Accelerating Optimal Integration of Energy Efficiency Strategies with Industrialized Modular Construction

Preprint

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Accelerating Optimal Integration of Energy Efficiency Strategies with Industrialized Modular Construction

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ABSTRACT

The National Renewable Energy Laboratory's (NREL's) Industrialized Construction Innovation team first introduced the Industrialized Construction Assessment Framework to achieve affordable, net-zero energy (NZE) modular multifamily buildings in the 2020 ACEEE paper "Integrating Energy Efficiency Strategies with Industrialized Construction for our Clean Energy Future." Since then, NREL has continued to drive the ambitious plan to accelerate optimal integration of energy efficiency strategies during industrialized construction with little or no additional cost, labor, and production time. This follow-on paper introduces the Energy in Modular (EMOD) buildings method and presents NREL's research efforts over the last two years in collaboration with industry, including affordable housing partners. NREL has developed an idealized NZE modular multifamily building design that incorporates five energy efficiency strategies well suited for industrialized construction in factories: (1) envelope thermal control, (2) envelope infiltration control, (3) mechanical, electrical, and plumbing systems, (4) smart controls, and (5) solar plus storage. This paper highlights results from leveraging design for manufacturing and assembly principles, testing, and validation pilots with factory partners; demonstrating pod prototypes in test stand at NREL; and performing simulations. Overall, these research efforts address barriers to whole-building system integration, such as poor installation quality of thermal and air barriers; lack of unitized systems for space conditioning, energy recovery and ventilation, and water heating; problematic on-site installation, commissioning, and configuration of controls; and lack of cost-effective integration for grid-friendly design and emerging technologies. Conclusively, the paper delineates next steps for future work with NREL's partners toward developing a transformational pathway for our clean energy future.

Introduction

NREL introduces the Energy in Modular (EMOD) buildings method as key approach that allows modular solutions to (1) maximize cost-effectiveness of energy efficiency solutions and (2) leverage industrial engineering and advanced manufacturing approaches to increase productivity and reduce first cost of construction. NREL's Industrialized Construction Innovation team developed and explored several industrialization approaches, advanced manufacturing tools, and process efficiency strategies to increase productivity in integrating these energy efficiency strategies into buildings. Energy efficiency strategies that cannot be easily manufactured and assembled into the apartment units at a typical modular construction factory would generally be disqualified by permanent modular builders, as per NREL's Industrialized Construction Assessment Framework (Podder et al. 2020). For example, continuous insulation on exterior walls, centralized building service systems with air-source variable refrigerant flow, and ground-source heat pumps add to on-site work and undermine factory-installed efficiencies by increasing costs, labor, and lead time. Instead, the project optimized and maximized off-site processes and minimized on-site tasks. With the aim to maximize off-site factory manufacturing and assembly work, the key benefits of EMOD method are:

1. Factory-installed energy efficiency strategies can simplify installation, better control scope and scheduling, enhance quality, standardize means and methods, increase construction productivity, and reduce overall construction timelines.
2. High-volume production means reduced cost, time, and complexity from off-site construction and eliminated site work.

The research question was "How can optimal integration of a wide range of energy efficiency strategies in industrialized construction be achieved with little or no additional cost, labor, or production time?" This paper is the result of a 3-year project funded by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy Building Technologies Office. The project, called Energy Efficiency in Permanent Modular Construction, allowed NREL's Industrialized Construction Innovation team to work with primary partners such as Volumetric Building Companies (wood-framed volumetric modular builder), Factory_OS (steel-framed volumetric modular builder), FullStack Modular (steel-framed volumetric modular builder) as well as other collaborators such as AeroBarrier Inc., VEIC, Solar Home Factory, STRATIS, KBS Builders, Denver Housing Agency, Group 14, Milender White, Stanford University's Center for Integrated Facility Engineering, BLOX Inc., and Blokable Inc. in the United States. The following energy efficiency strategies were part of the project scope, as discussed in detail later in this paper: envelope thermal control (eliminating thermal bridging and optimizing insulation), envelope infiltration control (attention to connections and air sealing with an ionized sealant added through a controlled spraying process), mechanical, electrical, and plumbing (MEP) systems, smart controls, and solar plus storage. Considering the constant changes and evolution in the modular industry, research and open-source knowledge dissemination is important to learn from and improve proposed practices by engaging with the relevant stakeholders. In support of this, NREL collaborated with construction innovators, modular construction factory operators, and developers on process and product innovation. Industry partners in NREL's national-scale shared research platform have:

1. Leveraged NREL's advanced time-and motion study and process-based digital twin capabilities to improve existing and upcoming factories
2. Achieved optimal integration of energy efficiency strategies and advanced controls with little or no additional cost, labor, time
3. Received recommendations, energy modeling assistance, and more from NREL experts to help reduce costs, improve efficiencies, and save energy in high-performance buildings
4. Provided insight into production processes, access to prototypes for study, and connections to real-world developments for validation.

Integrated Modeling for the Modular Approach

Manufacturing supports a significant deal of upfront engineering analysis before any production activities begin. Therefore, building performance simulations such as energy modeling are paramount to energy efficiency strategies in modular building products. Energy modeling can contribute to energy-efficient design at multiple, distinct stages of the design cycle (ASHRAE 2018). To maximize the energy performance of modular built projects, building energy modeling should be integrated into the design of the modules and during client meetings. Modular design cycles can be circular, and energy modeling can be continuously improved and integrated. At the earliest stages, a simple box model—which can be modular—suffices to identify significant energy users and reduction opportunities. Traditionally, the three primary fixed parameters are building type mix, project location, and gross square footage. Instead, a modular built project may not have a set project location and square footage at design inception. There is a tradeoff in design parameters such as project location. It may not fix the gross square footage, but other continuous parameters such as envelope and lighting will be constrained to a few select options. The modular approach requires complete execution of building energy design and modeling as part of the early prototyping stage to realize cost benefits (both upfront and operational) before the start of production.

Innovative envelope assemblies for thermal energy management often require moisture management studies. As highlighted in the Advanced Energy Design Guide for K-12 School Buildings (Zero Energy), the location of the vapor retarder within the assembly should be driven by climate conditions to avoid condensation within the assembly or on a vulnerable surface. While dew-point analyses can be useful for ruling out certain design options, dynamic hygrothermal analysis methods are required to fully vet an assembly with consideration for the physics of moisture transport and climate conditions. Demand for better performing calculation methods to assess the moisture behavior of building components has led to the development of software tools (Karagiozis, Künzel & Holm 2001). An integrated modeling effort includes creating the conceptual design of the modular units with pre-run energy modeling results, followed by product-process data integration to ensure the creation of a robust factory information model (as shown in Figure 1). Then, others can leverage these approaches to implement their versions.

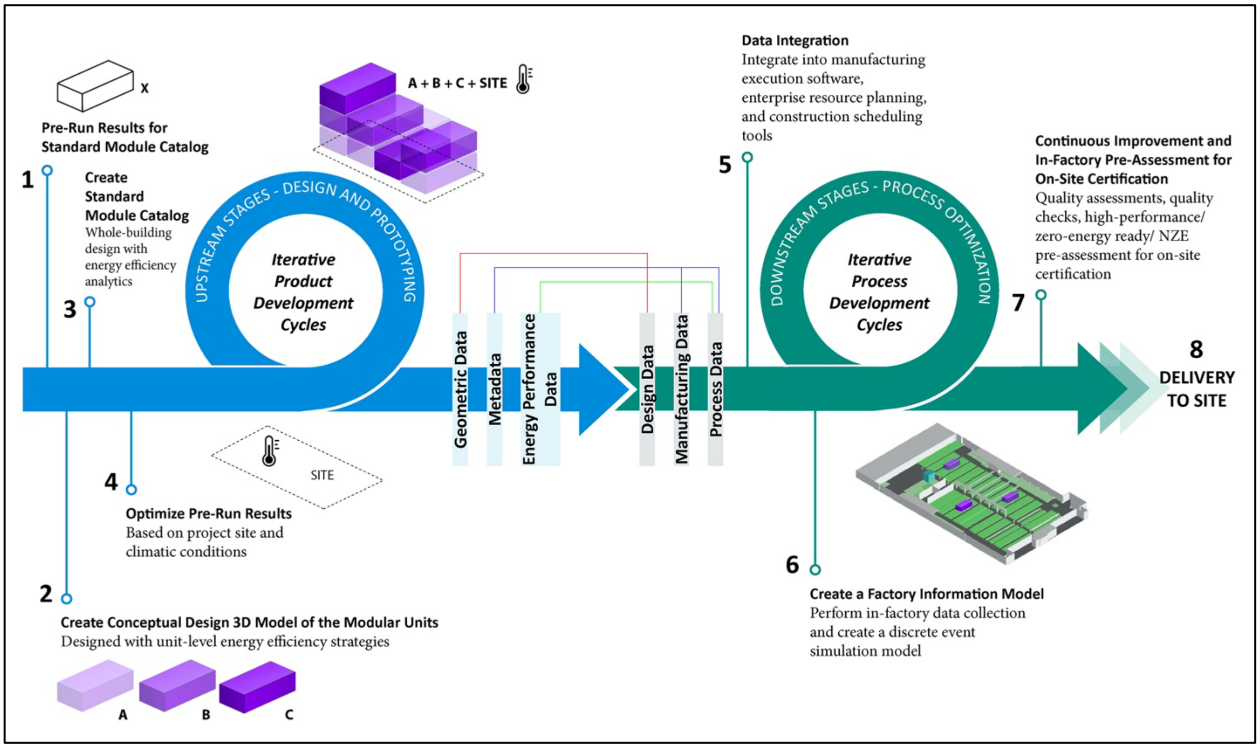

Figure 1. Integrated design-production process centered around the EMOD method, involving iterative development cycles in both upstream and downstream stages. *Source:* NREL.

Cost Compression Through Prototyping and Process Improvement

To modernize factories producing and delivering housing units, modular builders operating existing factories or gearing up to deploy new factories make decisions on factory planning and explore opportunities to improve productivity. First, this can happen in process simulation models, followed by real-world implementation. A construction process simulation model would be created for a particular factory using data from cameras and sensors. NREL, Louisiana State University, and VEIC recently published a report, "How Can Construction Process Simulation Modeling Aid the Integration of Lean Principles in the Factory-Built Housing Industry?" that discusses how digital recreations of factories can quantify and optimize their productivity, material flow, and labor dynamics (Podder et al. 2022). The modular builder can then readily inspect the performance of the factory under an endless number of what-if scenarios by changing various spatial and functional aspects of its stations or bays.

In the traditional site-built construction industry, the learning rate has historically been lower than what other industries employing more matured advanced manufacturing approaches (such as aircraft and solar modules production) have already achieved. As the traditional site-built construction industry attempts to reinvent itself to match the manufacturing industry in terms of labor productivity, industrialized construction approaches such as producing modular building units in factories have proven to maximize efficiencies and quality while reducing cost of construction. A recent McKinsey report highlights that industrialized construction approaches lead to economies of scale—one of the key drivers of cost savings. This requires large-enough factories as well as sufficient output to ensure repeatability and learning to allow a factory to produce and deliver approximately 1,000 dwelling units per year (Barbosa et al. 2017). Similarly, a significant cost reduction for energy efficiency strategies could be possible by maximizing the learning rates for each phase and leveraging prototyping and repetition. More recently, we worked with Blokable Inc.[1] to develop cost compression opportunities that address affordability for NZE buildings using industrialized modular construction (Klammer el al. 2021). According to our report, if the modular builder successfully produces and delivers on the order of 10,000 NZE dwelling units annually by 2030 (year 15) following the proposed development road map across three phases, it could reduce the approximately 8% incremental costs associated with achieving NZE to 1% incremental costs for its product, owing to learning and experience curves. By year 15, the 1% incremental cost can be seen as a 7% cost advantage over typical construction, as some codes will require net-zero design at this date.

The EMOD Method

As part of this project, we leveraged approaches such as design for manufacturing and assembly (DfMA) to bring together a set of energy efficiency strategies as a modularized solution where unitized components and systems serve the single apartment unit. Unit compartmentalization is a design objective to integrate energy efficiency strategies in an ideal NZE modular housing solution. NREL has successfully applied design for energy efficiency (DfEE) for site-built projects. The approach has been well documented and widely published as part of Advanced Energy Design Guides and other significant literature from the field. We now propose DfEE for the industrialized construction of modular buildings. Design for X (DfX) is a systematic methodology to achieve targeted design objectives, where X represents targeted

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[1] https://blokable.com

objectives. Since the late 1990s, hundreds of papers have been published pertaining to DfX method types, such as design for manufacturing (DfM), design for assembly (DfA), design for disassembly (DfD), and design for quality (DfQ) (Huang 1996). The EMOD method:

1. Applies to components and systems associated with energy efficiency strategies
2. Focuses on design objectives that includes unit compartmentalization to maximize work in factories, eliminate rework, and improve productivity
3. Identifies new kinds of interfaces between different energy efficiency strategies to enhance overall benefits and maximize unit compartmentalization.

The EMOD method involves three stages of design-centric evaluation and investigation:

1. Identify existing components and systems associated with energy efficiency strategies
2. Make decisions based on predetermined design objectives
3. Perform design evaluation and pilot studies.

We recently published a technical guide titled "The EMOD Buildings Method: A Guide to Energy-Efficient Design for Industrialized Construction of Modular Buildings" that documents the research and development efforts initiated by a set of design objectives to modularize a set of energy efficiency and low-carbon strategies into a housing unit while preserving and enhancing energy efficiency benefits and decarbonization pathways (Pless et al. 2022). During the project, we developed and explored several industrialization approaches, advanced manufacturing tools, and process efficiency strategies to increase productivity in integrating energy efficiency and grid interactive controls into buildings. We developed a decision checklist that allows modular builders considering building high-performance modular projects to evaluate energy efficiency strategies' components or systems based on predetermined design objectives (Table 1). These strategies are at the disposal of design teams involved in design, construction, and delivery of NZE housing projects, supported by performance curves and existing literature such as the Advanced Energy Design Guides. It is important to understand which energy efficiency strategies are best suited for integration in factories. The proposed methodology is a set of design objectives to achieve optimal integration to enable accelerated delivery of NZE modular housing. Checking every item on the decision checklist for an energy efficiency strategy would mean 100% success in achieving the design objectives. However, checking all but some or one would still indicate progress toward identifying the realistic targets for these objectives. Although this was an internal checklist developed by the project team, we envision process engineers and factory managers utilizing this checklist in their factories. The checklist could help evaluate opportunities associated with staging, construction scheduling, assembly, and commissioning in order to achieve specific design objectives.

Table 1. The EMOD method begins with a decision-making checklist to down-select energy efficiency strategies that maximize work in the factory.

Design objectives for the EMOD method	Decision checklist for energy efficiency strategies' components or systems
1. Maximize work in the factory	Staging: Can the energy efficiency strategy's component or system be easily staged and stored in the factory?
	Construction Scheduling: Can the modular construction schedule easily accommodate integration of the energy efficiency strategy's component or system into each modular housing unit?
	Assembly: Can the energy efficiency strategy's component or system be fully assembled into the modular housing unit in the factory?
	Commissioning: Can the final commissioning related to the energy efficiency strategy's component or system happen completely in the factory?

Design objectives for the EMOD method	Decision checklist for energy efficiency strategies' components or systems
2. Eliminate rework	Eliminate Custom Engineering: Can custom engineering of the energy efficiency strategy's component or system be eliminated for each project?
	Eliminate Design Variability: Can design variability of the modular housing unit be eliminated by selecting the energy efficiency strategy's component or system?
3. Increase labor efficiencies	Reduce Crew Conflict: Can crew conflict be avoided in the factory during the work associated with energy efficiency strategy's component or system?
	Increase Labor Productivity: Can labor productivity significantly improve in the factory by selecting the energy efficiency strategy's component or system?

Based on the proposed decision checklist, both unitization and decentralization of components and systems are most suitable to maximize work in the factory. The down-selected set of energy efficiency strategies are:

1. Envelope thermal control. The key strategies are eliminating thermal bridging and optimized insulation.
2. Envelope infiltration control. The key strategies are attention to connections and air sealing with an ionized sealant added through a controlled spraying process.
3. Mechanical, electrical, and plumbing systems. The primary objective is to modularize services including space conditioning, fresh air ventilation, domestic hot water, other services from high-efficiency appliances, and power distribution.
4. Smart controls. The key components are advanced controls for submetering, occupant engagement platform, grid-integrated HVAC and hot water controls, and utility price signaling.
5. Solar plus storage. The key components are rooftop solar PV, small, distributed battery energy storage system, along with the electrical distribution.

Idealized NZE Modular Multifamily Building Design

For complex energy efficiency strategies, it is challenging to maximize work (including staging, construction scheduling, assembly, and commissioning) in factories, eliminate rework, and increase labor efficiencies. According to Building Design+Construction's article "Net-Zero Energy Buildings: What the Case Studies Teach Us," in simpler projects where NZE is not the overriding goal, teams may be able to manage rework associated with mechanical/electrical design, but for projects with aggressive NZE goals, the design team must be given clear direction from the client and must fully embrace that directive (Horwitz-Bennett 2013). Overall, these design objectives could inform the decisions made in the early design stage of NZE modular multifamily buildings. The need for high-quality design and installation enables the adoption of energy efficiency strategies (such as rooftop solar PV for each modular housing unit) to achieve NZE goals. The EMOD method workflow, as illustrated in Figure 1, forms the core of approaches and tools that we followed during the project to arrive at a design for an idealized NZE modular housing solution (as shown in Figure 2). While a lot of these strategies are either already being implemented by builders or are being increasingly considered for implementation, the unique outcome of the EMOD method is how these strategies can be integrated into the design of a modular housing unit or apartment.

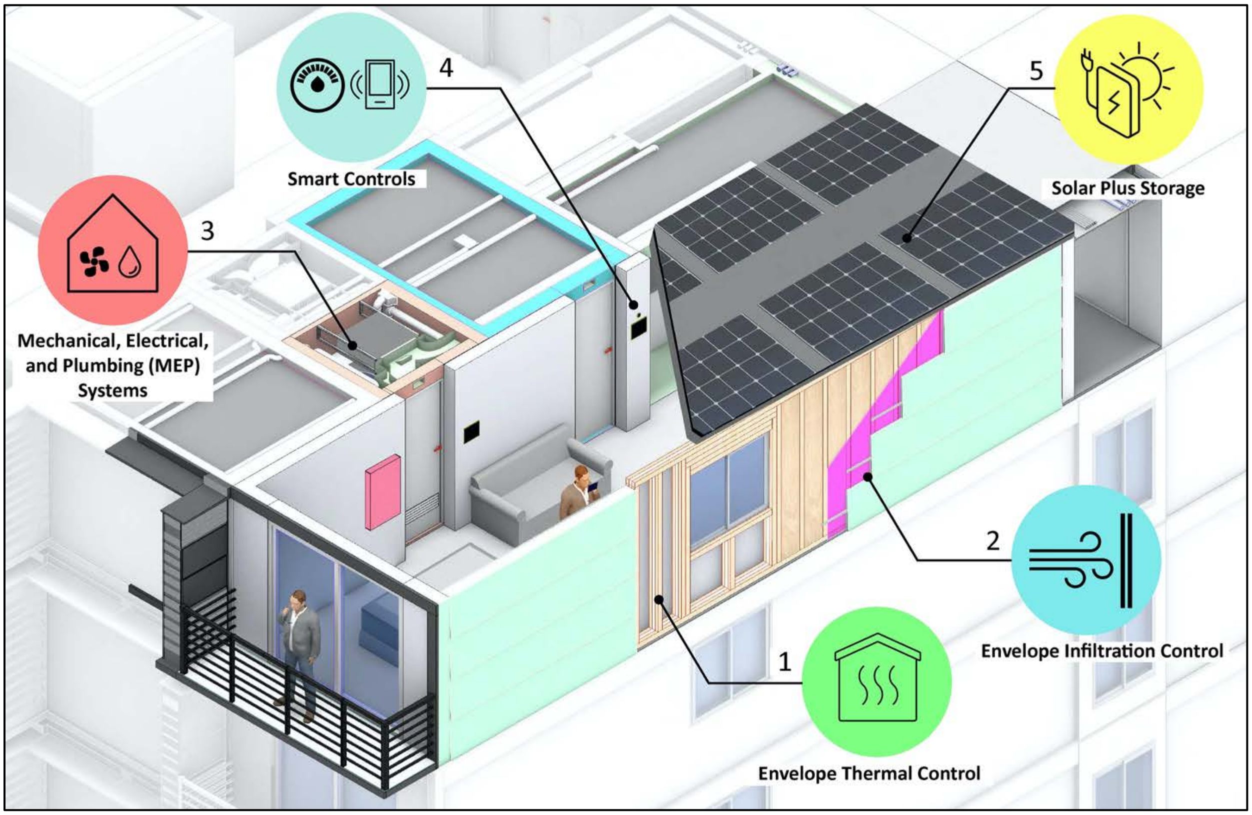

Figure 2. An ideal NZE modular housing unit for multifamily buildings as an output of the EMOD method by NREL and partners. *Source:* NREL.

The scope of work included developing the EMOD method and performing research and prototyping efforts informed by design objectives such as maximizing work related to integrating energy efficiency strategies (staging, construction scheduling, assembly, and commissioning) in factories, eliminating rework, and increasing labor efficiencies.

Strategy 1: Envelope Thermal Control

To optimize thermal control of the building, a superior quality insulation system can be installed in the factory, as opposed to traditional continuous exterior insulation applied on-site. To implement this, it is critical to design an EMOD-optimized factory-installed envelope system that achieves similar thermal performance as on-site continuous exterior systems. An example of factory-friendly thermal envelope assembly is using insulated truss studs (ITSs). Additionally, the envelope assembly can be combined with continuous insulation as part of the sheathing system and can also be built into structural insulated panels.

A key benefit from modular construction is standardization of processes, especially at assembly stations in the factory. Combined with sufficient training and quality control on the factory line, advanced framing methods can be proposed, demonstrated, and implemented with as much confidence as typical site-built approaches. Pushing the process-product innovation that is inherent to advanced framing further, standard studs can be replaced with thermally broken studs on framing and assembly stations. In partnership with Oregon State University, we demonstrated process optimization for advanced framing methods to reduce assembly cost, material use, and time (in labor-minutes). For volumetric modular projects, continuous insulation systems are usually installed on-site, which comes with the typical barriers of quality installation and additional site time. A potential factory-installed alternative is an insulated 2x6 framing system that can result in similar overall wall thermal performance but without on-site continuous exterior insulation. For future research, a new alternative product—ITSs with R-19 insulated structural 2x6 wall framing—is under consideration. For the purposes of this research, we refer to ITSs as the component along with the foam-in-place insulation.

Removing the need for continuous insulation on-site reduces the need for site work after setting or stacking the modular units. In addition, incorporating novel components like replacing standard studs during modular construction is an opportunity for energy efficiency integration into every modular apartment unit. As part of this project, we evaluated advanced framing methods with ITSs such as Tstuds.[2]

Strategy 2: Envelope Infiltration Control

As building codes demand tighter building envelopes, significant effort has been made to reduce the leaks in building shells through current construction practices. However, the problems of excessive labor costs, constant vigilance, and quality control remain with site-built construction. This section focuses on advanced envelope strategies of improving envelope infiltration controls through improved airtightness of modular units in the factory. There are several pathways to achieve this, such as using ionized sealing technology during industrialized construction. Compartmentalized unit air systems are airtight on all six sides to eliminate outdoor air infiltration. Furthermore, unit-to-unit and hallway-to-unit air transfer leads to better indoor air quality. We propose in-factory airtightness improvement for envelope infiltration control. An example of an in-factory airtightness improvement strategy is the efficient use of ionized sealing. Lessons learned from ionized sealing pilots could be leveraged to also identify opportunities for in-factory taping and caulking. We propose the following key steps to improve airtightness of modular units in the factory:

1. Use construction and manufacturing QA/QC tools and methods (such as nondestructive testing) to achieve a factory-installed airtight envelope. The key steps are:
    a. Plan for a QA/QC envelope design review
    b. Test the airtightness on a set of modular units in the factory to evaluate air-barrier quality and develop specific strategies to ensure all modules adopt well-known air-barrier details
    c. Test the airtightness on a representative sample of modular units at end of the factory production line.
2. Develop a dedicated factory station or bay to perform the ionized sealant process:
    a. Identify the optimal station or bay after drywall install station before the tasks associated with interior finishing installs
    b. Develop reusable seals and simple prep methods for quick covering of openings.

As part of this project, along with partner Momentum Innovation Group and leveraging AeroBarrier's ionized sealing process,[3] we explored and quantified airtightness degradation in the factory, compared the modules after they are set on the site, followed by comparison at completion to understand how tight units need to be when they leave the factory. Traditional air-sealing methods are well documented, but even when diligently applied can fall short of the

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[2] www.tstud.com

[3] https://aeroseal.com/aerobarrier/

ACH50 (air change per hour at 50 Pa) goal due to unrecognized leakage pathways. Very tight buildings would have an ACH50 of under 1.0 and very loose typical buildings would be over 7 ACH50. A good goal for most builders would be 3-4 ACH50, with upcoming IECC multifamily building codes looking to require 3 ACH50 or below for multifamily projects. Our pilots showed a pathway for 60% time reduction through in-factory airtightness improvement. Sealing time was also less due to lower starting ACH value (inherently tighter envelope from factory-built, compared to site built). Performing the sealing in the factory reduces preparation time as equipment are ready to use in a predefined workstation. We performed a series of pilots at Volumetric Building Corporation's (VBC's) factory in Hamlet, NC. The goal and key results of the pilot are:

1. Understand how airtight the modular units are from the factory construction process: Initial pilot results (3-5 ACH50) are better than typical unsealed apartments.
    a. Ionized sealing for 100+ site-built apartments show average unsealed tightness of 6-8 ACH50
    b. Specific energy modeling OpenStudio® simulations show climate zone specific optimal sealing vs. time vs. cost recommendation.
2. Understand unique opportunities and potential limitations to factory line sealing by sealing three modular studio apartment units at VBC:
    a. Opportunities: We demonstrated we can quickly seal compartmentalized apartments, so they are airtight to outside and to other interior apartments for odor and noise concerns. Also allows for compartmentalized mechanical ventilation solutions, limiting stack effect concerns impacting unbalanced ventilation system performance.
    b. Barriers: Need a way to reduce cleanup and setup time. Also need to further investigate (through a time and motion discrete event simulation) appropriate locations on the factory line to minimize setup and cleanup activities. A reusable prep sealing system could work, perhaps at a location in the line just after drywall is installed to eliminate cleanup and finished surface prep.

The key lessons learned are that airtightness starts with design and material selection, and ionized sealing should be used for fine-tuning. Overall, the leadership and continued engagement of the AeroBarrier team was critical for both pilots. The AeroBarrier team provided the following recommendations:

1. Based on the testing data, experience, and visual factory walkthrough of the station's activities and processes, there is much room to impact the overall quality of modular units positively.
2. With energy codes on the rise, minimizing tenant turnover is a leading concern for building owners and increasing utility costs and apartment living competition. A high leakage rate for modular units negatively affects all these areas.
3. Making minimal changes to air sealing details at design followed by incorporating ionized sealing into the build process in a streamlined and minimal interrupted manner will help the modular construction builders to produce and deliver the high-performance envelope.

Although the factory offers a controlled environment to perform sealing activities, a certain amount of "leak creep" can lead to change in the ACH50 value. Leak creep is the relative increase in ACH50 value of the modular unit after it has been set on-site and the project has been completed, compared to the AHC50 value achieved through sealing in the factory. One of the major reasons for leak creep is the penetrations that need to be made across mate-lines for vertical and horizontal distribution systems, after the modules are set on the site. We propose that QA/QC and blower door should be performed at relevant stages to monitor leak creep.

Strategy 3: MEP Systems

As mentioned in the previous section, many pathways are being pursued to reduce air leakage in building shells. A solution that could optimize airflow as well as other mechanical, electrical, and plumbing (MEP) systems is a unitized Energy Exchange Pod. We propose an EMOD optimization of MEP systems such as HVAC and domestic hot water. The objective is to design a unitized Energy Exchange Pod with space heating, cooling, ventilation, and domestic hot water so that these systems can be fully installed in the factory. This pod would enable:

1. Build-to-stock of subsystems through chunking and prefabrication for volume production in production lines
2. A unitized air system for each apartment.

The subassembly pod design offers several benefits:

1. Ensures proper ventilation that is hard to ensure with central ventilation systems and variable pressure across building height
2. Limits unit-to-unit air cross-contamination, reducing odor and noise.

The two design variations for the pod are:

1. Fully implemented idealized pod
2. Partially implemented solution:
    a. Site-installed with outdoor unit on roof
    b. In-unit equipment in ceiling and closets
    c. Partially decentralized shared systems.

Outputs from modular construction in factories come in several forms, such as volumetric modular systems, panel systems, and pod systems. Thus, the modularized NZE building service system could be in the form of a service pod. The term pod refers to one-room modules; the most common applications today are bathroom pods for site-built high-rises. More precisely, a pod is a turnkey prefabricated subassembly of multiple components, appliances, and equipment along with all structural and functional components that is pre-installed in the factory. Pods can be applied to both new construction and retrofits, designed to be multifunctional, and chunked into different form factors and scales such as bathroom pods, energy exchange pods, and kitchen pods. There are many unique design considerations that are inherent in factory-built housing, and this project focused on integrating all-electric HVAC, solar PV, battery storage, and hot water systems into homes before they leave the factory. We supported VEIC and KBS Builders in piloting a demonstration of an Energy Exchange Pod as part of their Zero-Energy Modular (ZEM) home project with focus on delivering affordable housing at scale. VEIC's ZEM project helps make zero-energy, resilient, and healthy homes affordable. VEIC's Mobile Home Replacement project is focused on delivering affordable, zero-energy, high-performance modular homes to vacant lots in existing, nonprofit-owned mobile home parks. Each home is custom designed to optimize the site available. Homes are sold to income-qualified buyers and offered as low-income rental units, owned by the park owner. The typical ZEM home is 14'x60' 2-bedroom or 26'x40' 3-bedroom, 1-bathroom with open kitchen, living, and dining room, along with a 5'x5' mechanical or utility room in conditioned living space. For NZE modular multifamily buildings and hotels, instead of a centralized mechanical system, a partially implemented pod was proposed.

Successfully designing and installing a compact, integrated space conditioning and ventilation system with all the ducting in conditioned space requires coordination and preparation early in the process to ensure routes are possible, clearances are met, and different MEP equipment isn't competing for the same space (as shown in Figure 3). A fully ducted mid-static heat pump integrated with a recovery ventilator can satisfy thermal loads, maintain acceptable humidity levels, and ensure optimal indoor air quality through high-quality distribution and filtration. Including all the ducting in the conditioned space means there is an opportunity for more coordination between trades, quality control, and commissioning before the unit goes to site. The choice of a mid-static heat pump and a slim-profile recovery ventilator allows the installer to hang the unit from the ceiling, which leaves square footage in the room for other MEP equipment like the water heater, inverter, battery, and laundry in this scenario. There is flexibility for fitting the equipment and ducting into drop ceilings or service cavities through rectangular ducting and transitioning to round ducts when more height is allowed but width is a premium, such as in a soffit.

The soffit—a box framed with wood and covered with wall board—functions as a service cavity for the heat pump's refrigerant lines in addition to the ducting. Avoiding use of the interstitial space between units for ducting means there is no need for radiation dampers in the ducting to meet hourly fire ratings.

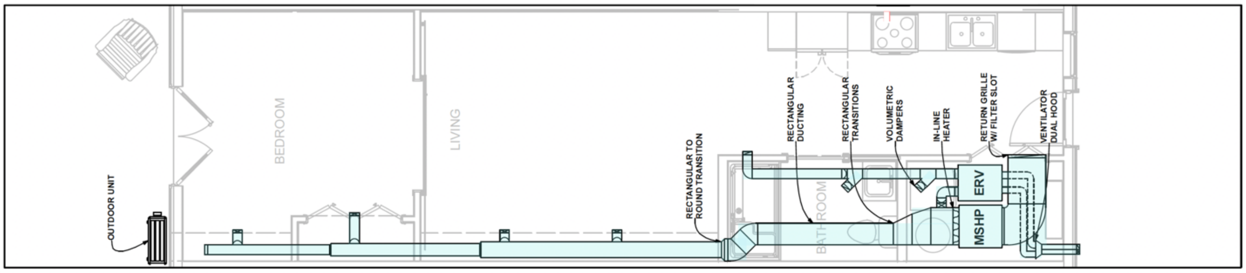

Figure 3. Floor plan layout demonstrating the ducting strategy as developed in collaboration with VEIC.[4] *Source:* NREL.

Duct fittings and transitions should be carefully selected to ensure adequate airflow, comfort, and noise levels, especially when using air handlers that are designed to operate at lower static pressures. Selecting off-the-shelf fittings for efficient transitions, such as in this reducing trunk system, may present a higher initial material cost but will reduce fabrication time while ensuring uniformity and repeatability across units.

Ideally, locating the outdoor and indoor unit close together will ensure shorter pipe lengths that are within the unit's pre-charged refrigerant weights, which will reduce costs for copper tubing and refrigerant. Designing the ducted return and filter combination to be a common, standard size will increase the likelihood that the system will be relatively easy and cost-effective to maintain. The ventilation system provides continuous exhaust from the bathroom, laundry, and kitchen areas. A dual hood for the ventilator, when climatically appropriate, used in accordance with a manufacturer's specifications allows the system to meet IMC 2021 clearance requirements between exhaust locations and mechanical air inlets without running ductwork lengthwise across the unit. A slim-profile recovery ventilator can be hung from the ceiling or mounted on the wall, providing flexibility for unit's layout.

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[4] https://www.veic.org

Strategy 4: Smart Controls

As smart, efficient, and grid-interactive technologies come down in price and become the standard, the unlocked potential of common residential loads can be realized, especially in repeated construction like modular buildings, which can be designed and manufactured to seamlessly integrate such grid-interactive efficient building (GEB) technologies. Smart controls can be optimized by minimizing site work and completing all system integration wiring, setup, and commissioning efforts in the factory Additionally, factory QA/QC opportunities can simplify final system start-up. The EMOD method applied to smart controls involves:

1. Designing smart apartment controls, sensors, wiring, and hardware integration to be installed and integrated in the factory
2. Developing a factory QA/QC method to streamline integration verification and setup.

GEB technologies in any building require integration to achieve a smart-apartment control system and usable platform. Platforms like STRATIS[5] and Senseware have plug-and-play solutions that work with diverse devices and aggregate them into one tenant-engagement system. Enabling this is the use of uniform communication protocols, such as Z-Wave, LoRa, Modbus, and BACnet. NREL is exploring the possibilities of modular GEBs by field-testing demand-side management technologies within modular apartment units, as well as integration of equipment on the production line in factories.

For modular multifamily buildings, where the design-build process of volumetric modular apartment units in the construction factory is repeated, a manufacturer can have a portfolio of appliances, mechanical systems, and lighting that add up to significant potential for interoperability. STRATIS explained that because modular construction can do away with fragmented trades and subcontractors, the installation, testing, integration, and pre-commissioning can all be done within the factory setting. The pilot project in this effort is in partnership with the Wells Fargo Innovation Incubator (IN2) program, where vertically integrated modular builder/developer, Blokable Inc., partnered with STRATIS to test integrated smart controls for energy efficiency, comfort, and demand-side management. Technologies in this project include thermostat floating, light dimming, plug-load reduction, dynamic shading (as shown in Figure 4), and heat-pump water-heater floating.

Figure 4. Dynamically controlled shading, triggered by demand response events at the NREL campus in Golden, CO. *Source:* NREL.

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[5] https://stratisiot.com

Looking toward a decarbonized future, the two Wells Fargo IN2 companies, Blokable Inc. and STRATIS, plan to further test modular GEB technology in anticipation of upcoming demand for grid interplay in California—Blokable Inc.'s primary market. As both a builder and owner of modular apartment buildings, Blokable Inc. can leverage dynamic savings from standardized integration of prepackaged, pretested modular GEB controls. While GEB integration may not initially be attractive to some developers given the focus on upfront cost, as a housing builder, developer, and owner, Blokable Inc. is uniquely positioned to benefit from energy bill savings from demand-side management, and to pass along this energy affordability to its residents.

Strategy 5: Solar Plus Storage

Factory-installed solar plus storage distribution design and integration is an energy efficiency strategy that is a promising new way of incorporating the resilience benefits of solar plus storage for each modular housing unit. Factory-installed solar plus storage and its lean benefits of reduced soft costs and lower installation time are not widely understood by factory homebuilders or the solar plus storage industry. This results in solar PV panels being attached on top of an existing building and batteries installed on-site—a more costly and time-consuming endeavor compared to factory-installed solar plus storage. Solar plus storage, energy efficiency measures, and demand management are key ingredients to ensure long-term affordability and must be integrated creatively during new constructions of housing units to lower soft costs. While hard costs (material and system costs) continue to be high for solar plus storage systems and components, our research focused on softs costs such as installation costs that also drive the overall cost of solar plus storage. The key EMOD method for solar plus storage is to maximize solar PV panels and balance-of-systems installation in the factory. Our proposed approach also includes using standardized components that do not require custom design, engineering, product customization, or approval processes. For solar plus storage, we propose the following EMOD practices to maximize work in the factory:

1. Design a modular roof system that enables ease of installation of solar PV panels in the factory while also allowing final on-site watertight connections to be made between modules
2. Implement learning outcomes from the Solar Home Factory case study, where they achieved significant reduction in installation costs. The case study also includes a three-story concept layout from their upcoming factory along with comparison of pros/cons between centralized and decentralized battery systems
3. Design the electrical distribution system to be easily completed on-site with simple final tie-ins to central meter or to in-unit electrical panels
4. Install in-unit battery systems for critical load
5. Streamline design code review with factory inspection for solar plus storage, eliminating on-site factory inspections and approvals.

According to a recent report by McKinsey & Company, prefabricated assembly of buildings has demonstrated up to 50% construction time savings and, in the right environment and trade-offs, it can cut costs by 20% (Bertram et al. 2019). Similarly, costs associated with procurement and installation of solar PV and residential batteries could be significantly lowered in order to increase their wider adoption. Off-the-shelf commoditized home battery products along with the electrical infrastructure and advanced control systems can be pre-assembled as a "skid" in the factory and shipped to the construction site. Off-site integration in a controlled factory environment ensures better coordination of standard installation procedures that are necessary for fire safety. In the factory, installers can perform their work at a predetermined station or bay suitable for activities related to integration of small, distributed home batteries. In the factory, installers and factory workers can non-intrusively carry out tasks such as electrical wiring and QA/QC of noncombustible enclosures surrounding the battery system, if any. The factory also lends itself to a quick test-fire run of the charging and discharging cycles as part of the extensive QA/QC protocol.

Along with partners Solar Home Factory and VEIC, we developed a "vertical tower design and delivery strategy" for the modules by incorporating factory-installed solar plus storage. This optimized design would make it possible to manufacture energy-efficient and resilient housing units at scale. Batteries can make housing more resilient to power outages—after any disaster event, it can take weeks before the grid can operate at the necessary capacity to support community-wide recovery and rehabilitation, so having backup support for households is crucial. Unfortunately, in the United States a high volume of additional battery energy storage systems is needed to achieve this type of resilience. Studies have shown that three times more battery energy storage systems by volume are needed for a high-risk vs. low-risk city. Solar Home Factory considered a residential battery system to meet resilience goals and encountered several decision points and barriers, most importantly high first costs from the additional storage volume as well as increased fire safety concerns associated with additional infrastructure. Solar Home Factory has shown that off-site construction could be the path forward, addressing both the challenges of cost and safety. For solar PV, they have achieved significant reduction in installation costs. However, there has been minimal work so far to creatively combine both the intrinsic benefits of off-site construction with the installation of residential batteries. Therefore, we performed a comparative assessment of centralized indoor or outdoor large battery systems that are site-installed for multifamily buildings vs. decentralized small battery systems that are factory-installed along with its critical infrastructure and controls.

Table 2. Comparison of centralized indoor or outdoor large battery systems (site-installed) vs. decentralized small battery systems (factory-installed) for multifamily buildings.

Key Consideration	Centralized Indoor/Outdoor Large Battery System, Site-Installed	Decentralized Small Battery System, Factory-Installed
Fire codes	Concerns with large central indoor battery	Less concern, less infrastructure and approvals needed in the decentralized system such as smaller distributed residential batteries
Commodification, off-the-shelf	Large central systems are custom engineered and installed by specialist, with larger custom designed infrastructure (like fire protection and cooling) required	Residential batteries are pre-engineered and commodity systems manufactured at scale that can be installed by solar installers or electricians. A modular and repeatable design approach to solar and storage suggest similar cost savings as other factory installed modular systems
Back-up allocation	Central storage can be used for easier backup and life safety loads like egress lighting and elevators	Decentralized storage can more easily be wired to provide backup power in apartments

Key Consideration	Centralized Indoor/Outdoor Large Battery System, Site-Installed	Decentralized Small Battery System, Factory-Installed
Location	Central storage systems can be located outside of the building in a dedicated space/power room, saving space in the apartment	Smaller distributed residential batteries located inside the apartment
Approval process by authorities	Questions on "who does what" on approvals with design and inspection when work is on-site	Contiguous or sequential and integrated approval process in the factory on design and inspection

Conclusion

This paper discusses our work with industrialized housing partners, showing great potential for delivering housing at scale as well as electrifying and increasing the grid friendliness of NZE buildings. With emerging codes in cities that require all electric buildings for new construction, there is a growing need to address high operational costs with all-electric technologies. As these codes become ever more stringent, there is a unique opportunity for high-performing modular builders to increase the use of industrialized construction. By demonstrating that industrialized construction can enhance energy efficiency, our efforts have the potential to elevate the U.S. modular industry to the cutting edge of the entire building industry. We continue to work with housing partners and agencies focused on delivering affordable housing, such as the project with VEIC and the U.S. Department of Housing and Urban Development (Podder et al. 2022). Future work should focus on demonstrating how to scale the energy efficiency strategies combined with industrialized modular construction to showcase how we can address affordability concerns with both energy and housing. Stakeholders could translate the proposed practices to hospitality and school buildings.

Successful adoption of the EMOD method and the key approaches, methods, and strategies are initial steps toward establishing thought leadership on the industrialized construction of NZE modular multifamily buildings, both nationally and globally. This work demonstrates how the EMOD method incorporates energy efficiency with the other benefits of industrialized construction to lower the energy burden of tenants and homeowners, demonstrate a scalable pathway to address the affordable housing crisis, invest in the U.S. construction workforce by improving productivity and increasing employment opportunities in underserved communities, and meet national goals of energy efficiency. The industrialized construction of NZE modular multifamily buildings is an essential step for developing a transformational pathway for our clean energy future.

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References

ASHRAE. 2018. *Energy Simulation Aided Design for Buildings Except Low-Rise Residential Buildings.* ANSI/ASHRAE Standard 209-2018.

ASHRAE. 2019. *Advanced Energy Design Guide: Achieving Zero Energy.*

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., et al. 2017. *Reinventing construction through a productivity revolution.* McKinsey. https://www.mckinsey.com/business-functions/operations/our-insights/reinventing-construction-through-a-productivity-revolution

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, J. 2019. Modular construction: From projects to products. *McKinsey & Company: Capital Projects & Infrastructure*, 1-34.

Horwitz-Bennett, B. (2013). “Net-Zero Energy Buildings: What the Case Studies Teach Us.” *From “Zero and Net zero Energy Buildings+Homes.* Building Design+Construction.

Huang G.Q. (1996) Introduction. In: Huang G.Q. (eds) *Design for X.* Springer, Dordrecht. https://doi.org/10.1007/978-94-011-3985-4_1

Karagiozis, A., Künzel, H., & Holm, A. 2001. WUFI-ORNL/IBP—a North American hygrothermal model. *Performance of Exterior Envelopes of Whole Buildings VIII*, 2-7.

Klammer, N., Kaufman, Z., Podder, A., Pless, S., Celano, D., & Rothgeb, S. 2021. *Decarbonization During Predevelopment of Modular Building Solutions* (No. NREL/TP-5500-81037). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Pless, S., Podder, A., Kaufman, Z., Klammer, N., Dennehy, C., Muthumanickam, N.K., Rothgeb, S., Louis, J., Swanson, C., Wallace, H. & Blazek, C., 2022. *The Energy in Modular (EMOD) Buildings Method: A Guide to Energy-Efficient Design for Industrialized Construction of Modular Buildings* (No. NREL/TP-5500-82447). National Renewable Energy Lab.(NREL), Golden, CO (United States). https://doi.org/10.2172/1875070

Podder, A., Pless, S., Nahmens, I., Labik, O. & Donovan, A., 2022. *How Can Construction Process Simulation Modeling Aid the Integration of Lean Principles in the Factory-Built Housing Industry?* Cityscape, 24(1), pp.331-344.

Podder, A., Pless, S., Rothgeb, S., Klammer, N., Blazek, C., Louis, J., & Rashid, K. 2020. *Integrating Energy Efficiency Strategies with Industrialized Construction for our Clean Energy Future* (No. NREL/CP-5500-77259). National Renewable Energy Lab.(NREL), Golden, CO (United States).