Lessons Learned on the Journey to Bring Zero-Energy Modular Homes to Scale

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ABSTRACT

Industrialized construction is being promoted as the building industry's next high-value practice, because it promises speed, quality, and cost advantages over conventional construction. However, little public data exist to support this claim. Energy efficiency programs can offer markets for this emerging technology because their jurisdictions are seeking equitable, long-term decarbonization strategies for low-income and disadvantaged communities. Nevertheless, a chronic shortage of affordable housing persists in the United States, putting the readiness of those markets in doubt. At the same time, the building construction sector has not kept up with productivity gains in manufacturing; single-family and multifamily residential construction productivity decreased from 2007 through 2020 (U.S. Bureau of Labor Statistics 2021).

For almost a decade, the authors have promoted zero-energy modular (ZEM) homes as a solution to bring all-electric, zero-energy homes to the affordable housing sector. This paper describes the results of, and lessons learned from, ongoing ZEM programs. The several cited development models draw from the installation of more than 200 ZEM homes in Vermont, Massachusetts, and Delaware. Findings describe cost performance, implementation hurdles and solutions, and strategies for bringing ZEM homes to scale. The authors offer preliminary findings from research projects funded by the U. S. Department of Energy (DOE) and U.S. Department of Housing and Urban Development (HUD). These projects have studied the construction systems of home designs and factory processes. The paper concludes with ways to decrease costs, increase construction productivity, and deliver homes that perform at zero energy.

Introduction

During the 2018 ACEEE Summer Study on Energy Efficiency in Buildings, VEIC presented a paper that described the program design, technical specifications, case studies, and an analysis of ZEM homes installed in Vermont (Schneider et al. 2018). It also presented data on energy use, thermal comfort, and indoor air quality of these homes. The paper laid out a vision to scale ZEM homes as a cost-effective replacement for traditional manufactured housing.

Since that time, VEIC has expanded the ZEM model to include single-family and multifamily development for affordable housing, and has exported the program model to Delaware, Massachusetts, New York, Oregon, and Colorado. With support from DOE, HUD, Efficiency Vermont, and the New York Community Trust, VEIC has teamed with Louisiana State University and the National Renewable Energy Laboratory (NREL) to study the intersection of factory construction, decarbonization, and affordability. Through new, creative pilot programs and applied research, the team has gained valid and reliable insights into what is possible with high-performance modular construction—and its limitations.

This paper describes the current state of factory-built (industrialized) construction, the U.S. market share of modular construction, and modular factory business models. It also enumerates best practices for factory construction to reduce costs, improve building quality, shorten development times, and help efficiency programs and their jurisdictions meet carbon reduction goals. This paper conveys the value proposition of ZEMs for occupants (particularly those in affordable housing), contractors, developers, and utilities on a path to building decarbonization.

The authors explain the factory build market in terms that will help energy efficiency programs understand how to design integrated initiatives, and recommend next steps for achieving effective scaling.

Factory-Built Housing: An Old Construction Practice with a New Purpose

The Types

Factory-built housing is a centuries-old construction technique. The process involves prefabricating boxes or panels in a factory and assembling and installing them at a building site. Unlike site-built construction, where individual materials are delivered and crews arrive to assemble them in outdoor field conditions, housing factories are different. These facilities store materials in climate-controlled environments, have full-time employees, and organize construction stations that apply industrial engineering principles. Contemporary factory-built housing involves three categories: manufactured housing, modular buildings, and panelized construction.

Manufactured homes are residences delivered on a chassis to a site, and are built in a factory in accordance with HUD Manufactured Home Construction and Safety Standards (HUD Code), established in 1974. The homes typically arrive nearly complete, containing mechanical systems, trim, flooring, appliances, and exterior finishes. Single-box homes are delivered 100 percent complete; multiple-box homes require additional site work to connect the boxes and to finish interior and exterior trim. Manufactured homes are built and remain on a steel chassis; they are delivered from the factory to the site. Once the homes arrive at the site, the axles and wheels are removed from the frame, which remains as part of the home. Manufactured homes are typically installed on a concrete slab for a permanent installation, or anchored on concrete block piers placed under the frame, for a temporary installation. Manufactured housing accounts for approximately 7 percent of new residential homes in the United States.

Modular buildings comprise boxes (*volumetric modules*) delivered to a site on a trailer, and then lifted off the trailer by a crane and placed on a permanent foundation. Modules can be stacked to create multi-story homes or multifamily buildings. They can also be delivered to the site—either complete with mechanical systems, paint, trim, and finishes; or incomplete, requiring additional site work. Modular homes must meet local and state building codes. Modular factories typically hire third-party organizations to perform inspections in the factory. These inspections would otherwise occur in the field and involve State and local code officials.

Panelized construction involves fabricating wall, floor, and roof panels that are assembled on site. The entire panel can comprise just framing members and sheathing, or it can arrive with insulation, wiring, and interior gypsum wall board. Factories transport panels to a site on a trailer, either as flat-packed units or stacked vertically if they contain windows. Site workers then assemble them on a permanent foundation. Panelized homes require more on-site construction than manufactured or modular homes. Like modular homes, panelized homes are built to the same State building code that applies to site construction.

Shifting site work to the factory offers significant economies. Because VEIC programs promote energy cost effectiveness to customers, the organization prefers modular construction practice. Further, fully integrated construction techniques allow quality control at all stages of production to be carried out more efficiently in a factory setting than in the field.

The Market

Serving the low-income / affordable housing market requires special considerations that do not exist in market-rate environments. With a growing priority placed on services to low-income households, an energy efficiency program must design initiatives for delivering products and services that avoid future frequent costly repairs and maintenance of buildings. Optimizing building operations is also an important element for evolving the concept of *affordable housing* to *affordable living.*

It is important to understand off-site construction advantages in the context of a market mindset. Whether known as *industrialized construction, modular housing,* or *factory-built housing,* off-site construction advantages inform the levers that enable ZEM delivery to the affordable housing sector. Emerging market factors are worth examining for new opportunities.

Factory-built homes comprise a decreasing share of the new construction market. In 2020, approximately 1 percent of single-family new construction nationwide was modular housing (10,000 homes), as shown in Figure 1. The highest concentration of these—approximately 4.5 percent—is in the Northeast. At its peak in 2002, modular construction accounted for less than 4 percent of residential new construction.

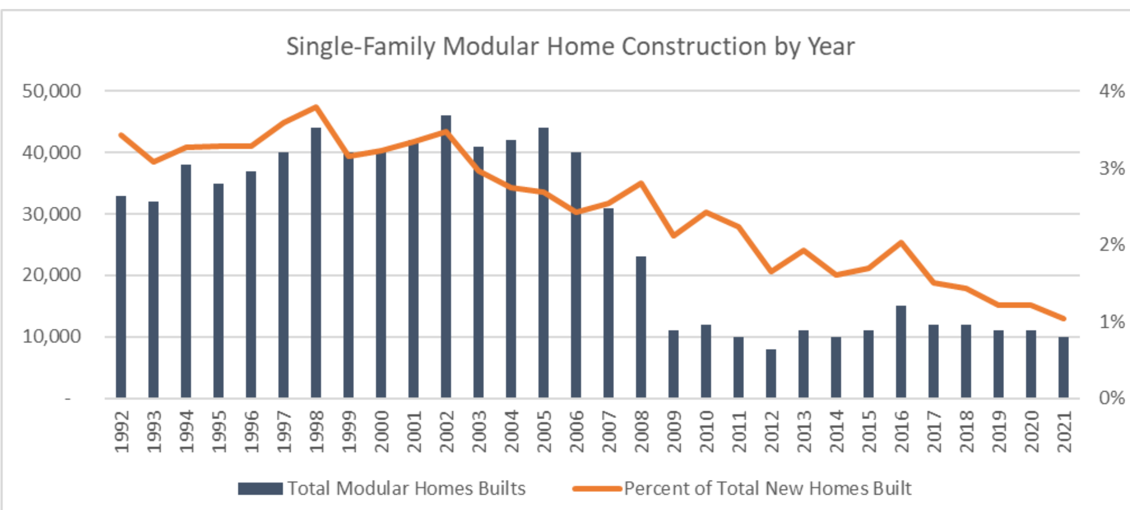

Figure 1. Type of construction method of new single-family houses completed and built for sale. *Source:* U.S. Census 2021.

Factory capacity is limited and regional. The Housing Innovation Alliance Off-Site Heat Map (2022) reports approximately 30 modular factories are building residential structures in the United States. Many of them are located near the East and West coasts, thus creating significant geographical gaps in the markets they can serve, as shown in Figure 2.

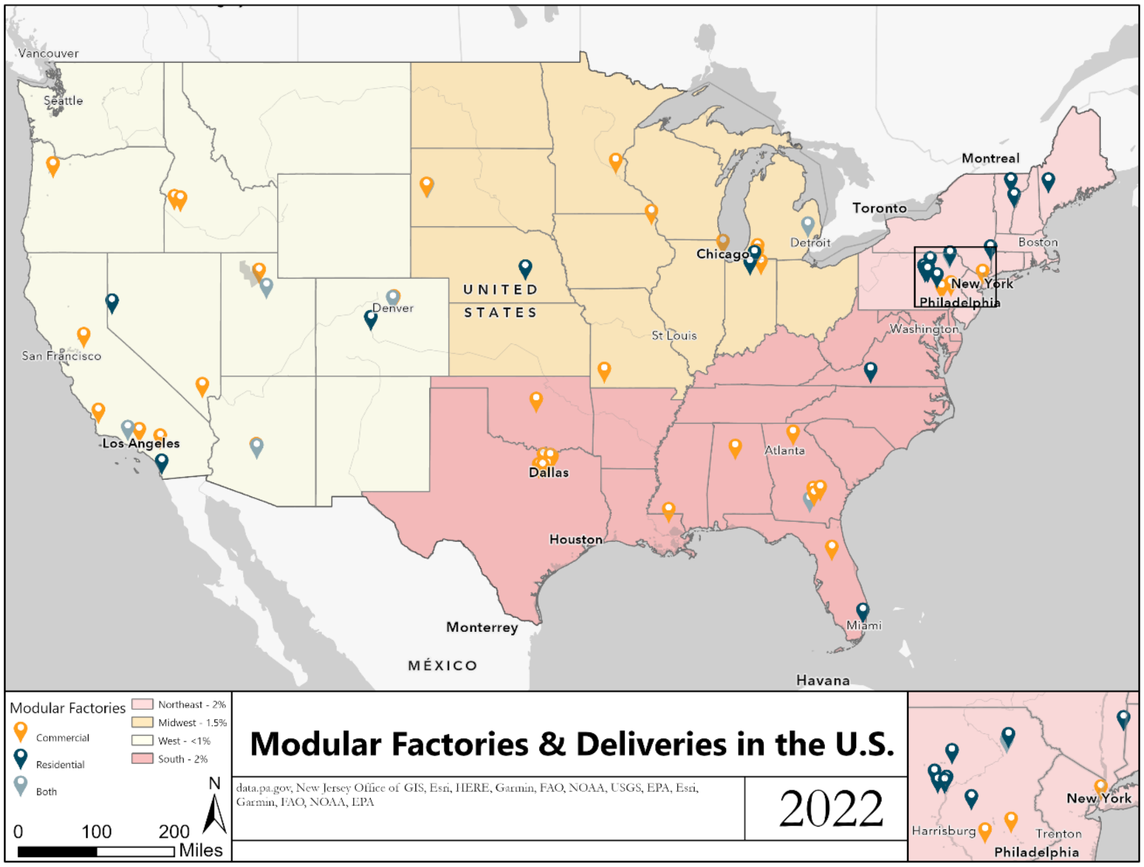

Figure 2. Location of modular factories in the United States. *Source*: Housing Innovation Alliance 2022.

A fractured market means slow growth in the industry. The industrialized construction market is not well coordinated nationwide. The lack of communication and information sharing among factories, for example, has prevented industry-wide efficiencies from demonstrating the value necessary to move the industry and the market forward. Despite the efforts of the Modular Building Institute, the Modular Home Builders' Association, and Housing Innovation Alliance, members tend not to orient their business decisions around data collection or emerging technologies, nor are they generally interested in considering other members' innovations. These attributes are typical of the business-as-usual construction industry. Even so, startups have entered the industrialized construction sector and bring a culture of innovation and goals to revolutionize the construction industry.

The added disruption of the COVID pandemic on U.S. commerce generally—affecting labor markets, the supply chain, and transportation—has also not propelled the market forward. However, the elements for success are abundant: (1) a cost-effective construction technique that minimizes the business and labor risks present in conventional construction; (2) the role of energy efficiency programs in supporting zero-energy construction; and (3) a national affordable housing market ready for revitalization.

How Modular Can Bring Zero-Energy to Scale

Through new, creative pilot programs and applied research, the team has gained insights into what is possible with high-performance modular construction. The programs and research have also yielded best practices on changes that can bring this solution to scale. Factory construction can save money by reducing project duration. The Modular Building Institute estimates that modular projects take 30 to 50 percent less time than conventional construction (Smith and Rice 2015). Endzelis and Daukšys (2018) have reported that the clearest advantages of modular construction come from the shorter duration of construction, higher quality of work performed, and improved safety for workers. Reduced time for development reduces soft costs for project management and financing carrying costs; both offer direct cost savings to affordable housing developers.

Labor costs comprise and estimated 40 to 60 percent of total construction costs in site-built housing. In modular projects, labor accounts for an estimated 8 to 12 percent of total costs (Windle et al. 2019). Factory workers are typically full-time employees with paid benefits, whereas many contractors for site-built construction are paid hourly wages without benefits. Factories are often located in rural areas with lower prevailing wages and cost of living, relative to costs associated with general contracting in urban areas. Factory management can choose to allow their staff to be union or non-union; each option comes with different baseline wages. In general, there are two major differences when using modular construction: (1) overlap between site preparation and the module construction phase; and (2) installation and site finishing take considerably less time. Bertram et al. (2019) estimate that modular construction can achieve an overall labor savings of up to 25 percent on a project compared with traditional on-site construction. Unlike site-built contracting, factories have overhead expenses for the facility, regardless of whether production is at full capacity, whereas site-built general contractors have more flexibility to hire on demand, as needed. The high initial costs of factory start-up, plus managing the pipeline to carry overhead costs, can be a barrier to creating new factories.

ZEM homes are all-electric, high-performance homes that incorporate solar PV, sized to generate annually as much energy as the occupants need. ZEM homes, like site-built zero-energy homes, typically use Passive House and Zero Energy Ready Homes guidance for envelope and equipment specifications, as well as testing and certification criteria. Successful zero-energy projects embrace integrated design as a guiding principle to facilitate communication within the project team, break down boundaries between disciplines, and establish clear goals at the beginning of the design process. Integrated design requires more time at the outset for collaboration and analysis, before decisions are made and implemented in the designs. There are four key elements for scaling, as shown in Table 2.

Table 2. Strategies appropriate for scaling, and how each aligns with four identified industry needs for meeting future housing supply in the United States

Strategy	Lower construc-tion costs	Higher quality	Increase factory capacity	Increase in demand for ZEM
1. Lean manufacturing	X	X		
2. Maximizing construction in the factory	X	X	X	X
3. Embedding support for factory construction within programs		X		X

Strategy	Lower construc-tion costs	Higher quality	Increase factory capacity	Increase in demand for ZEM
4. Supporting increases in number of factories			X	

Lean Manufacturing

Lean manufacturing refers to a production strategy for eliminating waste in all forms: defects, unnecessary processing steps, unnecessary movement of materials or people, waiting time, excess inventory, and overproduction. A 2007 study on the introduction of Lean production strategies in the factory-built housing industry revealed striking improvements in efficiency and quality for existing plants. Participating departments in nine plants experienced productivity improvements ranging from 10 percent to over 100 percent (MHRA 2007).

The foundation of Lean production is stability and standardization, achieved through streamlining operations while reducing waste. Lean manufacturing can change working methods and environments that can affect beliefs, values, and employee working practices—and in turn, organizational culture. Site-built construction could adopt Lean manufacturing concepts, but that construction practice prohibits rigorous implementation, given the transitory coordination of contractors / trades and their roles, when they are working on site.

The authors' work on a New State of the Art ZEM Multifamily Construction System under a grant from DOE's Advanced Building Construction Initiative—has resulted in a deeper understanding of how longstanding and emerging Lean manufacturing principles can be applied to the construction of cost-competitive, high-performance zero-energy homes. Through factory partners KBS Homes in Maine and Solar Home Factory in New York, the project team has acquired valid and reliable insights into what is possible with high-performance modular construction. Building to a zero-energy standard requires attention to detail and ongoing project commitments. Although site-built construction is associated with the majority of zero-energy buildings to date, the factory setting can better adopt systematic processes to ensure high quality and reduce construction costs.

The project team identified ways Lean manufacturing can be used to achieve cost-effective, high-quality zero-energy construction. This work can be standardized for zero-energy designs and supporting plan details, with a quality control manual. A top-level document that describes the quality management system of the factory, the Traveler, is assigned to each module that corresponds to the quality control manual and guides inspection remedies for noncompliance. An emerging strategy and a natural fit for Lean manufacturing is factory information models, which create a digital twin of the entire new-construction process of the off-site factory.

When partnering with modular factories to build zero-energy homes, contractors and efficiency programs can jointly consider embedding guidance on energy efficiency and renewable energy in existing processes. Table 3 demonstrates the intersection of strategic purposes and clean-energy program implementation.

Table 3. Ways Lean manufacturing can support zero-energy construction

Strategies	Strategy for combining with energy efficiency and renewable energy measures
Quality control manual	In addition to standard quality control, include descriptions of proper installation for energy efficiency and renewable energy specifications of thermal enclosures, mechanical systems, duct work, solar PV, and battery storage.
Traveler	The typical traveler contains a checklist to ensure building code compliance and quality of workmanship. In addition, it tests plumbing and electrical systems. The checklist can be expanded to include system checks of energy strategies to test solar PV, ductwork pressure drop, and heat pump operation.
Factory information model (FIM)	Creating a FIM allows factories to model scenarios for optimizing construction processes and integrating energy efficiency, and renewable energy measures on existing factory stations before making changes go live.

These strategies are complementary and can be integrated for optimized monitoring and construction quality in completing zero-energy homes. The final report on this DOE-funded project will be published in 2023.

Maximizing Construction in the Factory

Eighty percent of a standard modular building is constructed in the factory, and the remaining 20 percent of the process involves assembly and finishes on site. Site work typically comprises joining and sealing boxes; connecting electrical and plumbing systems; finishing interiors and exteriors; and installing HVAC, appliances, and solar PV and battery storage systems (solar + storage). Increasing the amount of factory work reduces the project scope on site and the handoffs between contractors and permitting agencies. This process controls costs and increases quality. Design for manufacturing and assembly (DfMA), an essential production technique for modular structures, concurrently considers building design and how it will be manufactured. It optimizes costs and the quality of products for construction and assembly. Unitizing HVAC systems and multifamily units (one living unit, one box) to minimize work at the building site similarly maximizes the cost and quality benefits of modular construction. Integrated mechanical pods installed in the factory minimize distribution losses and refrigerant runs, reduce horizontal plumbing and HVAC connections done on site, and facilitate submetering and controls—all of which are pain points in business-as-usual modular construction.

Under a HUD-sponsored project, "Resilient Homes and Resilient Power Systems—Optimizing Factory-Installed Solar + Storage (FISS)," the authors created a FIM to estimate cost savings of installing solar + storage under a controlled environment, using assembly line techniques and factory employees trained, scheduled, and managed by one employer. The team compared the efficiency of two scenarios for installing solar + storage systems: (1) on-site installation and (2) in-factory installation. The assessment analyzed on-site installation times and created a discrete event simulation model of a modular homebuilding production line with the integration of solar + storage. The preliminary results of this assessment show that the FISS approach resulted in a total savings of $10,126 per installed system; this translated to an approximate 27 percent potential cost reduction compared to on-site installation. FISS savings in total cost were due to the removal of a general contractor profit, improved workflow leading to fewer installation labor hours and reduced costs related to customer acquisition (for example, sales and marketing). HUD will publish the results in 2023.

Embedding Support for Factory Construction within Programs

VEIC has scaled its ZEM construction strategies from pilot and initial program stages in Vermont to Delaware, New York, and Massachusetts. The scope of the scaling is reflected in its development models: replacement of manufactured housing to enable ownership, single-family new construction to enable ownership, and rental units in multifamily buildings. The implementation programs recruit partner affordable housing developers and modular factories. VEIC provides technical assistance to the partner factories, guiding them toward building to the high-performance standards of the zero-energy specification. The programs also engage homeowners in understanding that the first cost of the home is higher (relative to code construction). But over the long term, the low or no energy bills will pay for the incremental cost of solar and energy efficiency features. VEIC has also engaged local nonprofit housing organizations to reinforce information sharing with renters, homeowners, and prospective homeowners about the benefits of appropriate operation and maintenance of ZEM units. The ZEM program staff also conducts up to three years of post-occupancy monitoring, collecting energy and environmental data to make sure the homes are performing as expected.

Implementation of comprehensive ZEM programs shows that the construction industry still has a long way to go from constructing with norms established in business-as-usual building codes to embracing and moving construction practice to a new, significant, level: zero-energy construction. To date, more than 200 ZEM homes have been installed—most of them in Vermont, where an initiative embedded under the statewide energy efficiency utility, Efficiency Vermont, provides comprehensive zero-energy services to affordable-housing developers, factories, and homeowners. To bring ZEM to scale, more programs will need to embed support of modular construction in existing new construction programs.

The ideal ZEM program design takes a comprehensive upstream approach to engage the market across sectors, understand and overcome barriers, make participation easy, and collect data to inform program refinements. Most modular factories build to code levels and building types, which reduces efficiencies of scale. Affordable housing developers support zero-energy construction but are concerned with upfront costs and long-term performance. Efficiency programs can support the creation of zero-energy housing "products" that are cost effective and of high quality by applying a systematic approach to understanding and engaging the market and establishing a clear value proposition to the factory, supply chain, and real estate developers.

Program design starts with targeting a new construction market with repeatable, high-volume, and / or a high-priority sector like multifamily or single-family housing, estimating demand and identifying a factory. The next step is engaging with real estate developers and the factory to create standard plans that maximize construction in the factory and identify energy efficiency specifications to achieve zero-energy performance. Working with the factory to create quality control manuals and travelers will embed quality checks of high-performance details into the existing factory process. By offering in factory training on high-performance construction techniques, the program will create a construction workforce skilled to build zero-energy homes.

Offering support for the FIM, simulating the changes before they are adopted on the factory floor, can de-risk line changes.

By engaging upstream, the programs can collect cost data and post occupancy data of standardized products and designs for energy and environmental performance after they are deployed. ZEM homes are designed to produce annually as much energy as they are modeled to use. In VEIC’s program homes, homeowners' behavior varies, but there appears to be an even distribution of homes that use less, the same, and more energy than was modeled. In aggregate (that is, looking at a portfolio of homes, rather than at homes individually), the variance of ZEM program home performance from modeled estimates falls in line with the federally recognized, variability factor (from occupant behavior) of + / - 28 percent (Glickman 2014). Post-occupancy monitoring equipment is also important in assessing indoor air quality, one of the key benefits of ZEM living. Balanced ventilation with demand-controlled operation leads to exceptional indoor air quality, and comfort for occupants. Post-occupancy monitoring is a high-value component of program design, but programs need to consider and budget for the cost of monitoring equipment, cellular data subscriptions, and labor costs to analyze data. There are also costs associated with continuing a relationship with homeowners. Periodically analyzing data can both provide a feedback loop to the product design and support homeowners.

Although energy efficiency program support and incentives can successfully promote zero-energy construction, housing policy needs to prioritize support for increased ZEM construction, given its clear short- and long-term benefits. Most financing products and policies are geared to site-built construction. When a program creates the product specification, it will need to demonstrate how ZEM products qualify for state and federal housing financing and tax credit programs.

Workforce development largely supports offsite construction. Starting at the high school level, national curriculums could increase the vocabulary around offsite construction and high-performance and zero-energy technologies.

Supporting Increases in Numbers of Factories

As states, cities, and utilities continue to set decarbonization and climate goals, modular new construction’s ability to incorporate energy efficiency, curb energy demand, and offer less wasteful construction options have become more valuable. Modular housing has historically been a fit for green building innovation and design.

What would it take for ZEM processes to ramp up to meet the market demand for affordable housing? The National Association of Home Builders expects the number of modular projects to increase, citing the need to “lift labor productivity amid declining housing affordability,” and the ability for modular building to increase efficiency of production (Nanayakkara-Skillington 2021).

According to Moody’s Analytics (2021), the United States needs an additional 1.8 million homes to fill the housing supply deficit. The 1.8 million units applies to both affordable and market rate housing. *Affordable housing* is defined as housing where the owner or renter pays less than 30 percent of their income on housing costs.

The authors modeled a scenario that stacks U.S. Census data for new construction with data on the housing deficit, to illustrate what it would take for modular construction to ramp up to meet the current demand for housing (Figure 3). Under this scenario, modular production would need to ramp up from 12,000 units a year to over 1 million a year in ten years. Assuming there are approximately 30 modular factories that serve the residential market, each builds, on average, 400 units a year. If modular construction were to ramp up to build enough housing to meet current and projected housing needs, in ten years the industry would need to substantially increase productivity in existing factories, and to bring online approximately 2,500 new factories with similar productivity rates. There would also need to be a massive shift from construction built according to current local codes to high-performance, all-electric construction and adoption of solar PV.

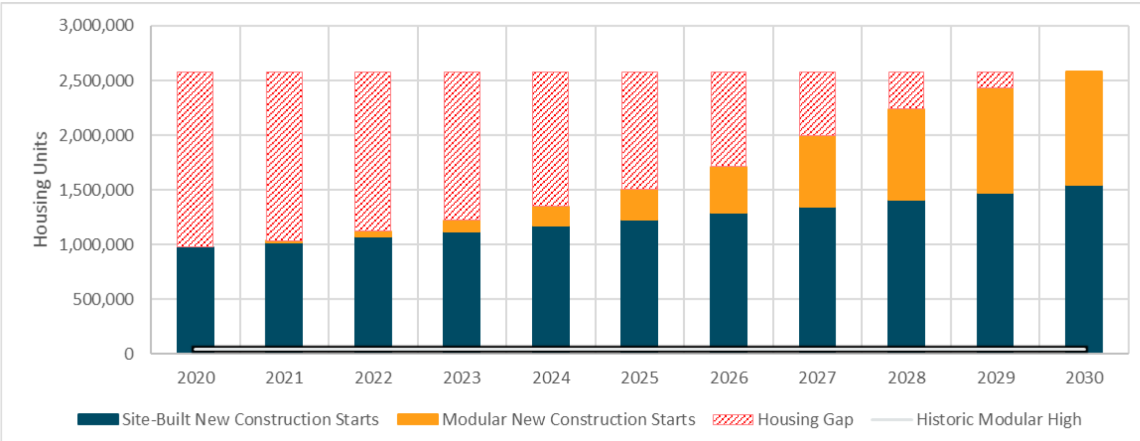

Figure 3. The number of site-built new-construction projects, manufactured homes, and modular new-construction units, projected to 2030, showing the opportunity for meeting the targeted need for housing with modular construction (derived from U.S. Census data and Moody's Analytics projections of the housing deficit).

Conclusions

There is no question that the construction industry must fundamentally change, if decarbonization of the residential sector is to occur at scale. The industry can achieve state and regional targets if it looks comprehensively at both affordable housing and market rate construction. At a minimum, the industry must advance toward a market transformation mindset for products and services that achieve a high level of energy performance, taking into consideration, and budgeting for, the special needs of the affordable-housing sector.

Such a shift will require the removal of the traditional siloing of processes and functions to include coordination with the incentives and other assets of energy efficiency programs. It will also require a change in traditional business models toward advanced industrial processes for achieving economies of scale in the construction industry. The goal for meaningful decarbonization is zero-energy construction.

With only 1 percent of new construction built in a factory, and a fraction of that 1 percent built to a zero-energy standard, the ZEM wave is only just beginning. But it contains everything necessary for greater adoption: appropriate technology, well-tested cost-optimization processes, building designs for optimal indoor operations and functions, established coordination procedures with utilities and efficiency programs, and an environment ripe for innovation.

VEIC programs have resulted in the installation of more than 200 ZEM homes in the states where its programs are in place. Construction costs for ZEMs have increased along with the market for conventional construction. VEIC cannot yet quantify cost benefits from installing the same home design, through economies of scale in materials and labor. However, program experience indicates that an increase in the number of factories that only produce ZEM homes would likely result in increases in factory optimization, volume purchasing, and other attributes that can produce significant cost savings.

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