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Market Opportunities and Challenges for Decarbonizing US Buildings

An Assessment of Possibilities and Barriers for Transforming the National Buildings Sector with Advanced Building Construction

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About Us

ADVANCED BUILDING CONSTRUCTION
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About ADL

ADL Ventures is a venture consulting firm that focuses on developing new products and services, and launching new businesses, on behalf of corporate and government clients in critical infrastructure sectors. We are a team of experienced entrepreneurs and technologists with strong backgrounds in the building construction, power, and transportation sectors. ADL has offices in Boston, Denver, San Francisco, and Washington, DC.

About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

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Abstract

The United States (US) buildings sector is at a crossroads. A range of institutional barriers and market failures have impeded national efforts to boost construction productivity, energy efficiency, decarbonization, and affordability. As the building construction industry faces this confluence of challenges, however, innovative new technologies and approaches are emerging with the potential to break traditional barriers, bridge technical gaps, and create added value. Whether these can effect the necessary market transformation depends on the constructive participation of a wide range of emergent and incumbent organizations in the private and public spheres.

The Advanced Building Construction (ABC) Collaborative brings together a network of buildings sector actors to catalyze this market transformation while ensuring that building decarbonization, housing affordability and availability, and workforce equity and inclusion are at its core. The Collaborative's goal is to decarbonize the US built environment with a globally competitive domestic construction industry.

This report employs key findings from hands-on market research conducted by the ABC Collaborative spanning the entire value chain. These findings help establish the foundation of a substantive action plan we ultimately aim to coordinate and galvanize in partnership with industry. This foundation work investigates systemic problems across the buildings sector, examines critical technologies and approaches, analyzes market segments, and summarizes interviews with key industry stakeholders. We have identified and exposed institutional barriers and market failures across the buildings sector and its constituent industries to capture a high-level "wish list" that highlights crucial needs in response to shortcomings and technology gaps that hinder advanced building construction.

This report translates the concepts outlined by this stakeholder wish list into a set of cohesive and integrated recommendations. These will inform strategic activities the ABC Collaborative and its partners can pursue as part of a broader vision of transforming the buildings sector.

Executive Summary

The United States (US) buildings sector faces a confluence of major challenges across its constituent industries, impacting ordinary Americans across the country and creating a pivotal decision point for the sector.

These changes include:

- the threat of catastrophic climate change (of which emissions related to construction and buildings are a significant driver) and increasingly frequent extreme weather events;
- a large housing deficit driving high prices and the cost-burdening of many households, which hinders the broader economy and worsens the crises of housing insecurity and of unhoused individuals and families;
- flat or declining labor productivity in building construction exacerbated by labor shortages and low investment in R&D and innovation; and
- supply chain disruptions and sharply climbing materials costs that are aggravating volatility in project schedules and costs.

At the same time, increased use of industrialized approaches to construction manufacturing (including off-site construction)—while offering improved productivity and performance—has made constructing buildings an increasingly global industry. This has enabled an emerging trend of importing prefabricated building products for US projects from suppliers abroad.[1] Taken together, all of these factors put enormous pressure on the sector to adapt. If the US buildings sector—including the construction and real estate industries—does not transform to respond promptly to these challenges and trends, it risks increasingly severe—and already evident—economic and societal consequences. How, then, can the buildings sector confront the range of institutional barriers and market failures that continue to impede efforts to boost construction productivity, energy efficiency, decarbonization, affordability, and resilience?

To rise to this challenge, RMI and its team—ADL Ventures, Association for Energy Affordability (AEA), Passive House Institute US (PHIUS), and Vermont Energy Investment Corporation (VEIC)—founded the Advanced Building Construction Collaborative (ABC Collaborative) with the support of the US Department of Energy (DOE), the California Energy Commission (CEC), and the Massachusetts Clean Energy Center (MassCEC). The ABC collaborative will align and enhance the work of incumbent and emergent stakeholders. The goal is to accelerate the uptake of advanced building construction (ABC) to achieve critical national building efficiency and climate goals, while supporting—and leveraging—the modernization of the US construction industry.

The Collaborative will serve as a hub for cooperation and market facilitation. As part of its work, the Collaborative is creating a framework for coordinated Collaborative Working Groups aligned around collectively addressing key challenges and areas for action. This will give buildings sector stakeholders a unique venue to identify roadblocks, implement mutually beneficial solutions, and drive the widespread adoption of ABC.

This report provides: a synthesis of technologies and approaches that can help to implement streamlined, high-quality, low-carbon solutions for new construction and building retrofits; a summary of the most opportune regions and market sectors for those innovations; a buildings sector stakeholder needs assessment to outline how to best support industry players; and a clear articulation of institutional and market barriers that must be overcome.

Overview of the Research Methods and Structure of this Report

We used several research methods for this report, including a literature review, a meta-analysis, a quantitative state ranking, and industry interviews. These methods allowed us to both summarize previous research relevant to ABC while adding important new market insights about a prospective US ABC market.

The report consists of five sections.

Section 1 provides market context and the case for ABC and the ABC Collaborative. ABC refers to new construction and retrofit solutions that: offer superior energy efficiency and low carbon footprints; are cost-effective for developers and consumers; provide faster and less disruptive on-site deployment; are appealing to owners and users (with added value, such as better indoor air quality, improved comfort, resilience, and reduced maintenance); and are compatible with new business models that enable market transformation in the construction industry.

The ABC Collaborative—a hub for cooperation and market facilitation—brings together an array of construction and building stakeholders to identify roadblocks, drive mutually beneficial solutions to overcome them, and accelerate the mainstream adoption of innovative high-performance construction.

Section 2 discusses major ABC technologies and approaches, examines various industry case studies, outlines related workforce considerations, and comments on the complementary relationships among technology trends relevant to ABC and between building efficiency and industrialized construction.

Section 3 provides an initial analysis to quantify and assess geographies and market segments that ABC players should prioritize in the United States to maximize near-term market impact. A geographical analysis ranks states based on five accessible metrics relating to early implementation of ABC technologies and practices: energy-related emissions, energy cost, economic environment, construction and buildings sector needs, and political environment. A meta-analysis of innovative construction-related technologies examines areas of high activity and potential gaps. And an overview of major market segments examines their points of suitability and drawbacks for implementing ABC.

Section 4 discusses the findings of 65 industry interviews across four stakeholder categories: demand; supply; market enabler; and research, development and scale-up (R&D). Based on the findings from the stakeholder interviews, challenges and barriers to implementation of ABC technologies and to delivering on the stakeholder wish list are outlined and segmented into five categories: technical, social, workforce, financial, and political.

Finally, **section 5** summarizes this report's findings and lays out its recommendations. A synopsis of notable findings and the report's top-line recommendations are listed below (see section 5 for additional details).

Major barriers to ABC include weak supply chains, lack of adequate labor, uncertain demand, tight margins, lack of validating data, and general risk aversion.

In summary, challenges include a cumbersome fragile supply chain, an inexperienced and undersupplied labor force, fragmented code and code compliance regimes, the uncertainty of fabricator supply and demand pipelines, tight margins, a lack of validating data for novel options, and risk aversion in the buildings sector. The Recommendations (section 5.2) provide an overview of recommended actions for addressing these barriers.

Many ABC technologies and approaches already exist, but mass adoption will require clearer, more integrated solutions that are accessible to demand actors and that achieve the necessary cost compression via improved project delivery, targeted innovation, market experience, scale, and technology-to-market mechanisms.

The core operational focus of the Collaborative is to drive ABC activity by linking demand-side building owners and developers to qualified supply-side teams that benefit from Collaborative market and technology scaling efforts. Our ABC Collaborative research indicates there is no shortage of interest in high-performance technologies—provided, however, they satisfy key market criteria for first cost, operational cost, and risk. Beyond technical performance, widespread adoption of these technologies requires cost-competitiveness to business-as-usual approaches, which is often contingent on manufacturing scale, as well as familiarity and ease of use in deployment and installation. A combination of a vanguard of forward-looking demand actors, a clearer initial set of supply-side solutions and willing providers, and accessible capital can unlock a virtuous cycle of compounding market experience, scale, construction productivity, and cost compression that support broad adoption of ABC.

Global thought leaders and stakeholders who have experienced both successes and failures provide guidelines and lessons useful for the US market.

Sweden's up-front focus on and investment in automation and Japan's emphasis on both affordability and quality are instructive examples that show the importance of aggressive investment driven by a longer-term view toward more ambitious objectives. Early owner interest and pilot progress made by market enablers in California and New York demonstrate the potential to adopt elements of successful international approaches for use in the United States, and our state prioritization analysis (section 3.2) paves the way for identifying the US geographies most promising for the early implementation of ABC technologies and processes.

Near-term ABC market opportunities exist in several US states and select market segments.

The five states that ranked the highest for ABC implementation based on quantitative analysis (see section 3.2) were California, New York, Texas, Massachusetts, and Pennsylvania. Additional federal and state legislation for energy-efficiency building retrofits, along with more general infrastructure improvements, create a potential window of opportunity for other states to rapidly take market leadership positions.

Research into major ABC market segments uncovered important opportunities for ABC deployment, with near-term opportunities in several sub-segments (see section 3.3).

- **Single-Family Housing** – The single-family segment is a massive addressable market, but the individualized ownership structure and potentially higher per-unit first costs create apparent barriers to broad, near-term adoption of ABC solutions across this segment. However, the commitment of one or more consolidated single-family rental housing portfolio owners could create a highly attractive opportunity for ABC in this sub-segment.

- **Multifamily** – Multifamily retrofits represent a key market segment of near-term interest, in part due to the backlog of deferred maintenance in many multifamily buildings, particularly in affordable (restricted and naturally occurring) and workforce housing. New multifamily construction, both market-rate and affordable, can also benefit immediately from ABC. Impacted by the COVID-19 pandemic and volatility in materials prices and availability, multifamily starts are projected to fall in 2021. ABC approaches that increase productivity and reduce material waste can play a key role in helping the sector rebound in 2022 and beyond. Additionally, sustainable attributes may increase the appeal of housing in upmarket sub-segments.

- **Commercial** – The lodging (hospitality), healthcare, and small retail (e.g., banking) and foodservice chain commercial sub-segments may be promising targets for ABC approaches due to the use of repetitive units and the desire for immediate return resulting from faster time to occupancy. Commercial buildings are more attractive for ABC retrofits when a single entity owns or has influence over a significant portfolio and can drive decisions across the properties. Most ABC-related deployment in commercial buildings has been for new construction, but some leading manufacturers and suppliers have growing retrofit programs.

Supplementing its traditional market segmentation analysis, the ABC Collaborative also performed a meta-analysis revealing top areas of interest in relevant research, patent, and trade publication materials—these are HVAC and prefabrication, HVAC and retrofits, and enabling technologies, respectively.

The meta-analysis examined several key elements pertinent to ABC:

- **Industry Needs** – Areas that the industry considers require in-depth research (based on peer-reviewed literature). In the research literature, HVAC was the most active area for peer-reviewed activity in the United States, while prefabrication was more active in Asia.
- **Intellectual Property Assets** – Technologies and approaches that hold considerable perceived market value (based on filed patents). The patent literature indicated an acceleration in patent activity since 2019 with HVAC and retrofit the number one and two areas of activity, respectively.
- **Key Innovation Trends** – Concepts and topics that generate excitement or concern among professionals and tradespeople (based on a major trade publication). The findings from trade publication articles focused more closely on enabling technologies for construction such as drones and robotics than the research and patent literature.

Recommendations for the ABC Collaborative and its partners:

- **Support market characterization**
- **Streamline financing and insurance**
- **Improve the codes, standards, and permitting landscape for ABC**
- **Prioritize and engage certain demand segments**
- **Facilitate integrated project teams**
- **Guide solution development**
- **Support supply capacity utilization and development**
- **Nurture new technologies**
- **Help develop a qualified and equitable ABC workforce**
- **Create framework for cooperative stakeholder activities**

1. Introduction

1.1 The Problem: Inefficient Construction and Inefficient Buildings

US construction labor productivity today is virtually at the same level as it was in 1940. In fact, productivity is lower today than it was in 1968.[2] It is no surprise that supply has struggled to keep up with growing demand, and a housing crisis has ensued for middle- and working-class families. For example, there are only 37 affordable homes available for every 100 low-income families, which has resulted in a shortage of around seven million affordable homes in the US for extremely low-income renters alone, with further shortages of attainable housing among other cost-burdened households.[3]

However, simply increasing housing supply without consideration for climate and energy impacts would have significant negative implications. Residential and commercial buildings consume 70% of US electricity and account for more than one-third of energy-related emissions, and there remains no large-scale, standardized approach for retrofitting inefficient existing buildings.[4] Construction materials and activities represent additional emissions beyond this. The entire construction value chain must work collaboratively to address the severe shortage of housing and its underlying causes, while emphasizing low-carbon solutions for residential and commercial buildings alike.

There is a major opportunity to revitalize America's housing and commercial building stock, and the way in which it is replenished. However, a recent trend by some US developers to offshore fabrication of building components and modules is concerning, as it illustrates a potential marginalization of yet another domestic industry—one once thought to be insulated from offshoring—by foreign competitors. Since 1997, the US has suffered a net loss of more than 91,000 manufacturing plants and nearly five million manufacturing jobs,[5] but it need not lose ground in construction.

By bringing construction productivity closer to that of other manufacturing segments, the United States has the opportunity to protect and create high-quality jobs and strengthen this critical $1.5-trillion domestic industry.[6] Integrating and scaling more advanced building construction (ABC) methods could significantly reduce timelines and costs, while ensuring superior energy performance and low carbon footprints in both new construction and retrofit applications. Enacting this type of industrially driven transition in the construction sector will be contingent upon leveraging latent capacity, technological know-how, and commercialization resources.[7]

No single player in the industry has turnkey knowledge and processes spanning all these areas, making industry cooperation—and the coordination work of the ABC Collaborative—vital.

Efforts across the country to boost construction productivity, affordability, and energy efficiency have been hindered by a number of factors. These include deep-seated localized practices and fragmented business structures, a relatively near-term financial focus by both demand- and supply-side actors that increases risk aversion and consequent resistance to new technologies, and lengthy adoption processes for novel techniques (such as industrialized construction).[8] To date, there has been no coordinated, national effort to create a qualified base of supply and technical expertise that can broadly serve demand-side actors seeking higher-performance, lower-carbon buildings with a streamlined delivery model.

Other nations like China, South Korea, Canada, Sweden, the Netherlands, and the UK have made significant investments in modernizing and streamlining construction. China, which has a burgeoning focus on decarbonization, plans to invest $13 trillion into its construction sector by 2030.[9] Some 13 Chinese cities have implemented policies to drive development of nearly zero energy buildings (NZEBs). Additionally, in 2019, Canada invested nearly CAN$1 billion in its Green Municipal Fund to increase energy efficiency for new builds and retrofit construction.[10] Without coordinated efforts, the United States is likely to lag behind nations that are making strides to modernize their construction sectors.

1.2 The Solution: Advanced Building Construction (ABC) and the ABC Collaborative

To address the challenges of the fragmented construction market, as well as the critical energy, sustainability, and affordability factors highlighted above, the US Department of Energy (DOE) has launched the Advanced Building Construction Initiative (ABC Initiative). The ABC Initiative takes a unique, systems-level approach to developing high-performance, low-carbon construction solutions that offer competitive overall value.

ABC refers to new construction and retrofit solutions that:

- **offer superior energy efficiency and low carbon footprints;**
- **are cost-effective for developers and consumers;**
- **provide faster and less disruptive on-site deployment;**
- **are appealing to owners and users (with added value, such as better indoor air quality, improved comfort, resilience, and reduced maintenance); and**
- **are compatible with new business models that enable market transformation in the construction industry.**

As part of the ABC Initiative, RMI and its core partners have launched the ABC Collaborative to act as a hub for cooperation and market facilitation, bringing together an array of construction and building stakeholders to identify roadblocks, drive mutually beneficial solutions to overcome them, and accelerate the mainstream adoption of innovative high-performance construction. With the support of DOE, the California Energy Commission (CEC), and the Massachusetts Clean Energy Center (MassCEC), and the leadership of RMI, ADL Ventures, Association for Energy Affordability (AEA), Passive House Institute US (PHIUS), and Vermont Energy Investment Corporation (VEIC), the ABC Collaborative is coordinating active participation across four key stakeholder groups that control, carry out, or influence the activities, rules, and resources acting on the built environment:

- **Demand stakeholders**, including private- and public-sector owners, developers, and serial builders
- **Supply stakeholders**, covering the whole supply chain of building and construction products and services
- **Research, development and scale-up (R&D) stakeholders** working to produce innovations and solve technical gaps
- **Market enablers**, such as government entities, financiers and insurers, trade and industry associations, code organizations, accreditation and testing bodies, utilities, and foundations

A 2020 report on emerging off-site construction markets compares existing market conditions for off-site construction in overseas markets such as Australia and Sweden.[11] The report notes that "prefabricated housing is a disruptive innovation struggling to take hold in a traditional complex product system." **It is clear that "younger industries need a focused industry association with diverse membership to act as an effective system integrator."[12] The ABC Collaborative fulfills this exact role.** It does so by bringing together the directives of market transformation and productivity enhancement, built on a deep foundational understanding of the real-world challenges of scaling technology and bringing new practices to market. The ABC Collaborative is creating an accelerated pathway to cost-effective, high-performance new and existing buildings at scale, while pursuing an aggressive emphasis on decarbonization. Similar in ways to how the SEMATECH consortium revitalized the US semiconductor industry by increasing productivity by more than 20% and reducing the required R&D investment per dollar of revenue more than threefold, the ABC Collaborative seeks to carve out a more efficient and scalable path to US leadership in the global advanced construction market.[13]

1.3 ABC Collaborative Goals for Market Impact

The key programmatic goal of the ABC Collaborative is a net-zero carbon US built environment by 2050 that relies on a vibrant ecosystem of domestic industry participants to deliver high-performance yet affordable and resilient buildings for both new and retrofit construction. Drawing inspiration from DOE's SunShot Initiative, which reduced installed costs for solar by 75% over a 10-year period, the ABC Collaborative is built around a comparably impactful and overarching set of goals, with interim targets in 2030 aligned toward the longer-term 2050 vision.[14]

- **2030 Retrofit Goal**: Three million net-zero carbon retrofits per year implemented across the US building stock
- **2030 New Construction Goal**: 100% of new construction starts in the United States are net-zero carbon
- **2030 Market Penetration Goal**: ABC is widely available and projects incorporating ABC technologies account for 25% or more of the total US building stock

Existing forms of energy-efficient construction such as LEED, net-zero, and Passive House–certified buildings already contain elements of ABC; however, they have limited deployment in select markets and regions. The total number of zero energy single-family and multifamily units in the United States has increased by 29% since 2015, to 24,547 units.[15] Yet, despite this uptick, zero energy construction remains niche when compared to total US residential units. The emergence of both innovative business models and production methods for streamlined delivery of ABC projects is a necessary supporting factor in making ABC mainstream and reaching the ABC Collaborative's objectives. The ABC Collaborative offers its partners a unique platform to work together and define nearer-term objectives and related workstreams. This will include the activities of partner-driven Collaborative Working Groups—a mechanism for participants to collectively define, prioritize, and take tangible steps that help enable ABC.

2. Discussion of Key Technologies and Approaches

2.1 Energy-Efficient New Construction and Retrofits

Opportunities for more energy-efficient new and retrofit construction rely on the availability of high-performance technologies that satisfy commercial and residential market demand criteria for first cost, operational cost, and energy efficiency. Among these are high-performing wall and roof systems (e.g., structural insulated panels [SIPs] and vacuum insulated panels [VIPs]), advanced electrified HVAC and DHW equipment (e.g., high-efficiency heat pumps), and advanced air sealing techniques. Increased industry productivity can also be enabled by higher manufacturing productivity via automation and other process improvements, software innovation that streamlines project flows, and improved envelope diagnostics that simplify retrofits of existing buildings.

In addition to technical performance, widespread adoption of these technologies requires cost-competitiveness to conventional technologies, code streamlining, availability via accessible supply chains, ease of installation and operation, a suitably trained workforce, and (in the case of retrofitting existing buildings) low disruption to existing building occupants.

2.2 Manufacturing and Assembly

To achieve building decarbonization in new construction and retrofits, the US buildings sector needs solutions that synergistically address building performance issues, as well as broader construction issues of productivity, cost control, and building quality.

At the heart of the ABC approach is an emphasis (although not exclusive) on industrialized construction, which leverages innovative digital workflows, product manufacturing, installation, and operations methods. This has the potential to achieve superior energy and carbon performance, improved productivity, faster construction timelines, and increased affordability. It can also offer a safer work environment and support greater inclusivity in construction jobs. Industrialized construction encompasses a wide spectrum of existing construction practices, such as volumetric modular and panelized construction, as well as emerging production methods, like automation of manufacturing processes, digitized workflows, and incorporation of augmented reality into both manufacturing production and site installation.

Industrialized construction focuses on optimizing a process through a suite of innovations, as opposed to a narrow focus on any one approach or technology. This can include, but is not limited to, off-site construction manufacturing in a controlled environment, volume production of standard components, use of digital tools and digitized workflows, automation and robotics, and feedback loops for regular process and design improvements.

The beneficial results of these process improvements are manifold. Precise tolerances achievable in a controlled environment can deliver assemblies that are, for example, more airtight, leading to more energy-efficient buildings. Higher-quality insulation installation (either continuous or cavity) is also possible. Up-front planning required by factory manufacturing almost invariably reduces waste and offers opportunities for lean manufacturing and more systematic optimization, further reducing construction waste.

Industrialized construction has the potential to upend traditional construction practices by enabling suppliers to produce greater volumes of better-quality high-performance buildings faster and more cost-effectively. However, the full benefits of industrialized construction can only be realized with investment in construction manufacturing capabilities, appropriate workforce development, and more energy-efficient building components and equipment to integrate into industrialized construction assemblies.

2.2.1 New Construction

Off-site fabrication of building components for new construction is not a new concept. Production home builders have used partial off-site construction for decades. Factory-built HUD-code homes and relocatable buildings are also commonplace. On a smaller scale, HVAC systems and window assemblies routinely come pre-assembled from a factory environment.

What is new is the push for sophistication being explored in industrialized construction. There is a growing interest in using a modernized set of technological tools to achieve an increased level of completion in prefabricated assemblies for a wider array of building components destined for a broader set of building types. The global off-site construction market is growing at 6.5% per year, roughly twice as fast as the broader construction market.[16] Off-site fabricators are uniquely positioned to produce high-performance building components due to the controlled nature of their manufacturing process, helping meet demand for net-zero carbon new construction.

However, the industry is still maturing and going through a natural evolution that includes heavy consolidation and financial restructuring, along with variability in both supply and demand. This highlights the urgent need for a more efficient value chain, streamlined operational practices, and coordination of transacting, leading to easier planning and investing by fabricators. The following is a discussion of important approaches and technologies that can be leveraged.

Volumetric Modular

Image courtesy of Mighty Buildings

Volumetric modular construction is the fabrication of three-dimensional volumetric units—essentially, boxes—which can be stacked and joined together for a wide range of architectural massing and geometries. There is growing interest in this type of construction in multiple segments including hospitality, multifamily, and healthcare, where there is a higher prevalence of reasonably consistent repeating units. Single-family use cases are also emerging. Early adopters in this market include major hotel chains such as Marriott and Hilton, and various multifamily housing developers.[17]

Panelized Construction

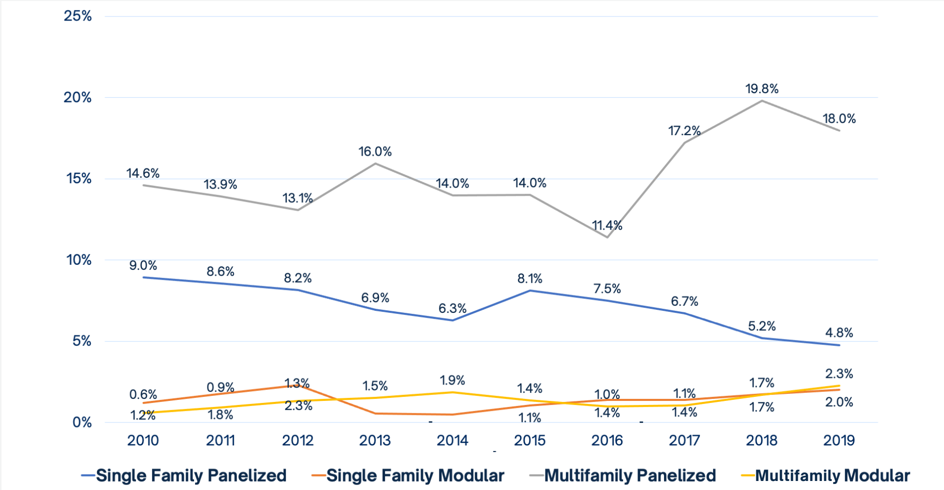
Panelized construction consists of flat wall, floor cassette, or roof sections that can be stacked for shipping. Panelization can be as simple as a stud wall or roof truss section—or as sophisticated as a finished wall section with insulation and façade materials (and even mechanical, electrical, and plumbing components) already neatly incorporated. SIPs and precast concrete panels are types of panelized construction with a relatively long history of use and many examples of high-performance applications. SIPs consist of an insulating foam core sandwiched between two structural facings. SIPs can be fabricated to fit nearly any building design.[18] The major advantages of SIPs are reduced construction timelines and improved energy efficiency; however, they have struggled to gain major traction in the market. Although few panel manufacturers are currently incorporating mechanical, electrical, and plumbing (MEP) systems into their panel products, the possibility exists to do so, potentially with additional productivity benefits. The greater complexity of connection points between panels with integrated MEP systems can be a challenge with this approach.

Use cases of panelized and modular construction remain limited in scope compared with traditional on-site construction, although panelized construction is more common than volumetric modular. Home Innovation Research Labs' 2019 Annual Builder Practices Survey reported that less than 2.5% of single-family and multifamily builders use modular approaches, whereas roughly 5% of single-family builders and 18% of multifamily builders used panelized walls (see Exhibit 2.2.1.1).[19]

Even so, examining other use cases in which prefabrication has been entrenched suggests great potential for growth of prefabrication in other construction areas. In 2019, trusses—the vast majority of which are prefabricated—were used in 62% of new roof construction in single-family homes and 76% of new roof construction in apartments (see Exhibits 2.2.1.2 and 2.2.1.3). The case of residential roof construction, albeit narrow, indicates that high penetration of prefabrication as part of broadly accepted construction practices is possible and could be viable for other assemblies (or packages), as well.

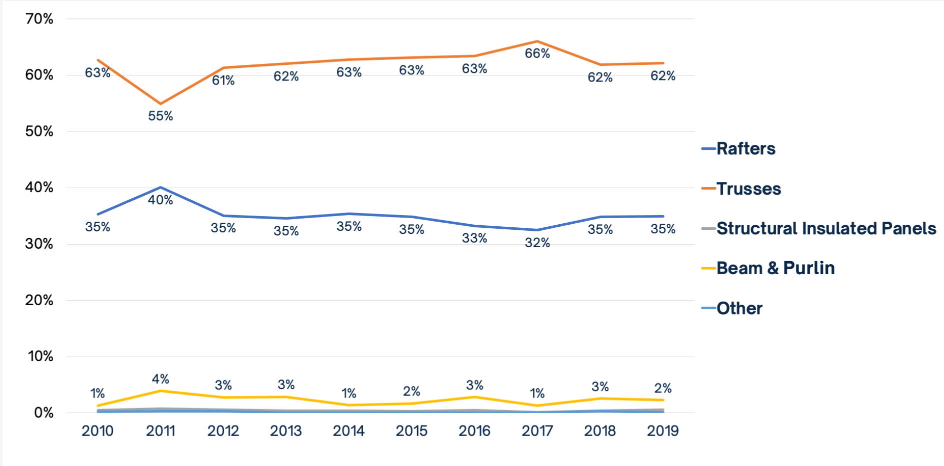
Image courtesy of Sto Corp.

Exhibit 2.2.1.1 Share of New Single-Family and Multifamily Homes Using Panelized and Modular Approaches.



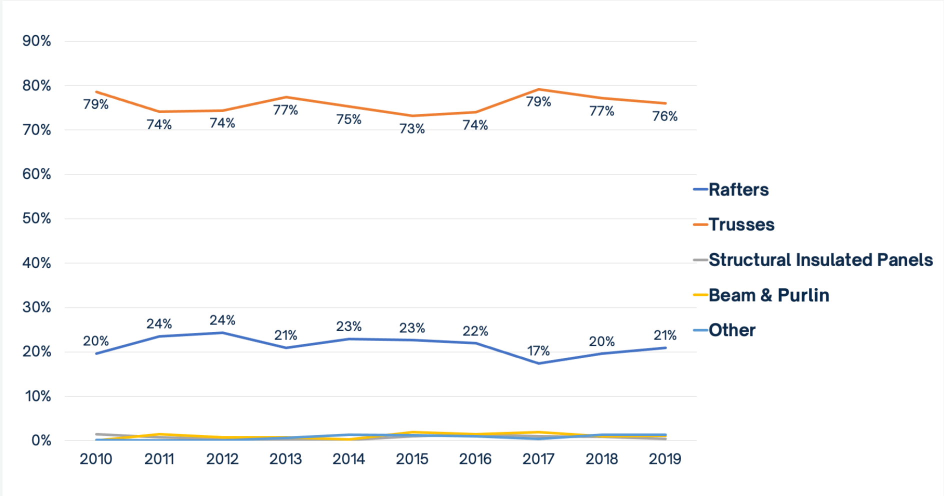
Source: Annual Builder Practices Report, Home Innovation Research Labs, 2020.

Exhibit 2.2.1.2 Distribution of Roof Construction Method in Single-Family Homes.



Source: Annual Builder Practices Report, Home Innovation Research Labs, 2020.

Exhibit 2.2.1.3 Distribution of Roof Construction Method in New Apartments and Townhomes.



Source: Annual Builder Practices Report, Home Innovation Research Labs, 2020.

Precast Concrete

Although perhaps less touted as an advanced fabrication technique, precast concrete is one of the most common examples of prefabricated construction. Prepared at an off-site facility using molds, precast concrete is used most typically for structural elements like wall panels, beams, and floors. However, it can be utilized for a wide range of products for various construction needs.[20] The casting of concrete in a controlled environment increases safety as well as quality replication.[21] The global precast concrete market size is projected to grow from $130.6 billion in 2020 to $174.1 billion by 2025, at a compound annual growth rate of 5.9%.[22]

Additive and Subtractive Manufacturing

Additive manufacturing builds objects by layering material. Three-dimensional (3D) printing is an emerging example of additive manufacturing technology. Utilizing software and robotic machinery, 3D products are printed by precisely layering complex sections.[23] Depending on the technology, design, and materials, printing can be executed either directly on-site or in a factory (with printed products then delivered to and assembled at the site). Although novel, there are use cases of 3D printing for single-family homes (such as by California-based Mighty Buildings) and commercial office buildings.

Subtractive manufacturing utilizes computer numerical control, laser removal, electrical discharge machining, and water jet cutting to remove material from wood, polymers, and metals to create parts for prototyping, manufacturing tooling, and end-use applications.[24] Subtractive manufacturing is ideal for products with unique geometries that are difficult to produce with traditional methods. The adaptability of additive and subtractive manufacturing can make these advanced manufacturing technologies more attractive for a variety of jobs. In addition to the adaptability, other advantages inherent to additive and subtractive technology are reductions in overall construction timelines and waste.

Pods and Functional Modules

A pod is a turnkey prefabricated subassembly of multiple equipment systems that is installed as a single module, often with all associated components and accessories. These include premanufactured elevator modules; staircases; rough-in ready electrical systems; and bathroom, mechanical, medical, and research pods. These elements have high value as premanufactured products because of their inherent complexity and because, with a conventional approach, multiple separate trades are required in a tight physical and temporal space for on-site fabrication, often leading to scheduling complexity, inefficiencies, missed hand-offs, and delays.[25] There are successful use cases of mechanical pods containing HVAC, DHW, controls, and even a solar photovoltaic inverter used as an element of zero energy retrofits (for example, by the European Energiesprong program), and this is an area of active research.

Images courtesy of Clark Pacific, Energiesprong, and Mighty Buildings

2.2.2 Retrofit of Existing Buildings

A largely untapped application for industrialized construction is the retrofitting of existing building stock. In the US, there are some four billion square feet of new buildings constructed per year. However, the potential addressable retrofit market—conservatively, buildings built prior to 1980—is approximately 160 billion square feet of existing buildings, or more than forty times larger.[26] Inclusion of buildings that were constructed prior to 1990 in the retrofit market increases the addressable square footage to 204 billion.[27]

Notable retrofitting initiatives have been successfully implemented in other countries, but a robust technical approach and value chain has yet to be established and scaled up for multi- and single-family (as well as commercial) retrofits in the US market. Energiesprong, a Netherlands-based program that integrates several envelope and MEP retrofit measures in a streamlined delivery program, has recently been rolled out to multiple countries in Europe and provides a model for successful retrofitting of residential buildings.[28]

Energiesprong has proven the technical and practical viability of producing refreshed net-zero energy buildings with substantially reduced disruption compared with traditional deep-energy retrofits or other major rehabs. Energiesprong retrofit packages include prefabricated unitized wall panels (windows and doors are included in the assembly); insulated roof panels (optionally with pre-installed solar panel racking); and a mechanical pod with a heat pump for space heating and domestic hot water, energy recovery ventilator, controls, and (where rooftop solar photovoltaics could be installed) a solar inverter. These technologies can be manufactured and delivered with the high quality and speed of industrialized construction, precisely built based on an accurate digital scan site capture of existing conditions.

The Energiesprong program accelerated the development of energy-saving concepts by taking an integrated (supply chain) approach to design and construction, while also pushing acceptance of novel systems by using energy performance contracts that guarantee performance for at least 30 years. Energiesprong scaling plans include facilitating 100,000 multifamily unit retrofits across Europe.

Retrofitting initiatives in the United States, such as RMI's REALIZE initiative and NYSERDA's RetrofitNY, have adapted elements of the Energiesprong model and are demonstrating feasibility in the US market. These Energiesprong-inspired US programs have shown early success in California and New York. REALIZE and RetrofitNY have been leaders in exploring and promoting the possibilities of an Energiesprong-style approach, with the goal of delivering cost compression via increased market experience and scale.[29]

The overall scope and pace of retrofit activities in the United States, however, must well exceed those undertaken in Europe due to the size of the US building stock. The challenge may also be greater in the United States, as less of the domestic multifamily housing stock is publicly controlled, and neither the climate zones nor the building typologies are as uniform as in some European countries. Additionally, multifamily housing represents only one major building segment; retrofit solutions for single-family housing and commercial buildings will require innovative new technical, financing, and deployment approaches.

Adapting the most successful elements of Energiesprong's methodologies to the diverse national building stock—and to major segments including single-family housing and commercial buildings—will require a varied but coherent set of innovative technical, financing, and deployment options that can be deployed to provide suitable solutions for a range of retrofit needs. Due to these considerations, a streamlined cost-optimized process for retrofit and flexible off-site manufacturing doctrine must be developed to allow for adaptability and customization on a project-by-project basis in the United States.

2.2.3 Production Capacity

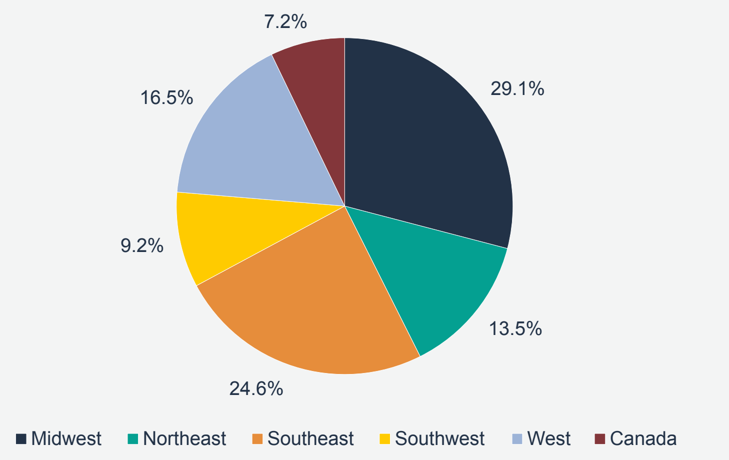
The production capacity numbers examined in this section are specific to off-site construction intended to meet requirements based on the International Residential Code (IRC). Off-site manufactured homes regulated by the US Department of Housing and Urban Development (HUD) are not included in this analysis. (Notwithstanding this exclusion, HUD code homes are an integral part of the US housing market, accounting for 9% of new home builds in 2017.)[30]

Although industry-wide prefabricated and modular production capacity is difficult to discern with certainty, an informed estimate puts current capacity at one million square feet of floor area per week.[31] This number was based on the total capacity of Modular Mobilization Coalition affiliates and the relative percentage of the market that they make up.[32] This represents a fraction of the likely market share addressable with modular approaches. Even without new factories, fabricators could add shifts to existing lines and implement process improvement automation to bolster throughput from existing facilities.

As an initial step to help clarify US production capabilities, the ABC Collaborative examined a total of 271 modular and prefabrication production companies to identify regional distribution and production classification of prefab facilities.

Exhibit 2.3.3.1

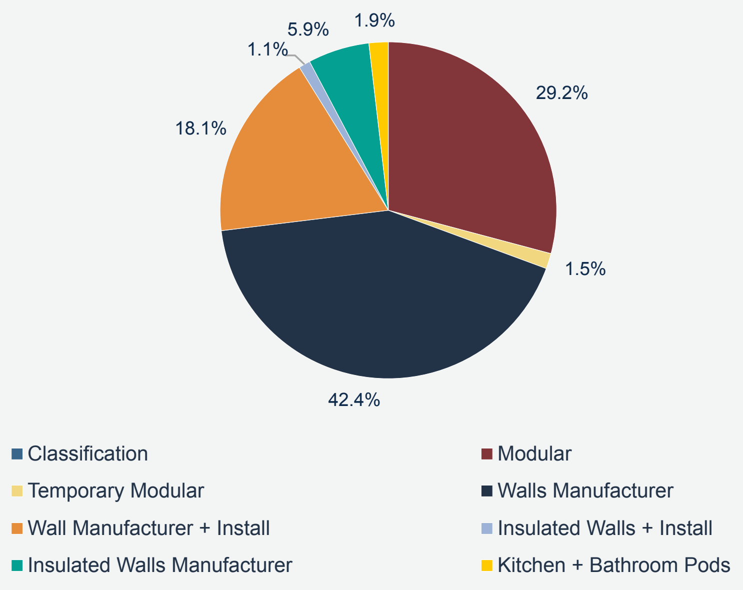
Regional Distribution of Modular and Prefabrication Production Facilities



Source: Analysis of Modular and Prefabrication Production Facilities, ABC Collaborative, 2021

Exhibit 2.3.3.2

Distribution of Modular and Prefabrication Facility Production Type Based on Housing Innovation Alliance Classification[33]



Source: Analysis of Modular and Prefabrication Production Facilities, ABC Collaborative, 2021

As shown in Exhibits 2.3.3.1 and 2.3.3.2, prefabricated and modular construction facilities are geographically concentrated in the Midwest (29.1%) and the Southeast (24.6%). In terms of production type, wall manufacturers comprise the largest segment (42.4%). This research relied heavily on a database made available by the Housing Innovation Alliance.[34,i] The ABC Collaborative will continue to gather data on capacity and opportunities to increase production to inform its activities and support the objectives of the Collaborative, its members, and other partners.

2.3 Case Studies: Examining Overseas Best Practices to Guide US Innovation

There are several global and US-based initiatives with operating models and case-based evidence to highlight the barriers and success factors for new technologies in construction specific to ABC. This section discusses a few of these examples in the context of both global and US adoption trends.

2.3.1 A Mature Market Overseas

The two case studies in the current section, from Sweden and Japan, illustrate some key elements of successful off-site construction.

Lindbäcks Bygg

Sweden's industrialized construction industry has reached a remarkable 84% share of the country's detached-home market by emphasizing the sustainable and affordable characteristics of modular construction.[35] The industry's proven success with consumers has increased and maintained confidence, a significant hurdle faced by other markets struggling to implement industrialized construction in the face of misgivings around quality and limited customer familiarity.

Lindbäcks Bygg (Lindbäcks) is a model of Sweden's impressive automation capabilities. Lindbäcks, a company with more than 500 employees, has been working in the industrialized construction space for decades and can produce more than 25,000 square feet of turnkey housing per week.[36] One facility Lindbäcks built in 2018 is staffed by 150 workers and has a capacity of 16 volumetric units per working day—equivalent to roughly 2,060 square feet. Together with its older manufacturing facility, Lindbäcks can produce 2,400 modules per year.[37] The company has managed to increase its production capacity and outcompete its rivals by successfully integrating assembly line robotics equipment from Randek.[38]

i The database available via Housing Innovation Alliance's website is continually updated as current data on geographical distribution and type of prefabricated and modular facilities becomes available.

Sekisui Heims

As of 2018, 15% of Japan's newly constructed homes and apartments were manufactured off site.[39] Sekisui Heims, the house-building subsidiary of the 27,000-employee Sekisui Chemical Company, has eight factories across Japan and is one of the largest Japanese home manufacturers, regularly producing more than 14,000 new prefabricated homes every year.[40] Sekisui has leveraged its high-technology approach to edge its way into foreign markets such as the UK and the US after acquiring one of the top 30 homebuilders in the United States, Woodside Homes, in 2017.

Although Japan's off-site industry has been in place since the 1950s, the primary selling points have changed over the years. After initially highlighting the speed and affordability benefits of prefabrication, Japan's modular industry shifted to marketing the quality improvements supported by standardization. Concurrently, the industry realized the demand for customization and adapted accordingly.

A few aspects in Japan's housing market facilitated the growth of off-site construction. Until recently, Japan's residential property owners often chose to demolish rather than renovate homes.[41] This choice is influenced by rapid property depreciation and structural code revisions. However, recent trends in Japan point toward higher refurbishment, and the high quality of modern industrialized construction has fueled the desire for homes with greater longevity while still maintaining affordability.

2.3.2 Growing Pains of a Nascent Sector in the United States

High-profile efforts to "reinvent" US construction have generated excitement both within and outside the industry in recent years, with increased demand and appetite for financial investment helping fuel a healthy competitive environment with varied approaches and strategies. From 2015 to 2019, venture capital firms invested $5.1 billion in 571 deals related to construction technology.[42] This venture capital (VC) activity, along with other corporate investment and M&A, family office, private equity, and search fund activity, have helped bring industrialized construction and related enabling technologies into the "early innings" of an exciting transition to mass production scale.

McKinsey estimates that total investment across all asset classes into construction technology totaled $25 billion from 2014 to 2019.[43] Without improved market coordination, however, these aggressive scaling efforts also bring increased financial and operational risk during the maturation phase, which can unduly increase the perceived risk of industrialized construction to customers and investors.

Katerra was founded in 2015 and raised more than $2 billion before shuttering US operations in 2021. It is an example of a company that attracted significant strategic and venture capital support to transform the industry utilizing a proprietary approach built around closed digitization and production platforms.[44] Katerra attempted to address barriers such as split incentives and fragmentation through vertical integration of supply and design. In June of 2021, Katerra announced it was ending all US business operations and exiting several existing construction projects.

The full background behind this industrialized construction company's abrupt end remains unclear. However, some major outliers in Katerra's business strategy include a heavy focus on both horizontal and vertical acquisitions, with limited commitment to real business unit integration. Backed by investors and management from the high-tech sector, the start-up sought to build a broad innovation platform similar in ways to those built by Apple, Google, Microsoft, and other highly successful technology companies.

However, the slow and fragmented construction industry lacks two of the most critical market characteristics for generating the necessary network effects fueling these rapid growth businesses. For one, the industry lacks fast innovation and short product life cycles, which enable rapid switching and updates. Additionally, there is no market concentration, which enables tipping toward a solution of choice.[45] McKinsey research predicts that platforms that do become successful in construction will likely start out much narrower to enable that more rapid acceptance in a high-value niche.

It is worth noting that, while active, Katerra demonstrated some operational advancements and successes in its cross-laminated timber work, where it took an integrated approach that brought together design, software and digitized workflows, fabrication, and field operations. This supports the case for value chain coordination and integration as a potential component of success in advanced industrialized construction, while also reinforcing the need to include and utilize the perspectives and resources of a much broader set of industry players.

The recent rise and fall of Skender's exciting efforts in off-site construction provide another data point showing the need for a more collaborative approach. Skender entered the off-site market in 2019 with strong financial backing and much fanfare around a significant push in the hospitality segment. But, after seemingly aggregating substantial demand, Skender's effort was derailed by the COVID-19 pandemic. "It's a chicken-and-egg problem," a Skender spokesperson said. "How do you get that scale when there's a lot of uncertainty? It takes the whole ecosystem from the developer, the investor, the construction company, and the manufacturer to make a concerted effort to see the big picture."[46]

In contrast, Prescient, another well-funded player, which was founded in 2012 and has raised $295.4 million, focuses tightly on the steel frame high-rise market. It has avoided major financial issues to date in part due to its vertically integrated but focused delivery system set up with supply chain partners involving strict control of the design by software, as well as factory automation provided by trusted outside vendors where possible.[47]

Several regional volumetric and panelized players have also maintained profitability focusing on narrower niches within regional markets with urgent near-term needs that are a natural match for prefabrication (e.g., educational or medical facilities).

Finding exact product-market fit and strong demand early in the development processes is a common theme across many ABC successes to date. Frey-Moss Structures is a modular building manufacturer specializing in small retail, convenience, and fast-food projects. Founded in 1992, Frey-Moss recently partnered with Chick-fil-A, one of America's largest fast-food chains, to rebuild one of the chain's restaurants using modular construction. Frey-Moss has partnered with other fast-food restaurants and gas stations to offer efficient construction in a timeframe that fits the needs of its service sector clients.

Canada-based Nexii appears poised to make similar inroads as it significantly scales up its facilities and operations in North America with a flagship customer in foodservice franchising, and emerging relationships with other national and international brands. Nexii plans to adapt the general elements of this offering to other foodservice operations as well as other segments of commercial construction, potentially in cooperation with the ABC Collaborative.

The Collaborative aims to learn from past examples of successes, limitations, and failures relevant to ABC. For additional examples of successes and failures in industrialized construction, please refer to section 6.2 in the Appendix.

2.4 Construction Workforce

> ***"There is such localization of job creation when you're talking about retrofitting buildings that this has the potential to be one of the biggest jobs programs that we've ever had. It's intensely local, and it requires really smart people to have really good skills in plumbing, in wiring, electricians: Incredibly important occupations we can rebuild."***
>
> ***– US Representative Peter Welch (VT)***[48]

ABC and related industrialized construction approaches have significant "up-skill" benefits, which can be leveraged to increase diversity, equity, and inclusion in the construction workforce and widen the accessibility of jobs. Off-site construction in controlled factory environments with increased comfort and safety can reduce typical labor pool constraints (e.g., a requirement to lift 25 or 50 pounds on a job site) and risk of injuries. This, along with effective workforce training, can enable unemployed or underemployed low-skill and unskilled labor to transition into construction, addressing worker shortages. Overall, off-site manufacturing facilities have doubled or tripled both the indirect (supply chain) and induced (community) job multipliers of on-site construction because they are permanent and more vertically integrated.[49]

However, these facilities have significant capital and carrying costs, requiring a steady pipeline of demand to support them. Building retrofits represent a tremendous source of new work volume and can potentially offer a rich training and employment opportunity for trades in urban areas for the foreseeable future. Leveraging high school programs, community colleges, and trade associations to provide curricula could also offer localized pathways to educate and train new workers, leading to a younger and revitalized workforce. Additionally, the logistically strategic siting of industrialized construction manufacturing facilities could support skilled and semi-skilled employment in rural and economically depressed areas. In addition to the trades, construction and manufacturing management throughout the supply chain will require integrated product delivery and lean manufacturing skills.

Thoughtful implementation of new building construction norms also needs to recognize that up-skilling is not the only requirement in this area. Barriers to participating in new opportunities must be addressed. These considerations can include a shift in work location (by geography and urban–rural shifts), in the demographics of people performing the work, and in accompanying support required (e.g., transportation or childcare). By comprehensively looking at the changes required by ABC, the industry can find the workers needed, provide worker-focused opportunities and benefits, and improve the productivity of the sector significantly.

2.5 Converging with Technology Trends

Building efficiency and electrification are critical to building decarbonization and are congruent with a shift toward a low-carbon, renewables-based grid. Without energy-efficient envelopes and mechanical systems, electrification of (undiminished) building thermal loads may tax the grid, an issue compounded by the increasing penetration of electric vehicles and associated charging needs. Broadly reducing the total energy requirements of buildings (and increasing on-site generation) lessens the demand placed on the grid. Meanwhile, electrifying building loads allows the benefits of increasingly low-carbon power generation to carry through to building operation and opens the door to more comprehensive grid interactivity.

Effective, intelligent building operation goes hand in hand with efficiency and electrification. Beyond the use of more efficient, electrified equipment, an optimally run building management system can generate substantial cost, energy, and carbon savings—and, when it interacts dynamically with the grid, can provide local and grid-level resilience benefits. Additionally, in existing buildings, initial savings from optimized operation may free up resources to invest in further efficiency measures.

Manufacturing approaches to construction dovetail with building efficiency, electrification, and smart building systems. Beyond the general benefits of factory production—such as productivity and profitability from repeatability and scale—industrialized construction provides a highly suitable platform for the precise incorporation of building energy efficiency measures and integration with complementary technologies. These can include smart controls, energy generation and storage, and grid interactivity. The controlled nature of manufacturing facilities meets the need of energy-efficient design for quality and tight tolerances and eases the incorporation of sensitive technologies for monitoring energy consumption, collecting building operations data, and connecting to community information infrastructure.

Current costs of deep energy retrofits and highly efficient electrified mechanical systems make a wholesale transformation of the building stock difficult. Emergent ABC technologies and approaches as well as ongoing cost compression driven by increasing supplier experience and project volumes must be leveraged to address the cost challenge. The sheer volume of retrofit and new construction activity needed to meet climate goals requires modernized construction manufacturing approaches. Likewise, this volume represents a set of potential demand pipelines that can justify the development and scaling of such approaches—although the substantial investments this entails make private- and public-sector participation as well as strategic market prioritization essential.

Image from Shutterfly

3. Market Prioritization

To assess relevant challenges for adopting ABC technologies and draw conclusions for how to overcome them, the ABC Collaborative researched the status of ABC and off-site methodologies through literature reviews, data analysis, and expert consultation. This section focuses on the literature review and data analysis components and is composed of three parts: (1) meta-analysis (section 3.1), (2) a state prioritization analysis aimed at establishing a geographical prioritization model (section 3.2), and (3) a review of key market segments and the opportunity for implementing high-performance building technologies (section 3.3).

3.1 Technology Meta-Analysis

To help identify both areas of already robust activity, as well as potential gaps relative to critical market needs, the ABC Collaborative conducted a detailed, three-part meta-analysis examining innovative construction-related technologies. This meta-analysis compares and contrasts what the industry considers to be areas requiring in-depth research (the research literature), technologies and approaches that hold considerable perceived market value (the patent literature), and concepts and topics that generate excitement or concern among professionals and tradespeople (a major trade publication). The meta-analysis is intended as a resource for deeper investigation into areas of interest and cutting-edge developments of high value to the industry and can help inform prioritization of ABC investments by federal and industry stakeholders.

The ABC Collaborative worked closely with national laboratory staff to compile a comprehensive list of technology topics related to building prefabrication, retrofit, and HVAC. The Collaborative used ADL Ventures' proprietary ProblemSpace tool, which has an intrinsic natural language processing layer that ranks the relevance of each article, to identify and extract peer-reviewed academic journal articles and patents relevant to these technology topics. To complement this analysis, the Collaborative ran a similar analysis on a widely read industry trade publication (Construction Dive), searching for commonly mentioned terms. After ranking and cleaning, the data were grouped by technology topic, publication or filing year, and geographic location, and visualized in a series of interactive web-based dashboards.

This indexing work covered more than 5,000 patents and 4,000 journal articles spanning 80 years of research and patent activity. A clear trend is a significant uptick in published research activity in ABC technology areas from 2016 to 2021, while patent activity has been steadily increasing since 2010 and accelerating since 2019. The trade publication represents a smaller dataset from 2015 to 2021 and is presented to complement the summary of academic and patent activity with current developments within the construction industry.

The following trends emerged from this meta-analysis:

1. **Patent Filings**
   - Activity in the areas of interest is dominated by the United States and Asia.
   - HVAC was the most active area for patent activity in the United States, while prefabrication was more active in Asia. In Europe, with relatively less activity, prefabrication was the top area of activity. Within the HVAC patents, controls were of highest interest.
   - In the patent literature concerning prefabrication, walls were mentioned prominently, and attachment methods were highly represented, including both sealant and fastening topics.

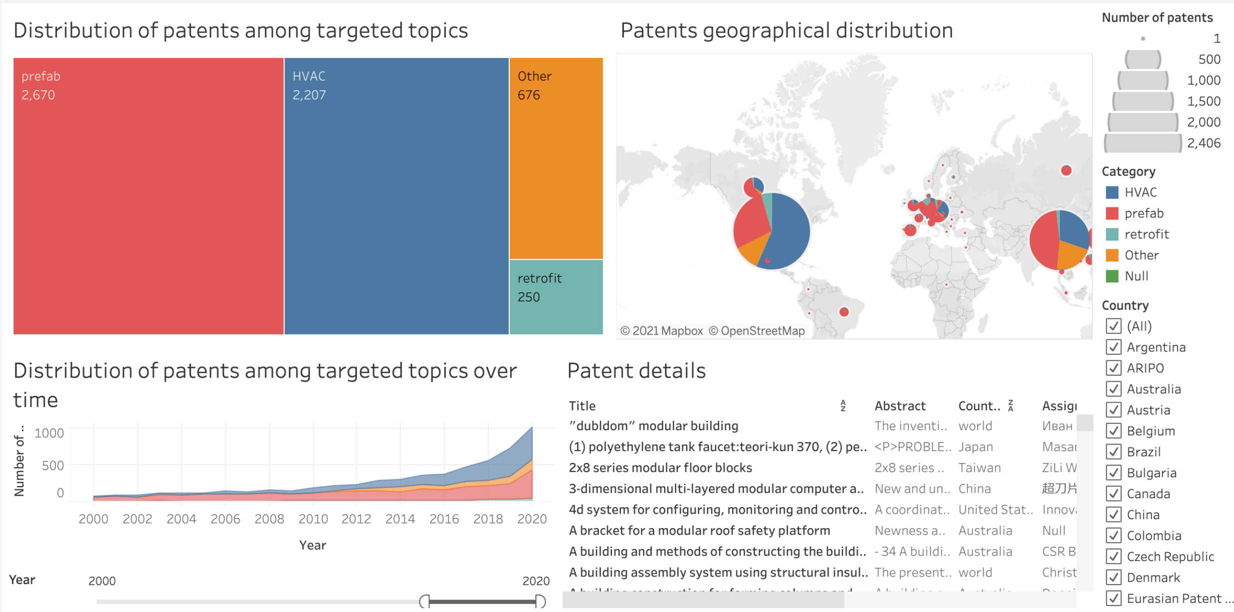
2. **Peer-Reviewed Publications**
   - HVAC was the top area of activity, with retrofit second. The building type most mentioned overall was residential, followed by office buildings.
   - Mentions of sensors and diagnostics appeared frequently in the literature for retrofits.

3. **Industry Trade Publication**
   - HVAC literature showed a focus on air quality in addition to technologies for efficient heating and cooling.
   - There was a much greater focus on enabling technologies for construction such as drones and robotics as compared to what was found in patents and research literature.
   - The safety and health of workers also appeared as an area of high interest, especially during 2020 with COVID-19.

View the Patent Dashboard, Research Dashboard, and Trade Publication Visualizations.

Exhibit 3.1 Illustrative Screenshot of the dynamic ABC Meta-Analysis Dashboard for Patents

View the Patent Dashboard, Research Dashboard, and Trade Publication Visualizations.



Source: Meta-Analysis, ABC Collaborative, 2021.

3.2 State Prioritization Analysis

As part of characterizing the opportunities to implement emerging ABC solutions, assessing the unique geographies and markets in the US and their current and potential suitability to ABC is critical in determining which regions and segments offer the most promise to maximize near-term market impact. This is especially true given differing policy and regulatory environments, as well as differing requirements for buildings by climate zone.

This broader and more holistic state prioritization analysis differs in notable ways from previous efforts that have mainly focused on states' policy environments surrounding energy efficiency. The ABC Collaborative and DOE began by conducting this analysis at the state level, as opposed to the city or local level, primarily because of the availability of data inputs for states, especially for the construction industry, building codes and standards, and policy incentive data. Focusing the analysis on states enables the inclusion of directly comparable metrics while returning a set of findings that is both manageable and specific enough to be useful. This analysis is based primarily on market and political factors as well as system-level metrics to provide a broad assessment of state-level opportunities.

It complements the quantitative US Building Stock Characterization Study currently in development by NREL with the support of the ABC Collaborative team.

3.2.1 Scoring Structure

The outcome of the study is a top-down ranking of US states based on their energy-related emissions, energy costs, economic environment, construction and building sector needs, and political environment. These factors determine the suitability for early implementation of ABC technologies and practices and identify where these innovations can have the most impact. Five primary metrics of equal weight were used to calculate the final score (out of 100):

1. **Energy-Related Emissions**: Two metrics are applied to residential and commercial building sectors: (1) total energy-related CO2 emissions (tons CO2) and (2) average CO2 intensity of energy consumption (kg CO/ft2), both of which are from 2017, the most recent year of available data. Higher scores are given for larger CO2 emission values because both metrics indicate greater opportunities to reduce emissions in pursuit of a carbon-neutral building sector.

2. **Energy Costs**: Three metrics are applied to the residential and commercial building sectors: (1) the retail cost of electricity (cents/kWh), (2) the retail cost of gas (cents/kWh), and (3) the ratio of the cost of heating with gas to heating with electricity, all for the year 2019. A higher ratio indicates the retail cost of heating with gas is higher relative to the retail cost of heating with electricity. To capture the opportunities for utility cost savings via electrification of heating end uses, states with higher ratios have higher scores.
3. **Economic Environment**: Three individual metrics are applied: (1) the state's existing programs incentivizing renewable energy and advanced manufacturing, (2) the contribution of the state's construction sector to the state's GDP in 2019, and (3) the size of the state's 2019 construction workforce relative to the national construction workforce. Collectively, these metrics are used to assess the ability of each state to incorporate ABC manufacturing and deployment into its economic development strategy.
4. **Construction and Buildings Sector Needs**: Two metrics are applied to residential and commercial sectors: (1) the number of building permits issued per total existing building area in 2019 and (2) population change in each state in 2018, inclusive of net migration and natural population change. States with higher values in these metrics are assigned higher scores, suggesting more building construction activity and increased need for new construction.
5. **Political Environment:** Five metrics are applied including three metrics from the 2020 ACEEE State Efficiency Scorecard: (1) state scores for building policies, (2) state scores for state-led initiatives, and (3) available incentives for energy efficiency.[50] The other metrics are (4) a binary indicator for whether the state is a member of the US Climate Alliance and (5) a binary measure of whether a state has a statewide carbon reduction target. A high political score indicates a favorable political environment for ABC development and deployment.

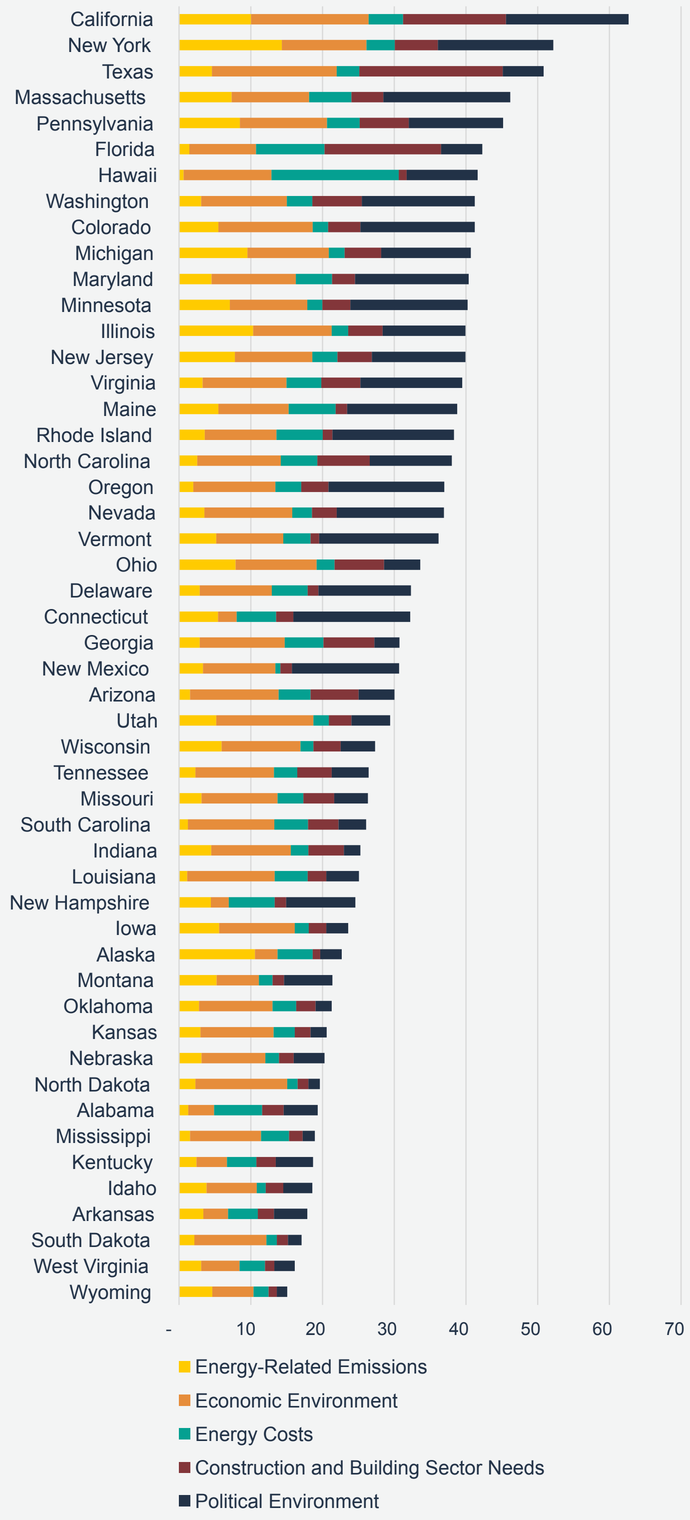
3.2.2 Results and Takeaways

Exhibit 3.2.2.1 presents all the composite scores in descending order. For a comprehensive overview of the scoring methodology, including metrics, sources, and assigned weights, refer to Exhibit 3.2.2.2 in Appendix section 6.1.

As shown in Exhibit 3.2.2.1, California, New York, Texas, Massachusetts, and Pennsylvania received the highest composite scores of 62.66, 52.17, 50.81, 46.17, and 45.18, respectively. Conversely, Wyoming received the lowest score of 15.07, followed by West Virginia, South Dakota, Arkansas, and Idaho. It is important to note, however, that these metrics are dynamic, not static, and that suitable opportunities for ABC exist nationwide.

Exhibit 3.2.2.1

State Prioritization Analysis Results by Metric Category



Source: State Prioritization Analysis, ABC Collaborative, 2021

The Top Five

This section presents a detailed overview of metric rankings and drivers for the top five ranking states. For a complete layout of state rankings across all categories, refer to Exhibit 3.2.2.3 in Appendix section 6.1.

1. California

California scored nearly 10% more points than New York, the second-highest scoring state, and ranked within the top five states in four out of five categories. California ranked second in the Political Environment metric due to its statutory and executive carbon reduction targets, US Climate Alliance membership, large number of state-led initiatives, and strong policies for building energy efficiency.

In the Construction and Building Sector Needs and Economic Environment metrics, California ranked in the top three behind Texas and Florida. These scores include California's $123-billion construction sector contribution to state GDP and an 11.6% share of the national construction workforce in 2019.[51] California ranked 4th in the Energy-Related Emissions metric primarily because of its high total energy-related CO2 emissions.

California's lowest ranking was 16th place in the Energy Costs metric. Despite comparatively high retail electricity and gas rates, gas being cheaper than electricity in California reduced the state's score due to less favorable costs for electrification. In addition to the metrics contributing to California's score, the state is in the midst of a well-documented housing crisis that has prompted bold and ambitious responses to address housing shortages. Roadmap Home 2030, released by Housing California and California Housing Partnership, outlines an ambitious goal to build 1.2 million new affordable homes for low-income residents by 2030.[52] California is well suited for the initial deployment of ABC to meet this level of housing demand in a cost-effective and high-performance manner.

2. New York

Energy-Related Emissions are the driving force for New York's second-highest composite score. New York's CO2 emissions score, compiled from total and building square foot–normalized residential and commercial energy-related CO2 emissions, was the highest of any state. The state's scores in Political Environment, headlined by cutting-edge initiatives like NYSERDA's RetrofitNY in building retrofit and underlying technology development, and Construction and Building Sector Needs rank 8th and 10th, respectively.

New York received a high score on the Political Environment metric given a policy environment that is similarly supportive for building efficiency as California's, though New York has slightly lower 2020 state energy efficiency scores for state-led initiatives and building policies. New York ranked 23rd in Energy Costs and 14th in Economic Environment metrics. Regarding the former ranking, New York is similar to California in that it has relatively high retail energy rates but less favorable economics for electrification given electricity rates that are nearly double its rates for natural gas. Regarding the latter ranking, New York's construction sector contributes substantial value when compared with other states, but as a percentage of its own GDP, New York's construction sector contributes comparatively little.

3. Texas

Texas ranked first in the Construction and Building Sector Needs metric due to having the largest population influx in 2018 and issuing the highest number of building permits per total existing building area in 2019. Texas also narrowly ranked first in the Economic Environment metric, with California trailing, due to its comparatively larger construction sector contribution to state GDP (5.3% in 2019).

Texas ranked close to the average in the other three metrics: 20th in Energy-Related Emissions, 26th in Political Environment, and 32nd in Energy Costs. A catastrophic series of recent cold-weather events, which caused rolling blackouts and exposed the inefficient nature of existing infrastructure in many parts of the state, show that opportunities in specific building markets within Texas may be more significant than the current scoring metrics suggest. This is because these are based on averages, whereas short-term energy costs (as well as related negative externalities) can be amplified during extreme weather events. This impact may be especially pronounced in Texas, given its peculiar deregulated energy market and the reported chronic lack of political action to address significant grid vulnerabilities.[53]

4. Massachusetts

Massachusetts ranked first in the Political Environment score. Like California, Massachusetts has statutory and executive carbon reduction targets, and strong state-led initiatives related to building energy efficiency. Massachusetts received a higher Political Environment score than California because of more ambitious Energy Efficiency Resource Standards (EERSs), which target higher electricity and gas savings as a percentage of total retail energy sales. Massachusetts scored in the top 20 states for all other metrics: 7th in Energy Costs, 9th in Energy-Related Emissions, 25th in Economic Environment, and 18th in Construction and Building Sector Needs. Factors contributing to these rankings include above-average residential and commercial retail electricity prices and energy-related CO2 emissions, as well as substantial construction sector employment.

5. Pennsylvania

Pennsylvania's composite metric score put the state in fifth place, narrowly leading sixth-place Florida. Pennsylvania's highest score was on the Energy-Related Emissions metric due to having high energy-related CO2 emissions for the most recent year of available data. Pennsylvania ranked 10th in Economic Environment, consistent with the state's construction sector contribution to state GDP and national construction workforce share.

Pennsylvania's lowest ranking is in the Energy Costs metric where it ranked 17th. Like in California and New York, the costs of heating with electricity are higher than with gas in Pennsylvania, though only by a factor of 1.15, which is a lower ratio than in either California or New York. Pennsylvania ranked 8th in Construction and Building Sector Needs and 16th in Political Environment, largely due to its lack of state-wide statutory carbon reduction targets and low EERS scores.

Key Takeaways

Together, California, New York, Texas, Massachusetts, and Pennsylvania issued 406,215 building permits in 2019, which is over 29% of the total building permits that were issued in the United States that year.[54] The construction workforce of the five states combined makes up 32% of the entire US construction workforce.[55] Similarly, these five states represent 31% of total building sector CO2 emissions from energy consumption using the most recent year of available data (2017).[56]

This analysis indicates regional variability in opportunity, with New York, Massachusetts, and Pennsylvania in the Northeast, Texas in the South, and California in the West. These five states represent the most initial markets for ABC solutions and, taken together, amount to a substantial share of US construction activity. Placing an initial focus on technology development addressing the needs of these large states could support sufficient near-term demand (and decarbonization potential) to justify significant external investment. Additionally, creating ABC solutions for these states and their large construction share could influence standards and conventions used elsewhere.

Outside the top five states, Florida (ranked 6th) and Hawaii (ranked 7th) had high scoring in metrics that may be particularly strong drivers for near-term market adoption of ABC, in particular, rapid construction growth in Florida and high energy costs in Hawaii. Florida ranked second in the Energy Costs and Construction and Building Sector needs metrics. Florida had the second-largest number of building permits issued in 2019 and the second-largest population influx resulting in a Construction and Building Sector needs score that ranked second overall. The reasons for Hawaii's high ranking include high scores on the Energy Costs metric, due to very high relative electricity prices as a result of high oil prices and fixed infrastructure costs, as well as high scores for Economic Environment, due primarily to its productive construction sector.[57]

With the right investment to achieve statewide scale, Hawaii could become a strong market for ABC activity, which could create higher-quality employment opportunities and buildings in a state that struggles with both. However, Hawaii also presents several unique challenges for ABC solutions deployment given its remote location, somewhat limited new construction activity, and small building and carbon footprint.

It is important to note that the states near the bottom of the composite score rank have substantially lower populations (and, in many cases, population densities) than those at the top. For example, Wyoming, West Virginia, South Dakota, Arkansas, and Idaho each contribute less than 1% of the US population. Wyoming and West Virginia, the two lowest-ranking states, had the largest shares of US coal production in 2019.[58]

Regions transitioning out of legacy fuel sectors in the coming years could be well-positioned to capitalize on the employment and economic benefits resulting from ABC. In particular, performing off-site construction that can be deployed in higher population areas may help facilitate a more equitable transition for workers in these sectors. A successful example of this from the renewables industry is Pueblo, CO, which dropped from the 2nd to 10th largest city in Colorado following the closing of steel production facilities in the 1980s and 1990s. It is now the site of a Vesta wind turbine plant, which employs 900 people and has a five-year sales backlog.[59]

This analysis serves as a starting point to help broadly inform the geographical prioritization of US states for ABC technologies to create near-term impact, based largely on state-level market, political, and energy-related metrics. This study is not meant to discourage current efforts, nor to take the place of more regionalized or localized prioritization analyses (which may be highly useful). The ABC Collaborative believes every state would benefit from implementing ABC solutions.

Analyzing opportunities with a different set of parameters might result in different interpretations or results. This prioritization analysis is intended as a foundation for more detailed future assessments that could, for instance, re-weight certain metrics as more or less important given evolving program goals—or based on the requirements of an investor or other business. Moreover, its utility may be enhanced when used in concert with the US Building

Stock Characterization Study being executed by NREL that analyzes and categorizes the US building stock based on specific building characteristics.

3.3 Key Market Segments

Independent of state boundaries, single-family housing, multifamily housing, and commercial buildings represent the largest market segment opportunities for ABC. The forthcoming US Building Stock Characterization Study will detail a range of building typologies within these major market segments to provide a clear outline of which specific building types are most common in the United States and how much energy they use. This section provides a high-level overview of the addressable market size of, and suitability for ABC intervention in, the single-family, multifamily, and commercial segments. In determining where to expand ABC development efforts, there is a near-term need to prioritize areas where the greatest demonstrable impact can be achieved.

Single-Family Residential

According to the American Housing Survey, 84% of owner-occupied housing units and 28% of renter-occupied housing units are single-family homes.[60] The single-family market segment is one of the largest addressable markets for ABC. There are more than 85 million detached and attached single-family homes in the United States, representing almost 70% of residential units. These homes contribute approximately 17% of 2019 US energy consumption compared with roughly 4% from multifamily and 19% from commercial buildings.[61] Despite these favorable factors, the case for early adoption of ABC in the single-family market segment is less clear than in multifamily housing and some commercial market sub-segments. The individual ownership structure and high first cost of both new construction and retrofit discourage widespread adoption of ABC especially in the owner-occupied single-family segment. Real estate investors with large single-family housing portfolios, however, may be well suited to be early adopters of ABC interventions due to their long-term investment outlooks and ability to finance portfolio-wide improvements, leveraging volume purchasing or economies of scale.

Major production homebuilders have been employing basic prefabrication strategies for decades but have mostly avoided significant deviation from conventional practices. Off-site production in this sector largely uses the same tools and methods as traditional on-site construction under a factory roof. Early adopters of advanced technologies have failed to gain traction because of the high capital investment and cyclical nature of single-family home development. For example, Pulte, a major production homebuilder, aggressively entered panelized construction in the early 2000s but shuttered these efforts only three years later due to the economic downturn.[62]

Regional builders appear to have a greater appetite for energy efficiency measures and could be an early-adopter market for ABC in single-family construction, as demonstrated, for example, by Dvele. Dvele is a California-based venture capital–backed builder founded in 2017 that acquired facilities and IP from Hallmark and Blu Homes and builds prefabricated, high-performance homes, including the first fully self-powered homes built off site in the United States. Dvele's "smart homes" are built to Passive House standards and offer an 84% energy reduction per square foot compared with a conventional home. Additionally, Dvele's single family homes appeal to regions prone to wildfires and outages by relying on solar panels and battery storage to enable resilience.[63]

Most smaller custom homebuilders are not focused on technology differentiation and generally use traditional single-family construction methods. Ones that do pursue ABC-related approaches—such as Bensonwood, Unity Homes, Connect Homes, GO Logic, and Plant Prefab—typically have in-house architectural, engineering, and construction capabilities that enable them to push the design and performance envelope. Modern prefabrication methods often play a key role in the production of these homes because they represent a controlled, lower-cost environment for achieving the necessary performance and quality metrics.

On the retrofit side, the tremendous variability in construction, geometry, and current condition of the existing single-family housing stock is a significant barrier to the application of industrialized methods, which depend on some degree of standardization to drive manufacturing efficiency. Even most contractors that offer energy efficiency retrofit services for traditional stick-built construction are highly localized. One exception is Dr. Energy Saver, which offers insulation and HVAC installation in 25 different states.

Recent private equity roll-ups of HVAC contracting firms may also offer a future path to scale, though these acquisitions are typically driven by near-term cash flow and scale. As home equity loans and home improvement loans are less readily available and more costly to owners of older single-family properties, financing is a critical consideration as well. Some start-ups such as Sealed are now using a managed services model to provide specific aspects of energy efficiency such as high-performance HVAC, while mitigating the up-front costs using financing.

To date, no player has yet emerged offering holistic decarbonized retrofit products for the single-family market, leaving room for further market innovation. Again, barriers in the single-family housing market segment include a high first cost to execute a single-family home retrofit and a fragmented ownership landscape, with many single-family homes under individual ownership (making project acquisition costs a significant consideration). This segment could be made more attractive for ABC retrofits by streamlining financing and insurance considerations.

Multifamily Residential

According to the 2019 American Housing Survey, more than 60% of rental households lease a unit in a structure with two or more units.[64] Of those renters, 50% rent a unit in a complex composed of 10 or more units. While the multifamily housing market segment is comparatively smaller than the single-family housing market, 25% of all US households live in multifamily units.[65] Additionally, only 37 affordable and available homes exist for every 100 extremely low-income renter households, with further shortages for other cost-burdened households.[66]

Multifamily housing is characterized by multiple residential units on a single property and includes: high-, mid-, and low-rise apartment complexes, townhouses, and various forms of condominiums and cooperatives. Multifamily represents a significant share of US homes. Many larger multifamily buildings often feature simpler layouts and geometries as well as consolidated ownership structures (especially true among public and affordable multifamily developments). These factors make multifamily housing a potential priority entry point for emerging ABC retrofit approaches.

Furthermore, given the prevalence of deferred maintenance backlogs in multifamily housing—particularly in affordable (restricted and naturally occurring) and workforce housing—many buildings may already need interventions that could be combined or replaced with ABC retrofits. ABC retrofits of these buildings would help expand the availability of high-quality, low-carbon, healthy, and comfortable affordable housing. Urban centers pose unique opportunities for multifamily retrofits. This is especially true in the northeast, which has 20% of the nation's housing stock and close to 30% of the nation's multifamily housing stock.[67]

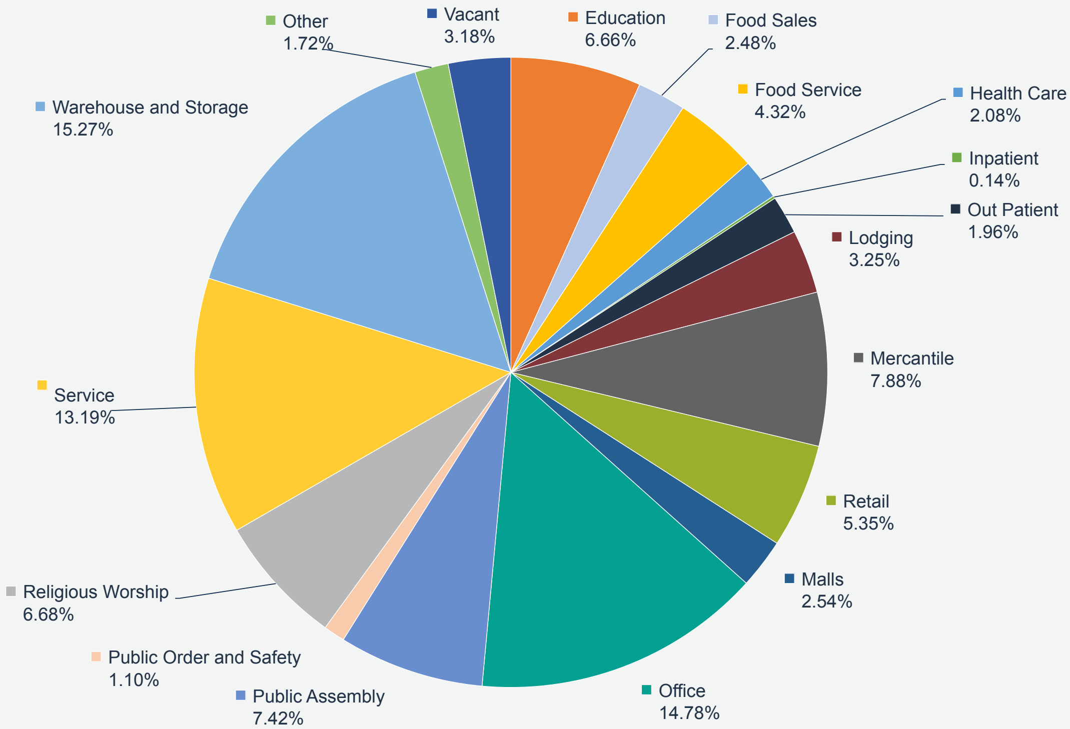
New multifamily construction can also benefit from ABC approaches. Freddie Mac estimates the US has an immediate need for more than two million additional housing units to make up its current shortage.[68] There are varied examples of multifamily new construction projects utilizing industrialized construction approaches, including The Graphic, a 136,000-square-foot five-story modular wood-framed residential development in Charlestown, Massachusetts. Similarly, the company VBC has deployed modular construction to address market-rate multifamily housing shortages in Philadelphia, Pennsylvania. Factory OS recently raised $17 million in funding from Google and Autodesk to build 300–1,000-square-foot affordable housing modules, while others such as Boxabl are focusing on the accessory dwelling unit sub-segment.[69] Incorporating sustainable attributes can increase the appeal of housing—and consequently the achievable rent or sale price, at least in less cost-sensitive upmarket sub-segments.

While innovative construction players have successfully built new modular multifamily housing, there remains opportunity for increased innovation in high-performance ABC approaches and technologies for multifamily new construction and retrofit. Notably, the states identified by the state prioritization analysis as best suited for early implementation of ABC technologies and practices have large housing deficits, with California, Texas, Massachusetts, and Florida among the top ten states in this regard. California may be a particularly strong beneficiary of recent announcements by large technology companies such as Apple, Facebook, and Google (the initial customer of Factory OS) to increase affordable housing supply around their Silicon Valley headquarters. Oregon, Minnesota, and Colorado are other states with notably large deficits.

Multifamily housing is uniquely situated to address affordable housing deficits, particularly in high-cost housing markets. Industrialized approaches to multifamily construction could respond to this deficit, creating an ideal opportunity to rapidly create additional housing capacity that is also highly energy efficient. There does appear to be a trend toward greater use of off-site construction in multifamily projects. The National Institute of Building Sciences conducted a 2018 survey across a range of construction to indicate where off-site construction is most often utilized. Out of 517 respondents, more than 38% said that they were most often using off-site for multifamily construction, up from 24% in the 2014 running of the survey.[70]

Commercial

Exhibit 3.3 2018 CBECS Percentage of Buildings per Principal Building Activity



Source: Analysis of Commercial Building Energy Consumption Survey, US Energy Information Administration, 2018

The 2018 Commercial Building Energy Consumption Survey reports that warehouse/storage, office, and service buildings are the three largest commercial sub-segments (as shown in Exhibit 3.3 above), suggesting they merit attention from ABC technologies and approaches.[71] However, potentially low average baseline energy use in warehouse and storage buildings and high building variability in office and service buildings could lessen the immediate appeal of these subsegments, despite their market share. In comparison, the healthcare and lodging (hospitality) industries have larger, more standardized buildings and more new construction investment, making them more conducive to the use of off-site approaches.

These sub-segments' use of repetitive unit designs, and the immediate return resulting from faster time to occupancy, also increases the attractiveness of off-site construction. For instance, a survey by a major general contractor on off-site hotel construction estimated average schedule reductions of two to six weeks.[72] For a 200-key property generating $150 per key per night of revenue, a six-week schedule reduction would result in more than $1 million in additional revenue. Furthermore, one survey among construction professionals—general contractors (GCs), architects, engineers, and trades contractors—predicted the most likely building types to use prefabrication would be healthcare facilities followed by hospitality.[73] The education sub-segment may also be of interest, as it commonly features repeating and relatively standardized spaces, although factors such as time to occupancy carry lesser financial implications.

Existing industrialized construction suppliers have found success through partnerships with commercial companies across several sectors—including healthcare, banking, e-commerce, and software—that have sustained long-term demand for building space. Identifying organizations with substantial existing portfolios or new building space needs should be an initial priority for ABC technologies and approaches due to their ability to commit long-term demand to suppliers. Furthermore, organizations with a demonstrated commitment to environmental and sustainability goals and fostering progressive company culture are well suited to ABC technologies and approaches, as they may place more value on the energy, carbon, and health performance that ABC solutions can offer.

Commercial buildings are more attractive for ABC retrofits when a single entity owns or has influence over a significant portfolio and can drive decisions across the properties. The top five holders of commercial office buildings in the United States control more than $300 billion in assets, so providing early validation examples that those owners find credible and compelling will be a critical step in acceptance.[74] Other aggregation opportunities include large corporate owners and/or occupants (that in some cases work exclusively or predominantly with a specific third-party owner, such as Amazon's use of JBG Smith for its HQ2 project), government portfolios, and universities.[75]

Retail bank chains have sometimes been targeted for energy efficiency upgrades and could be potential targets for ABC retrofits as they offer a large portfolio (or pipeline) of sites and are controlled by companies that are increasingly embracing sustainability goals. Fast food restaurants are also a potentially interesting application for ABC construction due to the repetition of models and high energy usage per square foot, provided that the transaction costs of dealing with individual franchisers can be reduced. In the 2018 National Institute of Building Sciences survey of construction stakeholders, more than 50% responded that they were most often using off-site for commercial construction.[76]

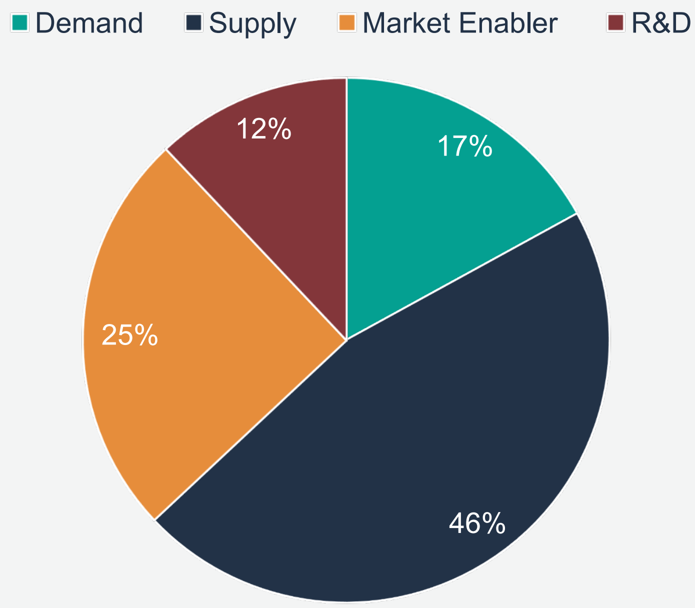
Large companies have been facing increased pressure from customers, investors, and public-sector stakeholders to take proactive steps toward environmental and sustainability goals. For many organizations, buildings can be a major emitter of carbon emissions across their assets. ABC technologies and approaches can help organizations decarbonize their building portfolio and provide pathways to recoup their investment through energy cost savings. They also provide improved comfort (translating into better customer experience and employee retention and productivity), healthier buildings (benefiting employees and residents), increased resilience, and lower maintenance. However, clear mechanisms do not yet exist to monetize (or even consistently quantify) the added value of these co-benefits in all subsegments, particularly where buildings are occupied by a user other than the owner.

Image courtesy of Nexii (rendering by PEG Companies)

4. Industry Interviews

4.1 Overview

Exhibit 4.1 Stakeholders Interviewed by Category: Demand, Supply, Market Enabler, and R&D



Source: Stakeholder Interviews, ABC Collaborative, 2021

The ABC Collaborative team conducted a total of 65 stakeholder interviews to identify barriers to increased uptake of ABC solutions, gather information on market conditions, and understand key industry values and assumptions. The interviews covered a broad range of industry stakeholders, representing diverse perspectives across the overall buildings sector. These stakeholders are segmented into four broad categories: demand, supply, market enabler, and Research, development and scale-up (R&D) (see Exhibit 4.1). The ABC Collaborative defines these categories as follows:

1. Demand stakeholders include building owners and developers in single-family, multifamily, governmental, institutional, and commercial market segments.
2. Supply stakeholders include builders, fabricators, product suppliers, material suppliers, tradespeople, laborers, and design and engineering professionals.
3. Market enabler stakeholders include regulators and government agencies, financial and insurance services, industry associations, code organizations, accreditation and testing bodies, utilities, and philanthropic organizations.
4. Research, development and scale-up (R&D) stakeholders include national labs, research-focused NGOs and industry groups, and academic research institutions.

The following sections synthesize key insights from conversations with demand, supply, market enabler, and R&D stakeholders.

4.2 Key Findings

"Someone needs to train the developers to believe that this is less risky than the other method."

—Demand Stakeholder

"Innovation is killed by the cost of third-party testing and that still doesn't prevent people from being sued."

—Supply/Demand Stakeholder

"The dream is just to give a list of requirements and not have to direct the orchestra. They [the integrated solution providers] go behind the curtain to orchestrate the complete package."

—Demand Stakeholder

The construction industry, in general, appears to be receptive to industrialized and energy-efficient construction but recognizes significant barriers to implementation, given that most projects and practitioners tend only to target the minimum required by code and to use familiar, conventional methods, materials, and equipment. Frequently mentioned challenges include the following:

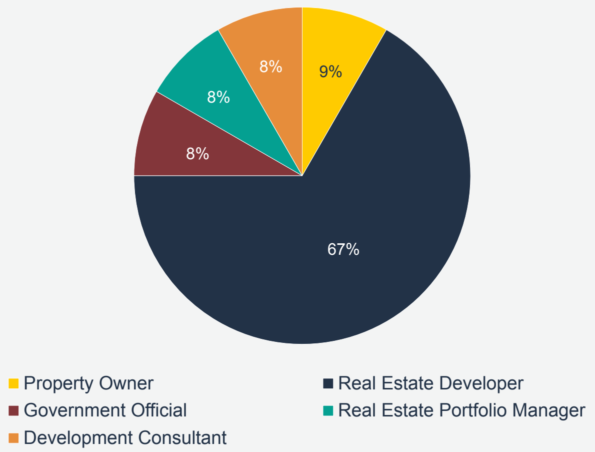
- Fragmented codes and code enforcement
- A regional construction labor force that feels threatened or is unfamiliar with industrialized construction practices leading to resistance in adoption
- The uncertainty of fabricator supply and of demand pipelines
- Perceived uncertainty of construction schedules when using new approaches
- Tight margins that often must be shared across several layers of the value chain
- Financing practices that are not compatible with off-site construction

There is also a persistent resistance to industrialized construction because of a perceived lack of customizability, architectural character, and aesthetic appeal. Another common theme among both demand and supply stakeholders is the belief that most construction projects are "one-offs." It takes many repetitions with a process or technology to optimize it, and many new technologies, including factory production of most building construction assemblies, do not have this full history of iteration, hence the importance of aggregating demand in the building types and market segments mentioned previously.

4.2.1 Demand

Exhibit 4.2.1

Stakeholders Interviewed by Category: Demand



Source: Stakeholder Interviews, ABC Collaborative, 2021

The ABC Collaborative team interviewed a range of demand-side stakeholders, including property owners, real estate developers, government owners, real estate portfolio managers, and development managers, as shown in Exhibit 4.2.1. The interviews indicated that demand customers are generally interested in industrialized construction practices and energy-efficient technologies. However, they are reluctant to adopt these rapidly due to the lack of proven performance, scarcity of reliable supply-side providers, uncertainty around other risks, and sometimes higher up-front cost. A major $20-billion real estate brokerage and development firm that is vertically integrated into facilities management noted that its adoption of energy efficiency offerings (and new product and service offerings in general) is ultimately controlled by its corporate client base.

The risk of being a first mover is substantial in the construction industry due to the capital intensity of assets and projects, the long operational lifetimes of buildings, the significant potential liabilities associated with safety and performance, and the prevalence of costly litigation. There is a sense that a developer going down a different path can easily be penalized for trying something new, whereas when an issue occurs with an accepted and widely used approach, individual actors are less likely to be blamed.

Some owners also say they struggle to find GCs and trades that are willing and able to implement new technologies. Owner representatives determined to champion innovative technologies and approaches must often convince not only their own internal leadership but also designers and contractors, who may try to steer them toward more familiar options. Off-site manufacturers, GCs, and trades all repeatedly highlighted the importance of materials and systems that are "drop-in replacements" for existing products.

When considering unitized industrial construction approaches, some demand stakeholders flag the risk of a supplier going out of business without a ready replacement. They note that, when dealing with panelized systems or volumetric modules and the fabricators that make them, the prefabricated components are not as interchangeable as the basic pieces of traditional stick-built and other conventional construction. **In short, there is a need for fungibility or greater supplier stability in ABC products.**

Many of the largest residential homebuilders have incorporated some form of off-site construction (e.g., engineered roof trusses, wall panels, floor cassettes, etc.) into their production process, but none have consistently deployed advanced industrialized processes (e.g., incorporating MEP, using greater automation or designs and processes optimized for manufacturing) or prioritized energy efficiency. Although more vertically integrated demand stakeholders such as production homebuilders would like to see greater adoption of off-site construction, the capital cost for new technologies and infrastructure (and the associated risk) looms large. So does the learning curve (and potential costly downtime) when incorporating new technologies in a factory environment.

Capturing the full value of energy-efficiency improvements and other building innovations from customers and end-users remains difficult as well. New technologies are often hard to procure or marked up substantially because they are low-volume specialty items for distributors and are not supported by economies of scale. Unfortunately, for many demand stakeholders, energy efficiency measures must "pencil out" to be seriously considered, and current building valuation methods largely fail to capture any real equity value for these improvements.

First cost is a significant criterion for demand stakeholders. Moreover, developers and building owners typically have specific payback timelines in mind. And while a sure way to increase adoption of novel technologies would be to meet those windows, in practice the timelines are often too short for this to be feasible (e.g., three to five years, or sometimes as little as one year) when weighing only the narrow, immediate benefits of interventions. Although the financing solution of property-assessed clean energy (PACE) financing was created to solve this issue, it is not available in all markets and still a niche product that not all owners are familiar with or willing to use.

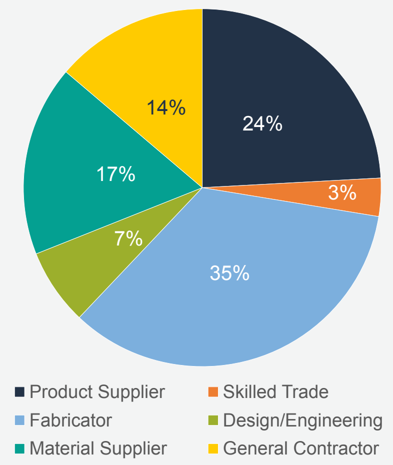
Despite these challenges and the resistance from many demand stakeholders, some report a recent uptick in pressure from clients and investors to lead on environmental and social issues, including sustainability and emissions reduction. For instance, JP Morgan has announced a $2.5 trillion commitment to "sustainable development" initiatives over the next 10 years, which encompasses both deploying and financing emerging technologies. Its corporate real estate group has been a key early adopter of technologies aligned with that vision, including the second-largest rooftop solar project in the United States at its Columbus, Ohio, office complex.[77]

Demand stakeholders with that type of national scale and scope require industrialized construction to increase both the quality and scale of their work, extend useful life, and reduce the risk of downtime due to extreme weather events or other stressors. Industrialized construction offers the ability to systematically design, manufacture, and construct more resilient buildings, compared with traditional construction practices. Forward-looking demand stakeholders may choose to further prioritize the resilience of their building portfolios, operating under the philosophy that it is more cost-effective to build a building right the first time.

4.2.2 Supply

Exhibit 4.2.2

Stakeholders Interviewed by Category: Supply



Source: Stakeholder Interviews, ABC Collaborative, 2021

Exhibit 4.2.2 depicts the various Supply stakeholders, including product suppliers, skilled trades, fabricators, design/architecture/engineering, material suppliers, and GCs, that the ABC Collaborative team interviewed. Across all of these sub-categories, existing supply stakeholders expressed interest in the development of industry-wide best practices for incorporating advanced manufacturing capacity into existing factory infrastructure as a way of improving their capabilities without having to undertake an individual study of their own. Creating this base of knowledge on a nationwide scale, in a way that incorporates the capabilities of a broad set of supply stakeholders, is the only way in which the construction industry can competitively address the ambitions of the large demand players mentioned previously.

This coordination of investment-grade demand with qualified supply remains a critical core principle that guides all of the ABC Collaborative's work, and a significant challenge that will require additional innovation and teaming to solve. Fabricators and manufacturers in volumetric modular and prefabricated panelized construction report that it is challenging to justify their workforce and capital investment when project timelines may be unexpectedly disrupted and demand is uncertain. Even when top-level demand is strong and buyers have placed orders, disruption of project timelines can leave fabricators with unused inventory and idle production capacity.

Supply stakeholders also expressed difficulty scaling factory production capacity due to variable commitment from demand stakeholders commitment specifically to modular and prefab approaches. Long-term demand pipelines are critical to scale factory production capacity and will become more prevalent if suppliers can deliver consistently.

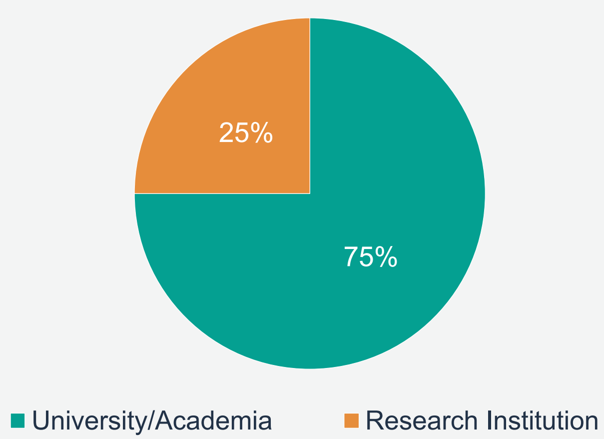
Building materials suppliers may need to design non-standard form factors and sizes specifically for off-site fabrication, which hinders some possibilities for realizing increased productivity. This can cause particular tension given that many building materials suppliers still view off-site as a niche market. Additionally, the bulk of their traditional supply chain goes through large-scale relationships with established distributors, creating a potential disconnect between the development of materials and the needs of more innovative fabricators and installers.

Materials suppliers also acknowledge that the entire construction market is risk averse, including them. Timelines for testing and third-party certification of new materials required for initial sales (e.g., ASTM, UL) can be long relative to the schedule of an individual construction project, leading to a significant risk to introducing new solutions. Even a successful certification is no guarantee of protection from liability should a new material or product fail on a large scale.

Some stakeholders identified limited access to traditional forms of construction financing for off-site and ABC projects as a challenge. Due to incumbent lending practices, supply stakeholders take on added cash flow risk and timeline challenges for off-site production. This is because traditional construction lenders may not release funds until major milestones of on-site project work are met, rather than allowing payment to the manufacturer prior to production or delivery of prefabricated products.

Exhibit 4.2.3

Stakeholders Interviewed by Category: Research, development and scale-up (R&D)



Source: Stakeholder Interviews, ABC Collaborative, 2021

4.2.3 Research, Development, and Scale-Up (R&D)

Many construction lenders are also wary of viewing off-site products as collateral, posing further financing challenges for off-site manufactures. Compounding these challenges, insurance and financing entities do not consistently value the benefits of industrialized construction, making it difficult to underwrite high-capital investments (see section 4.4.4 for more details).

Exhibit 4.2.3 shows the breakdown by percentage of university and academia and research institutions interviewed when surveying the R&D stakeholder category. Many R&D stakeholders lack experience successfully scaling up their inventions to the market and addressing several formidable barriers facing new products in the buildings sector. These stakeholders also lack robust connections to private-sector players that could help commercialize promising R&D work by taking it across the "valley of death" between demonstration and scale-up.

As a result, the market-readiness aspect of high-performance technology remains a substantial challenge. R&D organizations need a significant amount of scaling assistance to commercialize and deploy their innovations, not to mention scale the innovation to a profitable product or business. Without robust assistance in this area, the spillover effects of R&D supported by DOE and other research institutions in this sector will ultimately fail to gain widespread acceptance on the demand side, reinforcing highly risk-averse behavior throughout the value chain. A new product to be deployed at scale in advanced construction must pass several critical viability checkpoints, including the following:

1. **Seed funding for product prototyping and validation**: ABC technologies usually require significant materials and/or system development even at the very early stages of demonstration. This added capital intensity makes them more difficult to bootstrap and self-fund than IT or software businesses. Whether they be angels, venture capitalists, corporates, or government funding programs, many traditional sources of seed capital utilize stricter decision criteria with ABC-related financing than with other sectors. This additional scrutiny makes it hard for even qualified parties to pass the bar, creating a significant "chicken-and-egg" dilemma for even highly capable innovators.

   Furthermore, the engineering and R&D facilities required for these activities can be specialized and often exceed those offered by traditional accelerators and incubators. Where they do exist, the facilities are more suitable to well-established, larger companies as they often have higher volume commitment thresholds that are prohibitive for start-ups.

2. **Precisely defining product-market fit and finding suitable first customer or partner**: Most incumbents that could buy new ABC technologies at scale are large organizations where it is difficult to find the key decision maker(s) and specific initiatives or product lines where a nascent technology can achieve the greatest initial impact. These companies also tend to move slowly unless there is a pressing need. Therefore, it is critical (yet difficult) for emerging technologies to develop a value proposition for their initial product that is specific and validated enough to be compelling for these incumbents. Commercialization assistance programs that accompany government funding, such as the National Science Foundation's Innovation Corps and Small Business Innovation Research Commercialization Assistance, are beginning to target this issue by funding market discovery activities. However, more open innovation activities that enable corporate decision makers to broadly solicit and engage start-up players appear to be strongly desired by both types of participants.

   An example of this occurred in 2018–19, when Sto ran a first-of-its-kind Building Materials Challenge. This open innovation challenge was triggered in part by industry events such as the Grenfell Tower fire in London that created a drastically heightened need for non-flammable materials such as insulation in Sto's exterior wall systems. The Challenge attracted more than 400 applicants and funded three winners in 2019 that have since raised additional private funding ranging from two to five times the amount provided by Sto. Since then, similar challenges from corporate groups such as Cemex, as well as prizes such as DOE's American-Made Challenges, show an uptick in needed support for bridging the gap between concept and product.

3. **Capital and scale-up requirements and funding**: Despite the promising influx of recent capital into advanced construction–related start-ups, many of these technologies remain difficult for institutional investors to fund. This is because a full-scale stand-alone ramp-up would exceed both the amount of money and exit timeframe typically contemplated by a closed-end venture or private equity fund (e.g., five to seven years). On the flip side, partnering with corporate strategics and/or syndicating deals to co-investors leads to dilution and loss of control that is inconsistent with many of the core frameworks used by these investors. As a result, innovators must be creative in striking deals with multiple investors and partners that do not create untenable conflicts of interest between those parties.

   Recently, there has been an encouraging initial wave of "patient capital" flowing into the sustainability sector, including PRIME Coalition (supported by DOE's Innovative Pathways program) and Breakthrough Energy Ventures, which both have a stated mandate to support climate-friendly investments that do not fit typical VC criteria. A number of funds pursuing "construction tech" or "proptech" such as Brick & Mortar Ventures (which has the largest GC in the US, Bechtel, as a limited partner) and Fifth Wall have also emerged, providing additional investment avenues for ABC technologies.

   Providing DOE awardee and other promising ABC technologies with the right scaling resources (e.g., cost analysis, market sizing, product requirements, etc.) to conduct productive conversations with such investors, is a critical value-added role the ABC Collaborative can play in increasing capital flows into this area.

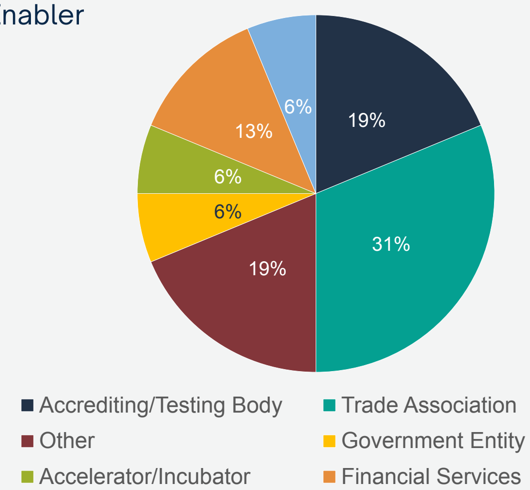
A brief initial summary of key capabilities requested from the ABC Collaborative by interviewees includes the ability to conduct thorough market discovery. This includes finding interested and qualified customers and scale-up partners with the distribution and manufacturing channels to take new products into a slow-moving market. It also includes helping develop commercialization plans that recognize the substantial testing and certification required to get a product into the hands of willing customers. Field-validation projects, demonstrations, and pilots, including those enabled by the ABC Initiative, are an important element along this path, but just the beginning of where the Collaborative could solve longstanding market barriers.

Continuing to bring in sources of private capital, including both financial and strategic investors, and helping provide funding and other technical collaboration mechanisms that can reduce the cost and time to market, will be critical as the Collaborative grows and technology scaling efforts advance.

4.2.4 Market Enabler

Exhibit 4.2.4

Stakeholders Interviewed by Category: Market Enabler



Source: Stakeholder Interviews, ABC Collaborative, 2021

Exhibit 4.2.4 shows the various subcategories of market enabler stakeholders interviewed by the ABC Collaborative team. While some market enablers recognize the potential value in cost reduction, improved productivity, and reduced construction timelines of ABC, several systemic barriers remain in the way of widespread adoption and support. Key observations from this stakeholder group include statements about difficulties navigating regional variations in standards and building codes, challenges with insurance and supplier warranties for ABC products, limited access to traditional forms of construction financing, and lack of a robust workforce with the necessary skill sets for ABC.

Throughout the stakeholder interview process, widespread confusion and frustration with applicable standards, building codes, permitting, and approval processes continued to appear across multiple stakeholder types when discussing industrialized construction. Specifically, due to the regionality of building codes and standards and an inconsistent interpretation of applicable rules, code officials are often unfamiliar with new technologies or processes being implemented, leading to increased scrutiny, construction delays, and (sometimes) unjust rejections. Supply stakeholders assert that reforming building codes and standards to consider ABC processes—including greater use of industrialized construction—will increase efficiency and reduce timelines in the approval and permitting process.

Market enabler experts in standards and building codes pointed to the potential for developing evaluation standards that suppliers can adhere to and that enable permitting approval of ABC technologies and approaches. This would ease barriers imposed by code officials and allow concentrated fabrication facilities to respond to demand from a wider geographic range without losing time tailoring production to many different codes. Building standards and codes are a crucial barrier to overcome for widespread adoption of advanced building construction, and further research is required to identify a workable solution set to this barrier. Another key market mechanism where continued streamlining may be useful is insurance (see section 4.4.4).

Market enabler, demand, and supply stakeholders mention the lack of workforce and workforce skills, but this issue is multifaceted and increasingly complex to address. One component is the lack of workforce supply (i.e., labor shortage) for both on-site and off-site construction. Another is a deficit in the skills and training required to execute industrialized and highly efficient construction. Industrialized construction promises better-quality and more comfortable, safer jobs that could potentially be filled by a broader labor pool than traditional construction.

Even so, stakeholder interviews reveal that industrialized construction work is struggling to fill positions. Another consideration is that permanent industrialized construction will shift jobs from distributed construction worksites to centralized factory locations near, but not within, areas of high market demand. In contrast, retrofit work will continue to require more distributed on-site labor in population-dense areas. This shift in the work location may be coupled with innovative trends such as pop-up factories that move to where the work is, adding another wrinkle to obtaining the labor required. What is clear, however, is that knowledge and training in ABC and modern industrialized construction methods (including digitized workflows) are a necessary enabler of this transformation at all levels of the construction ecosystem, from labor to construction management.

4.3 Stakeholder Needs

To identify the potential fit and value-add of the ABC Collaborative, Stakeholders were asked about the needs, shortcomings, and technology gaps they perceived. A key theme emerged from these conversations in that most of the issues highlighted are not issues that can be solved by a single industry player or, in some cases, even a single part of the value chain or category of stakeholders. Cooperation across players and the value chain is imperative, with a focus on lessening institutional barriers and embracing advanced practices centered around digitization, industrialization, and efficiency.

4.3.1 Compiled "Wish list"

The following points summarize key needs that stakeholders actively expressed interest in having the ABC Collaborative accelerate and/or facilitate:

Finance and Business Models

- Demand: Streamlined financing packages for ABC projects with simplified capital stacks and the ability to monetize the co-benefits of ABC. Packages tailored to specific market segments and ownership structures.
- Supply: Widely available insurance and financing products for industrialized construction with reasonable terms that appropriately account for its operational differences and risk reduction benefits relative to traditional construction. Examples include a project insurance wrapper or performance-based contracts that are dependent on the outcome of the entire project.
- Integrated delivery models for ABC solutions that address concerns around delivery and performance risk and simplify the customer experience (e.g., through a single "solution provider").

Innovation Scaling

- Opportunities for market discovery as well as meaningful interactions between emerging technologists and interested and qualified customers or scale-up partners with the distribution and manufacturing channels to take new products into a slow-moving market.
- Guidance for creating commercialization plans that recognize the substantial challenges in bringing a novel construction or building product to market.
- Co-development of innovative building materials designed specifically for the needs of prefabrication to optimize productivity and minimize waste, including enabling factory trials and pilot production.

Codes and Approvals

- Standards and technical resources to support the validation and acceptance of new technology and practices.
- Virtual and standardized inspection processes for existing and new technologies and processes, including off-site construction.
- Greater uniformity of key building codes and standards, their interpretation, and enforcement as it relates to ABC.
- Guidance on successfully navigating the substantial testing and certification required to get a product approved and deployed.

Technology Validation and Demonstration

- Real-world demonstration data that can articulate the value of energy-saving technologies and measures and support robust warranties and/or guarantees that improve customer uptake.
- Improved analysis and tools to calculate the ROI of energy-efficiency measures for building envelope and HVAC retrofits.
- Development and implementation of retrofit installation methods that pose minimal disruption to existing tenants.

Workforce

- Education and training for GCs, subcontractors, and other providers on new technologies and practices to create a robust pool of qualified suppliers.
- Education and training for building staff and other O&M staff from the building management side.
- Education for appraisal professionals on energy-efficiency retrofits and off-site new residential construction to recognize the full value of these, giving owners greater financial flexibility.
- Research into changing labor demands (such as volume of work, roles or occupations, displacement, and location).

Industry Guidance

- Research-backed guidance on how to adapt current risk allocation throughout the supply chain.
- Availability of benchmarking data to allow for comparison between projects and determine value of ABC.
- Specific technical guidance on technologies and approaches that achieve given levels of energy and carbon performance.

4.3.2 Technology Gaps

DOE is continuing to work to identify technical gaps through public stakeholder workshops and roadmapping of technology needed by the industry. This will culminate in a forthcoming ABC Roadmap, which supplements previously developed roadmaps for individual technologies. On an ongoing basis, the Collaborative will share information collected from its membership and other partners to the DOE to advise its future research, work, and funding.

Frequently mentioned needs on the technology side that supplement other DOE efforts and tie closely to ABC and industrialized construction include ensuring consistent, high-quality assembly in the field, including solutions for air gaps, mate lines, and finishing details. Market Enablers and Suppliers also point to the lack of accessible and fully integrated software solutions as a bottleneck slowing the industry.

For retrofits, the ability to quickly, cost-effectively, and accurately assess an existing structure's condition, map its configuration, and address moisture management issues is a vital technological need. Cost of solutions remains an overriding theme in all cases (e.g., equipment for and installation of heat pumps and insulation), and one that the Building Technologies Office is actively addressing through a number of existing funding opportunity announcements such as BENEFIT, which have a significant ABC component.

4.4 Overcoming Market Barriers

This section outlines ways the ABC Collaborative could work with its partners to address market barriers. The challenges discussed are segmented into five categories: technical, social, workforce, financial, and political.

4.4.1 Technical

Technology Availability

There are a number of challenges facing the supply chain in bringing ABC technologies to market. New technology costs are typically high and often out of an individual project's or consumer's budget range. That is because these technologies lack economies of scale and go through traditional distribution channels, which are often not incentivized to promote innovative products. Newly released, novel materials and systems are often marked up significantly, if they are available at all. Local GCs are often unfamiliar with or unwilling to use new technologies, so it can be difficult to find one willing to do the work, unless a product is a drop-in replacement for an existing product from an installation and commissioning standpoint.

Significant skepticism remains about whether a new product or system design will reliably provide the needed performance, adding concerns around liability. The ABC Collaborative could address these challenges by leveraging DOE's forthcoming ABC Roadmap and incorporating technology-to-market planning to help emerging industry suppliers of ABC products scale and commercialize their technologies.[78] Additionally, the Collaborative could align suppliers with validation resources such as the national laboratories. The Collaborative could also disseminate supplier data from successful demonstrations to bolster the credibility of new technologies and approaches.

Fabricator Capacity and Dependability

There is a notable lack of knowledge regarding what is available from prefabrication approaches, especially in commercial construction. Developers that do not have in-house capacity worry about the track record, stability, and location of US fabricator manufacturing facilities and struggle to understand whether capacity will be available if development needs to scale up. These concerns extend to a lack of understanding around the benefits aligned with off-site construction practices.

The Collaborative could address these challenges by helping to organize and up-skill supply nationwide and conducting analysis to survey and validate the capacity and other essential operational metrics of these suppliers. The Collaborative could also help aggregate and publicize a pipeline of demand, including for retrofits, which could provide a buffer of work to suppliers as new construction demand ebbs and flows. Fabricators seeking the protective effects of this hybrid new construction and retrofit approach could explore (jointly with peers, for greater efficiency) adapting their manufacturing capacity so that it can be switched between new construction and retrofit products.

4.4.2 Social

Large-scale developers, due to the litigious nature of the sector, are reluctant to adopt uncommon construction approaches and be too far out on the adoption curve relative to their competitors. This therefore creates little incentive for suppliers, many of whom already have limited R&D budgets due to low margins as well as near-term financial pressures from shareholders, to invest in innovation. This leads to a "chicken-and-egg" dilemma where the demonstration of technology with these parties becomes unachievable due to lack of interest, making large-scale acceptance even more difficult. Collective action is thus required to establish new industry norms and acceptance of new technologies and construction methods among peers. Moreover, high demand for traditional stick-built construction today disincentivizes alternative investments, even if there is potential for significant gains.

The Collaborative could provide a forum for competitor-peer developers and builders to discuss and agree to move collectively on implementing ABC technologies and approaches (while respecting applicable regulations regarding anticompetitive practices). This will reduce perceived risk among developers and builders by creating mutually held objectives.

4.4.3 Workforce

Industry adoption of ABC practices will require changes to the construction workforce through several dimensions: technical training, policy, politics, and the involvement of organized labor. A broad set of solutions is required to ensure an equitable transition to ABC.

The implementation of ABC will likely shift a portion of the workforce to off-site factory settings outside of major population centers. There may be technical dislocation, in terms of required skills for on- and off-site construction labor, and geographic dislocation of where construction work is performed. This will impose constraints on national, state, and local political leaders and policymakers influencing where factories are located. Navigating the complexities of technical and geographic dislocation is critical to reducing potential friction toward successful implementation of ABC. The logistics and effects of the geographic shift of a portion of the workforce to off-site factories will need to be better understood and addressed. The ABC Collaborative could look to support industry stakeholders in determining economic and political effects of workforce relocation.

Significant opportunity exists for training and retraining of the existing construction workforce, as well as expansion of recruitment to workforce demographics previously underutilized by the construction sector. Additionally, new workforce recruitment should be inclusive of women, people of color, indigenous communities, and veterans, while expanding geographic scope to include rural communities. According to the 2019 US Department of Energy's Advanced Building Construction Funding Opportunity Announcement, women make up 47% of the national workforce but just 23%

of the energy efficiency workforce and 3.4% of building energy auditors.[79] African American workers make up 8% of the energy efficiency workforce compared with 12% of the national workforce. Developing retraining/reskilling, new training, and workforce recruitment programs is critical for an equitable and just transition to ABC.

The specific measures used to address geographic dislocation and workforce retraining and recruitment will evolve as the effects of a construction workforce transition are further researched and mutually understood. To ensure an equitable and prosperous ABC workforce, it remains critical that stakeholders from across the construction sector engage local communities, governments, and other relevant groups. The ABC Collaborative could facilitate workforce conversations and develop equitable solutions to address identified challenges.

Potential solutions to workforce challenges include:

- Increasing existing investment in vocational high schools, which are often underfunded in low-to-medium-income urban environments.
- Developing specialized training programs that ensure coverage of minority contractors and workers as well as those employed in waning legacy industries.
- Incorporating curricula on ABC into traditional construction continuing education programs.
- Updating applicable higher education curricula so that construction management and real estate professionals are better equipped to drive ABC projects and make appropriate hiring and procurement decisions.
- Working with relevant stakeholders to locate factories in communities affected by the national transition away from fossil fuels.

4.4.4 Financial

Financing for ABC

The low-interest-rate environment has shifted asset allocation from cash toward commodities and real assets, as evidenced by broader sector transactions such as CalPERS' $1 billion direct investment in Blackstone's real estate debt fund.[80] However, financing specifically for ABC projects remains heavily application- and sector-specific, as the largest and most well-capitalized institutional buyers of real estate still focus predominantly on creditworthiness/economic value and repeatability/scale when deciding which projects to purchase.

ABC approaches require the deployment of emerging technologies at smaller scales with early adopters, many of whom are not well suited to obtain large-scale construction financing or sell portfolios of projects to major investors/owners. However, in the mid-term we do see the potential to attract this kind of portfolio-scale investment to ABC as market share for ABC increases through successes with early adopters.

Similar to how "bankability" issues around emerging equipment, materials, and processes hindered financing for renewable power generation projects involving solar, storage, wind, etc., the use of off-site construction and other industrialized approaches can add yet another layer of difficulty in financing successful transactions. Off-site construction specifically is still viewed as unproven and risky by some financial institutions because of the perceived risk of logistics, transit, and on-site craning and installation. As a result, many panelized and volumetric modular products built in factories cannot qualify for traditional construction loans because the work in process is classified as inventory and cannot be collateralized.

Therefore, off-site fabrication often requires a larger fraction of payment from the client before fabrication occurs. Alternatively, the fabricator must be able to float the cost of the work in progress, tying up funds and increasing risk, which is often not possible because of the cash-intensive nature of construction and the smaller size of these emerging supply players. Typically, financing institutions have little short-term incentive to take what they see as new risks, particularly in a low-interest-rate environment, to create and offer appropriate construction loan products for off-site construction that are replicable and that scale.

Financing measures from renewables and certain targeted measures (e.g., lighting) show us that this may require new entrants that are more flexible in their assessments of what they can underwrite, in exchange for higher near-term rates of return, as well as new types of financing products. Clearer and firmer standards for appraisers and lenders to value energy efficiency and other high-performance characteristics would also help support a longer-term recognition of the benefits of ABC. The Collaborative could work with both existing and prospective financiers to initiate the development of best practices and issue recommendations on potential products and structures that can increase deal flow and lower soft costs to help accelerate market transformation.

Insurance for ABC

In theory, ABC approaches provide a more predictable, repeatable, and scalable way of doing business. However, insurers do not always understand the changes in risk associated with more efficient and standardized approaches such as industrialized construction. This information gap in how legacy insurers classify and quantify risk makes insurance costs higher and transactions more complicated across the value chain. As a result, industrialized construction projects often require many insurance layers including down to the individual component level, creating higher costs and uncertainty for building owners.

More integrated insurance products that could back a larger set of building construction risk factors have been highlighted by both demand and supply players as a potentially transformational tool for advancing industrialized construction. Examples of market barriers include the following:

- Off-site construction increases the value of finished goods in transit, as well as increased use of cranes on-site for finishing/installation. Most manufacturers use third-party logistics firms for shipping, while craning is done by a third-party GC or sub-contractor, all of which increase the complexity and cost of builder's insurance policies. The latter is particularly significant because insurers remain hyper-focused on on-site safety since safety risks present the largest potential for significant unexpected payouts.
- Off-site construction is generally classified as "work" versus "product" in the event of a claim. This means that fabricators are essentially a sub-contractor, and both the GC (usually in the form of builder's insurance) and the manufacturer (usually in the form of a master policy that covers their entire manufacturing operation, since it is difficult to segregate projects) have to carry their own insurance.

Insurance carriers also remain hesitant to acknowledge the benefits of new technical approaches, in part because of past failures related to underdeveloped technical approaches, and not the targeted energy improvements themselves. For instance, exterior insulation and finish systems (commonly abbreviated as EIFS) often had significant issues with moisture prior to the design of proper drainage systems. Today, these systems are often produced off-site with sophisticated drainage products. Yet some insurers continue to charge high premiums for those systems, impeding the adoption of ABC-friendly technologies such as air sealing, insulation, and high-performance windows that are integrated into those systems. Furthermore, the creditworthiness and liquidity of manufacturers, and their ability to honor long-term warranties, remains a concern as well. Other industries such as solar have adopted warranty insurance backstops that honor warranty claims in the event of a manufacturer's insolvency.

The Collaborative could work with insurers to develop potential templates and guidelines for advanced insurance products, and identify the appropriate legal, regulatory and underwriting hurdles that may need to be overcome to commercialize and scale such products for ABC.

4.4.5 Political

Landscape and Receptiveness

Most building codes and industry standards are written (at least implicitly) from a site-built perspective hindering progress in off-site construction. Additionally, fragmentation and complexity of codes at the state and local levels increase barriers to entry for ABC manufacturers attempting to develop products that satisfy code compliance standards across a multitude of jurisdictions. In certain regions, this gap of perspective is compounded by a negative stigma toward manufactured housing and an inability of inspection officials to observe all steps of construction.

One of the most considerable challenges is fluid communication between building code officials and the rest of the industry, leading to instances where code officials are not familiar with new technologies. Supporting jurisdictions to utilize existing model codes and methods for off-site construction, as well as alternative compliance pathways for innovative products, can help mitigate the effects of regional code fragmentation. Possible solutions are remote inspections and "productization" of building components, so an ABC process or product is approved and every unit does not have to be individually inspected. The ABC Collaborative will work closely with industry enablers who are working on these solutions already, which can be more widely disseminated and implemented.

Authorities committed to driving higher-performance new construction and retrofits in their jurisdictions could use the enforcement latitude they commonly have to direct their officials to work cooperatively and constructively with ABC projects. This more flexible approach is, paradoxically, likely to result in effectively higher-performing projects in these jurisdictions.

Direct and Indirect Policy Support

Incentives for new technologies vary among (and sometimes within) state and local jurisdictions due to fragmented energy codes, utility service areas, and other authorities. Incentives are often limited to incremental individual measures or pieces of equipment, have a restrictive cost-effectiveness test, and generally do not support market transformation. Several urban areas have expressed explicit support for industrialized construction methods, notably San Francisco and New York, driven by a desperate need for affordable housing. Wider enactment of policies such as New York City's Local Law 97 will drive building owner regulatory compliance, stimulating demand for ABC projects.

In addition to incentive alignment, there is a further opportunity for public-sector support of ABC through demand- and supply-side channels. Government stakeholders like GSA can update procurement policies to incorporate requirements for using relevant advanced building construction technologies and processes (or, more generally, for specifying higher-performance designs and equipment). Further, government stakeholders can utilize several financial mechanisms to support suppliers building manufacturing capacity of off-site construction and other ABC technologies.

Image courtesy of Energiesprong

5. Conclusions

5.1 Summary of Findings

On paper, high-performance construction that integrates high energy efficiency, low carbon, and resilience can be produced, shipped, and deployed more efficiently, and can meet the significant desires and requirements of large US building owners (and the users they serve). However, clear options for these solutions today are lacking, and a collaborative approach that starts with the current DOE-supported ABC effort and extends to include a wide range of other private-and public-sector players is needed.

Major barriers to ABC include weak supply chains, lack of adequate labor, uncertain demand, tight margins, lack of validating data, and general risk aversion.

In summary, challenges include a cumbersome, fragile supply chain, an inexperienced and undersupplied labor force, fragmented code and code compliance regimes, the uncertainty of fabricator supply and demand pipelines, tight margins, a lack of validating data for novel options, and risk aversion in the buildings sector. The recommendations (section 5.2) provide an overview of recommended actions for addressing these barriers.

Many ABC technologies and approaches already exist, but mass adoption will require clearer, more integrated solutions that are accessible to demand actors and that achieve the necessary cost compression via improved project delivery, targeted innovation, market experience, scale, and technology-to-market mechanisms.

The core operational focus of the Collaborative is to drive ABC activity by linking demand-side building owners and developers to qualified supply-side teams that benefit from Collaborative market and technology scaling efforts. Our ABC Collaborative research indicates there is no shortage of interest in high-performance technologies—provided, however, they satisfy key market criteria for first cost, operational cost, and risk. These optimized products include: high R-value insulation products with low embodied carbon; efficient designs and systems for HVAC and domestic hot water (including integration into mechanical pod units); and energy-efficient unitized envelope and structural products (including volumetric modular and panelized assemblies) with advanced air sealing and moisture management.

Beyond technical performance, widespread adoption of these technologies requires cost-competitiveness to business-as-usual approaches, which is often contingent on manufacturing scale, as well as familiarity and ease of use in deployment and installation. A combination of a vanguard of forward-looking demand actors, a clearer initial set of supply-side solutions and willing providers, and accessible capital can unlock a virtuous cycle of compounding market experience, scale, construction productivity, and cost compression that support broad adoption of ABC.

Global thought leaders and stakeholders who have experienced both successes and failures provide guidelines and lessons useful for the US market.

Sweden's up-front focus on and investment in automation and Japan's emphasis on both affordability and quality are instructive examples that show the importance of aggressive investment driven by a longer-term view toward more ambitious objectives. Early owner interest and pilot progress made by market enablers in California and New York demonstrate the potential to adopt elements of Energiesprong for use in the United States, and our state prioritization analysis paves the way for identifying the US geographies most promising for the early implementation of ABC technologies and processes.

Near-term ABC market opportunities exist in several US states and select market segments.

The five states that ranked the highest for ABC implementation based on quantitative analysis (see section 3.2) were:

- California
- New York
- Texas
- Massachusetts
- Pennsylvania

Three of the five (California, New York, and Massachusetts) have building retrofit initiatives in which RMI is already involved, while Pennsylvania was an early mover in ABC as the first state to enact affordable housing tax credits for highly energy-efficient Passive House construction. Additional federal and state legislation for energy-efficiency building retrofits, along with more general infrastructure improvements, create a potential window of opportunity for other states to rapidly take market leadership positions.[81]

Research into major ABC market segments, including single-family housing, multifamily housing, and commercial buildings, uncovered important opportunities for ABC deployment, with near-term opportunities in several sub-segments (see section 3.3).

- **Single-Family Housing** – The single-family segment is a massive addressable market, but the individualized ownership structure and potentially higher per-unit first costs create apparent barriers to broad, near-term adoption of ABC solutions across this segment. However, the commitment of one or more consolidated single-family rental housing portfolio owners could create a highly attractive opportunity for ABC in this subsegment.

- **Multifamily** – Multifamily retrofits represent a key market segment of near-term interest, in part due to the backlog of deferred maintenance in many multifamily buildings, particularly in affordable (restricted and naturally occurring) and workforce housing. RMI has been an early mover in engaging demand in this area through approaches modeled after the Energiesprong program (see section 2.2.2). New multifamily construction, both market-rate and affordable, can also benefit immediately from ABC. Impacted by the COVID-19 pandemic, multifamily starts are projected to fall 11% from 2020 to 2021, due in large part to material price increases and shortages. ABC approaches that increase productivity and reduce material waste can play a key role in helping the sector rebound in 2022 and beyond. Additionally, sustainable attributes may increase the appeal of housing in upmarket sub-segments.

- **Commercial** – The lodging (hospitality), healthcare, and small retail (e.g., banking) and foodservice chain commercial sub-segments may be promising targets for ABC approaches due to the use of repetitive units and the desire for immediate return resulting from faster time to occupancy. (The education sub-segment may also be of interest, as it commonly features repeating and relatively standardized spaces.) Commercial buildings are more attractive for ABC retrofits when a single entity owns or has influence over a significant portfolio and can drive decisions across the properties. Most ABC-related deployment in commercial buildings has been for new construction, but some leading manufacturers and suppliers have growing retrofit programs.

Supplementing its traditional market segmentation analysis, the ABC-Collaborative also performed a meta-analysis revealing top areas of interest in relevant research, patent, and trade publication materials—these are HVAC and prefabrication, HVAC and retrofits, and enabling technologies, respectively.

The meta-analysis examined several key elements pertinent to ABC:

- **Industry Needs** – Areas that the industry considers require in-depth research (based on peer-reviewed literature). In the research literature, HVAC was the most active area for peer-reviewed activity in the United States, while prefabrication was more active in Asia.

- **Intellectual Property Assets** – Technologies and approaches that hold considerable perceived market value (based on filed patents). The patent literature indicated an acceleration in patent activity since 2019 with HVAC and retrofit the number one and two areas of activity, respectively.

- **Key Innovation Trends** – Concepts and topics that generate excitement or concern among professionals and tradespeople (based on a major trade publication). The findings from trade publication articles focused more closely on enabling technologies for construction such as drones and robotics than the research and patent literature.

5.2 Recommendations

Building on the industry wish list and the identified barriers to delivering on this wish list, the following recommendations—informed and validated by individual and collective stakeholder engagement—are proposed for the ABC Collaborative and its partners:

- **Support market characterization**: Produce a holistic characterization of the opportunities to implement ABC solutions in the United States based on takeaways from stakeholder interviews, the state prioritization analysis, and the NREL US Building Stock Characterization study (once complete).

- **Streamline financing and insurance**: Work with emerging lenders, or construction and sustainability leads within larger lenders, as a commercial entry point to support the development of ABC-enabling financial and insurance products, with specific products or product variations developed for priority market segments. Help inform public-sector finance decision makers' understanding of the needs and pain points of industry stakeholders.

- **Improve the codes, standards, and permitting landscape for ABC**: Support development and acceptance of evaluation standards that enable permitting approval of ABC technologies and approaches. Provide guidance to innovators to help novel products meet alternative compliance pathways, if appropriate. Provide educational resources for more consistent interpretation and application of codes. Coordinate with and complement performance-focused code-related efforts carried out by other organizations.

- **Prioritize and engage certain demand segments**: Consider prioritizing and directly engaging owners in market segments with consolidated ownership across large portfolios, by typology, in order to aggregate large volumes of demand to jump start the adoption of ABC using their scale.

- **Facilitate integrated project teams**: Develop a process for creating integrated teams throughout the supply chain that can seamlessly deliver to demand stakeholder specifications.

- **Guide solution development:** Define performance expectations for ABC and provide guidelines on suites of measures that will achieve this performance for a given project type and location. Consider creating an ABC certification or label.

- **Support supply capacity utilization and development**: Help collect and disseminate data on industrialized construction capacity to help the market understand what capacity is available, can be adapted, or needs to be added.

- **Nurture new technologies**: Showcase and support the development, evaluation, and commercialization of new technologies, drawing on public- and private-sector investment and support.

- **Help develop a qualified and equitable ABC workforce**: Solicit and provide input into research to better understand changing buildings sector labor and training needs. Inform inclusion of high-performance and industrialized construction technologies and approaches in vocational and construction management curricula. Advocate for inclusive recruitment to ABC-related training and jobs to provide a robust and diverse labor pool; support specific outreach to marginalized and underrepresented demographics.

- **Create framework for cooperative stakeholder activities:** Create focused, action-oriented opportunities for stakeholders to collectively address shared challenges. Building on this recommendation, the ABC Collaborative has established a structure for industry actors to identify and prioritize significant barriers, recommend near-term actions, and participate in carrying out those actions where possible—manifested as stakeholder "Working Groups" intended to operate in a coordinated and industry-informed fashion. These Working Groups fit integrally into the Collaborative's strategy and will both recommend and drive actions to work on identified barriers and needs. Select Working Groups kicked off during the inaugural Collaborative Convening, validating and identifying potential activities to advance or address many of the barriers and recommendations in this report.

6. Appendix

6.1 State Prioritization Analysis

Exhibit 3.2.2.2 Summary Table of Category Metrics, Data Sources, and Weights

Category	Metric	Data Source	Metric Weight	Total category weight
Energy-related CO_2 emissions	Total energy-related CO_2 emissions from residential and commercial buildings	(EIA, 2020a)	50%	20%
	Average CO_2 intensity of energy consumption	(EIA, 2020a, 2020b)	50%	
Energy costs	Average retail electricity price	(EIA, 2020c)	33%	20%
	Average retail gas price	(EIA, 2020d)	33%	
	Ratio of gas to electric heating costs	Assumptions: - Gas—90% furnace efficiency, 10.36 therm/MCF - Electric—2.5 COP ASHP, 29.3 kWh/therm	33%	
Economic development	Incentives for advanced manufacturing and renewable energy	From state economic development office websites	33%	20%
	Contribution of construction sector to state GDP	(Simonson, 2020)	33%	
	Percentage of state workforce in construction industry	(Simonson, 2020)	33%	
Construction and buildings sector needs	Building permits issued per square foot of total building floor area	(US Census Bureau, 2019)	50%	20%
	Net population change	(JCHS, 2018)	50%	
Political environment	ACEEE State Efficiency Scorecard building policies score	(Berg et al., 2020)	20%	20%
	ACEEE State Efficiency Scorecard state/government-led initiatives score	(Berg et al., 2020)	20%	
	EERS (incremental savings as % of total retail sales, average of electricity and gas EERS)	(ACEEE, 2019)	20%	
	Member of US Climate Alliance	(Igusky, 2020)	20%	
	Statewide carbon reduction target	(C2ES, 2021)	20%	

6.1.1 Methodology

As part of characterizing the opportunities to implement ABC solutions, we conducted industry research to assess the geographies and market segments in the United States that should be prioritized to maximize near-term market impact. This section provides an overview of the analytical approach used to rank states based on their suitability for early implementation of ABC technologies and practices. It includes a description of the categories and specific metrics used for the state prioritization analysis as well as an overview of the approach taken to combine these metrics into composite scores for each category. These scores are then used for the final state ranking.

The approach taken in this analysis is grounded in several previous efforts to assess the performance of states in regard to building energy efficiency. These include the American Council for an Energy Efficient Economy (ACEEE) State Energy Efficiency Scorecard and a state electrification readiness assessment conducted by RMI. These reports helped guide the design of the scoring methodology as well as the selection of specific attributes to include in the assessment.

This state prioritization analysis differs in notable ways from these previous efforts. The ACEEE State Energy Efficiency Scorecard focuses primarily on states' policy environments surrounding energy efficiency and RMI's assessment focuses specifically on the opportunity for electrification. However, this analysis ranks states based on metrics that are central to identifying the geographies best suited for early implementation of ABC technology adoption. The following section describes these metrics.

This analysis is conducted at the state level as opposed to the city or local level primarily because of the availability of data inputs for states, especially for construction industry, building codes and standards, and policy incentive data. Focusing the analysis on states enables the inclusion of metrics that can be compared in a consistent manner. Future assessments could examine similar market opportunity data in cities or localities within states that receive high scores in this initial prioritization.

Evaluation Categories and Metrics

The state prioritization for ABC solutions implementation is based on five categories of metrics: energy-related CO2 emissions, energy costs, economic development indicators, construction and buildings sector needs, and political environment. Each of these categories and the specific metrics and data sources included is described in turn.

Energy-Related CO2 Emissions

Given the ABC initiative's long-term vision of accelerating progress toward a carbon-neutral buildings sector by 2050, CO2 emissions are a key metric for prioritizing geographic opportunities for early implementation of ABC solutions. This category consists of two metrics: total energy-related emissions and the average CO2 intensity of energy consumption for each state's buildings sector. The first metric sums energy-related CO2 emissions (million metric tons) from residential and commercial buildings in 2017, the latest year for which data are available, and the second metric takes the average CO2 intensity of energy consumption (kgCO2/ft2) across residential and commercial buildings, using energy consumption-weighted building square footage estimates from the US Energy Information Administration (EIA) *Annual Energy Outlook*.[82]

Including both total emissions and emissions intensity of energy consumption for each state allows a balanced assessment of emissions-saving opportunities, whether across a state's full construction and buildings sector or on an individual building basis. States are given higher scores for larger values because both metrics indicate greater opportunities to reduce emissions.

Energy Costs

The costs of energy are also key to prioritizing opportunities for early implementation of ABC solutions given the potential to save consumers money on their utility bills and make retrofits and other efficiency upgrades more likely cost-effective. This category consists of three metrics: the retail costs of electricity, the retail costs of gas, and the ratio of the cost of heating with gas to heating with electricity. The first two of these metrics are simply the average residential and commercial retail electricity price (cents/kWh) and gas price (dollars/MCF) for each state, where state electricity rates are taken from the EIA's 2019 summary tables of electricity sales, revenue, and average price and state gas rates.[83]

The ratio of the cost of heating with gas to electricity, which is commonly called the "spark spread" when referring to wholesale market prices, is calculated by dividing the cost of one therm when heating with gas (assumes 90% furnace efficiency, 10.36 therm/MCF) to the cost of one therm when heating with electricity (assumes 2.5 COP ASHP, 29.3 kWh/therm).[84] In other words, a higher ratio indicates that the retail cost of heating with gas is higher relative to the retail cost of heating with electricity. States with higher ratios are thus given higher scores to capture the opportunities for utility cost savings via electrification of heating end uses.

Economic Environment

The economic environment category in this analysis assesses economic factors that are related to ABC solutions deployment. The total score is composed of three individual metrics, which assess the state's existing programs incentivizing renewable energy and advanced manufacturing, the contribution of the state's construction sector to the state's GDP in 2019, and the size of the state's construction workforce relative to the national construction workforce. Collectively, these metrics are used to assess the ability of each state to incorporate ABC manufacturing and deployment into its economic development strategy.

The first metric measures the extent to which a state is focused on attracting organizations in advanced manufacturing and renewable energy. This binary metric is calculated using a qualitative assessment of each state's economic development initiatives to assign a score. Data was aggregated from individual state economic development office websites. States with economic development initiatives that include an existing incentive program targeting either sector receive a 1 whereas states without an existing incentive program receive 0.

Two construction industry-related metrics are included in the economic environment score. First, states receive a score based on their construction sector's contribution to state GDP, using a compilation of state construction industry fact sheets that are based on data from the US Bureau of Economic Analysis, US Census Bureau, and US Bureau of Labor Statistics.[85] Next, a metric based on this same data assigns a score to states based on their construction workforce's contribution to the national construction workforce.[86] These two metrics attempt to capture whether a state's construction sector productivity and workforce can accelerate adoption of ABC solutions.

Construction and Buildings Sector Needs

Understanding the needs of the construction and buildings sector in each state is critical to evaluating where ABC solutions can best be deployed. This analysis examines two metrics that, combined, yield the score for construction and buildings sector needs. The first metric measures building sector activity by calculating the number of building permits issued per total existing residential and commercial building area in each state. This metric is calculated using data on annual building permits issued for privately-owned housing units in 2019 from the US Census Bureau and state building square footage totals from the EIA.[87] The second metric is a simple calculation of population change in each state in 2018, inclusive of net migration and natural population change.[88] States are assigned higher scores for having higher values in both of these metrics, as this suggests greater building construction activity and increased need for new construction.

Political Environment

Policy factors are clearly important for targeting opportunities where ABC solutions can be quickly and successfully implemented. We examine five metrics that comprise the political environment category. These include three metrics from the ACEEE State Efficiency Scorecard—state scores for building policies and for state-led initiatives as well as incentives for energy efficiency. It also incudes a binary indicator for whether the state is a member of the US Climate Alliance and a metric measuring whether a state has a statewide carbon reduction target.[89]

The ACEEE's building energy efficiency policy metric scores states based on building energy code stringency and adoption, code compliance, and building energy use transparency. Its state- and government-led initiatives metric awards points to states for offering financial incentives through state agencies, passing lead-by-example policies to improve the energy efficiency of public facilities and fleets, and developing and passing pricing around carbon policy.[90] Raw points totals for these two metrics are used to calculate scores for each state in our analysis.

The other ACEEE Scorecard–based metric is the existence and ambition level of statewide incentives for energy efficiency as indicated by the enactment of an Energy Efficiency Resource Standard (EERS) for electricity and natural gas. EERS policies set targets for energy savings that utilities and other program administrators must meet through customer efficiency programs, providing support for cost-effective investment in energy efficiency.[91] The raw input for this metric in our scoring methodology is the incremental energy savings as a percentage of retail sales (averaged across electricity and gas savings/retail sales) from the most recent year for which data are available.[92]

Finally, the political environment score also incorporates a binary metric that indicates membership in the US Climate Alliance, wherein member states commit to implementing policies that advance the goals of the Paris Agreement. It also includes a metric that assesses whether the state has a statewide carbon reduction target and, if so, the stringency of that target. This metric is scored on a [–1, 1] scale, where states without a target are given –1, states with an executive target are given 0, and states with a statutory target (which could be in addition to an executive target) are given 1.

Scoring Methodology

A methodology was developed to create composite indices for each of the five main categories based on their respective individual metrics. This section summarizes the methodology. A summary of the ranking categories, metrics, data sources, and the weights used to create composite indices and to calculate final scores for all states is presented in Exhibit 3.2.2.2.

Score Normalization and Index Composition

Because the individual metrics measure buildings sector indicators on varying scales, with real values for some inputs (e.g., retail prices or CO2 emissions), percent values for others (e.g., EERS, construction industry metrics), and binary or ranked values for yet others (e.g., US Climate Alliance member, statewide carbon reduction target), it was necessary to use a normalization method in order to render individual metrics comparable so they could be combined into composite scores for each category we evaluated.

Numerous approaches exist for constructing composite indicators.[93] These include ranking, standardization (z-score transformation), min-max scaling, and others. Our motivation in this analysis was to develop a simple and straightforward approach for combining metrics that would preserve the ranking of states within each metric but that would yield a wider distribution of final scores to assist with prioritizing states.

Exhibit 3.2.2.3 States versus Complete Metric Rankings

State	Region	Energy-Related Emissions	Economic Environment	Energy Costs	Construction and Building Sector Needs	Political Environment	TOTAL SCORE	Rank
Wyoming	West	4.63	5.77	2.07	1.15	1.45	15	51
West Virginia	South	3.09	5.37	3.53	1.32	2.86	16	49
South Dakota	Midwest	2.16	10.05	1.43	1.56	1.87	17	48
Arkansas	South	3.37	3.47	4.13	2.27	4.63	18	47
Idaho	West	3.82	7.02	1.25	2.45	4.02	19	46
Kentucky	South	2.42	4.26	4.08	2.72	5.21	19	45
Mississippi	South	1.54	9.89	3.91	1.88	1.72	19	44
Alabama	South	1.28	3.59	6.71	2.98	4.75	19	43
North Dakota	Midwest	2.31	12.77	1.45	1.53	1.60	20	42
Nebraska	Midwest	3.12	8.92	1.88	2.07	4.29	20	41
Kansas	Midwest	3.01	10.19	2.95	2.18	2.23	21	40
Oklahoma	South	2.77	10.27	3.30	2.68	2.25	21	39
Montana	West	5.22	5.92	1.89	1.59	6.75	21	38
Alaska	West	10.61	3.12	4.89	1.08	2.98	23	37
Iowa	Midwest	5.61	10.53	1.96	2.42	3.05	24	36
New Hampsh	Northeast	4.42	2.50	6.41	1.62	9.62	25	35
Louisiana	South	1.12	12.22	4.62	2.60	4.52	25	34
Indiana	Midwest	4.51	11.06	2.46	4.94	2.33	25	33
South Carolir	South	1.24	12.05	4.67	4.26	3.88	26	32
Missouri	Midwest	3.13	10.60	3.61	4.32	4.68	26	31
Tennessee	South	2.31	10.91	3.28	4.80	5.14	26	30
Wisconsin	Midwest	5.92	11.01	1.81	3.82	4.80	27	29
Utah	West	5.17	13.57	2.14	3.16	5.38	29	28
Arizona	West	1.53	12.38	4.41	6.69	5.04	30	27
New Mexico	West	3.32	10.10	0.72	1.61	14.95	31	26
Georgia	South	2.90	11.83	5.39	7.10	3.49	31	25
Connecticut	Northeast	5.43	2.61	5.47	2.42	16.32	32	24
Delaware	South	2.89	10.05	4.99	1.47	12.93	32	23
Ohio	Midwest	7.87	11.33	2.47	6.91	5.05	34	22
Vermont	Northeast	5.20	9.36	3.79	1.21	16.65	36	21
Nevada	West	3.56	12.22	2.78	3.46	14.95	37	20
Oregon	West	2.01	11.44	3.56	3.80	16.17	37	19
North Carolir	South	2.56	11.64	5.06	7.31	11.46	38	18
Rhode Island	Northeast	3.59	9.98	6.47	1.33	16.94	38	17
Maine	Northeast	5.48	9.81	6.57	1.57	15.34	39	16
Virginia	South	3.29	11.68	4.86	5.44	14.21	39	15
New Jersey	Northeast	7.78	10.79	3.51	4.79	13.03	40	14
Illinois	Midwest	10.32	10.97	2.28	4.81	11.52	40	13
Minnesota	Midwest	7.08	10.80	2.12	3.89	16.35	40	12
Maryland	South	4.53	11.73	5.08	3.21	15.84	40	11
Michigan	Midwest	9.55	11.32	2.22	5.08	12.52	41	10
Colorado	West	5.50	13.14	2.13	4.50	15.94	41	9
Washington	West	3.08	11.95	3.53	6.94	15.72	41	8
Hawaii	West	0.66	12.22	17.75	1.12	9.89	42	7
Florida	South	1.42	9.33	9.52	16.26	5.75	42	6
Pennsylvania	Northeast	8.50	12.11	4.58	6.85	13.14	45	5
Massachuset	Northeast	7.32	10.81	5.92	4.42	17.71	46	4
Texas	South	4.60	17.38	3.13	20.00	5.70	51	3
New York	Northeast	14.33	11.82	3.91	6.00	16.10	52	2
California	West	10.01	16.44	4.79	14.33	17.09	63	1

Source: State Prioritization Analysis, ABC Collaborative, 2021

For this reason, we applied min-max scaling to each metric, which normalizes the metric to have a range [0, 1] by subtracting the minimum value and dividing by the range of all values for that metric, as given by:

$$x'=(x-\min(x))/(\max(x)-\min(x))$$

Where x' is the scaled metric and x is the original, unscaled metric. After applying min-max scaling to each metric, a weighted sum was taken to calculate a composite score for the respective category, where the weights for each metric were specified in advance (see Exhibit 3.2.2.2 for the metric weights). A final step, multiplying the weighted sum scores for each category by 100, allowed for a more interpretable final score for each category, which could range from 0–100.

To compute the total scores for each state, we again took a weighted sum of the five main categories to preserve the score range of 0–100. The weights for each category were specified in advance and are listed in Exhibit 3.2.2.2. Our aim in this analysis was to create an approach that can easily be updated with new weights (either for individual metrics or for entire categories), such that different audiences can choose to prioritize different indicators and yield a new ranking of states. Our results in Section 3.1 show a baseline prioritization, where each individual metric and each category is given an equal weight in the ranking.

6.2 Additional Case Studies of Success and Failure in Industrialized Construction

Integration of BIM with ABC Technology Allows for Aggregated Savings

Summary: ACQBUILT, Inc. is an off-site construction manufacturer in Edmonton, Canada, specializing in residential construction. It underwent a research exploration with a team of research scientists to examine the waste reduction potential that building information model (BIM) technology, in combination with ABC off-site construction, can offer.

In traditional construction, roof sheathing is traditionally cut ad hoc, on-site, by experienced professionals using learned "rules of thumb." In this traditional practice of cutting roof sheathing as it gets attached to trusses, there is no prior design or planning. This often leads to waste through inefficient resource use, with the potential of additional waste in reworking sheathing. In contrast, the use of BIM technology allows for preemptive design of roof sheathing using algorithms to optimize design and increase efficiency, resulting in the reduction of wasted sheathing materials. The ACQBUILT case studies utilized a hybrid algorithm of both greedy and particle swarm algorithms, in combination with the design algorithm to optimize design of prefab roof sheathing.

The case study buildings include one attached garage single-family home and a detached garage single-family home. Researchers found that the prototyping system was able to accurately calculate sheathing quantity needed and monitor the usage level of material throughout the manufacturing process.[94]

Following review by seasoned industry professionals, case studies confirmed that the BIM system was able to accurately integrate and apply design rules as used in traditional construction to the roof sheathing system for an effective and efficient fabrication process. Material waste was reduced to 12.1% in the attached garage home and 12.91% in the detached garage home, compared with averages of 20.09% and 20.73% respectively for similar building and roofing types previously built by ACQBUILT, Inc. This level of waste reduction was a record low in the company's history in terms of wasted material. Furthermore, the designs generated in early project stages also supported stronger communication within the project team.

Key Learnings: BIM technology, while not exclusive to prefabricated construction, is an important tool to examine in off-site construction case studies. The benefits BIM technology offers are maximized in tandem with off-site construction as manufacturing processes provide the opportunity to effectively engineer construction design and industrialize the manufacturing processes. Off-site construction is recommended to take advantage of the full range of benefits offered by BIM technology as the virtual workshop BIM offers, and its related computational algorithms, allow manufacturers to evaluate and optimize all construction plans prior to even touching the involved materials. Off-site manufacturing also allows fabricators to execute on designs in a standardized and controlled environment.

Optimizing an installation plan using ABC methods requires BIM technology to accurately design, plan, and execute high-efficiency design. The combination of these two practices in tandem allows for engineers to achieve maximum benefits from each, elevating and optimizing savings in terms of reducing waste, increasing efficiency, and decreasing costs.

It is also important to note further savings could be achieved via additional automation (in terms of sheath cutting, which in these case studies was completed by hand) or through the exploration and application of other algorithms, including a potential addition integrating different design standards or building codes. Finally, while these case studies highlight savings in roof sheathing, similar savings in areas such as inventory management, labor costs, time spent, and rework costs across other areas of the construction industry are possible.

BIM Successes in Application Across Full Construction Lifecycle

Summary: Clark Pacific is known as an innovator and trendsetter in the construction world, with the work in precast concrete supporting more than 2,500 structures on the west coast. These include commercial and residential buildings as well as larger-scale projects such as the San Francisco 49ers stadium in Santa Clara. The company credits much of its success to its use of BIM software throughout the construction lifecycle. From drafting a bid and providing customer estimates, to concept design development, to product fabrication, to the on-site erection process, BIM helps the team to communicate more clearly, streamline workflows, and remain efficient in their use of time and resources.[95]

Key Learnings: Clark Pacific utilizes BIM software to standardize processes across all workstreams, which allows coordination across engineering, fabrication, procurement, and management teams simultaneously. This practice results in faster build time, with lower lifecycle costs for building owners. Its usage of BIM software goes beyond coordination across trades in the design stage to ensure higher productivity and revenue for the company.

The BIM software allows for more accurate cost estimation and therefore higher quality bids, which in turn allows Clark Pacific to leverage this software to secure more business. The accessibility and transferability of BIM outputs have allowed Clark Pacific to ensure all trades and parties operate on the same assumptions, reducing rework and enabling design teams to review structural components at a more detailed level. BIM also allows for the proactive identification of issues while in the design phase instead of needing to retroactively solve issues arising during on-site fabrication.

The standardized library of build components and parts offered by the BIM software enables design of accurate, feasible, and replicable projects, thus reducing the design timetable and adding value and efficiencies to Clark Pacific projects. BIM software also allows for tangible project management status updates and proactive identification of issues, again helping to keep project timelines short and allowing Clark Pacific to continuously deliver high quality products, while remaining under budget. The clear and concise reporting features allow teams to provide stakeholders with accurate and relevant updates to keep fabrication on track.

In terms of manufacturing, BIM software helps to eliminate errors, and reduces wasted time spent on reworking models by highlighting parts that don't fit accurately. BIM is also used to optimize supply chain management, as the software easily exports reports regarding material needs and quantities to allow for easy, rapid procurement. The platform also allows Clark Pacific to apply cost tracking to stay within budget and to communicate directly with production software and machinery to utilize material efficiently, therefore reducing waste and keeping material inventory lean. Finally, BIM software is used to preplan erection processes on site, allowing for easy, clear communication, and greater on-site safety.[96]

The efficiencies offered by the platform provide savings in both time and costs. Clark Pacific credits the usage of this software across not just the design phase but also all aspects of its industrialized construction workflow with helping its teams to be successful. It does this while increasing the quality of products provided to its customers, keeping budgets lean and accurate, and increasing safety and efficiency on job sites.

Modularity in Process as Well as Product

Summary: In examining two case studies regarding the development of modular steel structural systems, we can better understand how modularity, when applied to the construction process in addition to the architectural product, can provide greater savings in terms of both cost and efficiency.

The Advanced Technology for Large Structural Systems (ATLSS) Centre at Lehigh University in Pennsylvania developed the ATLSS Integrated Building Systems, which consists of structural steel beams engineered to slide into place during the structural erection process. The system was designed with beam-to-column connection components that allows for self-alignment, adjustment as needed, enduring load-bearing strength, and product modularity.

With these standard connection components, the ATLSS system allowed for the build of custom beams, with the ability for customized length as needed. ATLSS entered this venture with the goal of automating construction by engineering a system that facilitates its own beam-column connection and installment on site, thus avoiding the need for workers to engage in the process and increasing safety on job sites. This system required the development of an automatic robotic crane to facilitate beam installment in lieu of on-site labor, which increased costs considerably. The system was never used commercially, and its lack of success is credited to the expense of the crane.

ConXtech Inc., based in California, separately developed a connection system utilizing beam-to-column connection technology, with the end goal of creating a structural steel system with a high degree of modularity to provide mass-customized solutions to a broad construction market. Its product range included three kinds of beam-to-column connections, with each of these connections coming in a range of predetermined lengths. When challenges arose regarding tolerances in the foundation related to column placement, ConXtech worked to decouple the uncertainty in the foundation location by creating a jig to position anchors precisely on site.

Other innovations in the ConXtech system include visual aids in the bolting process to ensure standardization in bolt tensioning. This allows for quicker review and reduced rework, as well as the ability to erect the steel structure in modular increments, allowing overlap in on-site work by ConXtech and other on-site trades. ConXtech also developed a BIM components library of its products that can be utilized across different BIM platforms, reducing rework, allowing for specific product planning in early design stages, and reducing design lead time. Overall, in comparison with traditional construction methods, a sample of nine ConXtech projects were found to be much higher in terms of productivity (person-hours per tons produced), with costs remaining relatively equal. The similarity in cost is due to the high expense of precise machinery required for the ConXtech process.[97]

Key Learnings: Modularity was applied differently in these two case studies—while both utilize product modularity, the cases differ in their approach to process modularity and strategies for managing tolerances. While ATLSS' system would appear more modular in that only one type of connection was developed, the system allowed for beam lengths of any size, making design highly variable and reducing standardization. In contrast, the ConXtech system offers a limited range of beam lengths, but this limited offering (especially when coupled with BIM software allowing for design to integrate standard beam options) resulted in greater standardization and reduced lead time.

Furthermore, the ConXtech approach to the jig solution allowed for reduced uncertainty while ATLSS' system was forced to accept normal deviations in foundation positioning, in turn reducing precision and increasing uncertainty in the process.

ConXtech, in utilizing a modular approach to process in its reduced range of components, allowed for greater standardization and repetition using its products while still providing the ability for designers and customers to build unique structures. Its efforts resulted in reduced lead time, uncertainty, need for rework, and higher productivity. It is especially notable that the company was able to standardize design processes as this step has been proven to be one of the areas with highest cost variability in prefabricated construction.[98]

A failure of ATLSS system was considering tolerance management to be "an inherent property of the structural steel system," resulting in a lack of control of uncertainty in the system, compared with ConXtech where uncertainty due to tolerance management is effectively controlled, resulting in reduced services costs and site assembly lead time. While the need for the expensive automated crane in the ATLSS system greatly reduced commercial interest in this system, the team failed to utilize modularity to its fullest in order to streamline and standardize processes.

ConXtech embodies a full adoption of modularity not just in product structure but in the full life cycle of the steel structure system process. This case study also shows the importance of a reduced range of modular components, as exemplified by ConXtech's limited beam length offerings. ConXtech was successful in creating a platform system for its clients, and thus enabled standardization across all related processes from design to system erection. The system was proven to be successful compared with traditional methods, with higher productivity at no additional costs whereas the ATLSS system was not able to succeed commercially. ConXtech's system was able to reduce complexity in design by offering a standardized range of products, simplify the assembly process, reduce uncertainty in on-site construction, and reduce lead time while keeping costs steady by expanding its application of modularity to not just the product, but the process as well.

List of Exhibits

Glossary of Core ABC Organizations

ABC Collaborative: Advanced Building Construction Collaborative (led by RMI)
ABC Initiative: Advanced Building Construction Initiative (led by DOE)
ADL Ventures
AEA: Association for Energy Affordability
DOE: US Department of Energy
NREL: National Renewable Energy Laboratory
PHIUS: Passive House Institute US
PNNL: Pacific Northwest National Laboratory
RMI (formerly Rocky Mountain Institute)
VEIC: Vermont Energy Investment Corporation

Glossary of Terms

Advanced building construction (ABC): Innovative low-carbon new construction and retrofit solutions that are faster to deploy (including through use of industrialized construction), high quality, affordable, and appealing to owners and users.

Architects/Engineers (also designer): Entities that plan, design, and review the construction of buildings, often in close collaboration with general contractors and trades.

Emissions: In this context, greenhouse gas emissions.

Financiers (project investors): Entities that finance long-term construction based on a financial structure in which debt and equity used to finance the project are paid back from cash flow generated by the project.

General contractor (GC): Contractor with main responsibility for construction, improvement, or renovation project under contract.

Government agencies: Any public legal entity or public agency, created by federal, state, tribal, territorial, county, or local government.

Industrialized Construction (IC): A general term for applying modern manufacturing methods, tools, and practices to construction. This can include, but is not limited to, off-site construction manufacturing in a controlled environment, volume production of standard components, use of digital tools and digitized workflows, automation and robotics, and feedback learning loops for regular process and design improvements.

Insurers: Entities providing financial coverage in the case of events causing financial loss; today this is typically a third-party financial services company.

Investors: Corporations, foundations, individuals, or investment funds that generally invest on a non-recourse basis and seek to be paid back through investment returns generated by a liquidity event or principal repayment.

Manufacturer (also, original equipment manufacturer [OEM]): Entity that integrates sub-components and materials to develop integrated advanced building systems.

Materials suppliers (also subcomponent suppliers): Entities that provide materials to be used in pre-integrated advanced building systems (e.g., sheathing, drywall, insulation, air/moisture barriers, etc.)

Modular: A method of building construction relying on factory production of units, or modules, with some degree of standardization. In common usage, this often refers to volumetric modular construction, wherein three-dimensional modules are produced.

Net-zero carbon: Buildings designed and operated in such a way that their energy use is not a net producer of greenhouse gas emissions. This can be achieved through a combination of energy efficiency, electrification of building systems, on-site generation of renewable energy, and use of grid power generated from carbon-free sources.

Off-site: A general term referring to construction activity occurring in a controlled environment other than the final site of the building (such as a factory), with the construction components (assemblies, panels, modules, etc.) being delivered to and, if necessary, assembled at the site. Off-site construction frequently, but not always, involves the use of industrialized approaches.

Prefab/prefabrication: A specific method of industrialized building construction relying on assemblies being prefabricated either off-site or on a temporary site adjacent to the building location. This can include panelized and volumetric modular construction.

Research institutions: Any institution that is primarily not-for-profit, conducting research related to construction materials and processes, including two-year and four-year educational institutions, government laboratories, and other nonprofit research laboratories.

Serial builders (also repeat builder): A broad term referring to any demand-side entity with significant decision-making power and responsibility over many similar construction projects. This may include corporate entities that directly control the specifications of large numbers of branches or franchises; developers that either build, own, and operate projects, or build, own, and transfer properties; or, in some cases, heavily involved investors or financiers that impose new construction or renovation guidelines as a precondition of financing.

Solution providers: Supply-side entities that deliver a unique offering that differs from both traditional energy service contracting and conventional construction in that they: 1) are responsible for an entire project—including energy performance and non-energy related elements; 2) create a turnkey experience for the owners managing everything from design and engineering, to manufacturing, to installation, to ongoing commissioning and maintenance inclusive of a performance guarantee; and 3) in many cases are vertically integrated and manufacture prefabricated components of the construction package (e.g., unitized high-performance wall panels).

Subcontractors (also subs or trades): Entities responsible for a specific, partial scope of work within a construction project, typically performing work under a GC.

Trade associations and industry associations: Organization representing businesses that operate in a specific industry, or interests within a given industry. The Collaborative may deal with construction-related trade associations representing all or part of some of the other stakeholder groups defined here, as well as trade associations representing broad interests related to advanced building construction (energy efficiency, energy savings, manufacturing, etc.).

Utilities: Regulated entities that provide essential resource-based services such as water, electricity, and natural gas. This includes local distribution companies (LDCs).

Workforce training programs: Educational and experience-based activities (including apprenticeships, coursework and seminars, instruction and training through organized labor groups, workshops, etc.) that develop or enhance the skills of workers and prospective workers. The Collaborative will have specific interest in programs that equip workers with the skills to build, retrofit, operate, and maintain energy-efficient buildings in an advanced construction environment.

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