Sarcouncil Journal of Applied Sciences

ISSN(Online): 2945-3437

Volume- 06| Issue- 07| 2026

Review Article **Received:** 01-06-2026 | **Accepted:** 25-06-2026 | **Published:** 09-07-2026

Decarbonizing U.S. Manufacturing and Construction Sectors: A Review of Low-Carbon Materials, EPDs, and Buy Clean Policies

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Abstract: With the decarbonization of U.S energy systems, embodied emissions from manufacturing and construction materials are gaining attention. This critical review examines recent work on low-carbon material pathways, the role of Environmental Product Declarations (EPDs) in quantifying embodied carbon, and the emerging Buy Clean procurement policies. This paper synthesizes advances in alternative cements (high-blast-furnace slag, calcined clay, novel binders) and recycled inputs (recycled concrete aggregate, fly ash, industrial by-products) as means to cut emissions. We also describe how Environmental Product Declarations (EPDs) (governed by product-category rules) provide cradle-to-gate carbon data for construction materials and discuss their rapid adoption as transparency tools. Key findings are that low-carbon material technologies consistently promise large emissions reductions but often face cost or performance constraints. EPDs improve product comparability but are hindered by inconsistent methods and data gaps. Similarly, Buy Clean policies create demand signals but are limited by material coverage and incomplete data. This study identifies four gaps: insufficient domestic life cycle inventory data, poor integration of material innovation and procurement practices, immature circularity pathways, and a lack of harmonized benchmarks for embodied carbon.

Keywords: Decarbonization; Low-carbon materials; Embodied carbon; Environmental product declaration.

INTRODUCTION

Globally, the building and construction sector remains one of the major contributors to greenhouse gas emissions (21%) and is responsible for around 31% of energy-related carbon releases (IPCC, 2023). A substantial share of the load comes from the manufacture of construction materials such as cement, steel, aluminum, and glass, which drive emissions before a building becomes operational. As key contributors, cement and steel production account for 7% to 8% of the global CO_2 emissions, indicating heavy dependence on carbon-intensive materials (Tautorat *et al*., 2023). Over the period 1990-2019, global cement production grew by 4.9%, and steel production grew by 4.1% yearly, thereby increasing CO_2 emissions from buildings by 50% (Tautorat *et al*., 2023; IPCC, 2023). In the U.S., this issue has become increasingly important because emissions linked to the industrial sector represent a major portion of the national carbon profile. In 2022, the industrial sector produced about 30% of the total U.S. greenhouse gas (GHG), while residential and commercial operations contributed 31% (US EPA, 2025). The construction of buildings spans both sectors because it depends on the energy used in buildings (heating, cooling) and the embodied energy of materials (cement, steel, glass, etc.). For many years, decarbonization efforts focused on reducing heating, cooling, and electricity demand, but as buildings become more efficient, the embodied carbon of materials has become a critical frontier.

Despite the significance of these materials, many embodied emissions have been invisible to policy, creating a growing gap. Currently, construction materials industries are facing pressure to innovate due to demand for low-carbon options and green building programs (Leadership in Energy and Environmental Design (LEED), Living Building Challenge). There is a growing preference for products with Environmental Product Declarations (EPDs), and public agencies are incorporating embodied carbon into sustainability targets. In sum, these decarbonization options offer potential to reduce emissions from the manufacturing and construction sector: (a) material innovations (low-carbon cement, recycled steel, bio-based materials) as technical solutions, (b) EPDs as measurement tools, and (c) procurement policies like Buy Clean as market drivers. Together, these connected strategies target embodied carbon rather than just energy use in buildings.

Carbon Intensity of U.S. Manufacturing and Construction Systems

The manufacturing of construction materials is highly carbon intensive. The production of cement clinker requires heating limestone to 1450°C (releasing tons of CO_2 from calcination), and steelmaking traditionally uses blast furnaces at even higher temperatures (>1500°C) fueled by

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DOI- https://doi.org/10.5281/zenodo.21284496

coal, which are fossil-based raw materials. Considering the usage of the materials, in 2018, U.S. public projects used roughly half of all domestic cement and almost 18% of steel, generating tens of millions of tons of CO_2. In that year, 46% of U.S. cement went into public construction, generating 36 Mt CO_2 emissions, and 18% of U.S. steel led to 21 Mt CO_2 emissions (Hasanbeigi *et al*., 2021). Across the world, trade in concrete, steel, and other building materials produces about one-third of total emissions, with material manufacturing stages (extraction, processing) contributing the largest, yet these impacts are not fully captured (Fritzeen *et al*., 2025).

Why Material Decarbonization Now Matters in Engineering Practice

Many low-carbon materials are moving from the lab into real-world practice. The demand for “green concrete,” recycled steel, and bio-based composites is rising as developers seek certifications and comply with mandates. Procurement frameworks are incentivizing this shift through green building standards (LEED, Living Building Challenge) awarding points for EPD-qualified materials, and major clients now require embodied-carbon reporting (Hasanbeigi *et al*., 2021). Sustainability targets, corporate and governmental, increasingly include value-chain emissions. Furthermore, the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA) allocated billions for clean building and transportation materials, contingent on the procurement of low-carbon products (Rajagopalan & Landrigan, 2023). These policies create immediate economic pressure. In practice, manufacturers of cement, steel, glass, etc., are beginning to adapt; some cement plants add slag or calcined clay to reduce clinker, steel producers expand electric-arc furnace (EAF) capacity (which can use renewable electricity), and glass makers test oxy-fuel burners or external heat recovery (Tautorat *et al*., 2023). At the same time, clients are specifying higher-performance insulations (vacuum panels, natural fibers) and engineered timber, where appropriate, to cut embodied carbon. Overall, the interplay of demand-pull (procurement) and supply-push (materials R&D) makes this an urgent time for focusing on materials as a decarbonization vector.

Positioning Low-Carbon Materials, EPDs, and Buy Clean as Linked Mechanisms

Low-carbon materials, EPDs, and Buy Clean policies form a connected triad. Technical interventions of materials such as supplementary cementitious materials (fly ash, slag, limestone) or recycled aggregates directly reduce emissions per unit of product (Marandi & Shirzad, 2025). EPDs transparently report a product’s life-cycle impacts, enabling comparisons and setting baselines based on life cycle assessments (LCA) (Tautorat *et al*., 2023; Gate & Anyomi, 2026). Buy Clean policy tool leverages procurement to require the use of materials with low declared emissions (Rajagopalan & Landrigan, 2023). In real-world practice, a project might specify a maximum embodied carbon per cubic yard of concrete or per ton of steel, with compliance verified by third-party EPDs. This strategy creates incentives as material producers have market reasons to adopt low-carbon processes, engineers and owners get credible data to choose products, and policymakers see procurement lead to actual emissions reductions. Across both infrastructure and buildings, integrating these elements is essential to achieving large-scale decarbonization beyond what energy efficiency alone can deliver.

METHODOLOGY

This review follows a structured critical review rather than a formal systematic meta-analysis. The strategy used was a combination of database searching and expert knowledge. For academic literature, keywords and combinations such as “low-carbon construction materials”, “embodied carbon building products”, “environmental product declaration construction”, “Buy Clean policy US”, and “construction decarbonization” were searched on Scopus, Web of Science, and Google Scholar. Priority was given to peer-reviewed studies (journal articles, conference proceedings, book chapters) from 2020 to present but also included reports for policy context.

Inclusion and Exclusion Criteria

We limited references to 2020-2025 to reflect the latest progress. Works were included if they offered empirical data or authoritative analysis on decarbonization of construction/manufacturing materials, the use of EPDs in these sectors, or the design/impact of procurement policies. Preference was given to peer-reviewed articles; however, conference papers or theses were included only if no peer-reviewed version was available and they contained unique evidence. Review articles and meta-analyses were particularly valuable for synthesis. We emphasized U.S.-focused studies or data, including U.S. market surveys of EPDs, domestic LCA comparisons, but also drew on global analyses where relevant context was lacking domestically.

Approach to Critical Comparison

In contrast to a systematic meta-review, a critical narrative comparison was performed across the literature summarized in Table 1. Studies within each theme were compared according to scope boundaries, functional units, and key assumptions that influence reported decarbonization outcomes. This approach allowed evidence from experimental material studies, EPD analyses, and procurement policy evaluations to be interpreted within a common comparative framework rather than treated as individual findings.

Table 1. Summary of reviewed literature by thematic focus, study type, and main contribution

Theme	Representative literature focus	Study type	Main contribution to current knowledge
Cement and concrete alternatives	Supplementary cementitious materials, clinker substitution, calcined clay binders	Experimental studies, comparative life-cycle assessments	Demonstrates that clinker reduction remains the most immediate pathway for lowering concrete embodied carbon
Recycled and secondary material inputs	Recycled aggregates, industrial by-products, waste-derived fillers	Laboratory studies, field validation, material performance assessments	Shows that secondary inputs can reduce virgin material demand and embodied emissions, although durability and quality control remain major adoption constraints
Steel and advanced industrial materials	Electric arc furnace steel, recycled steel systems, low-carbon glass and insulation	Sectoral LCA studies, industrial process assessments	Identifies process electrification and recycled feedstocks as major decarbonization routes outside cement-based materials
Environmental Product Declaration frameworks	Product category rules, declared unit consistency, database selection	Review studies, methodological comparisons, database analyses	Reveals substantial inconsistency across EPD datasets, especially where functional units and background inventories differ across manufacturers
Embodied carbon benchmarking	Regional carbon intensity benchmarking across U.S. materials	Large EPD dataset analysis, comparative carbon modeling	Confirms that carbon intensity varies significantly by production geography and supply-chain characteristics
Buy Clean procurement policy	Federal and state procurement frameworks using embodied carbon thresholds	Policy review, implementation analysis	Shows that procurement policy increasingly uses EPDs to shift market demand toward lower-carbon products
Procurement outcomes and market adaptation	Manufacturer responses to public low-carbon procurement requirements	Policy evaluation, industrial response analysis	Indicates that reporting requirements are expanding faster than verified low-carbon supply availability

(Marandi & Shirzad, 2025; Jamil *et al.*, 2025; Zhang *et al.*, 2025; Algers *et al.*, 2025; Ramesh & Lee, 2025; Hasanbeigi *et al.*, 2021;)

Low-Carbon Materials as the Technical Foundation of Decarbonization

This section reviews major pathways for low-carbon construction materials, which form the technical basis for reducing embodied emissions. They are grouped by material type and approach.

Cement and Concrete Alternatives

Cement is by far the largest carbon emitter in construction, so decarbonizing it remains a top priority. Supplementary cementitious materials (SCMs) like fly ash, slag, and calcined clay (metakaolin) can replace a portion of Portland cement clinker, lowering CO_2 per ton of cement. Studies have demonstrated that partial replacement of clinker with calcined clay (LC3 cement) can lower clinker content by up to 50%, roughly a 40% reduction in CO_2 and cost (Marandi & Shirzad, 2025). Other advanced binders include carbonate-based cement (calcium sulfoaluminate) and alkali-activated materials (geopolymers). The review by Marandi & Shirzad (2025) also highlights many promising formulations: calcium-based alternative cements capture CO_2 during curing, activated glassy cements use recycled glass to eliminate virgin raw inputs, and magnesium-based cements (magnesium oxychloride) avoid limestone decarbonation. Some binders use CO_2 directly in the form of carbon-cured cements to sequester emissions.

Importantly, these low-carbon cements must meet performance standards. Recent literature reports that high-volume fly-ash or slag concretes can achieve similar long-term strength as normal concrete, and some new binders perform well in durability tests (Akbulut *et al*., 2025; Marandi & Shirzad, 2025). However, certain constraints remain because SCM availability depends on industrial by-product supply, and some novel cements are currently costly or require new kiln technology. Overall, the consensus is that cement blends can reduce emissions by almost 30-60% compared to ordinary Portland cement, depending on formulation.

Recycled and Secondary Material Inputs

Another pathway is to substitute virgin materials with recycled or waste-derived inputs. For concrete, this means using recycled aggregate from construction and demolition (C&D) debris. A recent review indicated that Recycled Aggregate Concrete (RAC) can markedly cut embodied emissions. The LCAs show 10-30% lower GHG compared to conventional concrete because it avoids quarrying new aggregate (Akbulut *et al*., 2025). Similarly, industrial byproducts like slag (ground granulated blast furnace slag) and rice-husk ash serve as both SCMs and recycled inputs. Urban slags and wastes can replace part of raw materials in brick, insulation, and even asphalt mixtures (Oyejobi *et al*., 2024).

However, recycled inputs also result in trade-offs. Recycled concrete aggregate often contains old mortar, making it more porous and sometimes weaker than natural gravel. Studies highlight durability challenges as RAC may have lower compressive strength and higher water absorption (Jamil *et al*., 2025; Zhang *et al*., 2025). To compensate, engineers use pre-treatment (additional washing or crushing) and strengthen mixes with fibers or SCMs (Jamil *et al*., 2025). Despite such limits, the environmental payoff demonstrates that life-cycle analyses consistently show RAC and other waste-based materials slash embodied energy and carbon. Circular economy principles are motivating this trend by converting waste into recycled aggregate to prevent landfill and conserve virgin resources (Oyejobi *et al*., 2024). As one review notes, “RAC utilizes aggregates from construction and demolition (C&D) waste, contributing to resource conservation, landfill reduction, and carbon footprint mitigation.” (Akbulut *et al*., 2025)

Glass, Insulation, Steel, and Advanced Material Systems

Decarbonization extends beyond concrete. Glass production is extremely energy-intensive (melting sand at nearly 1500°C). A systematic review (Furszyfer Del Rio *et al*., 2022) finds that container and flat glass manufacturing emit on the order of 60 Mt CO_2 globally each year. Advanced options in this industry include electric melting, oxy-combustion, and heat recovery. Additionally, cutting-edge research is exploring glass formulations with alternative fluxes or more recycled cullet to lower the melting energy (Furszyfer Del Rio *et al*., 2022).

Insulation materials such as mineral wool and foam also have embodied carbon, though generally less than concrete or steel. Yet, interest is rising in low-carbon insulations (wood-fiber panels, recycled denim, aerogels). Each has trade-offs, including the fact that bio-based insulations may be more moisture-sensitive or require greater thickness for equivalent R-value. Research suggests that optimizing insulation requires balancing operational energy savings with embodied emissions, thus a full LCA approach (Abdelsalam *et al*., 2024).

For steel, a recent article by Algers *et al*., (2025) emphasizes that decarbonizing steel is increasingly essential as the sector accounts for 7% of global emissions. The primary strategies include maximizing scrap-based EAF steel, which is powered by renewables, and shifting ironmaking from blast furnaces to hydrogen-based direct reduction (DRI). Studies agree that if green hydrogen from electrolysis and renewable electricity are used, steel CO_2 emissions can fall by almost 90% in new plants (Algers *et al*., 2025; Chang *et al*., 2023). U.S. steelmakers have begun investing in EAFs and pilot hydrogen DRI (H-DR) facilities.

The use of advanced materials like engineered timber (mass timber) is a promising niche as it stores carbon and can replace steel or concrete in mid-rise buildings. For instance, cross-laminated timber (CLT) can significantly reduce embodied carbon in a building (Schenk & Amiri, 2022). However, sustainable forestry constraints and life-cycle studies on forest carbon must accompany any timber expansion. Other innovations include self-healing concrete and 3D-printed structures with optimized geometry.

Performance Trade-offs and Adoption Constraints

Most low-carbon materials involve trade-offs, making durability and lifecycle performance key concerns. Some SCM-blended cements have slower early strength development, or recycled concrete may be more prone to cracking if not carefully engineered (Akbulut *et al*., 2025). Cost poses another challenge to the adoption of the materials alternative. While materials like fly ash, an industrial by-product are often cheaper, emerging binders such as magnesium cements and bio-concretes can be costly due to limited production scale (Marandi & Shirzad, 2025). Supply chain limitations also matter. High-grade SCMs (fly ash, slag) are geographically restricted to regions with coal or steel industries. If demand rises, supply could tighten or costs could increase. Similarly, hydrogen-based steel requires new and high-cost infrastructure and typically varies based on each country's strategies and capacity (Bararzadeh Ledari *et al*., 2023).

In practice, U.S. adoption varies by sector and region. States with robust coal or steel industries may more readily supply SCMs and EAF steel (Indiana slag, U.S. scrap steel). Coastal regions lacking these may rely on imported alternatives or focus on timber. A comparative view (Table 2) would show:

Table 2: Comparative performance of major low-carbon material pathways in U.S construction and manufacturing

Material pathway	Typical embodied carbon reduction potential	Main technical limitation	Current U.S. adoption status
Concrete with SCMs (slag, fly ash, calcined clay)	20-50% depending on clinker replacement ratio	Declining fly ash supply, slower strength gain	Widely adopted in concrete specifications, but regionally uneven
Blended clays (L3)	25-45%	Cost-effective where clays exist	Emerging in pilot infrastructure projects
Recycled aggregate concrete	10-30%	Reduced strength/durability	Moderate adoption in urban areas with high C&D waste
Electric arc furnace (EAF) steel	40-70% relative to blast furnace routes	Scrap quality dependence and electricity source	Strong U.S. presence because of scrap-based production
Hydrogen direct-reduced steel	Up to 90% under renewable hydrogen scenarios	Very high infrastructure cost and hydrogen availability	Early pilot stage, limited commercial penetration
Glass and insulation systems	10-30%	High energy process; new tech (like vacuum insulation)	Moderate industrial uptake, emerging niche market
Engineered timber systems	20-60% at structural system level	Code limitations, supply scalability	Growing but concentrated in selected building types

(Akbulut *et al*., 2025; Marandi & Shirzad, 2025; Algers *et al*., 2025; Furszyfer Del Rio *et al*., 2022; Schenk & Amiri, 2022)

In summary, the materials reviewed have significant potential to reduce carbon emissions. The literature shows that concrete-related interventions remain the most scalable because they operate within existing specifications. By contrast, decarbonizing steel and glass depend heavily on industrial processes that are often constrained by cost, regulation, and supply. Overcoming these limits will require integrated strategies such as scaling waste processing and incentivizing new material standards alongside continued research.

Publisher: SARC Publisher

Environmental Product Declarations as Carbon Transparency Tools

Environmental Product Declarations (EPDs) translate material performance into standardized data. They are third-party verified reports of a product's life-cycle environmental impacts, typically following ISO Type III standards and Product Category Rules (PCRs) specific to each material. EPDs commonly use a cradle-to-gate boundary (raw material extraction through factory gate), although some extend to cradle-to-gate with options or cradle-to-grave (Ramesh & Lee, 2025). By enforcing uniform categories (via PCRs), EPDs allow specifiers to compare products on a common basis. They are not performance standards themselves but disclosure documents.

What EPDs Measure and Why They Matter

An EPD reports on the key environmental impacts of making a product. The most cited metric is Global Warming Potential (GWP, kg CO_2e), which covers CO_2, CH_4, and N_2O emissions in production. It can also include energy use, water, acidification, etc. Crucially, EPDs are based on life-cycle assessment (LCA). They specify a declared unit (e.g., per ton of steel, per cubic meter of concrete) and outline scope (often cradle-to-gate). Each EPD follows a PCR (Product Category Rule) that defines the module boundaries, system assumptions (allocation, cut-off rules), and required indicators (Ramesh & Lee, 2025). For example, there are PCRs for "Concrete Products" or "Steel Rebar" that ensure different manufacturers use the same methodology.

EPDs matter because they create a common language for embodied carbon. Without EPDs, specifiers have no reliable way to quantify the carbon footprint of different products. In practice, EPDs are being adopted by industry across building materials. The U.S. Environmental Protection Agency notes that manufacturers of construction materials are seeing a "growing trend of requests for EPDs" from customers (US EPA, 2024). This is due to awareness of embodied carbon and green procurement policies requiring disclosure. EPDs allow engineers to quantify the carbon impacts of alternative materials in design choices (e.g., choosing recycled steel with an EPD vs conventional steel).

EPD Development in U.S. Manufacturing Sectors

EPD programs (The International EPD System, UL Environment, product programs for cement, steel, etc.) are seeing rapid uptake in the construction sector. By late 2025, the International EPD System reported over 18,000 valid EPDs worldwide, of which an overwhelming majority (86.4%) were for construction products. In North America, growth has been strong but is still modest compared to Europe. In 2025, North America registered about 558 EPDs (5.9% of new EPDs) (Alessia *et al*., 2026). Within the U.S., industries leading EPD publication include concrete, steel, glass, insulation, and wood products (often via industry associations or large manufacturers). Federal agencies also encourage EPD development. The 2024 EPA guide notes that GSA now requires contractors to provide EPDs for construction materials to quantify federal projects' embodied carbon (US EPA, 2024). Similarly, the U.S. EPA's "Label Program for Low Embodied Carbon Construction Materials" mandates EPDs for participation. State 'Buy Clean' laws often specify that only materials with Type III EPDs will be eligible for low-carbon procurement programs. These trends suggest EPD availability is quickly increasing, though gaps remain (for example, not all manufacturers have published EPDs yet, especially smaller firms and new materials).

Methodological Inconsistencies Across EPDs

Despite the standard format, EPDs are not fully comparable out of the box. Different PCRs and practices lead to methodological variation. Some PCRs allow cut-offs for material inputs, while others allocate differently (mass vs. economic), and declared units can vary (per kg vs. per m^2 vs. per assembly). Moreover, databases used to supply background data (electricity mixes, transport distances) differ across programs and countries. A recent review of EPD quality found "very few studies have assessed the challenges in developing and utilizing EPDs," and highlighted that most databases lacked indicators of data reliability (Olanrewaju *et al*., 2025). For example, one material's EPD might use U.S.-specific inventory data while another uses a global database, leading to potential bias. There are also differences in boundary, as U.S. EPD PCRs often use cradle-to-gate, but some European declarations include transport to site (cradle-to-site) or end-of-life (Ramesh & Lee, 2025).

These inconsistencies mean that two EPDs for the same product may yield different numbers even if the actual manufacturing processes are similar. The policy implication is that thresholds or comparisons must be carefully specified (Ramesh & Lee, 2025). In fact, Buy Clean California found early on that many submitted EPDs were not consistent enough to be directly compared, leading agencies to develop standardized industry-average values or to simplify reporting criteria (Hasanbeigi *et al.*, 2021). Thus, while EPDs improve transparency by publishing numbers, EPD reliability and consistency tend to be better in well-established sectors where PCRs and industry data are mature (Olanrewaju *et al.*, 2025). Users should be aware of these differences when applying EPD data and should ideally be interpreted with oversight by LCA experts or regulators.

BUY CLEAN POLICIES AND PROCUREMENT AS DRIVERS OF INDUSTRIAL CHANGE

Over the past few years, public procurement has been explicitly leveraged to reduce embodied carbon. Buy Clean refers to policies that require or encourage government projects to purchase materials with lower declared carbon footprints.

How Buy Clean Uses EPDs in Procurement Decisions

Buy Clean policies operationalize embodied carbon targets through procurement criteria. Commonly, a qualifying supplier must submit an EPD for the product. Some policies then score bids based on the declared GWP. The law of California sets a maximum allowable GWP per unit of material (initially high to start, with plans to reduce annually), and only products below that threshold can be used (Hasanbeigi *et al.*, 2021). Other states use more qualitative approaches by requiring agencies to “accept and consider” EPD data and explicitly list low-carbon products as preferred. The GSA IRA pilot went further by setting absolute limits. Reports indicate that GSA adopted EPA’s Interim Determination limits, capping CO_2e for each material; asphalt, concrete, glass, and steel must each meet a GWP ceiling (US EPA, 2024).

In practice, these programs share several common features that shape how embodied carbon is evaluated in procurement decisions. Most policies establish quantitative benchmarks or scoring systems, often expressed as kg CO_2e per unit of material, against which suppliers must demonstrate compliance using EPD data. The scope of coverage typically prioritizes the most carbon-intensive materials, including steel, concrete, asphalt, and glass, although some jurisdictions are beginning to consider broader material categories. There is also a strong preference for domestically produced materials, reflecting both economic objectives and the relative ease of verification within U.S. regulatory frameworks. To ensure credibility, procurement requirements generally mandate third-party verified Type III EPDs developed in accordance with established standards such as ISO 14025 and issued by recognized program operators. Importantly, most policies adopt a phased approach to stringency, introducing initial thresholds that are deliberately achievable while signaling progressively stricter carbon limits over time. Collectively, these shared features reinforce the central role of EPDs in procurement by standardizing how carbon performance is measured, verified, and compared across competing material suppliers.

Policy Strengths and Implementation Gaps

Despite its promise, Buy Clean policy frameworks are not without important limitations that complicate their effectiveness in practice. While these policies are intended to generate market demand for low-carbon materials through EPD requirements and carbon thresholds, their actual impact on emissions reduction remains contingent on scale and adoption, as even optimistic estimates rely on partial procurement coverage (Hasanbeigi *et al.*, 2021). Similarly, although the policies aim to promote transparency and stimulate innovation in cleaner production, this progress is uneven and often constrained by the varying capacity of manufacturers to respond effectively (US EPA, 2024). The anticipated co-benefits, such as job creation linked to low-carbon transitions, are also not guaranteed and depend heavily on how labor provisions are implemented alongside environmental criteria.

More fundamentally, the scope of Buy Clean initiatives remains limited, as current policies focus primarily on a narrow group of high-emission materials like concrete and steel, leaving many other relevant sectors insufficiently addressed. Market readiness presents another challenge, particularly for smaller manufacturers that may lack the financial and technical resources to produce verified EPDs, raising concerns about exclusion and competitiveness. In addition, persistent inconsistencies in EPD data reduce comparability across products, making it difficult for policymakers to apply thresholds reliably and often forcing reliance on simplified benchmarks or industry averages (Olanrewaju *et al.*, 2025). As a result, although Buy Clean has succeeded in advancing transparency, its ability to deliver consistent and measurable carbon reductions is still evolving and depends on more comprehensive coverage, improved data quality, and broader industry participation.

Industrial Response to Procurement Pressure

Evidence that manufacturers are beginning to respond is visible in sectors where Buy Clean took effect early. California steel producers have started publishing EPDs and exploring efficiency improvements. Major U.S. steel mills are investing in upgrades to reduce furnace coke use, and concrete companies are experimenting with low-carbon cement blends to qualify for public contracts. At the same time, purchasers (architects, contractors) are retooling procurement processes to include embodied carbon checks alongside cost and quality (Hasanbeigi *et al*., 2021).

Reports suggest EPD publication rates saw nearly 9,400 new declarations in 2025, driven largely by construction materials, and some supply chains have begun "self-regulating" (Alessia *et al*., 2026). Large corporations and developers voluntarily require EPDs of their suppliers even without regulation, partly to prepare for upcoming Buy Clean rules. Nonetheless, much of the response is still emergent. The cleanest versions of materials (e.g., hydrogen-steel, carbonated cement) are not yet widespread in U.S. commerce. In that sense, the industrial shift is nascent; the anticipation of procurement requirements is spurring change, but deeper transformation will take years as technologies scale up.

WHERE LITERATURE CONVERGES AND WHERE IT CONFLICTS

This section synthesizes the overall findings, highlighting consensus conclusions and areas of debate or uncertainty in the reviewed literature.

Agreement Across Studies

Materials Effectiveness

Nearly all studies agree that advanced low-carbon materials lead to significant embodied carbon reductions. For instance, analyses of SCMs, recycled aggregates, or timber consistently report lower life cycle GHG than conventional counterparts (Akbulut *et al*., 2025; Marandi & Shirzad, 2025). Similarly, life-cycle studies of steel confirm that switching to EAF or hydrogen-based processes can cut >50% of steel's CO_2 (Algers *et al*., 2025). In practice, case studies of bridges or buildings using low-carbon cement or rebar have demonstrated actual project-level savings.

EPDs Improve Transparency

There is widespread agreement that EPDs raise awareness. Reviews note that EPD publication itself is a positive step, even if imperfect: it forces companies to measure their footprint and makes that information accessible (Alessia *et al*., 2026; US EPA, 2024). Stakeholders (engineers, policymakers) generally find EPDs helpful to compare products on a common metric, especially once PCRs are harmonized.

Policy Potential

Analyses of Buy Clean (ACEEE, Carbon Leadership Forum reports) converge on the idea that procurement can multiply decarbonization impact by leveraging government spending (Hasanbeigi *et al*., 2021). There is consensus that the U.S. has ample opportunities because U.S. infrastructure spending is large (e.g., $110B in 2018 federal capital), so even partial low-carbon targets could reduce emissions by millions of tons per year (Hasanbeigi *et al*., 2021). The experts concur that without such policies, embodied carbon would remain an externality; with them, the market signals align with climate goals.

Persistent Methodological Disagreements

Despite agreements on goals, disagreements persist around methodological choices. Within LCA studies, there is no single standard. Assumptions about system boundaries (cradle-to-gate vs cradle-to-grave), functional units, and environmental impact factors often differ. For instance, some concrete LCA studies use a functional unit of 1 m^3 of concrete at 28-day strength, while others use 1 m^2 of concrete slab (including reinforcing steel). The results can vary accordingly (Ramesh & Lee, 2025). In steel studies, whether recycling of end-of-life scrap is credited and how alloying elements are accounted for can change the net footprint. Some research argues for stricter boundaries (including use-phase or demolition), while others maintain that the cradle-to-gate approach is sufficient for material comparisons (Tautorat *et al*., 2023).

Similarly, there are debates over policy design as economists may argue for carbon pricing or broader industrial decarbonization policies, while embodied-carbon proponents focus on procurement. Among policy analyses, some studies emphasize quantitative targets (e.g., kg CO_2e limits), while others emphasize qualitative reporting and market creation. There is also tension between making policies strict (high ambition) versus flexible (industry buy-in) (Feickert & Mueller, 2024; Hasanbeigi *et al*., 2021).

The literature diverges on technical details, including methodology and metrics, and policy mechanics (threshold levels, scope of materials). These disagreements usually reflect different study contexts or objectives. For example, studies aiming for top-down carbon budgets may criticize LCA differences more heavily, whereas on-the-ground practitioners focus on practical comparability. A critical reader must note these variations on how two LCA studies on "low-carbon concrete" might report different % reductions simply because they define system boundaries differently.

Emerging Research Gaps in Construction Decarbonization

Despite growing literature, several important gaps remain unaddressed. There is a lack of comprehensive LCA datasets for U.S. contexts. Many life-cycle studies still use European or generic data for things like electricity mixes or material transport. This limits accuracy. Comparative studies that explicitly analyze U.S.-made low-carbon products versus imports are scarce. The field needs more domestic, facility-level data on emissions for U.S. cement plants, steel mills, etc., to ground policies in reality.

Also, research tends to treat material science and policy separately. Few studies model how new materials and EPD-driven procurement would co-evolve. For example, what is the feedback loop from a Buy Clean law to incentivize R&D in novel binders? Similarly, we lack studies integrating LCA outcomes directly with procurement design (e.g., using LCA uncertainty to set robust policy thresholds). Bridging this gap would require interdisciplinary work between engineers, economists, and policy analysts.

CONCLUSION

The reviewed literature provides a picture of a construction and manufacturing sector on the verge of transformation. Technical advances in low-carbon materials such as green cements, recycled aggregates, and decarbonized steel have been validated by multiple life-cycle studies as effective at reducing embodied emissions. Environmental Product Declarations have emerged as the neutral language for reporting and comparing those emissions, though the community is still grappling with standardization issues. Simultaneously, procurement policies labeled as "Buy Clean" are moving these tools into the marketplace, creating demand for lower-carbon products and requiring that data.

Ultimately, achieving deep decarbonization of construction and manufacturing will require not just incremental improvements but a systemic shift: from the way we design materials, to how we measure impacts, to how we procure products. This review has laid out the current state of knowledge, and the collective effort of engineers, scientists, and policymakers can accelerate these innovations into practice.

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Source of support: Nil; **Conflict of interest:** Nil.

Cite this article as:

Dauda, M., Gate, C. & Anyomi, L. E. "Decarbonizing U.S. Manufacturing and Construction Sectors: A Review of Low-Carbon Materials, EPDs, and Buy Clean Policies." *Sarcouncil Journal of Applied Sciences* 6.7 (2026): pp 1-10.