© AUG 2026 | IRE Journals | Volume 10 Issue 2 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I2-1722363

Decarbonizing the Construction Industry: A Critical Review of Sustainable Materials and Circular Economy Approaches

SAMUEL AYENI[1], ABUBAKAR HALIDU[2], CHICHEBE VICTORIA MAURICE UWANAKA[3], ELIJAH KORDIEH MENSAH[4], ABDULTAWAB ADEMOLA ADERIBIGBE[5], YUSUF AYOBAMI MUSTAPHA[6], STEPHEN BOAKO BOATENG[7]

[1]*Wood Science and Engineering, Oregon State University, Corvallis, Oregon, USA*

[2]*Department of Civil Engineering Technology, Federal Polytechnic Nasarawa, Nigeria*

[3]*Department of Human Resources Management, University of Hull, Kingston Upon Hull, England*

[4]*Department of Environmental Studies, University of Montana, Missoula, Montana, USA*

[5]*Division of Construction Science, Christopher C. Gibbs College of Architecture, University of Oklahoma, Norman, Oklahoma, USA*

[6]*Department of Biochemistry and Molecular Biology, University of North Texas, Denton, Texas, USA*

[7]*Department of Civil, Environmental and Geospatial Engineering, Michigan Technological University, Houghton, Michigan, USA*

Abstract- ***The decarbonization of the construction sector requires accounting for emissions throughout the entire life cycle of a building's materials, including extraction, manufacturing, construction, maintenance, replacement, and end-of-life, rather than operational energy alone. This paper offers a critical, rather than descriptive, narrative review of the evidence for sustainable construction materials and circular economy strategies as levers for whole-life carbon reduction. Rather than treating reported decarbonization potentials as settled findings, the review interrogates the assumptions, system boundaries, and evidentiary basis underlying claims made for low-clinker cement, alternative binders, recycled and low-carbon steel, bio-based materials, and secondary resources. A recurring pattern emerges: reported benefits are frequently derived from laboratory-scale, pilot, or early-commercial data, extrapolated using inconsistent life-cycle assessment (LCA) boundaries, and rarely validated against long-term, in-service performance. Circular strategies, including material demand reduction, adaptive reuse, component reuse, high-value recycling, design for adaptability and disassembly, urban mining, and digital traceability, exhibit a similar pattern: plausible mechanisms supported by a thin, methodologically heterogeneous, and geographically skewed empirical base. Wood products warrant particular consideration because sustainably sourced wood can store carbon and may reduce fossil-intensive material demand through substitution, although the magnitude and durability of these benefits depend strongly on accounting assumptions not yet harmonized across the field. The review argues that the field's persistent framing of sustainable materials and circularity as self-evidently complementary and beneficial obscures unresolved trade-offs, weak causal evidence for claimed emissions reductions, inconsistent counterfactual assumptions, and a systematic evidence gap outside high-income economies. It concludes that progress is currently constrained less by a shortage of candidate technologies than by the absence of harmonized carbon accounting, longitudinal performance evidence, and critically appraised, rather than simply aggregated, evidence capable of supporting high-confidence investment and policy decisions.***

Keywords: construction decarbonization, embodied carbon, sustainable construction materials, circular economy, whole-life carbon, material reuse, life-cycle assessment, evidence quality

I. INTRODUCTION

The construction sector is routinely described as central to the transition to a low-carbon economy, given its material and energy intensity.(United Nations Environment Programme, 2026). Cement, concrete, steel, glass, timber, and aggregates require substantial resources to extract, process, transport, and assemble, and operational energy use adds a further, well-documented, layer of life-cycle emissions. This framing is not in dispute. What is far less settled, and what existing reviews in this space tend to understate, is the strength, consistency, and generalizability of the evidence used to justify specific decarbonization pathways. Much of the literature moves directly from a description of a material's or strategy's theoretical carbon-saving mechanism to an implicit endorsement of its practical decarbonization value, without interrogating the quality of the underlying evidence base.

This elision matters because the distinction between operational and embodied carbon, while conceptually well established.(Royal Institution of Chartered Surveyors, 2023), is often treated as though it were also methodologically settled. It is not. System boundaries, service-life assumptions, allocation rules for recycled content, and treatment of biogenic carbon vary substantially across studies, and these methodological choices, not just underlying material chemistry, frequently determine whether a material or strategy appears to reduce or merely redistribute emissions. A critical review must therefore treat methodological heterogeneity as a primary object of analysis, not a footnote.

Sustainable materials, including wood products, low-carbon concrete, recycled metals, bio-based products, and secondary raw materials, are commonly presented as delivering emissions reductions through substitution. This claim is frequently true in a narrow, cradle-to-gate sense, and considerably less certain once performance, durability, transport distance, production maturity, and end-of-life pathways are taken into account. (Guignot et al., 2015; Mouton et al., 2023). For bio products, the relevant question is therefore not simply whether it replaces a higher-emission material, but whether the resulting product can deliver comparable or superior service with efficient use of the renewable resources and sufficient durability to remain in service. Reviews that catalogue material options without systematically weighing the strength of the evidence for whole-life, as opposed to point-in-time, benefits risk overstating the field's maturity.

Circular economy approaches extend this logic by challenging the linear "take-make-use-dispose" model through material efficiency, reuse, recycling, design for disassembly, and material recovery. These strategies are conceptually coherent and have intuitive appeal, but their empirical evidence base is arguably thinner and more fragmented than that for material substitution, resting heavily on case studies, pilot projects, and modelled scenarios rather than large-sample, longitudinal, or comparative data (Benachio et al., 2020; Ossio et al., 2023). Treating sustainable materials and circular strategies as mutually reinforcing components of a single decarbonization system, as much of the literature now does, is a reasonable analytical move, but it should not be allowed to disguise the fact that the evidence supporting each component, and especially their interaction, remains uneven and, in places, weak.

This review therefore departs from the conventional narrative-review format in three respects. First, rather than summarizing what studies report, it evaluates how reliably they support the claims commonly attributed to them, including the maturity, boundary conditions, and generalizability of the underlying evidence. Second, it treats unresolved trade-offs and contested findings as central findings in their own right, rather than as caveats appended to otherwise favourable conclusions. Third, it explicitly identifies points in the argument that rest on claims requiring direct citation to primary literature, rather than presenting synthesized conclusions as though they were self-evidently supported. The result is intended to function as a critical appraisal of the state of the evidence, suitable for informing research prioritization and policy design, rather than a promotional account of decarbonization potential.

The remainder of the paper proceeds as follows. Section 2 examines the whole-life carbon framing itself and its limitations. Sections 3 and 4 critically appraise the evidence for sustainable materials and circular economy strategies respectively, including an explicit assessment of evidence quality for each major pathway. Section 5 interrogates whether the claimed integration of these two strands is itself evidenced or largely aspirational. Section 6 examines barriers to implementation, with particular attention to the geographic concentration of the evidence base. Section 7 sets out research priorities implied by the gaps identified, and Section 8 concludes, including an explicit statement of this review's own methodological limitations.

II. THE DECARBONIZATION CHALLENGE IN CONSTRUCTION

2.1 Sources of Carbon Across the Construction Life Cycle

Construction-related emissions arise from raw material extraction and processing, manufacturing of cement, steel, glass, brick, and insulation products, transport, on-site construction activity, operational energy use, maintenance and replacement, and eventual demolition and waste processing. This sequence is well established in the life-cycle assessment literature(European Committee for Standardization, 2011). What is less frequently interrogated is the unevenness of data quality across these stages: manufacturing-stage emissions for major materials are relatively well characterized through environmental product declarations, whereas transport, maintenance, and particularly end-of-life emissions are commonly estimated using generic default factors rather than project-specific data(Anderson et al., 2019; Sandin et al., 2014). Aggregate whole-life carbon figures therefore carry materially different levels of confidence depending on which life-cycle stage dominates a given claim, a distinction rarely made explicit when such figures are cited.

2.2 From Operational to Whole-Life Carbon: An Unresolved Accounting Problem

The shift in emphasis from operational to embodied carbon is usually presented as a natural consequence of improving operational efficiency: as operational emissions fall, embodied emissions constitute a growing share of remaining life-cycle carbon.(Röck et al., 2020). This is a reasonable inference but should not be mistaken for a resolved measurement problem. Whole-life carbon accounting requires assumptions about future electricity decarbonization trajectories, building service life, maintenance cycles, and end-of-life scenarios that are inherently uncertain and rarely made subject to sensitivity analysis in the studies from which "whole-life" claims are drawn(Feng et al., 2022; Li et al., 2023). A whole-life carbon comparison between two materials or strategies is therefore only as robust as its weakest assumption, and reviews that treat whole-life figures as more objective than operational figures risk substituting one set of unexamined assumptions for another.

2.3 Limitations of the Conventional Linear Construction Model

The industry's reliance on virgin resource extraction, single-use production, and demolition-based disposal is well documented and is not seriously contested in the literature. The more critical question, addressed unevenly in existing reviews, is where in this linear sequence intervention delivers the greatest, most reliably demonstrated decarbonization return. Much of the literature implicitly treats material substitution, demand reduction, and end-of-life recovery as additive and roughly comparable in impact. In practice, these interventions differ substantially in their evidentiary maturity: demand reduction and structural optimization build on established engineering principles, whereas the environmental benefits of large-scale component reuse and urban mining are still frequently assessed through estimated recovery potential, methodological frameworks, and relatively limited practical applications rather than demonstrated implementation at scale(Arora et al., 2021). This asymmetry in evidence quality, rather than a straightforward hierarchy of technical potential, should inform how confidently different interventions are prioritized.

III. SUSTAINABLE MATERIALS FOR CONSTRUCTION DECARBONIZATION: A CRITICAL APPRAISAL

3.1 Low-Carbon Cement and Concrete

Clinker substitution using supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast-furnace slag (GGBS), and calcined clay is the most technically mature and widely deployed low-carbon concrete strategy(Martirena, 2023; Orozco et al., 2024). Its evidence base is comparatively strong for cradle-to-gate emissions but considerably weaker for whole-life performance: fly ash and GGBS availability is itself contracting as coal power and blast-furnace steelmaking decline, meaning that reported reduction potentials calculated against current supply may not hold under future industrial conditions(Johansson et al., 2026; Snellings et al., 2023). This is a structural limitation rarely acknowledged in reviews that report SCM substitution rates as static decarbonization potential.

Alternative binders, including alkali-activated materials, are frequently presented as offering larger long-term reductions, yet the supporting evidence remains dominated by laboratory-scale and pilot studies, with limited independent verification of durability, structural performance, and standards compliance at commercial scale(Van Deventer et al., 2013). Recycled aggregate research shows a comparable pattern: demonstrated reductions in extraction and landfill diversion are relatively well evidenced, but claims of net carbon benefit are more fragile once transport distance, processing energy, and reduced structural performance in high-demand applications are incorporated, and many published comparisons do not consistently control for these factors(Marinković et al., 2010; Sabău et al., 2021). Overall, the concrete literature substantiates near-term, incremental decarbonization more convincingly than it substantiates the larger reductions attributed to binder innovation, and reviews that present these as comparably mature options understate this asymmetry.

3.2 Steel and Other Construction Materials

Scrap-based steel production via electric arc furnaces is well evidenced as lower-carbon than primary blast-furnace production, contingent on grid decarbonization (Yang et al., 2023). This conditionality is frequently stated but insufficiently emphasized: in regions with carbon-intensive electricity, the claimed advantage of recycled steel narrows substantially, meaning that generic “recycled steel is low-carbon” claims are regionally contingent rather than universally true. Hydrogen-based direct reduction of iron is regularly cited as a transformative pathway, yet as of the current evidence base it remains predominantly at demonstration or early-commercial scale, with cost, hydrogen supply, and infrastructure constraints that are acknowledged in specialist literature but often minimized in construction-sector reviews that cite it as an emerging solution without qualifying its scale-readiness(Fan et al., 2025; Rosner et al., 2023). Material efficiency, meaning reducing steel demand through structural optimization, has comparatively strong engineering evidence but receives disproportionately less attention in the literature than production-side innovation, a pattern that may reflect research and industry incentives rather than relative decarbonization potential.

3.3 Bio-Based and Renewable Construction Materials

The climate potential of bio-based construction materials, particularly mass timber, rests substantially on their ability to substitute for more emissions-intensive materials while storing biogenic carbon throughout their service life. Mass timber is frequently presented on this basis as a particularly promising pathway for reducing the embodied impacts of construction, but the magnitude of the claimed climate benefit depends partly on how biogenic carbon storage is accounted for, an issue whose methodological treatment remains contested rather than fully settled (Levasseur et al., 2013). Different accounting conventions can produce materially different, even opposite, conclusions about whether a given timber product is net carbon-negative over a defined assessment period. Reviews that report bio-based materials as unambiguously low-carbon without specifying the accounting convention used are, in effect, presenting a contested methodological choice as an empirical finding. Furthermore, the permanence of claimed carbon storage is contingent on forest management practices, harvest rotation, land-use change, and end-of-life treatment, and the evidence connecting specific sourcing practices to verified, rather than assumed, net climate benefit remains limited relative to the volume of literature asserting bio-based materials' climate advantages(Andersen et al., 2024). Durability, fire performance, and moisture sensitivity present additional, comparatively well-evidenced constraints that limit unqualified substitution claims across building types and climates.

This evidentiary caveat applies to the claimed climate benefit of bio-based materials, not to their technical or regulatory readiness, and the two should not be conflated. In non-structural applications, bio-based products are already in established commercial use rather than confined to laboratory or pilot demonstration, including as thermal and acoustic insulation displacing mineral and glass-fibre products and as structural sheathing. In structural applications, engineered wood products, particularly cross-laminated timber and glued-laminated timber (collectively "mass timber"), have moved beyond demonstration status: the 2021 edition of the International Building Code introduced construction Types IV-A, IV-B, and IV-C permitting mass timber buildings up to eighteen storeys, with the 2024 edition further relaxing exposed-timber limits within these types (International Code Council, 2024). Code approval of this kind addresses structural and fire performance rather than the durability of claimed biogenic-carbon benefits, and it does not resolve the accounting uncertainty discussed above. It does, however, mean that characterizing the practical application of bio-based materials as confined to laboratory-scale work is not accurate: commercial and code-validated deployment already exists for both non-structural and, increasingly, structural uses. The evidence gap this review identifies concerns the long-term, verified net climate benefit of these applications, not their technical feasibility or regulatory acceptance.

3.4 Recycled and Secondary Materials

Recycled and secondary materials are consistently linked to reduced virgin extraction, but the magnitude of the associated carbon benefit is highly method-dependent and, in the published literature, inconsistently reported. Metals recycling is comparatively well evidenced as delivering near-equivalent material value with substantially lower emissions(Broadbent, 2016; Peng et al., 2019), Whereas concrete and mixed demolition waste are frequently downcycled into lower-value applications that do not displace equivalent virgin production, a distinction that materially affects claimed carbon credits but is not consistently reflected in aggregate circularity statistics reported in policy and industry literature(Di Maria et al., 2018; Zhang et al., 2020). Industrial by-product availability (fly ash, slag) is also becoming a confounding variable rather than a stable input, since the industries generating these by-products are themselves subject to decarbonization or decline, meaning historic recycling-rate data may poorly predict future availability. Claims regarding secondary materials should therefore be treated as time-bound and application-specific rather than as generalizable evidence of a stable decarbonization pathway.

3.5 Evidence Synthesis: What the Material-Level Evidence Actually Supports

Read critically rather than descriptively, the material-level literature supports a narrower set of conclusions than is commonly implied. There is reasonably strong evidence that near-term, incremental interventions, including clinker substitution at established replacement rates, scrap-based steel where grid carbon intensity is low, and structural material efficiency, deliver measurable reductions under current conditions. There is considerably weaker evidence, resting substantially on laboratory, pilot, or short-horizon data, for the larger reductions attributed to alternative binders, primary steel decarbonization pathways, and the long-term net climate benefit of bio-based materials. Cutting across all categories, methodological inconsistency in system boundaries, allocation rules, and biogenic carbon treatment means that quoted decarbonization percentages are frequently not directly comparable across studies, even when they are presented as such in synthesis tables(AzariJafari et al., 2021; Gelowitz & McArthur, 2017). Table 1 summarizes not only the reported benefits and limitations for each pathway but also a critical appraisal of the maturity and generalizability of the supporting evidence, which is presented separately from the potential-benefit claims themselves precisely because the two are too often conflated in the literature.

© AUG 2026 | IRE Journals | Volume 10 Issue 2 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I2-1722363

Table 1. Sustainable construction material pathways: mechanisms, claimed benefits, limitations, and a critical appraisal of evidence strength

Material/approach	Decarbonization mechanism	Claimed benefits	Key limitations	Critical appraisal of evidence
Low-clinker cement and concrete	Partial clinker replacement with SCMs	Reduced embodied carbon; compatible with existing systems	Variable SCM availability, regional performance variability	Moderate-to-strong for current supply; weak for future supply as SCM feedstocks decline
Alternative binders	Replace Portland clinker chemistry entirely	Potentially large emissions reduction	Limited standards, variable feedstocks, uncertain scalability	Weak: predominantly lab/pilot-scale evidence; commercial-scale durability data scarce
Recycled aggregates	Substitute recovered material for virgin aggregate	Reduced extraction and demolition waste	Contamination, variable mechanical properties	Moderate for waste diversion; weak/inconsistent for net carbon benefit once transport and processing are controlled for
Recycled and low-carbon steel	Increased scrap use via EAF; emerging primary reduction routes	High recycling potential; substantial emissions reduction where grid is low-carbon	Scrap availability limits, grid-carbon dependency, nascent hydrogen-DRI infrastructure	Strong for EAF conditional on grid mix; very weak/early-stage for hydrogen-based primary reduction
Engineered timber and bio-based materials	Substitute carbon-intensive materials; temporary biogenic storage	Renewable sourcing; potentially low embodied carbon	Durability, land use, sourcing integrity, accounting contested	Weak-to-moderate; benefit is highly dependent on accounting convention and forest-management assumptions rather than an inherent material property
Reclaimed and secondary materials	Reuse/recovery avoiding virgin production	Preserves material value; reduces waste	Inconsistent quality, availability, certification	Moderate for high-value metal reuse; weak for downcycled concrete/mixed waste claims

IV. CIRCULAR ECONOMY APPROACHES: A CRITICAL APPRAISAL

4.1 Moving from Linear to Circular Construction

Circular economy framing extends decarbonization analysis from material carbon intensity to the retention, recovery, and recirculation of resources across building life cycles. As a conceptual reframing, this is well argued in the literature (Pomponi & Moncaster, 2017). As an empirically demonstrated decarbonization strategy, however, circularity in construction is considerably less mature

© AUG 2026 | IRE Journals | Volume 10 Issue 2 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I2-1722363

than the conceptual literature implies. Much of the evidence base consists of illustrative case studies and prospective scenario modelling rather than measured, comparative outcomes from implemented projects, and the review finds no strong basis in the literature for treating circular strategies as equivalently well evidenced to material substitution.

4.2 Reduce and Optimize Material Consumption

Demand reduction through structural optimization and adaptive reuse of existing buildings has a comparatively strong quantitative basis among circular strategies, since avoided material production can be directly estimated from reductions in material quantities and retained building components, with case studies demonstrating substantial reductions in embodied carbon relative to conventional design and new construction. (Dunant et al., 2021). Even here, however, claims require scrutiny: aggressive lightweighting can shift, rather than eliminate, material and carbon demand into more frequent maintenance, replacement, or reduced adaptability, and the literature on this trade-off is thinner than the literature promoting demand reduction itself(Grant et al., 2014).

4.3 Reuse, Recycling and Closed-Loop Material Flows

Component reuse is theoretically superior to recycling because it avoids reprocessing energy, and this mechanism is not in dispute. What is far less established is the frequency with which reuse is actually achieved at scale, as opposed to being technically feasible. The literature reports persistently low reuse rates for structural components relative to recycling or landfill, attributable to specification conservatism, uncertain residual performance, and absent markets(Bartsch, 2025; Rakhshan et al., 2020), yet reviews frequently cite reuse's theoretical carbon advantage without equally weighting this large gap between potential and realized practice. High-value metal recycling is the strongest evidenced closed-loop pathway; construction and demolition waste recycling into lower-value applications is common but delivers a materially smaller and less consistently quantified carbon benefit.

4.4 Design for Adaptability and Disassembly

Design for adaptability and disassembly (DfD) is well established conceptually, but its realized carbon benefit remains contingent on future disassembly, recovery, and component reuse actually occurring; consequently, much of the available evidence evaluates prospective recoverability and circularity rather than observed end-of-life outcomes from completed building life cycles(Cetin & Jaeger, 2026). Much of the DfD literature therefore reports design intent and technical feasibility rather than verified outcomes, a distinction this review considers important given how often DfD is cited as an established decarbonization strategy rather than a largely unverified one.

4.5 Urban Mining and Material Recovery

Urban mining is conceptually appealing but empirically underdeveloped: material stock estimates for cities are typically modelled rather than measured, recovery rates from real deconstruction projects are inconsistently reported, and the gap between theoretically recoverable material stock and material actually returned to equivalent-value use is rarely quantified in the same study(Arora et al., 2020, 2021). Claims about urban mining's decarbonization potential should therefore be read as upper-bound estimates rather than expected outcomes.

4.6 Digital Enablers of Circular Construction

Building information modelling, material passports, and digital twins are widely proposed as circularity enablers, but the literature offers comparatively little evidence that digital tracking alone changes material recovery outcomes, as opposed to documenting them(Markou et al., 2025). This is a meaningful distinction: digital infrastructure may be a necessary condition for circularity at scale without being a demonstrated driver of it, and reviews that present digitalization as a decarbonization intervention in its own right risk overstating what the evidence currently supports.

Taken together, the circular economy literature substantiates plausible mechanisms more convincingly than it substantiates realized, at-scale outcomes. The gap between technical potential and demonstrated practice is arguably the central,

© AUG 2026 | IRE Journals | Volume 10 Issue 2 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I2-1722363

underemphasized finding of this literature, and one that existing narrative reviews, which tend to enumerate strategies rather than interrogate their evidentiary maturity, have generally understated.

V. INTEGRATING SUSTAINABLE MATERIALS AND CIRCULAR ECONOMY APPROACHES: EVIDENCED OR ASPIRATIONAL?

Sustainable materials and circular economy strategies are now routinely presented in the literature as complementary components of a single whole-life decarbonization system. This is analytically coherent, but it is worth asking directly whether this integration is empirically demonstrated or primarily a conceptual synthesis imposed on two separately developed literatures. The review finds very few studies that quantify the combined, interactive effect of material selection and circular design choices within a single project or portfolio, as distinct from studies that separately model each strategy and additively sum their claimed benefits(Joensuu et al., 2022; Minunno et al., 2020). Additive summation is a simplifying assumption, not a validated finding, since interventions can interact non-linearly. For example, durable, higher-embodied-carbon materials may outperform lower-carbon alternatives specifically because of their compatibility with reuse, a synergy that whole-life comparisons based on static material substitution cannot capture.

This does not undermine the logical case for integration, but it does mean that the "systems perspective" increasingly invoked in this literature is, at present, more a research agenda than an evidenced conclusion. Claims that integrated strategies deliver materially greater whole-life carbon reduction than either strategy pursued independently should therefore be treated as a plausible hypothesis requiring direct empirical testing, rather than as an established result of the reviewed literature.

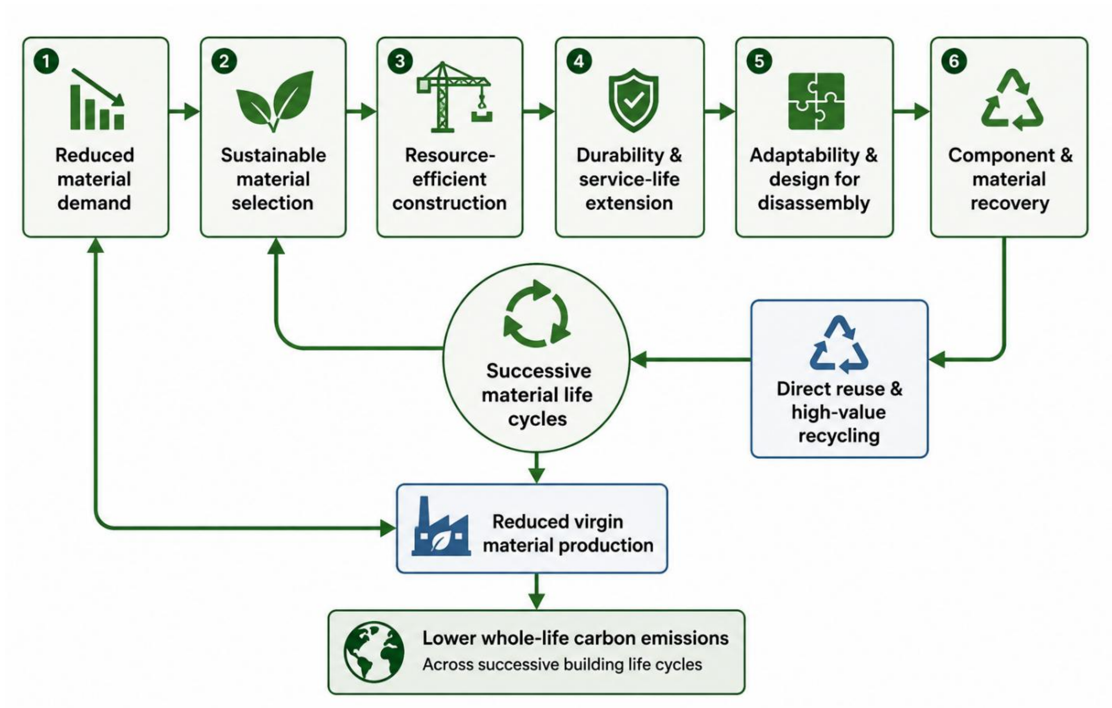

Figure 1. Proposed integrated framework for sustainable materials and circular economy approaches in whole-life construction decarbonization. The framework is presented as a conceptual synthesis of the mechanisms discussed in Sections 3–5; the strength of empirical evidence for the interactions it depicts varies by pathway and is critically appraised in the corresponding sections above, rather than implied uniformly by the figure itself.

© AUG 2026 | IRE Journals | Volume 10 Issue 2 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I2-1722363

VI. BARRIERS, TRADE-OFFS AND IMPLEMENTATION CHALLENGES

6.1 Technical and Performance Barriers

Performance uncertainty for secondary and reused materials is well documented and constitutes a genuine, rather than merely perceived, barrier: variability in composition, strength, and residual condition raises real specification risk(Qin Li & Chunhong Zhang, 2017). This barrier is frequently framed in the literature as a conservatism problem to be overcome through standardization, but an equally valid reading is that current caution reflects a real, unresolved evidence gap regarding long-term reliability, a distinction with different implications for how quickly standards should be relaxed.

6.2 Economic and Market Barriers

Cost competitiveness data for low-carbon materials and reuse pathways are unevenly reported and frequently commercially sensitive, meaning published cost comparisons may not be representative of typical market conditions(Bartsch, 2025). The literature's general claim that upfront cost premiums and split incentives across fragmented supply chains discourage adoption is plausible and consistent with broader innovation-economics literature, but sector-specific, quantified evidence of the scale of this cost gap over time remains limited.

6.3 Regulatory and Institutional Barriers

Regulatory and liability constraints on innovative materials and reused components are well documented in case-study and policy literature. Less well evidenced is the counterfactual: whether regulatory reform alone, absent parallel development of markets and recovery infrastructure, would meaningfully increase adoption(Corsini, 2025; Rakhshan et al., 2020). Treating regulation as the primary bottleneck, as some policy-oriented literature does, may therefore overstate its independent explanatory power relative to market and infrastructure constraints.

6.4 Methodological and Data Challenges

This barrier is, in the assessment of this review, the most consequential and the least adequately addressed in existing narrative reviews of the field. Inconsistent LCA boundaries, service-life assumptions, recycling allocation rules, and biogenic carbon treatment mean that a substantial share of comparative claims made across the literature discussed in Sections 3 and 4 are not strictly comparable, even where they are presented as such. This is not a peripheral limitation to be noted and set aside; it is arguably the central constraint on the field's ability to make reliable, comparative decarbonization claims at all.

6.5 Geographic and Contextual Inequalities

The evidence base is geographically uneven, with construction circular-economy research concentrated in a limited number of countries, potentially limiting its applicability across different economic, regulatory, and infrastructural contexts(Antwi-Afari et al., 2021). This is a limitation of the evidence itself, not merely a gap to be filled by future research: conclusions and recommendations drawn from this literature, including those in this review, cannot be assumed to transfer to low- and middle-income contexts where material availability, labour practices, informal reuse economies, and institutional capacity differ substantially. Reviews that append a brief acknowledgement of this imbalance without allowing it to qualify their substantive conclusions understate its significance.

Table 2. Major barriers to construction decarbonization, corresponding responses, and the strength of evidence for each barrier claim

Barrier	Key challenge	Corresponding response	Evidence strength for the barrier claim
Technical and performance	Variable quality/durability of alternative and recovered	Standardized testing, improved processing,	Strong: directly measurable material variability data exist

© AUG 2026 | IRE Journals | Volume 10 Issue 2 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I2-1722363

Barrier	Key challenge	Corresponding response	Evidence strength for the barrier claim
	materials	long-term validation	
Economic and market	Cost premiums, uncertain secondary markets, fragmented supply chains	Whole-life costing, incentives, circular procurement	Moderate: plausible and theory-consistent, but sector-specific quantified cost data are sparse
Regulatory and institutional	Codes, certification, liability favour established materials	Updated standards, performance-based regulation, reuse protocols	Moderate: well documented descriptively; causal effect of reform in isolation untested
Methodological and data	Inconsistent LCA boundaries and circularity metrics	Harmonized whole-life carbon assessment, standardized indicators	Strong, and under-weighted in the literature relative to its consequences
Information and traceability	Incomplete material records limit tracking across life cycles	Interoperable material passports, BIM-supported traceability	Weak-to-moderate: feasibility demonstrated; causal link to improved outcomes not established
Geographic and contextual	Limited transferability of evidence across regions	Locally grounded research, regional datasets, capacity development	Strong: evidence base is verifiably concentrated in high-income settings

VII. FUTURE DIRECTIONS AND RESEARCH PRIORITIES

The priorities implied by this critical appraisal differ in emphasis from those typically listed in descriptive reviews of this literature, which tend to call generically for “more research” across all pathways. Read critically, the evidence points to a smaller set of higher-priority gaps. First, harmonization of whole-life carbon assessment methodology, meaning system boundaries, service-life assumptions, recycling allocation, and biogenic carbon treatment, should be treated as a precondition for, rather than a parallel activity alongside, further material and circularity research, since without it comparative claims cannot be reliably adjudicated(Birgisdottir et al., 2017).

Second, longitudinal, in-service performance data are disproportionately scarce relative to the volume of laboratory and modelled evidence, particularly for alternative binders, reused structural components, and design-for-disassembly outcomes. Research funding and publication incentives that favor novel laboratory findings over slower, less publishable longitudinal monitoring may partly explain this imbalance, and correcting it will likely require dedicated, long-horizon funding instruments rather than incremental additions to existing project-based research programs.

Third, studies that quantify interactive rather than additive effects of combined material and circular strategies are needed to test whether the “integrated systems” framing advanced in Section 5 is empirically justified or remains aspirational. Fourth, the geographic concentration of the evidence base should be treated as a first-order limitation requiring dedicated, locally grounded research programmes in low- and middle-income contexts, rather than a caveat attached to conclusions developed elsewhere. Finally, given the methodological heterogeneity documented throughout this review, meta-research examining the comparability and reliability of published decarbonization claims, rather than further primary studies reporting yet more point estimates,

© AUG 2026 | IRE Journals | Volume 10 Issue 2 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I2-1722363

may offer disproportionate value to the field at its current stage of development.

VIII. DISCUSSION

Drawing the preceding sections together, three cross-cutting patterns characterize the current evidence base for construction decarbonization through sustainable materials and circular economy strategies. First, evidentiary maturity does not track the magnitude of claimed benefit. The interventions with the strongest supporting evidence, namely established clinker substitution, scrap-based steel under favourable grid conditions, and structural material efficiency, are consistently the ones with the smallest claimed reductions, while the largest claimed reductions (alternative binders, primary steel decarbonization, bio-based carbon storage, large-scale circular strategies) rest substantially on laboratory, modelled, or case-study evidence rather than verified, at-scale, long-term outcomes. A review that reports potential reduction figures without this distinction risks implying a confidence the underlying literature does not support.

Second, the field's methodological heterogeneity is not a peripheral limitation but a primary explanatory variable behind seemingly contradictory findings. Differences in LCA system boundaries, service-life assumptions, recycling allocation rules, and biogenic carbon treatment (Section 6.4) recur across the material-level (Section 3) and circularity (Section 4) literatures alike, meaning that a meaningful share of the between-study variation in reported decarbonization potential reflects accounting choices rather than genuine differences in underlying performance. This has a direct practical implication: comparative claims drawn from the literature synthesized in Table 1 and Table 2 should be treated as boundary-condition-dependent rather than as directly comparable point estimates until harmonized accounting is more widely adopted.

Third, the claim that sustainable materials and circular economy strategies function as an integrated, mutually reinforcing decarbonization system (Section 5) is better characterized as a plausible and conceptually coherent research agenda than as an empirically demonstrated result. Very little of the reviewed literature quantifies interactive, as opposed to additively summed, effects of combined material and circular-design interventions, and the geographic concentration of the evidence base in high-income economies (Section 6.5) further limits how confidently this integrated framing can be generalized. Taken together, these patterns suggest that the construction decarbonization literature is currently better equipped to describe mechanisms than to support high-confidence, comparative claims about their realized, whole-life impact, a distinction with direct consequences for how the evidence should be used in standards-setting, procurement, and investment decisions.

8.1 Limitations of This Review

As a narrative rather than systematic review, this paper does not apply a reproducible search protocol, formal risk-of-bias assessment, or pre-registered inclusion criteria, and its selection and critical weighting of evidence necessarily reflect the authors' judgement rather than a fully auditable process. The critique advanced throughout this review, that much of the underlying literature is methodologically heterogeneous and unevenly distributed geographically, also applies, to some degree, to the sources this review itself draws upon, and readers should treat its conclusions as a critical synthesis of the current state of evidence rather than a definitive or exhaustive assessment. Future systematic reviews and meta-analyses incorporating transparent evidence-quality assessment frameworks, potentially adapted from established approaches used in environmental research, would strengthen confidence in conclusions regarding construction decarbonization strategies(Morgan et al., 2016).

IX. CONCLUSION

Decarbonizing construction will not be achieved by continuing to accumulate laboratory and modelled evidence of theoretical potential across an ever-wider set of materials and circular strategies. The evidence synthesized in this review indicates that the field's central constraint is not a shortage of candidate interventions, but the absence of harmonized whole-life carbon accounting, longitudinal in-service performance data, and research conducted outside high-income contexts, gaps that limit confidence in comparative claims regardless of how promising individual mechanisms appear in isolation. Promising options, including mass timber, warrant particular attention where whole-life benefits can be demonstrated under transparent accounting assumptions. Policy, procurement, and investment decisions that treat currently available decarbonization figures as directly comparable and high-confidence therefore risk resting on a less certain evidentiary foundation than is commonly assumed. Progress toward a genuinely low-carbon built environment depends less on identifying further isolated sustainable solutions than on building the measurement infrastructure, longitudinal evidence, and geographically representative research base needed to evaluate them with confidence.

REFERENCES

[1] Andersen, C. E., Stupak, I., Hoxha, E., Raulund-Rasmussen, K., & Birgisdóttir, H. (2024). Forest dynamics in LCA: Integrating carbon fluxes from forest management systems into the life cycle assessment of a building. Resources, Conservation and Recycling, 209, 107805. https://doi.org/10.1016/j.resconrec.2024.107805

[2] Anderson, J., Rønning, A., & Moncaster, A. (2019). The Reporting of End of Life and Module D Data and Scenarios in EPD for Building level Life Cycle Assessment. IOP Conference Series: Earth and Environmental Science, 323(1), 012051. https://doi.org/10.1088/1755-1315/323/1/012051

[3] Antwi-Afari, P., Ng, S. T., & Hossain, Md. U. (2021). A review of the circularity gap in the construction industry through scientometric analysis. Journal of Cleaner Production, 298, 126870. https://doi.org/10.1016/j.jclepro.2021.126870

[4] Arora, M., Raspall, F., Cheah, L., & Silva, A. (2020). Buildings and the circular economy: Estimating urban mining, recovery and reuse potential of building components. Resources, Conservation and Recycling, 154, 104581. https://doi.org/10.1016/j.resconrec.2019.104581

[5] Arora, M., Raspall, F., Fearnley, L., & Silva, A. (2021). Urban mining in buildings for a circular economy: Planning, process and feasibility prospects. Resources, Conservation and Recycling, 174, 105754. https://doi.org/10.1016/j.resconrec.2021.105754

[6] AzariJafari, H., Guest, G., Kirchain, R., Gregory, J., & Amor, B. (2021). Towards comparable environmental product declarations of construction materials: Insights from a probabilistic comparative LCA approach. Building and Environment, 190, 107542. https://doi.org/10.1016/j.buildenv.2020.107542

[7] Bartsch, H. (2025). Reuse of reclaimed steel components in construction: A systematic review of potential, challenges and future directions. Structures, 80, 110057. https://doi.org/10.1016/j.istruc.2025.110057

[8] Benachio, G. L. F., Freitas, M. D. C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. Journal of Cleaner Production, 260, 121046. https://doi.org/10.1016/j.jclepro.2020.121046

[9] Birgisdottir, H., Moncaster, A., Wiberg, A. H., Chae, C., Yokoyama, K., Balouktsi, M., Seo, S., Oka, T., Lützkendorf, T., & Malmqvist, T. (2017). IEA EBC annex 57 'evaluation of embodied energy and CO 2eq for building construction.' Energy and Buildings, 154, 72–80. https://doi.org/10.1016/j.enbuild.2017.08.030

[10] Broadbent, C. (2016). Steel's recyclability: Demonstrating the benefits of recycling steel to achieve a circular economy. The International Journal of Life Cycle Assessment, 21(11), 1658–1665. https://doi.org/10.1007/s11367-016-1081-1

[11] Cetin, C., & Jaeger, N. (2026). Design for Disassembly in Residential Buildings: A Systematic Review of Current Practices and

Emerging Digital Technologies. Research and Reviews in Sustainability, 2(1), 173–197. https://doi.org/10.65582/rrs.2026.012

[12] Corsini, L. (2025). A systems approach the Circular Economy: Policy recommendations to increase building components reuse. Sustainable Production and Consumption, 57, 292–305. https://doi.org/10.1016/j.spc.2025.05.019

[13] Di Maria, A., Eyckmans, J., & Van Acker, K. (2018). Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. Waste Management, 75, 3–21. https://doi.org/10.1016/j.wasman.2018.01.028

[14] Dunant, C. F., Drewniok, M. P., Orr, J. J., & Allwood, J. M. (2021). Good early stage design decisions can halve embodied CO2 and lower structural frames' cost. Structures, 33, 343–354. https://doi.org/10.1016/j.istruc.2021.04.033

[15] European Committee for Standardization. (2011). Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method (European Standard EN 15978:2011).

[16] Fan, C., Pan, F., Ma, S., Ge, Y., & Zhu, Q. (2025). Hydrogen Direct Reduction: History and Pathways for Cost Reduction. cScience, 1(1), e70003. https://doi.org/10.1002/csc3.70003

[17] Feng, H., Zhao, J., Zhang, H., Zhu, S., Li, D., & Thurairajah, N. (2022). Uncertainties in whole-building life cycle assessment: A systematic review. Journal of Building Engineering, 50, 104191. https://doi.org/10.1016/j.jobe.2022.104191

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

[19] Grant, A., Ries, R., & Kibert, C. (2014). Life Cycle Assessment and Service Life Prediction: A Case Study of Building Envelope Materials. Journal of Industrial Ecology, 18(2), 187–200. https://doi.org/10.1111/jiec.12089

[20] Guignot, S., Touzé, S., Von Der Weid, F., Ménard, Y., & Villeneuve, J. (2015). Recycling Construction and Demolition Wastes as Building Materials: A Life Cycle Assessment. Journal of Industrial Ecology, 19(6), 1030–1043. https://doi.org/10.1111/jiec.12262

[21] International Code Council. (2024). International Building Code (2024 ed.). International Code Council.

[22] Joensuu, T., Leino, R., Heinonen, J., & Saari, A. (2022). Developing Buildings' Life Cycle Assessment in Circular Economy-Comparing methods for assessing carbon footprint of reusable components. Sustainable Cities and Society, 77, 103499. https://doi.org/10.1016/j.scs.2021.103499

[23] Johansson, N. C., Rootzén, J., & Escudero Carmona, S. (2026). Concrete change: Exploring future scenarios for the supply of supplementary cementitious materials in the EU. Developments in the Built Environment, 25, 100831. https://doi.org/10.1016/j.dibe.2025.100831

[24] Levasseur, A., Lesage, P., Margni, M., & Samson, R. (2013). Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment. Journal of Industrial Ecology, 17(1), 117–128. https://doi.org/10.1111/j.1530-9290.2012.00503.x

[25] Li, J., Lützkendorf, T., Balouktsi, M., Bi, X., Alaux, N., Potrč Obrecht, T., Passer, A., Han, C., & Yang, W. (2023). Identifying uncertainties in the whole life carbon assessment of buildings: Sources, types, and potential actions. Building and Environment, 244, 110779. https://doi.org/10.1016/j.buildenv.2023.110779

[26] Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. Waste Management, 30(11), 2255–2264. https://doi.org/10.1016/j.wasman.2010.04.012

[27] Markou, I., Sinnott, D., & Thomas, K. (2025). Current methodologies of creating material passports: A systematic literature review. Case Studies in Construction Materials, 22, e04267. https://doi.org/10.1016/j.cscm.2025.e04267

[28] Martirena, F. (2023). Practical experiences in the use of a combination of calcined clay and limestone as clinker substitute in cement. Ce/Papers, 6(6), 382–385. https://doi.org/10.1002/cepa.2777

[29] Minunno, R., O'Grady, T., Morrison, G. M., & Gruner, R. L. (2020). Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. Resources, Conservation and Recycling, 160, 104855. https://doi.org/10.1016/j.resconrec.2020.104855

[30] Morgan, R. L., Thayer, K. A., Bero, L., Bruce, N., Falck-Ytter, Y., Ghersi, D., Guyatt, G., Hooijmans, C., Langendam, M., Mandrioli, D., Mustafa, R. A., Rehfuess, E. A., Rooney, A. A., Shea, B., Silbergeld, E. K., Sutton, P., Wolfe, M. S., Woodruff, T. J., Verbeek, J. H., … Schünemann, H. J. (2016). GRADE: Assessing the quality of evidence in environmental and occupational health. Environment International, 92–93, 611–616. https://doi.org/10.1016/j.envint.2016.01.004

[31] Mouton, L., Allacker, K., & Röck, M. (2023). Bio-based building material solutions for environmental benefits over conventional construction products – Life cycle assessment of regenerative design strategies (1/2). Energy and Buildings, 282, 112767. https://doi.org/10.1016/j.enbuild.2022.112767

[32] Orozco, C., Babel, S., Tangtermsirikul, S., & Sugiyama, T. (2024). Comparison of environmental impacts of fly ash and slag as cement replacement materials for mass concrete and the impact of transportation. Sustainable Materials and Technologies, 39, e00796. https://doi.org/10.1016/j.susmat.2023.e00796

[33] Ossio, F., Salinas, C., & Hernández, H. (2023). Circular economy in the built environment: A systematic literature review and definition of the circular construction concept. Journal of Cleaner Production, 414, 137738. https://doi.org/10.1016/j.jclepro.2023.137738

[34] Peng, T., Ou, X., Yan, X., & Wang, G. (2019). Life-cycle analysis of energy consumption and GHG emissions of aluminium production in China. Energy Procedia, 158, 3937–3943. https://doi.org/10.1016/j.egypro.2019.01.849

[35] Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. Journal of Cleaner Production, 143, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

[36] Qin Li & Chunhong Zhang. (2017). A statistical study on the compressive strength of recycled aggregate concrete. Chemical Engineering Transactions, 59, 421–426. https://doi.org/10.3303/CET1759071

[37] Rakhshan, K., Morel, J.-C., Alaka, H., & Charef, R. (2020). Components reuse in the building sector – A systematic review. Waste Management & Research: The Journal for a Sustainable Circular Economy, 38(4), 347–370. https://doi.org/10.1177/0734242X20910463

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

[39] Rosner, F., Papadias, D., Brooks, K., Yoro, K., Ahluwalia, R., Autrey, T., & Breunig, H. (2023). Green steel: Design and cost analysis of hydrogen-based direct iron reduction. Energy & Environmental Science, 16(10),

4121–4134. https://doi.org/10.1039/D3EE01077E

[40] Royal Institution of Chartered Surveyors. (2023). Whole Life Carbon Assessment for the Built Environment [Professional Standard]. Royal Institution of Chartered Surveyors. RICS Whole Life Carbon Assessment

[41] Sabău, M., Bompa, D. V., & Silva, L. F. O. (2021). Comparative carbon emission assessments of recycled and natural aggregate concrete: Environmental influence of cement content. Geoscience Frontiers, 12(6), 101235. https://doi.org/10.1016/j.gsf.2021.101235

[42] Sandin, G., Peters, G. M., & Svanström, M. (2014). Life cycle assessment of construction materials: The influence of assumptions in end-of-life modelling. The International Journal of Life Cycle Assessment, 19(4), 723–731. https://doi.org/10.1007/s11367-013-0686-x

[43] Snellings, R., Suraneni, P., & Skibsted, J. (2023). Future and emerging supplementary cementitious materials. Cement and Concrete Research, 171, 107199. https://doi.org/10.1016/j.cemconres.2023.107199

[44] United Nations Environment Programme. (2026). Global Status Report for Buildings and Construction 2025–2026 [Global Status Report]. United Nations Environment Programme.

[45] Van Deventer, J. S. J., Brice, D. G., Bernal, S. A., & Provis, J. L. (2013). Development, Standardization, and Applications of Alkali-activated Concretes. In L. Struble & J. K. Hicks, Geopolymer Binder Systems (pp. 196–212). ASTM International100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959. https://doi.org/10.1520/STP156620120083

[46] Yang, L., Hu, H., Wang, M., Chen, F., Wang, S., Guo, Y., Yang, S., & Jiang, T. (2023). Comparative life cycle assessment and techno-economic analysis of electric arc furnace steelmaking processes integrated with solar energy system. Journal of Cleaner Production, 425, 138868. https://doi.org/10.1016/j.jclepro.2023.138868

[47] Zhang, C., Hu, M., Yang, X., Miranda-Xicotencatl, B., Sprecher, B., Di Maio, F., Zhong, X., & Tukker, A. (2020). Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands. Journal of Cleaner Production, 266, 121718. https://doi.org/10.1016/j.jclepro.2020.121718