

Better, cheaper, faster, stronger: a new data collection campaign to capture the benefits of industrialized construction approaches for whole-building retrofits

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ABSTRACT

The building sector is responsible for 35% of current greenhouse gas emissions in the U.S. and approximately two-thirds of existing buildings will still be in operation in 2050. Improving existing buildings' energy performance via deep, whole-building retrofits is an essential component in the transition to a carbon-neutral electricity system because it can reduce the operational costs of electrified buildings and grid challenges associated with broad adoption of variable renewable energy. In many cases, however, deep retrofits are not cost-effective at the building level because their energy savings alone do not justify their high upfront costs. To scale whole-building retrofits, both more affordable retrofit strategies and more holistic approaches to building valuation are needed.

The Advanced Building Construction (ABC) Initiative aims to transform building construction and renovation practices in the U.S. using industrialized construction approaches to improve the speed, scale, and affordability of high-performance building retrofits. The ABC Initiative has developed a plan to collect key data related to construction productivity and speed, building resilience and durability, and other added value metrics, including occupant health benefits, across its portfolio of projects. Collecting these data in addition to verifying energy performance targets will support more holistic valuation approaches that can accelerate the deployment of whole-building retrofits. In this paper we introduce and define standard measurement criteria for collecting data on the benefits of industrialized construction approaches and provide recommendations to the building efficiency community on how to use this plan to enable more holistic assessments of whole-building retrofits.

Introduction

Residential and commercial building energy consumption is a substantial driver of U.S. energy-related carbon dioxide (CO₂) emissions, accounting for around 1.5 billion metric tons in 2021, or a third of the U.S. total (EIA 2022). The building sector also accounts for around 75% of annual U.S. electricity consumption (EIA 2020). While the U.S. is projected to add around 30 million homes and 33 billion square feet of commercial building floor area by 2050, approximately two-thirds of existing buildings will still be in operation in 2050 (EIA 2022). The development and adoption of building codes can help incrementally drive down the emissions associated with new construction, but the existing building stock will still account for the majority of building sector emissions by 2050. As such, retrofitting existing buildings is an essential component of achieving economy-wide decarbonization goals.

Previous research on pathways to deep decarbonization highlights the importance of building energy efficiency in the transition to a net-zero energy system (National Academies of

Sciences, Engineering, and Medicine 2021; Williams et al. 2021; Larson et al. 2020; Nadel and Ungar 2019). These and related analyses suggest building efficiency measures can drive emissions reductions in line with net-zero targets while also reducing the overall costs of the transition. Langevin et al. (2021) estimate a technical potential of 800 TWh of electric energy savings and 208 and 121 GW of respective summer and winter net peak electricity demand reductions in 2050 from co-deployment of best available building efficiency and flexibility measures under a reference case trajectory for the power sector. The authors find that these savings, when valued as early retirements of fossil-fired generation or avoidance of energy storage capacity, could total \$42 billion in electricity system benefits by 2050 (not including the benefits of avoided transmission and distribution infrastructure). Given the high costs of transitioning to a net-zero electric grid, especially for very high penetrations of renewable energy (Cole et al. 2021), the grid benefits and cost savings potential of building efficiency are likely much larger under rapid power sector decarbonization.

In addition to these power system and emissions benefits, energy efficiency can deliver benefits to building owners and occupants. These include energy-related cost savings, such as reduced utility bills, and non-energy benefits, such as improved indoor air quality and thermal comfort, increased home value and aesthetics, productivity gains for occupants, and greater building durability and resilience to extreme weather events (Dessouky et al., 2020; Hawkins et al., 2020; Caputo et al., 2017; Amann, 2006). Although non-energy impacts are not often monetized in assessments of the cost-effectiveness of energy efficiency programs, studying them and quantifying their impacts has been an active area of research for several decades (Dessouky et al. 2020). In some cases, non-energy benefits have monetary values that can exceed the value of energy savings associated with an energy efficiency program (Barkett et al. 2006), though other studies find that non-energy benefits do not yield large monetary savings (e.g., Tonn et al. 2018), indicating inconclusive evidence. Still, identifying and quantifying non-energy impacts where possible is important for holistic assessments of the benefits of whole-building retrofits.

Despite the clear role of building efficiency in least-cost pathways for economy-wide decarbonization, as well as the numerous non-energy benefits that building efficiency and, especially, whole-building retrofits provide to occupants, these types of upgrades are still uncommon in the U.S. York et al. (2015) estimate that for whole-home retrofit programs, annual participation rates of 1–3% of all residential customers are possible. For multifamily housing whole-building retrofits, rates reach 1–2% of units per year. These rates are for whole-building programs but not necessarily for retrofits that would be considered “deep”. The Global Alliance for Buildings and Construction estimates that deep renovation¹ rates are well below 1% of the existing building stock and that, in developed countries, these rates must accelerate to 2% by 2025 and 3% by 2040 to achieve net-zero targets by 2050 (Laski and Burrows 2017).

A number of challenges exist for scaling high-performance, whole-building retrofits to these deployment rates. First, deep retrofits have high upfront or installed costs that cause these projects to not be cost-effective in the near term based on their utility savings alone (Goldstein et al. 2018). A related challenge is that in most states, utility-administered energy efficiency programs calculate cost-effectiveness using tests that do not account for societal, environmental,

¹ The GABC defines “deep renovation” as achieving energy use reductions of 75% or greater compared to a building’s pre-renovation baseline (Shnapp, Sitjà, and Laustsen 2013).

or participant health benefits, thus limiting the ability for whole-building deep retrofits to pass these tests (ACEEE 2018). In addition to challenges related to project economics, whole-building retrofits are also time-consuming and disruptive for building occupants, do not have a streamlined delivery model, and entail greater risks due to their complexity and invasiveness. Further, it is well known that labor productivity in the U.S. construction industry has barely increased since 1945, whereas it has grown by as much as 1,500% in other industries, such as manufacturing, retail, and agriculture (Barbosa et al. 2017).

To address the challenges and opportunities present in the U.S. construction and renovation industries, the U.S. Department of Energy (DOE) Building Technologies Office (BTO) launched the Advanced Building Construction (ABC) Initiative in 2019 to transform these industries, improve lagging productivity in U.S. construction, and streamline the delivery of high-performance, industrialized construction solutions to decarbonize the built environment (Hasz, Ryan, and Glickman 2020). Industrialized construction encompasses both existing and emerging construction practices ranging from volumetric modular and panelized construction to digitized workflows, automation of manufacturing processes, augmented reality and robotics, and off-site, factory-based construction (Fisler et al. 2021). The ABC Initiative aims to spur innovation in these areas through R&D while also developing new delivery and business models to enhance productivity and transform the market for these innovations in the U.S. construction industry.

ABC innovations share four key attributes that all contribute to achieving these objectives. First, ABC refers to new construction and retrofit solutions that attain both low operational and embodied energy use and CO₂ emissions. Specifically, the ABC Initiative's first Funding Opportunity Announcement (FOA) called for retrofit solutions that could achieve a 75% reduction in building thermal site energy use intensity (EUI) and new construction technologies that are 50% more energy efficient than current code levels. Second, ABC solutions must be cost-effective for developers and consumers and be delivered for the same or less cost than the current code-minimum offering. Third, they must provide faster and less disruptive on-site deployment in comparison to traditional construction practices. And fourth, ABC solutions must provide additional value, such as improved resilience and durability, better indoor air quality (IAQ) and thermal comfort, or other features that can stimulate demand for these technologies among building owners and occupants.

The current use of ABC approaches is rare in the U.S. and has mostly focused on the new construction context, but it is growing rapidly. While the global off-site construction market is growing nearly twice as fast as the entire construction market, only around 2.5% of single-family and multifamily builders use modular construction practices. These shares rise to 5% and 18% for the use of panelized walls (Hudson 2019). Prefabricated approaches to new roof construction have seen greater levels of adoption², demonstrating the potential for integrating these approaches into existing and broadly accepted construction practices. Still, especially in the context of whole-building retrofits, the U.S. market for industrialized construction remains largely untapped.

As this nascent industry continues to grow, an important objective is assessing the performance and benefits of industrialized construction approaches in both new construction and

² Fisler et al. (2021) report that trusses, the majority of which are prefabricated, were used in around 62% and 76% of new roof construction in single-family homes and apartments, respectively.

retrofits. Given the limited nature of the current market for ABC, as well as the absence of a central entity that tracks and assesses the activity of the market as well as the efficacy of ABC approaches in achieving the goals mentioned previously, the ABC Initiative has developed a Data Collection Plan (DCP) to ensure projects are assessed using standard, consistent, and measurable criteria. This standard approach to measurement and verification (M&V) “at the initiative scale” will allow the ABC Initiative to track the advance of this industry while identifying key strengths and weaknesses of individual technologies and approaches for industrialized construction.

This paper introduces the high-level goals of the ABC Initiative and outlines the key metrics and data requirements that comprise the DCP for both ABC-funded and industry-led industrialized construction projects. While the focus here is on applications of the DCP in the whole-building retrofit context, the metrics and data requirements are applicable to new construction as well. In the next section, we introduce the main criteria, metrics, and data requirements that will enable the ABC Initiative to track progress toward its goals. The third and final section presents a discussion of some of the challenges and opportunities for collecting these data and provides recommendations for how the building efficiency industry can use the DCP for holistic assessments of whole-building retrofits.

Metrics and Data Requirements for Assessing the Potential of ABC Technologies

This section presents an overview of the metrics and data requirements that are included in the ABC DCP and discusses existing evidence from the literature, where relevant. The DCP provides guidance on collecting a standardized set of data from industrialized construction projects to create an evidence base for their performance and benefits. This uniform set of data will be used to identify key strengths and weaknesses of industrialized construction approaches to further advance the industry. The data requirements presented in this section are based on the attributes of ABC innovations outlined in the introduction:

- High energy performance with low operational and embodied CO₂ emissions
- Cost-effective for both developers and consumers
- Faster and less disruptive than traditional construction practices
- Provide additional value to building owners and occupants

After a brief introduction of each attribute, we present the metrics and data requirements that will enable their evaluation in the context of a whole-building retrofit project.

Energy performance and CO₂ emissions reduction potential

In line with the initial ABC FOA’s goal of achieving a 75% reduction in building thermal site EUI for retrofit technologies, the first attribute of ABC innovations is that they deliver substantial energy efficiency gains and, as a result, reduce the building’s CO₂ emissions. ABC’s definition of thermal end uses includes space heating and cooling as well as water heating and building ventilation (DOE 2019). The focus on thermal end uses is an intentional one, as together

these account for over 50% of the building sector’s site energy use and CO₂ emissions (EIA 2021a). Figure 1 shows how the building sector’s annual site energy consumption and CO₂ emissions are distributed by end use and fuel type (electric or “indirect” and non-electric or “direct”).

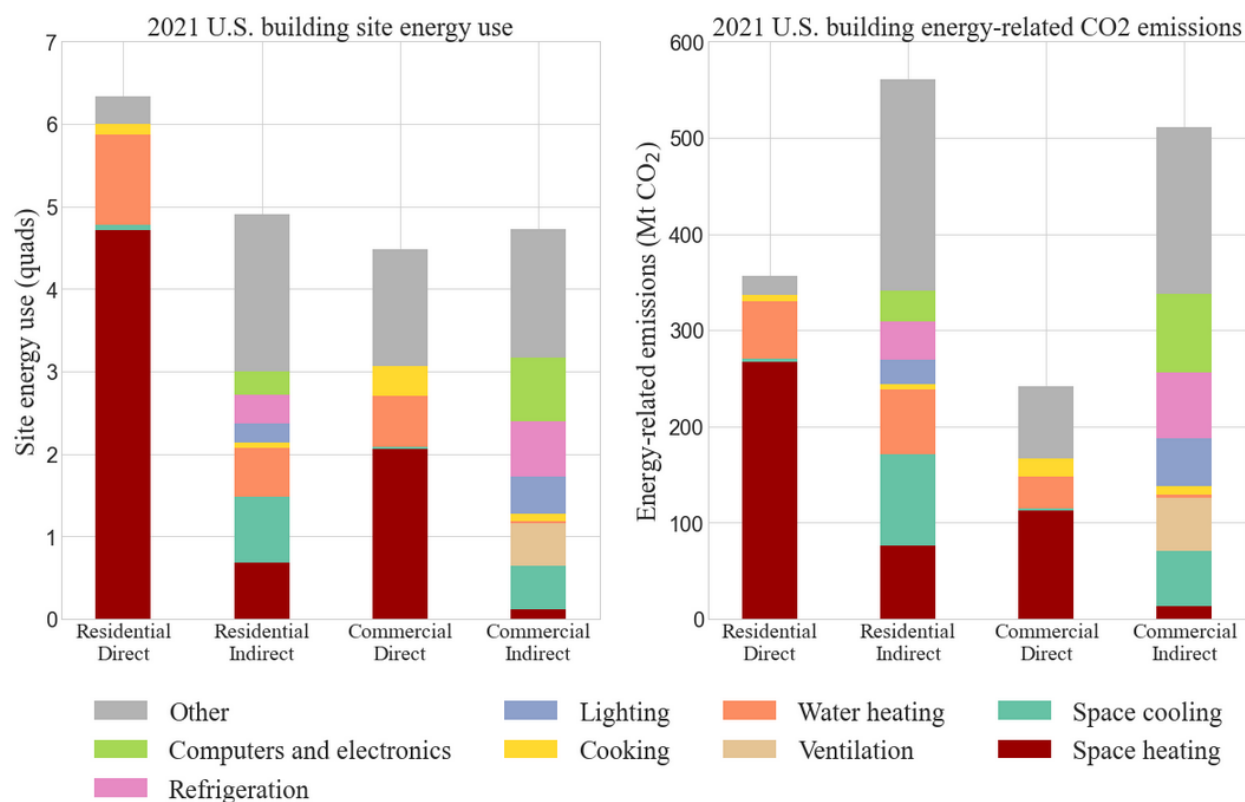


Figure 1. U.S. building site energy use and energy-related CO₂ emissions by sector, end use, and fuel type. “Indirect” represents electricity use, and “Direct” represents non-electric fuel consumption. Data are from DOE’s Scout modeling tool (scout.energy.gov) and EIA (2021a).

The ABC DCP is focused on the potential of whole-building retrofits to reduce both operational and embodied energy use and CO₂ emissions. “Embodied” refers to the total energy consumption and greenhouse gas (GHG) emissions associated with the embodied stages of a building or system, including the material production, transportation, construction/installation, and end-of-life decommissioning stages (Adams, Burrows, and Richardson 2019). Tracking the full life-cycle energy and emissions footprints of ABC innovations is important in order to highlight where further improvements in manufacturing, construction, and disposal or recycling of retrofit technologies can deliver lower energy use and emissions throughout those products’ life cycles. Given the different emissions sources associated with these stages, we adopt the convention of expressing these emissions in the equivalent amount of CO₂ emitted, or CO₂e.

Operational carbon emissions. Operational emissions are straightforward to measure if associated with fossil-fuel consumption, as the carbon content of each fuel determines how much CO₂ is produced when a fuel is burned (EIA 2021b). Tracking CO₂ emissions from electricity is more challenging because electricity is typically generated from a mix of fuels (e.g., natural gas, coal, and renewables), and this generation mix makes a big difference to the amount of CO₂e attributable to electricity consumption and savings. Further, there are different types of emissions

metrics, or factors, that can be used to assess emissions over time or at different times of day. This is important because the generation mix for electricity changes in both the short run and the long run. Two types of emissions factors are currently used for most decision-making around assessing and reporting emissions from the electric sector. These are average emissions rates (AER) and short-run marginal emission rates (SRMER). A third and lesser-known metric called the long-run marginal emission rate (LRMER) has recently been shown to outperform these other two emissions rates in terms of accuracy by incorporating both the operational and structural implications of changes in electricity demand (Gagnon and Cole 2022). While a detailed discussion of average and marginal emissions rates is beyond the scope of this paper, we note that this is an active area of research and that there are different levels of complexity with which one can assess the operational emissions from an energy efficiency intervention. Rather than requiring each retrofit project to calculate and report its own operational emissions estimates, which would lead to the use of different methods and emissions factors, the DCP focuses on collecting energy performance data at high temporal resolutions alongside geographic data that will enable consistent analysis of operational emissions impacts across all projects using one or several of the metrics mentioned above.

Table 1 presents the primary metrics and data requirements for evaluations of energy performance and operational CO₂ emissions. Some of these are common in evaluations of retrofit projects (Carroll et al. 2015; FEMP 2015), whereas other metrics, such as level of electrification and load flexibility potential, are important to measure and assess given their role in an increasingly connected and decarbonized building sector. Regarding the requirement at the bottom of Table 1 that data be collected for both pre- and post-retrofit periods, this is standard practice for M&V of energy efficiency projects. The preferred time duration for pre- and post-retrofit data is 12 months; however, this may not be feasible or practical for all projects, especially for field demonstration sites. In these cases, we recommend collecting as much pre-retrofit data as possible and supplementing this with at least one full year of utility billing data.

Table 1. Data requirements for assessing energy performance and operational emissions

Metric	Relevant Data	Notes
Building characteristics and asset data	Building metadata: • Building type • Vintage • Size • Conditioned floor area • Number of floors • Floorplan/layout • Space type • Climate zone • Fuel type(s) • Occupancy	Documentation
	Envelope characteristics: • Wall structure: ○ (residential) masonry vs. wood-frame ○ (commercial) concrete vs. masonry vs. steel vs. wood • Insulation • Infiltration level • Fenestration system and area • Building overall heat transfer coefficient (UA)	Documentation to include (where relevant): • Wall assembly thermal conductivity [(Btu·ft)/(h·ft²·°F)] • Type, level, and location of insulation in assembly • Infiltration – blower door test [ACH 50]
	Mechanical systems: • Heating/cooling equipment type, fuel, capacity, and efficiency rating • (commercial) RTU vs. PTAC vs. Other (specify)	Documentation

	(residential) specify type of heating/cooling and distribution system - Ventilation design - Domestic Hot Water (DHW) type, fuel, size, and efficiency rating	
	All other systems: - Lighting system - PV size (if present)	Documentation
Energy consumption	Electrical energy (whole building)	Hourly (minimum), 15-minute (preferred) +/- 0.5%
	Electrical energy (circuit level, by major end use)	Hourly (minimum), 15-minute (preferred) +/- 0.5%
	Natural gas or propane	Hourly (minimum) Diaphragm gas flow meter Typical Utility-grade meters have accuracy +/- 1 ft ³
	Fuel oil	Annual.
Onsite generation	PV production	Hourly (minimum), 15-minute (preferred) +/- 0.5%
Indoor environmental conditions	Living space temperature and relative humidity (T&RH)	[F, %]; Hourly (minimum), 15-minute (preferred) +/- 1.0F, +/- 10% RH; Ecobee ³ data if possible
Weather	Outdoor temperature & relative humidity (T&RH)	Hourly (minimum), 15-minute (preferred); from nearby station
Level of electrification	Percent of total energy use that is electric vs. other fuels	Annual/daily basis [%]
Load flexibility	Characterize daily, winter, and summer peak load (e.g., peak value, duration of peak period, end uses driving the peak, etc.)	Documentation
	Maximum daily peak load reduction potential (How much load can be shifted outside of peak periods during peak periods?)	[kW, %] Document assumptions of “peak period”
	Document features that enable load shift (e.g., energy management systems, smart appliances, smart thermostats)	Documentation
Retrofit Pre/Post	Preferred: 12 months of pre- and post-retrofit data for all above metrics Alternative: As much pre-retrofit data as possible, plus 12 months of utility bill data	

Embodied energy use and emissions. Assessing embodied energy use and emissions for retrofit projects is more challenging than measuring operational energy use and emissions because it requires data across a retrofit project’s full life cycle. The standard method for assessing full life-cycle emissions is a Life-Cycle Assessment (LCA), which quantifies the environmental impacts of a product throughout the primary stages of its life cycle, including production and manufacturing, construction and transport to the building site, use phase, and end-of-life demolition and disassembly (CLF 2020).

Given that the above section describes our method for assessing operational emissions, for this part of the DCP, we focus on emissions that occur during the life-cycle phases other than the “use phase” and adopt specifications in the Product Category Rule (PCR) of Buildings⁴, which sets guidelines for conducting whole-building LCA. The system boundary adopted for this work is “cradle-to-grave,” which encompasses the life-cycle stages mentioned above and, in contrast to the “cradle-to-gate” boundary, includes end-of-life practices related to recycling and technology reuse at the end of a product’s designed service life.

Table 2 lists the life-cycle stages and relevant data required to assess these for each retrofit project evaluated. For the manufacturing stage, we require a bill of materials for each

3 <https://www.ecobee.com/en-us/>

4 <https://unstats.un.org/unsd/classifications/unsdclassifications/cpcv21.pdf>

project that includes the major components and their weight or relative proportion by weight. Transportation involves transport of the project components from the manufacturing facility to the construction site, so data on modes of transportation, distance, and effective payload are required. Because transportation logistics are highly project-specific, we also request information on how these vary with applications in different markets or regions so that we can adopt consistent analysis assumptions when assessing this source of embodied emissions. The construction/installation stage is evaluated using data on energy use or material requirements and losses, and data on how the service life of the technology informs calculations on replacement requirements to assess embodied emissions of the use stage. Finally, end-of-life demolition/disassembly assessment requires details on specific decommissioning protocols (e.g., demolition waste hauling to landfill or recycling plant), including the most likely end-of-life scenario. For whole-building retrofit projects that include HVAC system replacement, we require data on the type and initial charge of refrigerants to assess the lifetime CO₂e from refrigerant leakage (based on standard assumptions of annual and end-of-life leakage rates) (Wan et al. 2021).

Table 2. Data requirements for assessing embodied emissions

Life cycle Stages	Relevant Data	Notes
Manufacturing	Bill of materials and their absolute weights or relative share by weight	The major components should make up >95% of the product by mass
Transportation	- Transportation mode (e.g., by truck or by rail) - Transportation distance	Discuss how the transportation details may vary with application in different target markets/climate zones
Construction/installation	- Any significant process energy and material use - Material loss/waste ratio	
Use (assessed using approach/methods outlined in Table 1)	Designed service life/durability of the technology solution (in addition to data requested in Table 1)	Specify how the designed service life may be different from default
End-of-life demolition/disassembly	Details on end-of-life decommissioning scenario	Provide the most likely end-of-life scenario and why
Other (specific to HVAC systems)	Type and initial charge of refrigerants	

Technology affordability for developers and consumers

The ABC Initiative’s goal around affordability is to bring technologies and new business models to market that can achieve deep energy savings at the same or less cost than current code-minimum offerings. Industrialized construction approaches show promise to reduce installed costs through improved productivity, reduced construction timelines, and supply chain optimization (Fisler et al. 2021), but there is limited existing evidence on these components of cost reduction.

While there exist numerous methods of defining whether a project or technology is cost-effective (ACEEE 2018), given the ABC Initiative’s focus on affordability, we do not define a single metric for assessing this goal. Instead, we focus on key metrics of project costs and the data required to track these that will permit various calculations of cost-effectiveness and affordability. Table 3 lists each of these metrics.

The main cost categories for which we require data include first costs (to both building owners and manufacturers), future or anticipated costs (understanding that potential strategies for

cost reductions vary across projects), operational/maintenance costs, and replacement costs. We also request information on project finance, including whether special subsidies or innovative financing mechanisms are employed (e.g., emerging models for Energy Efficiency as a Service or “EEaaS” (Henner and Howard 2022)). These metrics provide a holistic view of the primary costs and potential cost reduction opportunities associated with a new model of whole-building retrofit delivery.

Table 3. Data requirements for assessing affordability

Metric	Relevant Data	Notes
First costs (Building owner)	Price to building owner of building or system (cost of acquisition)	[\$/unit, \$/ft ²]
First costs (Manufacturer)	Start-up cost to doing things a new way	Includes estimated investments in: • New equipment • Protocol development • Product testing • Staff training • New hires/reorganization
	Cost to produce a building or system (inclusive of hard materials, which is also called out separately below)	[\$/unit, \$/ft ²]
	Cost of hard materials	[\$/unit, \$/ft ²]
Future/anticipated costs	How might you reduce costs to make the technology more affordable for end users and increase profit for the manufacturer? Discuss implications and most promising strategies: • Volume scale up • Manufacturer learning curve • Materials selection • Supply chain optimization and automation	Qualitative/documentation
Operational costs	Energy costs to operate (monthly/annual energy bills)	[\$/month, \$/year]
	Cost of maintenance (annual)	[\$/year] Could be related specifically to EE measures, or overall maintenance cost for the building, which could go down because of the retrofit or new construction technology
Cost of replacement	Cost of acquisition averaged over lifetime of equipment	[\$/year] If the equipment lasts longer, then the instance of ‘first cost’ is less frequent
Financing	Please describe how you financed the project. Were there any special subsidies, or innovative financing mechanisms employed?	Qualitative/documentation

Speed of construction and scalability potential

Another important category of metrics to track is the speed with which whole-building retrofits can be completed and scaled. Industrialized construction approaches include many potential gains in speed and construction timelines due to factory-based and off-site production processes that allow for much faster cycle times from factory to project completion (e.g., Goodier and Gibb 2007). These benefits have been documented for industrialized construction practices in limited fashion to date, in part because there are many factors that affect the potential for speed and scale, such as the availability of skilled labor and supply chain capabilities, as well as the time-consuming nature of collecting data on factory production processes.

Tracking potential gains in these areas requires an understanding of production steps that occur both on- and off-site to compare them with traditional modes of construction. For this reason, our approach for collecting these data focuses on understanding production and construction activities using time and motion documentation and other narrative data where applicable. Key data requirements shown in Table 4 include task-level process steps and documentation of procurement, production, and transport activities. These details can help identify potential production bottlenecks that could be addressed through design or production method changes. We also envision collecting data on typical production and construction practices to establish comparative baselines.

Table 4. Data requirements for assessing speed of construction and scalability

Metric	Relevant Data	Notes
Cycle time	Time from order to factory completion (typical)	Days/weeks; can be estimated if technology is a one-off
	Time from order to factory start (typical)	Days/weeks; can be estimated if technology is a one-off
Factory Production	Time per production activity	- Hours/days/weeks; can be estimated if technology is a one-off - Time and motion documentation of production activities using video documentation for later analysis OR in-person observation with pictures
	Description of production steps	- Picture/drawing of factory production stations with brief commentary about each station - Complements time and motion analysis - On-site vs off-site
Transport	Document type of transport to site	Identify use of truck(s) or other arrangements for transport to site. Note ability to combine loads across projects (if applicable)
Site Construction	Time per installation activity (for factory install)	Time and motion documentation of production activities using video documentation for later analysis OR in-person observation with pictures
	Document preparatory activities	Short narrative of preparatory activities on-site before installation of factory components/modules (note any typical install/quality problems) For retrofits: Also describe required disruption to occupant use of facility

Added value of retrofit

The final category of metrics included in the DCP focuses on the additional benefits or value of whole-building retrofits. As discussed previously, quantifying and tracking these benefits is critical for scaling deep-energy retrofits even as productivity innovations continue to drive down costs. We anticipate that even with significant cost compression, adopting whole-building retrofits at the scale needed to achieve decarbonization targets will require a much more comprehensive assessment of their benefits for occupants, building owners, and other stakeholders to improve their value proposition. In the DCP, we split the additional value data requirements into three categories: building resiliency and durability, occupant health and comfort, and other. The metrics and data requirements for each of these are shown in Tables 6–8.

Whole-building retrofits often include features that enhance a building’s robustness to various stresses, including natural disasters and extreme weather events. Durability is directly tied to the quality of design, construction, and installation, so to the extent that industrialized construction approaches can improve upon baseline practices in these areas, a post-retrofit

building can better handle events such as earthquakes, fires, hurricanes/tornadoes, and floods. An analysis of Federal Energy Management Authority (FEMA) grants for natural hazard mitigation via building structural upgrades found that every dollar spent saves society an average of \$4.00 (NIBS 2005). Another resiliency metric is passive survivability during extreme events, which refers to a building's ability to maintain adequate indoor thermal comfort during power outages due to temperature extremes and can be enhanced with building retrofit measures (Sun et al. 2021). Distributed energy resources such as rooftop PV and battery storage capacity provide resiliency through islanding and load shifting, which can benefit both building occupants and the local electricity system. These metrics and related measurements are included in Table 6.

Table 6. Data for assessing building resiliency and durability

Metric	Measurement or Information	Notes
Quality of design, construction, installation	Length of warranty	[years, months] Describe any relevant details or exclusions
	Number of callbacks in year 1 post-construction	Number and description of circumstance
	Moisture control	Describe what you are using for moisture control layers
Building envelope resilience	Ability to maintain a habitable environment during power interruptions. This could be: - Passive heating/cooling - Insulation levels, etc.	Document design features (Ayyagari, Gartman, and Corvidae 2020)
	Design features to withstand extreme weather Examples: - Hurricane-resistant windows - Deep roof overhangs to keep water away from foundation, walls - Other features that make the building more adaptable to future climatic conditions	Document design features
	Any additional durability/resiliency benefits (e.g., seismic, wind loading, buoyancy)	Document design features
Distributed energy resources (DERs) to provide load management or islanding (Overlaps with 2.1)	On-site generation	Document design features
	Document features that enable load shift (e.g., energy management systems, smart appliances, smart thermostats)	Document design features
	Document features that enable islanding (e.g., smart inverter, battery storage)	Document design features
	Battery storage capacity	[kWh]
	Non-battery storage type & capacity (incl. thermal)	
Water resources	Emergency storage	Document design features
	Rainwater harvesting	Document design features

Improved IAQ (Hawkins et al. 2020) and occupant thermal comfort (Tonn et al. 2018) are two well-researched non-energy benefits of whole-building retrofits. Especially when upgrading a building's envelope, ensuring adequate ventilation is essential to maintaining IAQ in line with standards such as ASHRAE 62.2 (ASHRAE 2019). Table 7 outlines the data requirements that are necessary to track how whole-building retrofits affect the indoor environment and occupant comfort.

Table 7. Data for assessing indoor air quality and occupant thermal comfort

Metric	Measurement or Information	Notes
Key air pollutants	Particulate matter < 2.5 mm (PM 2.5)	[mg/m3] Hourly (minimum), 15-minute (preferred); +/- 15% reading Measure for each zone
	Particulate matter < 10 mm (PM 10)	[mg/m3] Hourly (minimum), 15-minute (preferred); +/- 15% reading Measure for each zone
	Carbon dioxide (CO ₂)	[ppm] Hourly (minimum), 15-minute (preferred); +/- 10% reading Measure for each zone
	Carbon monoxide (CO)	[ppm] Hourly (minimum), 15-minute (preferred); +/- 10% reading Measure for each zone
	Volatile organic compounds (VOCs)	[ppb] Hourly (minimum), 15-minute (preferred); +/- 10% reading Measure for each zone
Thermal comfort	Zone-level space temperature and relative humidity (T&RH)	[F, %] Hourly (minimum), 15-minute (preferred); +/- 1.0F, +/- 10% RH To be measured by pollutant monitor

Finally, Table 8 lists other metrics that can impact the value proposition of whole-building retrofits, such as occupant satisfaction and aesthetic indicators. These could lead to increased home resale value, an important non-energy benefit to capture (Yun et al. 2019). We provide descriptive guidelines for data that could be collected on these metrics but acknowledge that there will likely be far less standardization of these in comparison to some of the other categories of metrics described above.

Table 8. Other “Added Value” metrics and descriptive guidelines

Metric	Information
Occupant satisfaction indicators	This could include things like: • Occupancy rates for rentals (residential or commercial) • Tenant satisfaction (surveys or other data) • Perceived or measured value increase of property
Aesthetic indicators	• Customizability • Testimonials from users/customers
Active management	Document features that provide ongoing/smart monitoring and management of IAQ via automated ventilation strategies

Discussion and Conclusions

As the ABC Initiative continues to promote and support the use of industrialized construction practices to address the many challenges facing the U.S. construction industry and buildings sector, an essential component of this work is building out the evidence base for which practices work best. At present, there is no standardized approach for collecting these data nor is there a centralized database that ABC and industrialized construction advocates can use to track progress toward the goals of a transformed, low-carbon buildings sector. The DCP we introduce in this paper is intended to serve as a starting place for this data collection and tracking effort.

The metrics defined in the previous section include several that are common to most, if not all, building efficiency M&V efforts (Granderson, Crowe, and Fernandes 2020). High-resolution meter and weather data for both the pre- and post-retrofit case, for example, are

standard in M&V protocols. However, several of the metrics sought in the DCP are novel in the building efficiency assessment context. Metrics related to productivity and scalability are far less commonly incorporated in M&V assessments, but these are especially important for documenting improvements if the broader construction and building decarbonization industries are going to take seriously the benefits of ABC approaches. Further, collecting data on the non-energy benefits of whole-building retrofits will help make the value case for these and can provide performance evidence upon which new methods of project evaluation could be based. We are confident that whole-building retrofits can deliver these benefits to both building owners and occupants, so tracking these benefits and making them a bigger part of the proposition to consumers and developers alike is important.

We acknowledge that the detailed level of this DCP and the granularity of the data we request could present challenges to some entities that would like to use it as a guideline for collecting data on high-performance industrialized construction innovations. Our initial audience for this data collection effort includes the awardees of DOE's 2019 FOA who were selected in March 2022 to demonstrate their innovations in low-income communities across the U.S. over the next several years (DOE 2022). These research teams will be required to meet the data requirements in the DCP and will thus serve as the initial cohort of projects for which these data will be collected. In order to ensure that ABC projects that exist outside of federally-funded R&D programs are also included in the effort to collect data and evidence on the benefits of these new approaches, we anticipate that a scaled-down version of the DCP that includes only essential metrics and data requirements will be developed and shared more broadly with the ABC industry. The ABC Initiative's industry consortium, the ABC Collaborative, will serve as a testbed for socializing this plan and revising the data requirements such that it is inclusive to a wide range of industry stakeholders. This process began in early 2022 and will continue in the coming years.

The current U.S. building sector faces numerous interrelated challenges, including flat or declining labor productivity, a housing crisis driven by a dramatic shortage of housing, supply chain disruptions due to the current pandemic that lead to increased material costs, and, most importantly, the ongoing urgency with which the U.S. building sector and the wider economy must transition away from fossil fuels to net-zero. This confluence of challenges requires a new approach to both new construction and retrofits. The ABC Initiative was launched to take on these challenges using innovative approaches that have seen substantial investment and adoption in other countries but limited growth in the U.S.

As the umbrella of technology innovations, new business models, and supporting policy environments for ABC are changing rapidly, it is essential that a standardized approach to tracking the progress of this industry is created. This paper outlines a plan for collecting the data and evidence necessary to demonstrate the efficacy of ABC approaches and how they improve on business-as-usual construction and renovation practices, saving time, money, and delivering more benefits to building owners and occupants in the process. We hope that by sharing the DCP and starting a dialogue on the need to collect industrialized construction project data in a standardized way (along with a blueprint for doing so) that we will expand the audience for this important work and create momentum for the adoption of novel, industrialized approaches in construction. Scaling these approaches is essential for decarbonizing the built environment while meeting the unprecedented challenges facing U.S. buildings in the 21st century.

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