contexts.

The results suggest that Paris-aligned decarbonisation of the BRE sector is technically feasible, yet institutionally fragmented and unevenly implemented. This gap between knowledge and action highlights that the primary challenge is no longer defining increasingly ambitious goals, but rather operationalising them coherently and in a timely manner.

DEs can be initiated immediately across multiple levels of responsibility, including cities, regions, institutions and sectoral actors, by building on existing scientific guidance and Paris-aligned frameworks. Accelerating progress will therefore require strengthened coordination, harmonisation and cross-level alignment rather than additional goal-setting exercises. Future efforts should prioritise translating established whole-life carbon principles into integrated, sector-wide pathways embedded within climate targets. Closer collaboration among researchers, policymakers, standardisation bodies and statistical institutions will be essential to ensure that scientific advances are effectively translated into measurable and timely climate action.

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AI DECLARATION

Artificial intelligence (AI)-aided tools (specifically Grammarly and DeepL) were used exclusively for spelling and grammar refinement. No AI tools were used in the design or execution of the systematic literature review, nor in the creation, alteration or manipulation of original research data, including images and measurements.

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COMPETING INTERESTS

The authors declare no conflict of interest that could have influenced the work reported in this paper. T. L. is a member of this journal's editorial board, but had no role in any editorial decisions regarding this manuscript.

DATA ACCESSIBILITY

The data are provided in the supplemental data online.

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SUPPLEMENTAL DATA

Supplemental data containing an Excel spreadsheet with search string results, final documents, data extraction and point system can be accessed at: https://doi.org/10.5334/bc.724.s1

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