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

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About ACEEE:

The American Council for an Energy-Efficient Economy (ACEEE), is a nonprofit research organization that develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

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Nora oversees ACEEE's research programs and activities, including Buildings, Industry, Transportation, Behavior, and Health and Environment. Prior to joining ACEEE, Dr. Esram was a chief engineer and team lead at the Pacific Northwest National Laboratory, where she spearheaded a variety of multidisciplinary projects advancing building energy efficiency and decarbonization. She is a licensed architect and holds a Ph.D. in architecture from the University of Illinois, Urbana-Champaign.

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Pavitra conducts research and analysis on technologies, programs and policies that facilitate decarbonization. She Co-leads the embodied carbon in buildings and infrastructure initiative at ACEEE. Before ACEEE, Dr. Srinivasan was a public health scientist assessing environmental-occupational health and industrial hygiene for government and industry. Her research focuses on techno-economic aspects of decarbonizing cement. She holds a DrPH and MPH from The George Washington University and B.Sc. from McGill University, Canada

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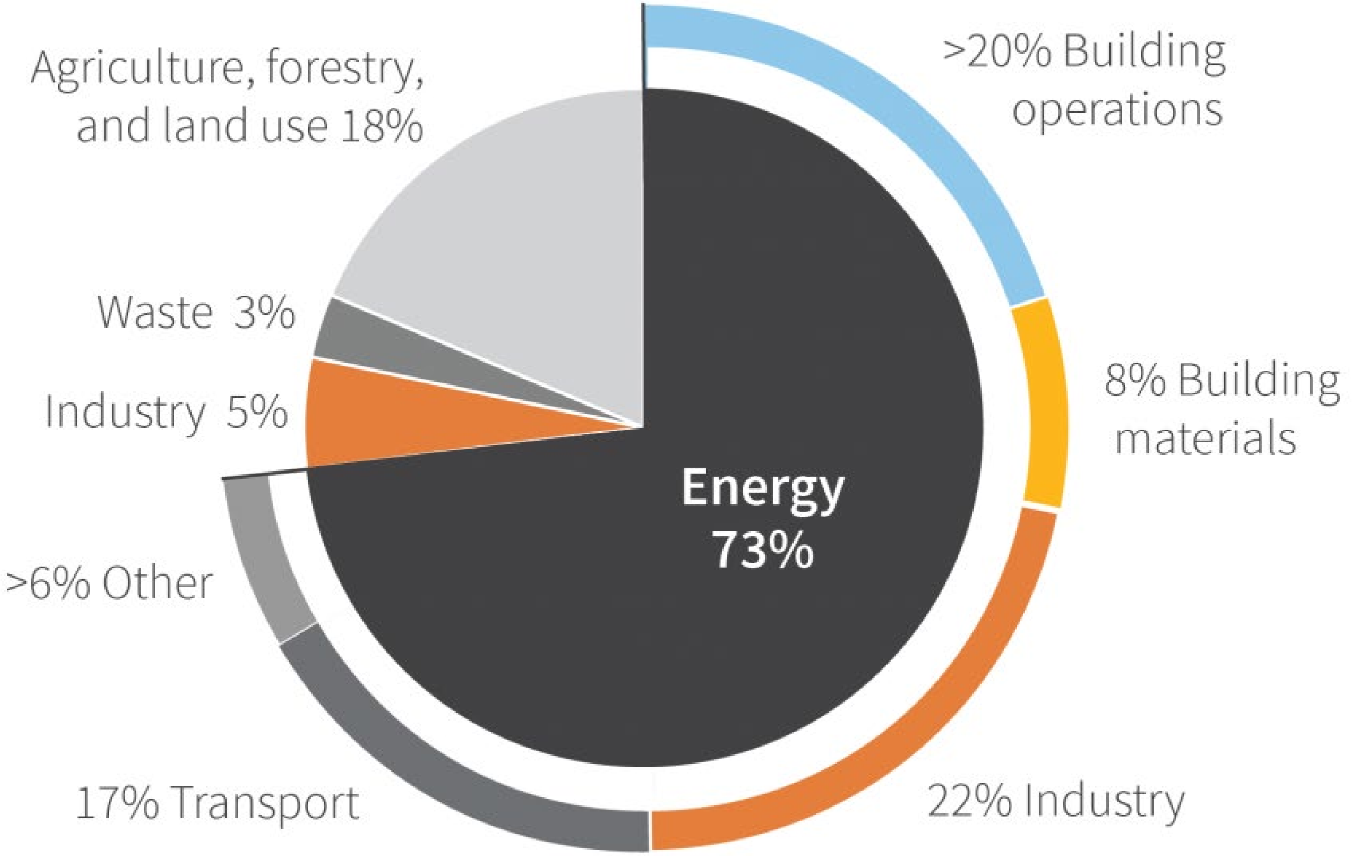
Outline

- Introduction
  - Understanding low-carbon concrete technologies
  - Why do we need an evaluation framework?
- Key Elements of an Evaluation Framework
  - Existing approaches: LCA, TRL, MRL, ARL
  - Three (3) pillars: Technical, Market, Financial elements
- Applying the Framework to Concrete Technologies
  - Primary evaluation criteria
  - Case studies
- Implementation Pathways

Embodied Carbon in the Buildings Sector

Approximately **30%** of all global carbon emissions are attributed to the building sector, with at least **8%** resulting from the manufacturing of construction materials



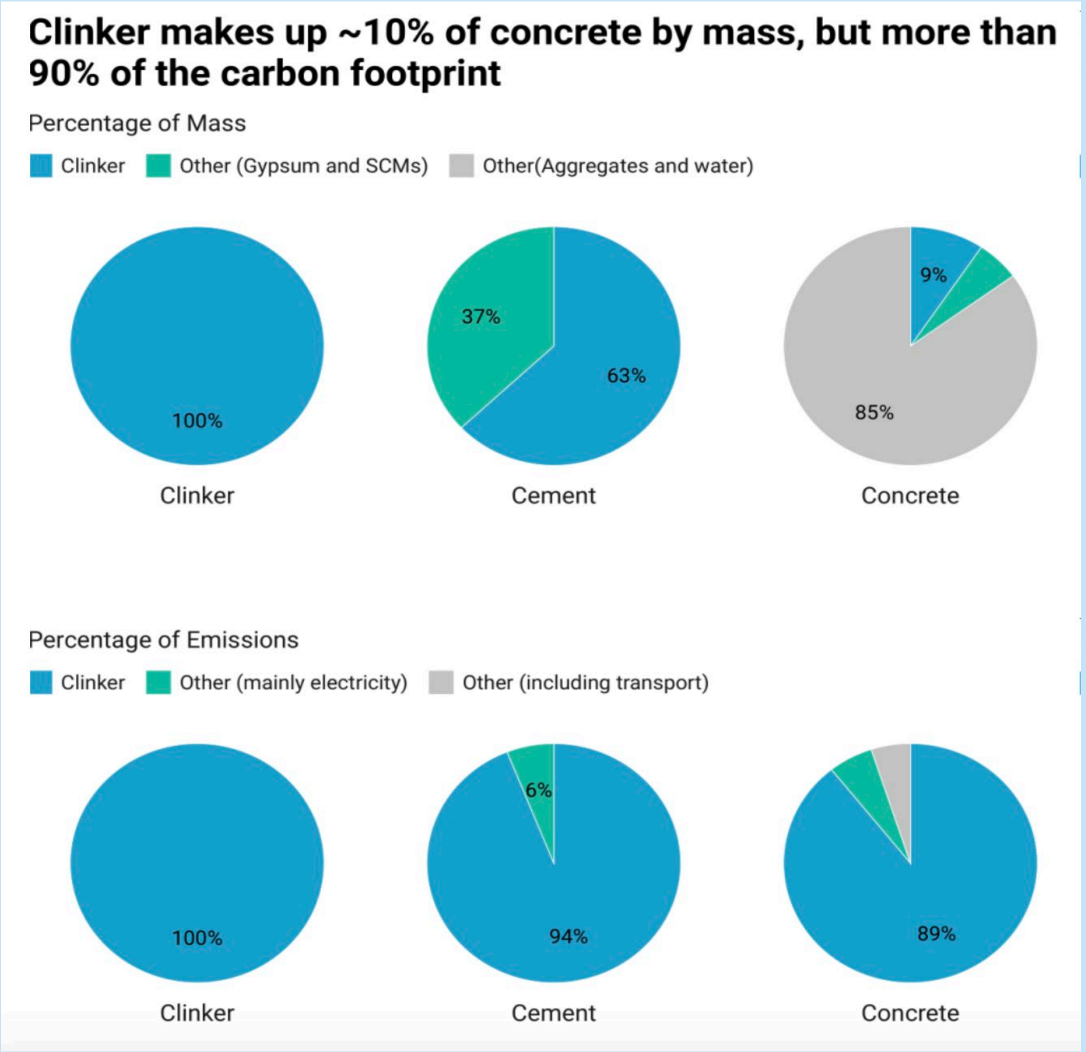
Global CO_2 emissions by sector. Adapted from the UNEP 2019 Global Status Report and OurWorldInData.org, based on data from Climate Watch and the World Resources Institute.

Embodied Carbon of Concrete

- Concrete has low embodied emissions (relative to other materials) but accounts for 8% of global emissions.
  - *Concrete: 1.2 MJ/kg*
    - Majority of emissions from the 10-15% of cement used as the binding agent in a concrete mix
  - *Structural steel: 32 MJ/kg*
  - *Asphalt: 50 MJ/kg*
- Comparatively, Steel accounts for about 7-9% of global emissions and aluminum about 2%.
- It is the **large quantity of concrete** used globally in construction that increases its overall emissions.
- The amount of concrete used in construction is expected to increase with the projected addition of 2.4 trillion sq ft to the global building stock over the next 40 years (equivalent of adding 1 NYC / month for 40 years)

Source of Concrete Emissions

- The production of clinker in cement manufacture is the emission intensive step in the process.
- Cement is a combination of clinker (60%) and other materials like gypsum etc (~40%).
- Concrete is a combination of cement (10%), materials like gypsum (5%) with aggregate and water comprising the buld of the mixture (85%)
- Majority (90%) of concrete emissions come from the ~10-15% of cement used as the binding agent in a concrete mix



Source: https://energypost.eu/concrete-8-of-global-emissions-and-rising-which-innovations-can-achieve-net-zero-by-2050/

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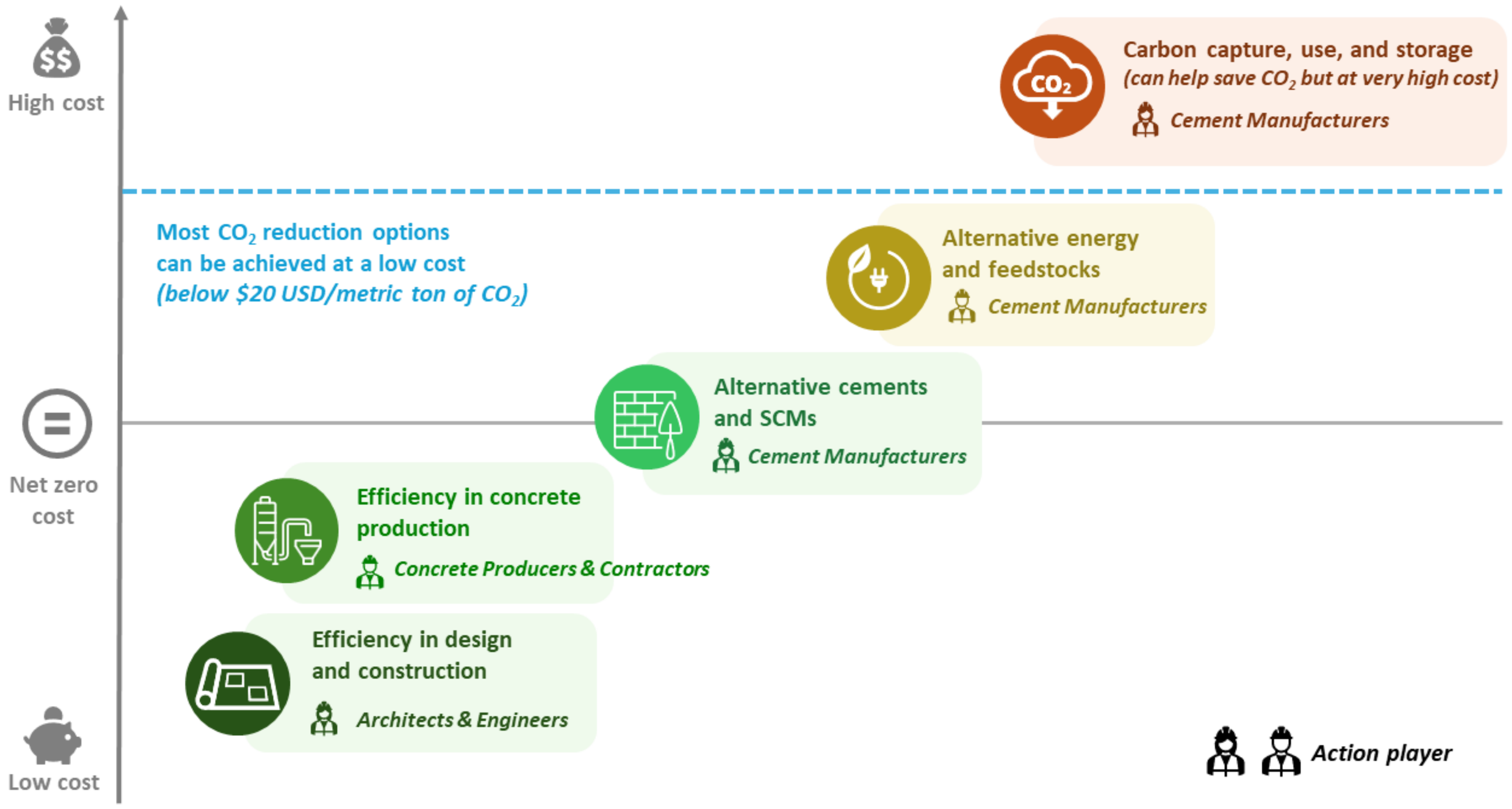
Options for Decarbonizing Concrete

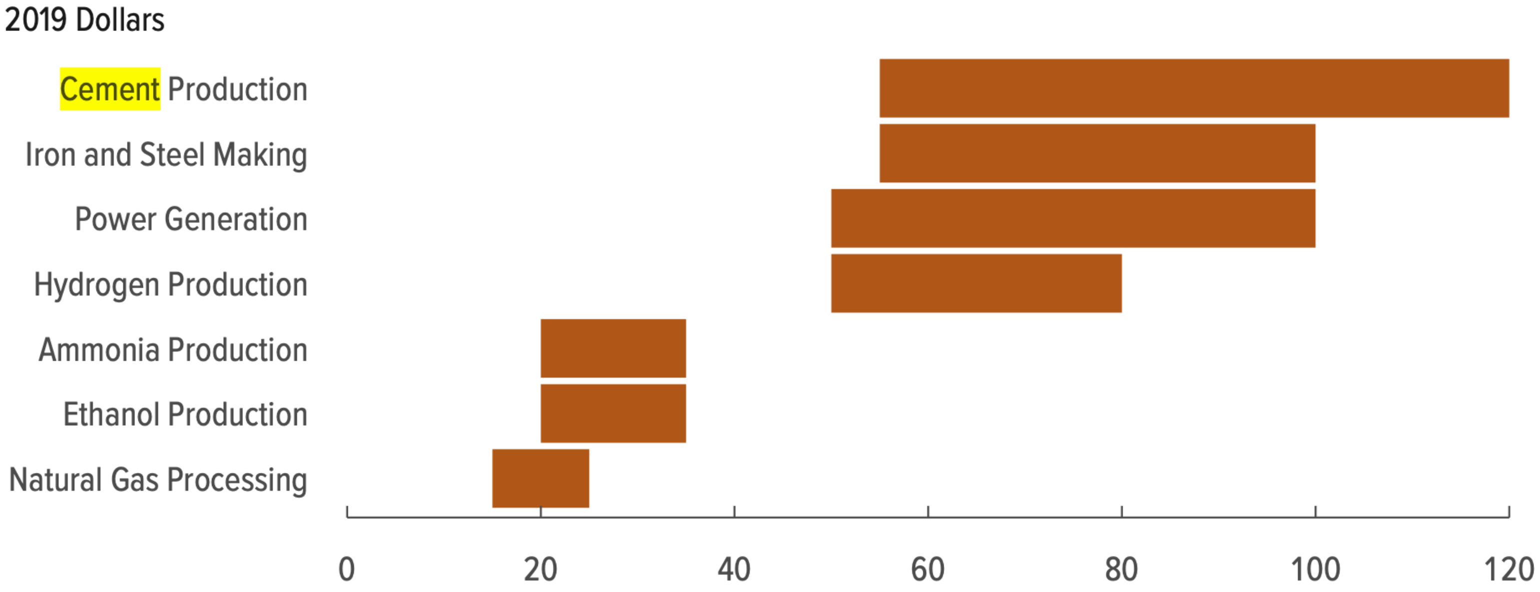
- Carbon reduction methods for concrete need to consider all lifecycle stages, contributing components, and the whole value chain.
- They include reductions through:
  - ❑ Efficient design and construction (avoiding over-design, large spans, tall buildings)
  - ❑ Efficient concrete production (admixtures, mix designs, aggregate grading to reduce cement use)
  - ❑ Use of alternative cements and SCMs (clays),
  - ❑ Use of alternate energy sources and feedstocks (calcium rocks, renewable energy) and
  - ❑ Carbon capture and storage.
- An approach which combines more than one of these above options has the potential to reduce concrete-related emissions by over 75%.



Adapted based on: www.linkedin.com/pulse/how-make-cement-greener-misconceptions-reality-lc3project-6rq0e/ and https://gccassociation.org/concretefuture/wp-content/uploads/2022/10/GCCA-Concrete-Future-Roadmap-Document-AW-2022.pdf

Cost of Carbon Capture from Cement/Concrete Production and Need for Other Technologies

Estimated Range of Costs for Capturing a Metric Ton of CO_2 in the United States in 2019, by Source



Estimates of the cost to capture a ton of CO_2 vary by industry and by such factors as the amount of exhaust gas from a plant, the concentration of CO_2 in that exhaust, and its pressure.

Given the high cost of implementing CCS in cement production, there is a need to use other less expensive technologies to decarbonize the process and limit the use of CCS for CO_2 that is un-abatable through other options.

Source: https://www.cbo.gov/system/files/2023-12/59345-carbon-capture-storage.pdf

Types of Low-carbon Cement/Concrete Technologies

1. **Efficiency in Concrete Production**
   - Using admixtures, concrete mix designs and grading aggregate to optimize concrete

2. **Alternative Cements/Binders or Replacing Clinker with Supplementary Cementitious Materials (SCMs)**
   - KLAW Industries: replacing clinker with waste glass diverted from landfills.

3. **Using Alternate Energy (Reducing Process Heat/Energy Use) and Alternate Feedstocks**
   - Sublime Systems: creating an alternative process using electrolyzer at ambient temp with renewable energy and non-carbonate feedstock.
   - Chement: replacing high-temp kiln with metal vat (electrochemical approach).
   - Saferock: making concrete from mine tailings, aggregate and activators.
   - Heirloom: producing cement and SCMs from carbon-free silicate rock.

4. **Carbon Capture, Utilization and Storage (CCUS)**
   - Heirloom, CarbonCure, CarbonBuilt: storing captured carbon in concrete.

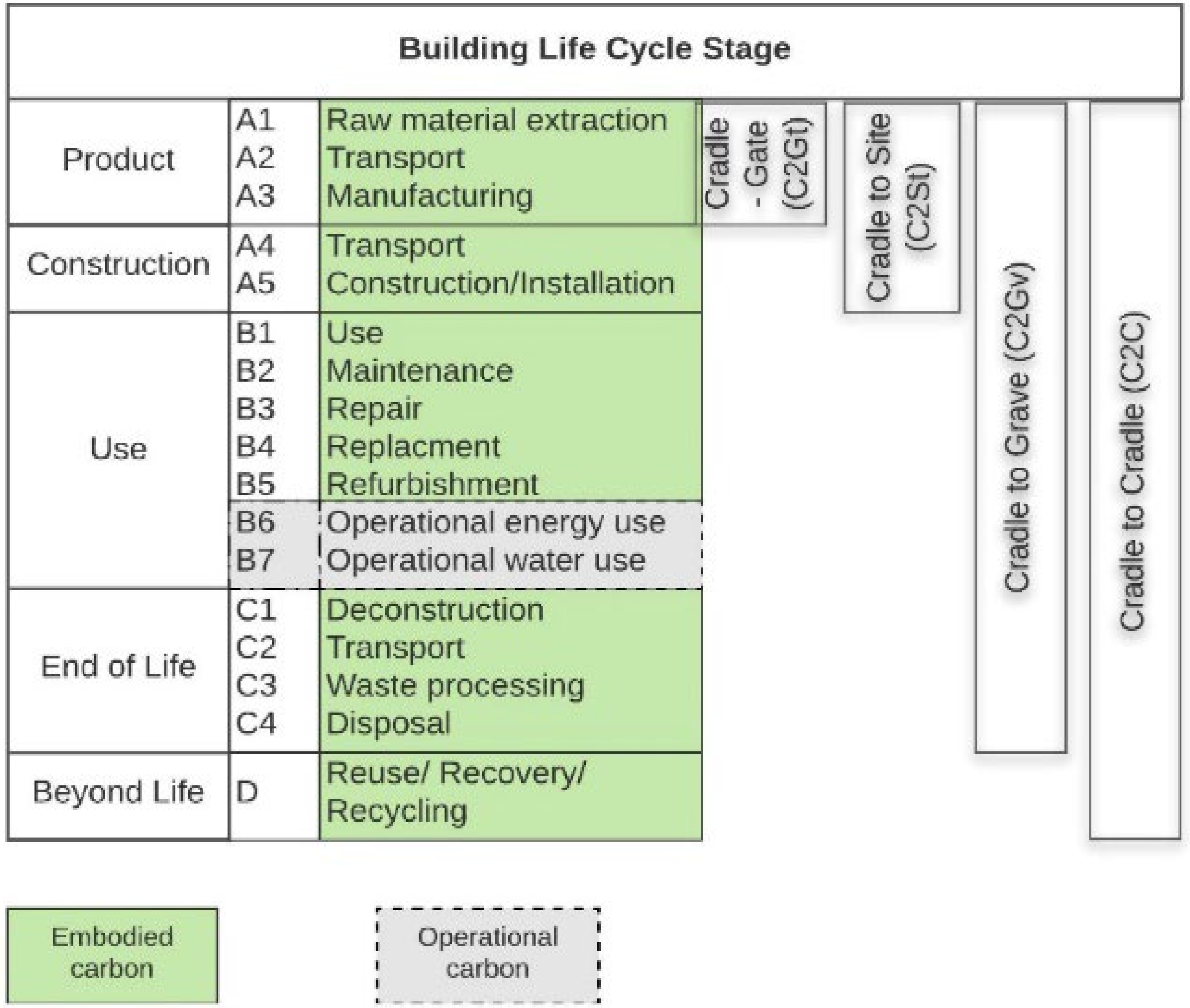
Which Technologies/Products to Invest In, Incentivize, or Procure?

- **Buy Clean Policies and Voluntary Rating Systems Rely on EPDs (Environmental Product Declarations). However –**
  - EPD generation requires one full year of production year;
  - An EPD is inadequate to measure total emissions from various quantities of cement and concrete use.

- **However, EPDs are inadequate to address other key questions:**
  - How much (more) does it cost to produce the new products?
  - Can the new products be mass produced?
  - Can the new products be widely distributed through existing supply chains?
  - Do the new products meet construction and building codes? (strength, durability, workability)
  - Can the new products be used the same way as the existing products?

Existing Evaluation Approach: LCA

- LCA is a method to assess the environmental impacts of a product or service throughout its entire life cycle.
- Embodied carbon quantification is derived from the global warming potential (GWP) output of LCA.
- An EPD is an externally verified and standardized description of the environmental profile of a product.
- A series of ISO, EU standards guide LCA, EPD development.



Existing Evaluation Approach: TRL, MRL

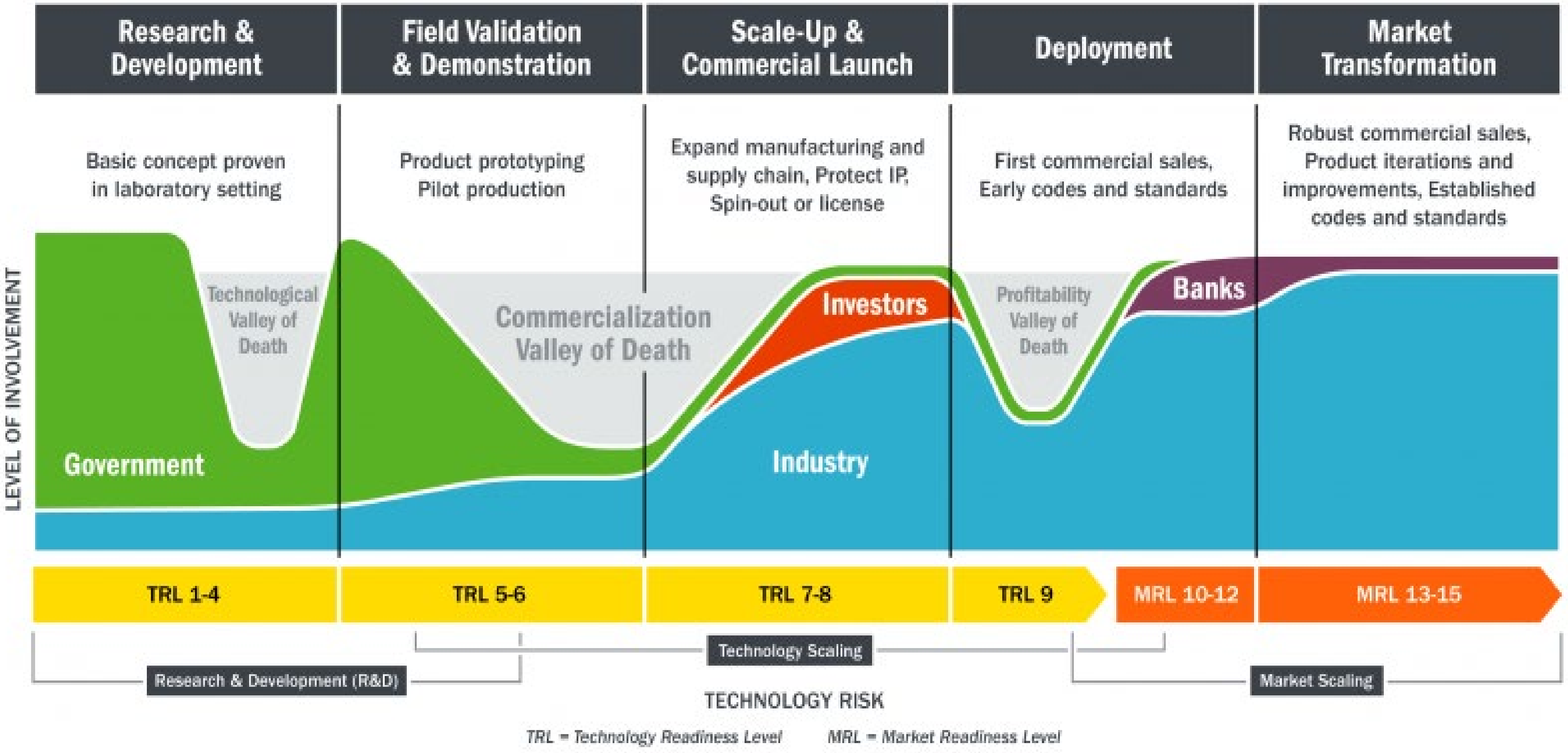
TRL = Technology Readiness Level, a metric used to assess maturity of evolving technologies (materials, components, devices, etc.) prior to incorporating it into a system or subsystem. It spans basic research(TRL 1-2) to deployment/ commercialization in the market place (TRL 8-9)

MRL = Market Readiness Level, refers to the readiness of a market to accept and adopt a new technology. Key indicators include market size, customer lifetime value, leads generated, customer usage

Alternate Feedstocks

Limestone calcined clays

CCS



Source: https://www.energy.gov/eere/buildings/technology-marketSource

Existing Evaluation Approach: ARL

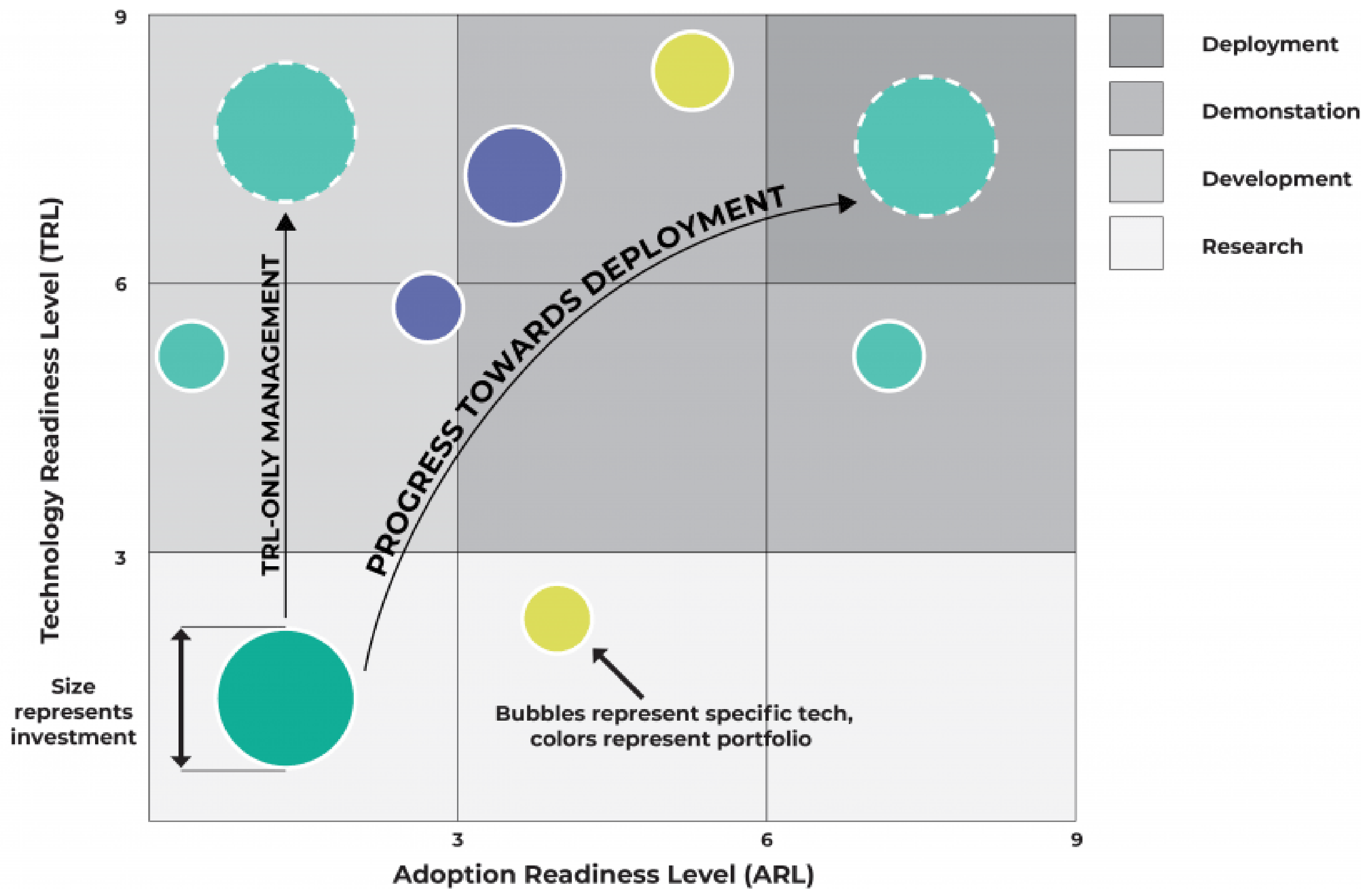
Adoption Readiness Levels (ARLs) assesses the adoption risks of a technology and translates this risk assessment into how ready a technology is to be adopted by the ecosystem.

ARLs comprise four (4) core risk areas and 17 dimensions:

1) **Value Proposition:** delivered cost, functional performance, ease of use/complexity;
2) **Market Acceptance:** demand maturity/market openness, market size, downstream value chain;
3) **Resource Maturity**: capital flow, project development, integration and management, infrastructure, manufacturing and supply chain, material sourcing and workforce; and
4) **Societal Non-Economic Risks:** the regulatory and policy environment, permitting/siting, environmental and safety, and community perception.

Technology Maturation Across RDD&D Continuum

- An illustrative example of how TRLs complement ARLs
- To describe how a suite of technologies may progress from research (R) to development (D), demonstration (D) and deployment (D) based on respective TRL and ARL maturity.
- A technology in the research stage would be at a low TRL and low ARL level.
- To be deployed a technology needs to both be at a high TRL and high ARL level



Source: www.energy.gov/technologytransitions/adoption-readiness-levels-arl-complement-trl

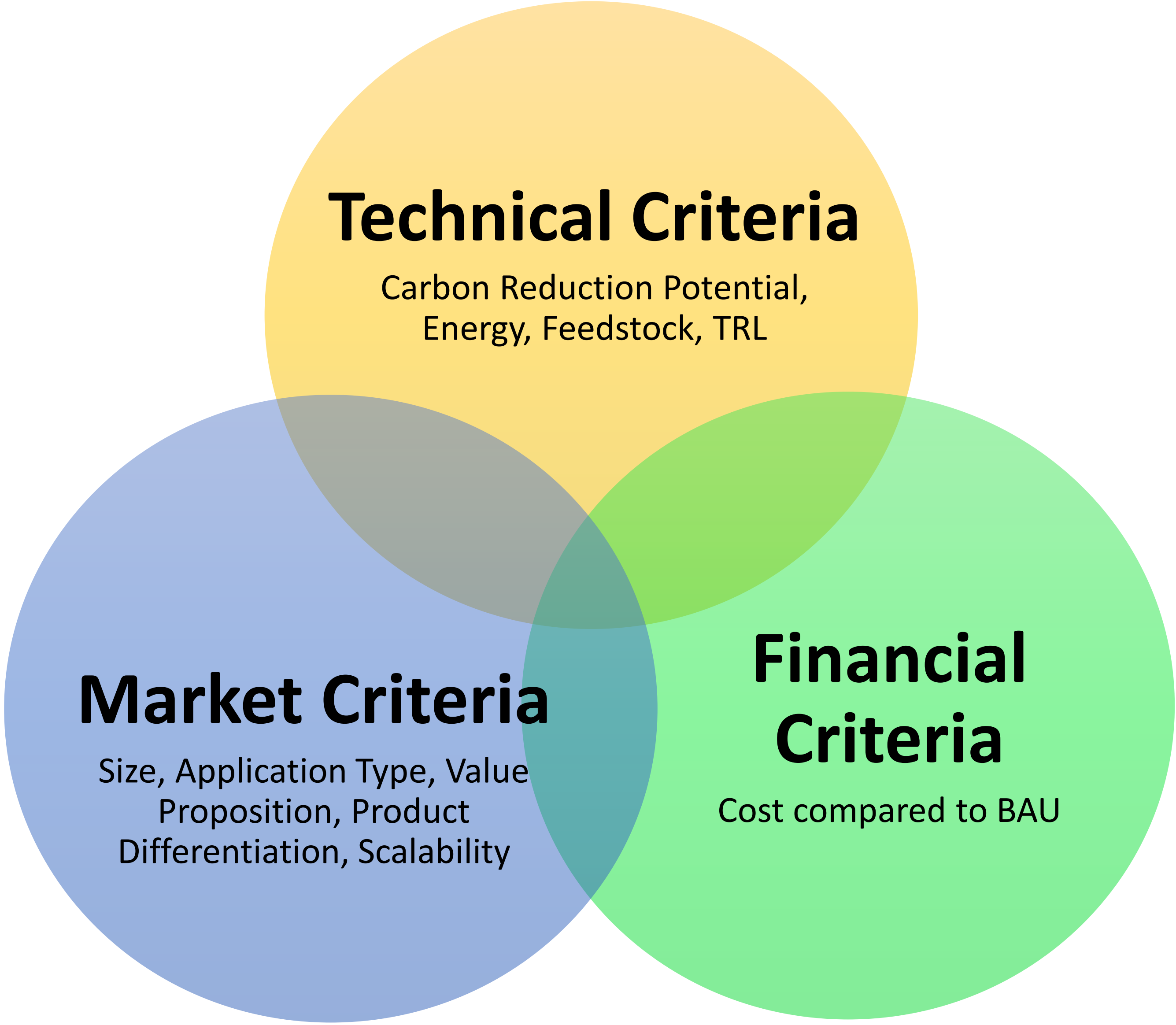
Key Elements of an Evaluation Framework

The proposed evaluation framework is intended to provide a standard and easy-to-use way to assess the **ULTIMATE** carbon reduction potential of low-carbon technologies, identify gaps, and drive investment and policy decisions.

The 3 main evaluation categories: technical, market and financial are drawn from the LCA and TRL/MRL/ARL schemes.

Each category includes several criteria to evaluate different aspects of a new or emerging technology.

This figure relates the three sets of criteria and illustrates how a technology may reside in the intersections of these categories.



Tiers of Evaluation Criteria

Primary: *"Threshold" or "Must Have" elements that need to be evaluated for most if not all emerging technologies.*
Secondary and tertiary: *2^0 and 3^0 attributes based on priority or need will expand the evaluation framework.*

Technical	Market	Financial
Primary T1 Carbon Reduction Potential T2 Technology Development State	**Primary** M1 Market Size M2 Market Scalability	**Primary** F1 Delivered Cost
Secondary (for concrete) T3 Performance-based Attribute (durability or slump)	**Secondary** M3 Product Differentiation	**Secondary** F2 Training Cost
Tertiary T4 … T5 …	**Tertiary** M4 … M5 …	**Tertiary** F3 …

Primary Criteria and Rating Scales

Technical	Market	Financial
T1 Carbon Reduction Potential Percent reduction compared to the business-as-usual (BAU) scenario in CO_2-eq/tonne 1 = **low** reductions (0 to 30%) 2 = **medium** reductions (30-60%) 3 = **high** reductions (60-100%)	**M1 Market Size** Potential demand for a product within the market based on product type or market share 1 = **Smaller markets** (special/misc use) 2 = **Concrete products** market (pre-cast, pre-stressed, reinforced concrete etc.), 11% of U.S. market 3 = **Ready mix concrete**; 70-75% of U.S. market	**F1 Delivered Cost** Cost increase or decrease compared to BAU technology 1 = **high delivered cost** (or **low-cost savings** only 0-10% lower compared to BAU) 2 = **medium cost** (10-20% lower than BAU) 3 =**low delivered cost** (or **high-cost savings** 20-30% lower compared to BAU)
T2 Technology Development State How close a product or technology is to commercialization 1 = **early-stage** technologies (TRLs 1-3) 2 = **mid-stage** technologies at the pilot or demonstration stage (TRLs 4 to 6) 3 = **late-stage** technologies close to being commercial (TRLs 7 to 9)	**M2 Market Scalability** Producing real-world quantities (tonnage), can process scale to produce volume needed by market 1 = **low scalability** (currently zero to low tonnage production) 2 = **medium scalability** (tonnage for few projects) 3 = **high scale** (tonnage for numerous projects	

Example Assessment of 7 types of low-carbon concrete technologies

New or emerging concrete technology*	Carbon reduction potential CO2-eq/MT (scale 1-3)	Technology development stage TRLs (scale 1-3)	Market size % (scale 1-3)	Product scalability (current) % (scale 1-3)	Delivered cost $/MT; $/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 Ready mix 75%	1 Low	Unknown	9
Calcium rocks	3 (Zero to low emission)	2 TRL 4-6	3 Ready mix 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 Ready mix 75%	3 High	Unknown	10
Limestone calcined clays without electrification (Hasanbeigi et al 2024, EPFL 2024)	2 (50%)	3 TRL 7-9	3 Ready mix 75%	3 High	3 25% lower than BAU	14
Mechano-chemical activation of clays/gypsum (lab technology) **	2 (50%)	2 TRL 4-6	3 Ready mix 75%	1 Still in evaluation	Unknown	8
Recycled glass concrete	Unknown	2 TRL 5-6	3 Ready mix 75%	1 Low	Unknown	6

Case Study: Limestone Calcined Clays

https://www.aceee.org/research-report/i2401

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Case Study: Limestone Calcined Clays

This technology would score well across many key technical, market and cost criteria. An in-depth evaluation conducted and published by ACEEE and Global Efficiency Intelligence recently (Hasanbeigi, Srinivasan, Chen, Esram 2024) shows how it meets the proposed evaluation criteria.

https://www.aceee.org/research-report/i2401

- 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 limestone is merely ground not calcined as in traditional portland cement production, thus LCC can offer a **40-50% 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.

Implementation Path

- Obtain buy-in from partner organizations and policy makers for a uniform framework
- Gather input/feedback from key organizations in buildings and industry sectors to refine criteria
- Establish a measurement and validation process
- Gather data …

ACEEE Conferences

2024 Summer Study on Energy Efficiency in Buildings	**August 4–9, 2024**	**Pacific Grove, CA**
2024 Energy Efficiency Policy Forum	**December 3, 2024**	**Washington, DC**
2025 Hot Water Forum & Hot Air Forum	**March 4– 6, 2025**	**Portland, OR**
2025 Summer Study Energy Efficiency in Industry (Embodied Carbon Workshop)	**June 16-18, 2025**	**Charlotte, NC**
2025 Energy Efficiency as a Resource	**October 7-9, 2025**	**Denver, CO**
https://www.aceee.org/events	**2025**	

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