A Proposed Evaluation Framework for New and Emerging Low Embodied-Carbon Concrete Technologies

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ABSTRACT

New opportunities for carbon reductions in buildings create a strong need for a common framework and method for those who design, build and influence construction to evaluate lifecycle carbon reductions from design decisions and technology choices. These opportunities include a wide range of low-embodied-carbon concrete materials being rapidly developed and introduced to the market. How to evaluate these newer materials and technologies has become critical for both public- and private-sector actors seeking to decarbonize building constructions by leveraging the Infrastructure Investment and Jobs Act (IIJA) and Inflation Reduction Act (IRA) funds. We propose an evaluation framework to assess the lifecycle carbon reductions from adoption of these technologies, including a subset of key "must have" (1) technical criteria (embodied carbon level, technology development stage); (2) market criteria (market size, scalability); and (3) financial criteria (cost of technology implementation compared to business-as-usual) from a range of options. We discuss how to use the framework and illustrate it using a "heatmap," rating score and short case study of a promising technology. We also propose a plan to implement this framework that includes (1) standardized measurement and validation methods for verifying emission reductions from these technologies, and (2) avenues to implement real world demonstrations. We conclude with recommendations for next steps on framework refinement and commercialization strategy development.

Introduction

Over the past 5-10 years there has been an explosion of new and emerging low-embodied-carbon building material (e.g., cement and concrete) technologies that have been funded, developed, and introduced in the building construction market. Embodied carbon refers to carbon emissions associated with the manufacture of building products and construction, from raw material extraction to manufacturing, transportation, and installation, to product use stages, to end-of-life disposal or recycling. These technologies emerge from several sources including university research labs, national labs, startup companies, and manufacturing company research and development (R&D) departments. They utilize a wide range of strategies to reduce the embodied carbon content of the materials and products, which include using low carbon raw materials, low carbon process heat, electrochemical processing instead of thermal process heat, carbon-negative/carbon sequestering materials, and other approaches (DC2 2024). We describe these technologies as few among an abundance of new and established options for life cycle carbon reduction in new and renovated buildings.

Why Focus on Concrete Technologies?

Concrete by itself has relatively low embodied energy (1.2 MJ/kg) compared to structural steel (32 MJ/kg) and asphalt (50 MJ/kg) (Bastianoni et al 2006), with the majority of its emissions arising from the 15% of cement used as the binding agent in a concrete mix. It is the large quantity of concrete used in construction that increases overall emissions, resulting in concrete accounting for 8% of global emissions. Thus, carbon reduction methods need to consider all lifecycle stages, contributing components, and the whole value chain; this combined approach has the potential to reduce concrete-related emissions by over 75% (Olsson et al 2023).

The main strategies to reduce embodied carbon in using concrete for buildings include the following: (1) Using concrete more efficiently in construction (e.g., by avoiding over design, large spans, tall buildings). The architect and engineering community and developers are the key stakeholders for this strategy. (2) Using cement more judiciously in concrete (using admixtures, aggregate grading to reduce cement use). Contractors are the key stakeholders to leverage this strategy. (3) Reducing manufacturing energy and emissions. Industrial manufacturers including climate technology startups are key stakeholders to use this strategy. Manufacturer strategies around energy and emissions have led to a wide variety of emerging low emissions technologies and products which may be further broken down into the following sub-categories:

Replacing clinker with supplementary cementitious materials (SCMs): Clinker and SCMs act as binders in cement. Most of the cement (and consequently concrete) emissions are produced in the clinker manufacturing process due to the burning of fossil fuels (for high kiln temperatures ~1450°C to form clinker following limestone calcination). For example, KLAW Industries produces a carbon-negative replacement for cement in concrete made from waste glass diverted from landfills thereby displacing clinker with a SCM like glass. (DOE 2023a).

Reducing manufacturing energy. For example, Sublime Systems uses an alternative process technology, an electrolyzer at ambient temperature with renewable energy and non-carbonate feedstock, reducing energy-based and calcination-based emissions for ready mix cement. Another company, Chement's electrochemical approach replaces the traditional fossil fuel-powered high temperature kiln with a metal vat powered by electricity at room temperature. This dramatically reduces energy demand and emissions. Additionally, since gaseous by-products are released in a highly concentrated stream, the reaction emissions can be captured at lower cost compared to traditional cement production. Heirloom produces ordinary portland cement and SCMs from carbon-free silicate rock.

Using alternate feedstocks. For example, Saferock uses mine tailings, aggregate and activators to make sustainable concrete instead of the traditional method of mixing carbon-intensive cement, aggregate and water.

Carbon Capture, Utilization and Storage (CCUS). For example, Heirloom uses carbon dioxide (CO_2) captured via Direct Air Capture (DAC) to permanently store it in concrete. CarbonCure Technologies injects captured carbon dioxide into ready mix concrete where it converts to a mineral, improving compressive strength, and gets permanently stored. Carbon Built uses a process to replace traditional cement with a low carbon, calcium-rich alternative binder that chemically reacts with captured CO_2, strengthening the concrete and permanently storing the CO_2. Additionally, there are other projects where CO_2 is captured as it is emitted, compressed to a liquid, then transported in pipelines to be permanently stored in deep underground saline aquifers.

The Need for a Framework to Evaluate Technologies

The uptake of these and other low carbon concrete building technologies has been slow due to several reasons including lack of understanding and measurement of their carbon reduction potential, lack of cost parity with traditional products, lack of distribution channels (e.g., through ready mix concrete companies), the absence of or inadequacy of product technical specifications, problems with understanding how they meet construction and building codes, and standards requirements, limited understanding of how to use them, questions about their longer-term durability and performance and their optimal use applications, and in some cases inability on the part of the marketplace and end users to adequately separate actual reductions from greenwashing (NETL 2023). In the absence of a good understanding of these new low embodied carbon concrete technologies, the default tends to revert to previously used, known options, especially in the context of tight construction deadlines and budgets.

Historic levels of funding from the Inflation Reduction Act (IRA) 2022 are being used by the federal government and states to push for lower carbon buildings while simultaneously the private sector is looking for opportunities to reduce emissions in its construction projects to meet their carbon reduction goals and targets. Thus, there is a strong need for the those who influence building design and use, i.e., architects, engineers, developers, owners, and procurers, to better understand the emissions reduction potential, what constitutes "lower carbon," and the use cases for these innovative technologies.

A group of some emerging concrete technology start-ups, The Decarbonized Cement & Concrete Alliance (DC2), who offer low embodied carbon concrete products leveraging a variety of emission reduction strategies, is advocating for policies that push the public sector, in particular to buy low carbon concrete products and materials for buildings and infrastructure projects providing further impetus to better understand what these technologies offer.

Currently, environmental product declarations (EPDs), a standardized document like a nutrition label is used to communicate product lifecycle environmental impacts in the form of the global warming potential (GWP) using data from a lifecycle assessment (LCA). LCA databases like OneClick and the Embodied Carbon in Construction Calculator (EC3) database managed by Building Transparency (and working with the Carbon Leadership Forum) include over 24,000 concrete EPDs for existing commercially available products manufactured in the USA and Canada.

Public sector procurement has also started to require EPDs under federal and state Buy Clean policies, incentivizing both manufacturers and contractors to produce and use clean, low carbon materials, respectively.

However, newer, more innovative low-embodied-carbon materials and emerging technologies lack EPDs due to EPD generation requirements for one full production year of data to establish their GWP, nor will the EPD be definitive for understanding the carbon intensities should multiple materials be used in various quantities. Additionally, there is no consistent framework to assess the wide range of innovative concrete technologies for the market and develop a way of comparing different technologies across a consistent set of parameters.

Most trade associations and standards organizations also do not want to be perceived as choosing between technologies or disrupting the use of traditional technologies currently dominating the market without commercially available viable alternatives.

Solution to the Problem

We propose a common platform in the form of an evaluation framework with specific criteria to assess low-embodied-carbon concrete technologies. This system includes (1) technical criteria (e.g., carbon reduction method, technology readiness level, manufacturing energy, performance—strength and durability); (2) market criteria (e.g., size, application type, value proposition, differentiation, scalability); and (3) financial criteria (e.g., cost of technology implementation compared to business-as-usual or BAU). We also recommend a plan to implement this framework including an initial prioritization scheme to identify the most promising technologies offering the greatest lifecycle carbon savings, examples of standardized measurement and validation methods for vetting these technologies, and the value of real-world demonstrations.

National labs, certification organizations, some standards setting entities and educational institutions offer valuable testing, validation tools and manufacturer programs that can be leveraged. Non-governmental organizations (NGOs) can play a key role in this process as a neutral entity by helping to develop an impartial evaluation framework for these technologies in conjunction with input from a key set of stakeholders.

Who Will Use the Framework Solution?

The primary audience for the proposed evaluation framework and criteria includes: (1) the architecture and engineering (A&E) communities who evaluate new and emerging technologies to better understand how to apply them in projects; (2) public and private procurement officials who need to evaluate which technologies meet their project needs and make selections on a consistent basis especially for infrastructure and other large projects; and (3) investors looking to invest in new and emerging building technology start-ups, to commercialize their products and understand their return on investment; and (4) Novel technology manufacturers may also use these evaluation criteria to understand marketplace needs and develop information to help end users choose the right product or technology for their needs.

Evaluation Framework Development

Our evaluation framework draws on the conceptual pathways and criteria from the technology readiness levels and adoption readiness level tools developed by the U.S. Department of Energy (DOE) and other agencies as well as the lifecycle assessment (LCA) framework and the whole building lifecycle assessment (WBLCA) approach.

Lifecycle Assessment Framework and Whole Building Approach

An LCA is a systematic assessment of the environmental impact of a product, material or process over the course of its entire life cycle in adherence with International Standards Organization Standards and Frameworks (ISO 2006). It evaluates carbon and other greenhouse gas emissions across four life stages: the product manufacturing process (Stage A1-A3) through the construction phase (Stage A4-A5) to the building use phase (Stage B), to deconstruction, disposal, end-of-life (Stage C) and finally to Beyond Life or Second Life which includes reuse and recycling (Stage D). Since data are rarely available across the entire lifecycle (stages A-D -- cradle to grave), the LCA typically focuses on the manufacturing contributions to embodied carbon (stage A -- cradle to gate). Figure 1 defines embodied carbon in a building lifecycle.

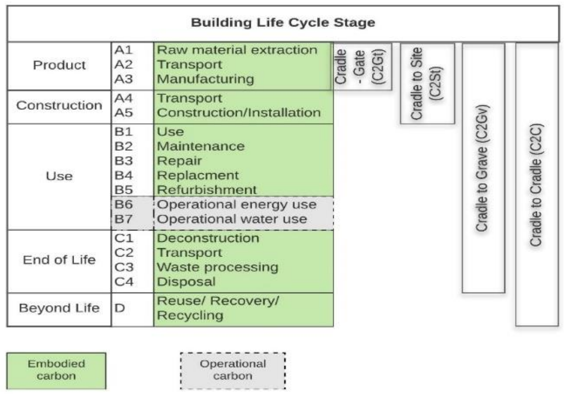

Figure 1. Building Lifecycle Embodied Carbon. *Source*: Esram & Hu 2021 (Adapted Pomponi & Moncaster 2016).

A more holistic approach should be applied to new, low-embodied-carbon materials to understand, measure, and validate lifecycle impacts of such materials within different contexts. WBLCA not only brings both embodied carbon and operational carbon into the evaluation but also illustrates the tradeoffs between the two. WBLCAs focus on the whole building system, in which designers analyze the impact of material reuse, systems design (mechanical, electrical, plumbing), potential for carbon sequestration (concrete absorbing CO_2 over its lifetime), operational vs. embodied carbon, or other comparative designs for sustainability and efficiency. Some WBLCAs can also compare new construction versus retrofit of a building to help designers understand which path offers the least impact and is more efficient (IMPEL 2024b).

Technology and Adoption Readiness Levels (TRLs/ARLs)

The **Technology Readiness Level (TRL) Framework** is used to assess the maturity of a new and evolving technology. Under this scheme a technology evolves through nine levels of maturity, starting with basic research (TRL 1-2) and proof of concept (TRL 3) progressing to development or system validation at lab scale (TRL 4-5) followed by demonstration in a pilot outside the lab (TRL 6) and demonstration at full scale (TRL 7), then culminating in deployment or commercialization in the marketplace (TRL 8-9). Examples of emerging technology start-ups include Sublime and KLAW (TRL 5-6), limestone calcined clays (TRL 7-8) and CarbonCure (TRL 9). To get to deployment, a technology must be completely de-risked, and each player in the value chain must have an economic value proposition to participate in the technology adoption process. Thus, evaluating an innovative technology solely based on its TRL is insufficient (DOE 2024b).

Therefore, to assess the adoption risks of a technology and translate it into a 'readiness for adoption by the market' score, DOE's Office of Technology Transitions (OTT) developed the **Adoption Readiness Level (ARL) Framework** to complement TRLs. The ARL scheme comprises four (4) core risk areas and 17 dimensions namely: (1) value proposition including delivered cost, functional performance, ease of use/complexity; (2) market acceptance, demand maturity/market openness, market size, downstream value chain; (3) resource maturity, considering. capital flow, project development, integration and management, infrastructure, manufacturing and supply chain, material sourcing and workforce; and (4) societal non-economic risks considering the regulatory and policy environment, permitting/siting, environmental and safety, and community perception (DOE 2024b).

The TRL and ARL assessment schemes can be used complementarily to better understand the readiness of an innovative technology as seen in Figure 2. As a technology moves from bottom to top and from left to right in the graph (based on technical, market and cost attributes), it is considered more ready for commercial deployment and use in the marketplace in real world projects and at scale.

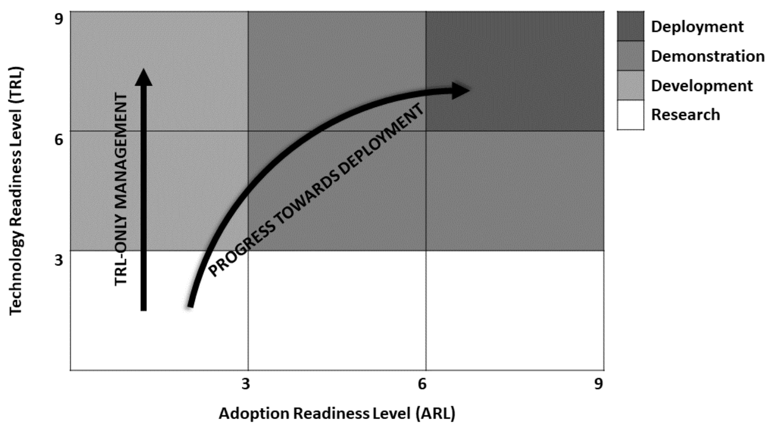

Figure 2. Combined TRL and ARL Assessment Matrix. *Source*: adapted from DOE 2024b.

Our Proposed Framework

Our framework identifies three main evaluation categories: technical, market and financial from the LCA and TRL/ARL schemes. Each category includes several criteria to evaluate different aspects of a new or emerging technology. Figure 3 relates the three sets of criteria and illustrates how a technology may reside in the intersections of these categories.

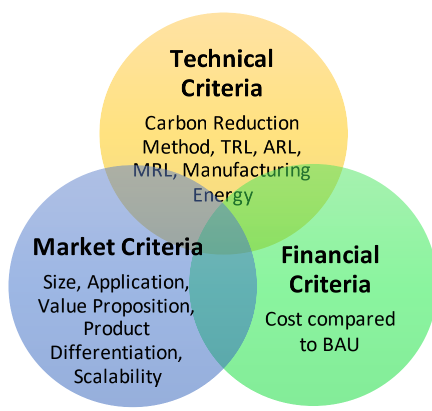

Figure 3. Framework Evaluation Criteria. *Source*: this paper.

For this paper within the suite of these available criteria we focus on a select list of key criteria under each assessment category that would serve as “threshold” or “must have” elements that need to be evaluated for most if not all emerging technologies. This is valuable because a particular technology may score well across a wider range of criteria but be missing a critical element without which it will fail in the marketplace. Secondary and tertiary evaluation criteria drawn from the source frameworks to assess other attributes based on priority would expand the framework. Next, we describe these “threshold” or “must have” evaluation criteria we selected for inclusion in the framework across essential technical, market and financial attributes.

Technical Criteria

T1 Carbon Reduction Potential (CRP). CRP is defined as the reduction in carbon emissions from the manufacturing process for a product and energy used in that process. This evaluation element encompasses the carbon reduction method, the manufacturing energy (thermal/electrical energy used in a process and lowered by use of renewables/clean energy) and to some extent the value proposition for an innovative technology. CRP would be measured as a percent reduction compared to the business-as-usual (BAU) scenario in CO_2-eq/tonne and reported using a scale ranging from 1 to 3 where 1 corresponds to low reductions (0 to 30%), 2 represents medium reductions (30-60%) and 3 represents high reductions (60-100%).

CRP would be estimated using an LCA (in the case of new/emerging technologies without an EPD) with commercially available LCA tools. One drawback is potential data gaps in the lifecycle inventories of these tools (Esram and Hu 2021). If a product-specific EPD exists, the reported global warming potential (GWP) in CO_2-eq/tonne of product serves as an estimate of the product CRP and could be verified in the validation stage. Some specific LCA options are described later in this paper under measurement and validation approaches. EPDs also report primary energy demand including renewable/non-renewable energy sources providing an estimate of manufacturing energy that is captured in the GWP.

T2 Technology Development Stage (TDS). TDS evaluates how close a product or technology is to commercialization and corresponds closely to the TRL schema. TDS would be measured and reported using a measurement scale ranging from 1 to 3 where 1 corresponds to early-stage technologies (TRLs 1 to 3), 2 represents mid-stage technologies at the pilot or demonstration stage (TRLs 4 to 6) and 3 represents technologies close to being commercial (TRLs 7 to 9). The TDS would be evaluated based on information from the company or independent assessments of the technology by experts and would need to meet the DOE TRL criteria.

Understanding the TRL within which an innovative technology falls is important in assessing if it is available for use in a commercial or real-world context and at scale for a project. In some instances, the technology may present excellent product technical specifications, cost and even some market attributes but may only be available in smaller quantities (especially in lower TRLs) for use in limited applications within a given project. Thus, the architect or designer would need to decide on how to use the innovative material in their design and if it still meets their cost-benefit requirements.

Market Criteria

M1 Market Size. At the most basic "threshold" or "must have" criterion level, market size refers to the potential demand for a product within the market based on product type or market share. In the case of concrete product type refers to the type of concrete. For example, this element would be evaluated and reported using a scale ranging from 1 to 3 where 1 corresponds to smaller markets such other and miscellaneous users, where 2 corresponds to the concrete products market (pre-cast, pre-stressed, reinforced concrete etc.), about 11% of the U.S. market – some of which like pre-cast offer advantages for testing emerging technologies, and 3 corresponds to the ready mix concrete which represents 70-75% of the U.S. market. Market size would be evaluated based on information from the company or a market segmentation analysis by an independent market research firm. Detailed segmentation analysis based on application type (infrastructure vs buildings including breakdown by building types for certain concrete performance requirements considering material re-use or over-design considerations) or even product differentiation (different products in different regions or geographic variability can open markets) allow nuanced assessments.

For example, a limestone calcined clay concrete product manufactured by a concrete company like Ash Grove CRH can be used in the ready mix format in the infrastructure market segment for a road paving application (this product is currently being piloted in Minnesota) (MnROAD 2023). Roughly 60% of highways in the U.S. are made of concrete (USGS 2006). The federal government alone spends $45 billion to purchase materials for publicly funded highways (CBO 2020). State and local government spending add to this. The size of this market demonstrates the potential for a large volume of material being required nationally. The market size indicates the demand or need for a product in the marketplace.

M2 Product Scalability. Product scalability refers to how close the technology is to producing real-world quantities (tonnage), and whether the innovative technology process can be scaled to produce the required volume needed by the market. If the technology cannot produce real-world quantities of material while retaining product technical and performance specifications, then its market acceptance and viability diminishes. The transition from lab bench scale to commercial production is critical in ensuring an innovative technology is market ready. This element would be evaluated and reported using a scale ranging from 1 to 3 where 1 corresponds to low scalability (currently zero to low tonnage production), 2 corresponds to medium scalability (tonnage for a few projects), and 3 to high scale (tonnage for numerous projects). Information to assess this element would be provided by the company and would meet the DOE ARL scheme. Furthermore, scalability may also be considered in terms of potential for scale based on known availability of raw material resources and production infrastructure. For the purpose of this paper, this element is snapshot of a point in time and scalability may also be dependent on non-technical factors such as investment and should be periodically re-evaluated.

Financial Criteria

F1 Delivered cost. Delivered cost is the cost of implementing the innovative technology which must generally be less than or equivalent to the BAU technology. This element would be evaluated and reported $/tonne or $/cubic yard of concrete using a scale ranging from 1 to 3 where 1 corresponds to high delivered cost (or low-cost savings compared to BAU 0-10%), 2 corresponds to medium cost (10-20% lower than BAU), and 3 to low delivered cost (or high-cost savings compared to BAU 20-30%). Information to assess this element could be obtained from the manufacturer or through construction cost estimation software such as RS Means, widely used by the A&E community.

This factor is especially important when it comes to a building material like concrete which operates on very low profit margins. Alternatively, the green premium will need to be subsidized to motivate the market to pick-up the innovative product. Otherwise, the construction industry with its tight budgets and timelines will tend to resort to the usual materials it is most familiar with, and which fit within their budget. This element feeds into the economic value proposition for an emerging technology and the business case for a company and its product line.

Evaluation and Scoring Approach

The results of the evaluation are converted into a simplified quantitative score for each criterion using a three-point rating scale with predetermined value ranges. These rating scores would be used to create a product or technology profile based on the technology's attributes and performance in each of the three criteria categories starting with the "threshold" or "must have" criteria to ensure basic technical, market and economic viability. The sub-elements within each evaluation category may be weighted equally or differentially based on a pre-determined rationale. The scores across each evaluation category are combined to form a total score and demonstrate the relative position of any two technologies being compared across a consistent set of criteria and rating scales. The total score is reported using a scale ranging from 1 to 15 where scores in the range of 1-5 correspond to currently low viability (based on available information), 6-10 correspond to currently medium viability (based on available information), and 11-15 correspond to currently high viability (based on available information).

Framework Implementation Plan

Identifying Promising Technologies

Some of the most promising technologies would offer strong technical attributes in the form of the greatest lifecycle carbon savings and preferably with strong market characteristics and at lower or equivalent cost to BAU. Establishing an actual technology shortlist of all the currently available new and emerging low-embodied-carbon concrete technologies in the market is outside the purview of this paper and has been attempted by other organizations such as The American Concrete Institute Center of Excellence for Carbon Neutral Concrete (ACI-NEU).

The attributes across the three sets of criteria may also be used to develop a decision matrix similar to the TRL-ARL matrix in Figure 2 showing the position of each technology depending on their profile attributes. A proposed prioritization scheme could then be based on the position of a particular technology on the readiness curve to indicate how close a particular innovative technology or product is to being usable in a pilot vs a demonstration project vs in a real-world full-scale commercial project setting. Subsequent iterations of this framework will refine the evaluation scoring approach and consider developing a decision-matrix based on the evaluation criteria for end-users.

Technologies would be able to strengthen their "ratings" under the criteria (e.g., improve their carbon reduction potential or their market scalability or product differentiation) to change their rating scores and move their position in the decision matrix over time based on their business evolution.

Heat Map and Rating Score

Table 1 represents a heat map evaluating a variety of new and emerging concrete building technologies using our proposed "threshold" or "must have" technical, market and financial criteria based on publicly available information Existing data gaps are shown in grey. This table illustrates our methodology; an actual evaluation will require more in-depth analysis and additional information from technology developers or vendors. The threshold criteria are equally weighted to reflect their equal value as a basic set of criteria any emerging technology should meet. However, users of this framework can adjust the weighting factor based on their interests. For example, R&D funders may prioritize carbon reduction potential and market size, while climate tech investors may focus more on the technology development stage and product scalability. Additionally, this evaluation only presents a snapshot of the current technology landscape, which will certainly evolve over time.

Table 1: Heat Map and Score Evaluating New and Emerging Concrete Building Technologies

New or Emerging Concrete Technology*	Carbon Reduction Potential CO_2-eq/ tonne *(Scale 1-3)*	Technology Develop-ment Stage TRLs *(Scale 1-3)*	Market Size % *(Scale 1-3)*	Product Scalability (Current) % *(Scale 1-3)*	Delivered Cost ($/tonne; $/m^3) *(Scale 1-3)*	Total Score *Scale (1-15)*
Non-carbonate rocks + Electrochemical process + Zero Carbon Energy	3 (Zero emission)	2 TRL 5-6	3 Readymix 75%	1 Low	Unknown	9
Calcium Rocks	3 (Zero to low emission)	2 TRL 4-6	3 Readymix 75%	1 Low	Unknown	9
3-D Printed Concrete	Unknown	3 TRL 9	1 Other	2 Medium	Unknown	6
Carbon Sequestration	1 (<30%)	3 TRL 9	3 Readymix 75%	3 High	Unknown	10
Limestone Calcined	2 (50%)	3 TRL 7-9	3 Readymix	3 High	3	14

New or Emerging Concrete Technology*	Carbon Reduction Potential CO_2-eq/ tonne *(Scale 1-3)*	Technology Develop-ment Stage TRLs *(Scale 1-3)*	Market Size % *(Scale 1-3)*	Product Scalability (Current) % *(Scale 1-3)*	Delivered Cost ($/tonne; $/m^3) *(Scale 1-3)*	Total Score *Scale (1-15)*
Clays w/out electrification (Hasanbeigi 2024, EPFL 2024)*			75%		25% lower than BAU	
Mechano-chemical Activation of Clays/ Gypsum (Lab Technology) **	2 (50%)	2 TRL 4-6	3 Readymix 75%	1 Still in evaluation	Unknown	8
Recycled Glass Concrete	Unknown	2 TRL 5-6	3 Readymix 75%	1 Low	Unknown	6

*Unknown refers to refers to publicly available information on company website as assessed at time this paper was developed and represents the current point in time.
**National Laboratory, personal communication, 2023.

Case Study on Limestone Calcined Clay

We present a brief descriptive case study of a strong candidate technology based on an in-depth evaluation conducted and published by ACEEE and Global Efficiency Intelligence recently (Hasanbeigi, Srinivasan, Chen, Esram 2024) to show how it meets the proposed evaluation criteria. Limestone Calcined Clay (LCC) offers wide scalability as a supplementary cementitious material for use in both cement (to displace clinker) and in concrete (to displace cement). It is based on a mix of ground limestone and clay that is calcined at half the temperature of clinker resulting in substantial energy savings. Additionally, clays are a non-carbonated material, and the ground limestone is merely ground not calcined as in traditional portland cement production, thus LCC can offer a 50% reduction in carbon emissions. In the US it is considered a TRL 7-8 technology and six OCED demonstration projects were awarded in 2024 with new plants anticipated at scale. It offers similar performance and mechanical characteristics as portland cement especially in the long term (durability, strength) for buildings and infrastructure and can be used directly in ready mix concrete. LCC offers at least a 25% cost savings for energy and raw materials compared to portland cement. This technology would score well across many key technical, market and cost criteria.

Measurement and Validation

While describing the attributes of a given technology across the three criteria and their sub-elements provides a starting point, the evaluation framework is only useful when applied and compared against other available tools to assess and confirm carbon reductions for low-embodied-carbon technologies. To sufficiently prove materials and technologies have as low carbon intensity as they claim, measurement and validation methods need to be administered from a whole lifecycle perspective at the project or building level.

The federal Buy Clean policy, state clean procurement policies, and initiatives like the First Movers Coalition (WEF 2024) have spurred many organizations to try to quantify the carbon intensity of building materials. There are ongoing efforts in the Buy Clean taskforce and the Environmental Protection Agency (EPA) to present a robust eco-label program, but these are still only capturing the embodied carbon associated with widely used materials. Additionally, while widely used for traditional concrete technologies, EPDs can be product specific, facility specific or industry averaged further leading to challenges in comparability of emissions reduction potential between newer innovative technologies and their traditional counterparts in the concrete sector.

While a plethora of tools already exist for both types of approaches, novel materials, and their associated processes and/or assemblies in R&D will not be captured in most existing tools and therefore will require more effort to conduct both material LCA and WBLCA because additional user inputs will be needed. In the R&D space, where moving from bench scale to deployment offers critical challenges and is associated with high uncertainty, implementing iterations into the analytical process at each TRL/ARL stage is key to ensuring measurement and validation results are accurate.

DOE's Incubating Market-Propelled Entrepreneurial Mindset at the Labs and Beyond (IMPEL) Program has been researching standardized evaluation, measurement, and validation (EMV) specifically for reducing carbon in the built environment. Their work convenes a range of stakeholders from NGOs, national labs, and others to help the building sector transition decarbonization technologies to market. Next, we present some examples of IMPEL partner organization efforts related to EMV.

To conduct WBLCA for R&D materials, the goal, scope, and functional unit should be clearly defined at the outset, as well as taking inventory of what will be included from a bill of materials or quantified processes (IMPEL 2024b). Subsequently, for each material and process, the environmental, energy, and cost impacts should be calculated to the highest level of granularity possible, based on the amount of material used (e.g., mass of materials in mix design or the volume of concrete rather than only calculating based on the thickness of the concrete in an application). The WBLCA results show the total impacts from embodied, expected operational carbon, and other impacts to give a holistic view of the project's footprint and can further inform the building's design.

Argonne National Laboratory (ANL) has developed one such model called GREET that conducts LCAs for both building materials and whole buildings to evaluate embodied carbon and air emissions as well as energy and water use (ANL 2024). The GREET model and other tools being developed by national labs should be used in conjunction with some of the calculators and LCA tools available online (e.g., EPIC, BEAM, Tally, OneClick LCA, OpenLCA, SimaPro, GaBi, and so on) for R&D materials. Conducting LCA modeling early and often is encouraged, using a combination of tools to capture any aspects that may not be integrated within one tool. Because carbon tools are still being developed and improved, there may be data gaps that need to be incorporated outside of a tool or set of tools, such as regional considerations e.g., fuel mix and price, availability of material supply, etc.

Most of the widely or publicly available measurement and validation tools appear to be focused on validating carbon reduction potentials. Additional publicly available validation tools are required for the other criteria used in our evaluation framework. In some instances, such as technology demonstration stage or market scalability or delivered cost, these maybe considered confidential business intelligence which limits their sharing. In other instances, such as with market size or other elements that may be developed as secondary or tertiary criteria such as value proposition, or product performance may represent a research or data gap to be filled.

Ultimately, measurement and validation for novel low-embodied-carbon materials and technologies need to be consistent so that a database can be built out and accurate comparisons can be made between materials within their project contexts.

How to Implement and Use Real World Demonstrations

Real world demonstrations of new and emerging technologies are critical to their evaluation and market adoption. There are several options for these including through large-scale flagship projects, demonstration projects funded by the DOE through the IRA, public private partnerships, and challenge programs.

Flagship projects are large construction projects that allow project owners to showcase innovative design, construction, engineering, building materials and other elements aligned with their environmental values. For example, APPLE, Bloomberg, Google, and Meta have either built or are building flagship low-embodied-carbon buildings in their real estate portfolio like headquarters or data centers (AD 2017; Google 2024; Meta).

The DOE is funding projects with IRA funds through their Office of Clean Energy Demonstrations (OCED) for higher TRL industrial demonstration projects that are ready to move into commercialization phases (i.e., building new or retrofitting industrial facilities to produce low-embodied-carbon cement and concrete), and the Industrial Efficiency and Decarbonization Office (IEDO) for lower TRL R&D projects (i.e., advancing lab and engineering scale research on novel cements and concrete to pilot scale and beyond with industry teaming partnerships) (DOE 2023b, 2023c). Such DOE funded projects also serve as examples of public-private partnerships with equal cost sharing between the agency and manufacturing companies who leverage private investment and equity.

Innovator cohorts such as those advanced by DOE's IMPEL, which is a tech-to-market program focused on building technologies, funded by DOE's Building Technologies Office (BTO) and implemented by LBL, offer another avenue to support and help early-stage entrepreneurs from business, academia, and DOE's national labs "translate the premise and promise of their technology into the language of business, boosting their chances of bringing it to market". The innovator cohorts are focused on a range of innovative technologies in the building sector such as design, construction, operations, circular technologies and energy technologies that integrate with buildings (onsite renewables or grid integration incorporating electrification, energy storage, and electric vehicle charging) (IMPEL 2024a, Singh 2022).

The value of real-world demonstrations lies in the opportunity these projects provide to collect real time, field data and feed that information into evaluation framework to allow more robust assessments of technology capabilities and to test and study their performance in real applications. In fact, a key element of the OCED Industrial Demonstration Grants Program is to ensure data sharing and testing of new technologies to build market confidence in their use and market acceptance.

Conclusions and Recommendations

In conclusion, this evaluation framework offers an approach for assessing new and emerging low-embodied-carbon concrete technologies by considering technical, market and financial criteria and using a decision matrix to select the best technology for the right application based on project needs. This framework may be used to evaluate the carbon reduction potential of a range of technologies or to focus on a particular technology of interest.

Some recommendations for next steps include: (1) gathering input and feedback on the proposed approach from key organizations in the buildings and concrete sector to further refine the criteria and decision matrix; (2) establishing an measurement and validation process; (3) obtaining buy-in from partner organizations for the evaluation framework towards a uniform approach. With such an approach, the market players can better work together to (1) create market demand for the new innovative technology, (2) identify the right people with the right skills and mindset to drive business entrepreneurship and scalability of the commercial venture and ecosystem for the product and (3) promote wider-scale technology adoption by onshoring manufacturing.

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