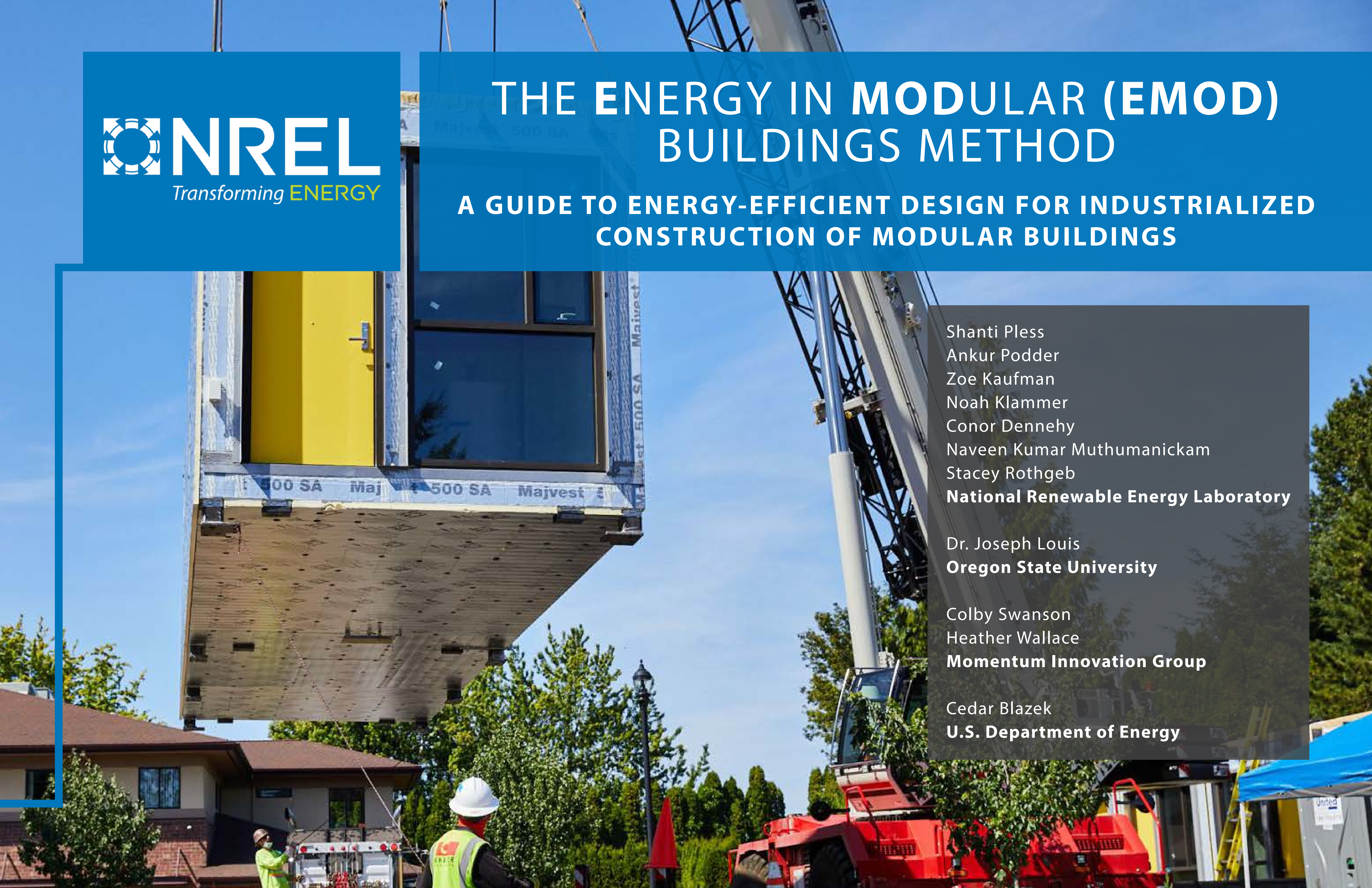

NREL
Transforming ENERGY

THE ENERGY IN MODULAR (EMOD) BUILDINGS METHOD

A GUIDE TO ENERGY-EFFICIENT DESIGN FOR INDUSTRIALIZED CONSTRUCTION OF MODULAR BUILDINGS

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Factory_OS

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VEIC

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This guide was developed with partners throughout the United States to demonstrate how integrating energy efficiency and low-carbon strategies during modular construction can be successful and scalable to achieving net-zero energy (NZE), low-carbon modular housing, and lead to an increase in affordability, integrated efficiency, decarbonization pathways, and improved resilience. The primary builder partners of the project were Volumetric Building Companies (wood-framed volumetric modular), Factory_OS (steel-framed volumetric modular), and FullStack Modular (steel-framed volumetric modular).

LIST OF ACRONYMS

ACH50
air change per hour at 50 Pa

AEDGs
Advanced Energy Design Guides

AHU
air handling unit (indoor)

ASHRAE
American Society of Heating, Refrigerating and Air-Conditioning Engineers

C.i.
continuous insulation

DfEE
design for energy efficiency

DfMA
design for manufacturing and assembly

DOE
U.S. Department of Energy

EMOD
Energy in Modular

ERV
energy recovery ventilator

GEBs
grid-interactive efficient buildings

GHG
greenhouse gas

HPWH
heat pump water heater

HVAC
heating, ventilation, and air conditioning

ITSs
insulated truss studs

MEP
mechanical, electrical, and plumbing

NREL
National Renewable Energy Laboratory

NZE
net-zero energy

o.c.
on center

PTHP
packaged terminal heat pump

QA/QC
quality assessment/ quality check

VBC
Volumetric Building Companies

TABLE OF CONTENTS

OVERVIEW

Industrialized construction means using industrialized production methods—such as high-volume off-site construction, prefabrication, and automation—to build buildings. The U.S. construction industry has recently begun incorporating industrialized construction to address affordability concerns and labor shortages. In addition to reducing the cost of construction and delivery times, industrialized methods such as permanent modular construction have the potential to deliver affordable housing at scale, along with building decarbonization, electrification strategies, and grid friendliness.

Industrialized construction has immense potential to address the growing need globally to build and upgrade the building stock to be affordable, energy-efficient, and resilient. It can also help **achieve the United States' goal of a 50% reduction in U.S. greenhouse gas (GHG) emissions by 2030.** Despite this potential, and the ever-increasing push for electrification and decarbonization of households in the United States, industrialized construction has not yet been leveraged specifically to help address these challenges and accelerate the pathway to meet these goals.

The National Renewable Energy Laboratory (NREL) aims to claim this missed opportunity by focusing on delivering affordable, grid-efficient net-zero energy (NZE) modular buildings for underserved communities to ensure an equitable transition to the future of clean energy, accelerate decarbonization of the built environment, and support the development of a high-productivity construction and energy efficiency workforce.[1] We draw synergies between design for manufacturing and assembly, process optimization, retrofit technologies, and digitization. Our goal is to influence the improvement and production of buildings to increase performance, enhance energy efficiency, and reduce GHG emissions.

The Energy in Modular (EMOD) method is our approach to **designing, producing, and delivering affordable, net-zero energy, low-carbon, and healthier buildings at scale** (as shown in Figure 1). NREL's Industrialized Construction Innovation Team[2] led the development of this guide, and our scope of work includes **whole-building level and subassemblies of components, pods, panels, and volumetric modules**.

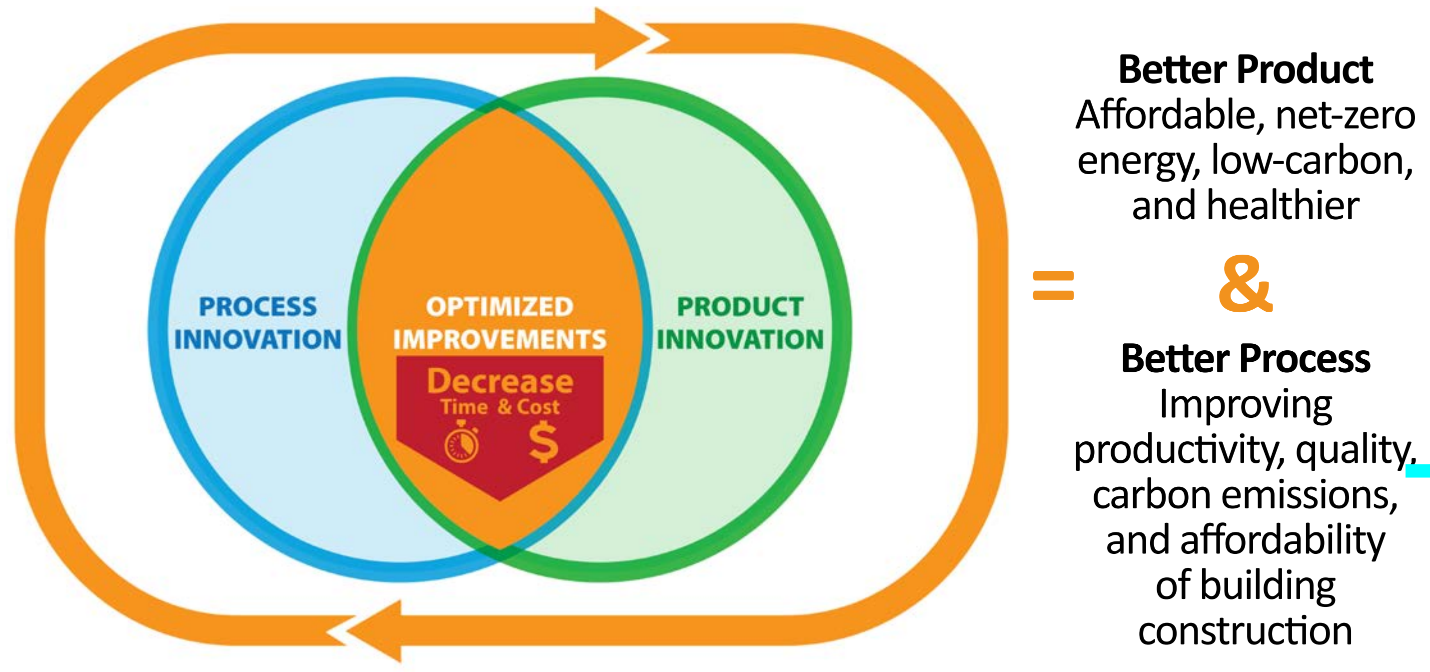


FIGURE 1 The EMOD method is an approach to energy-efficient design for industrialized construction of modular buildings. Figure source: NREL.

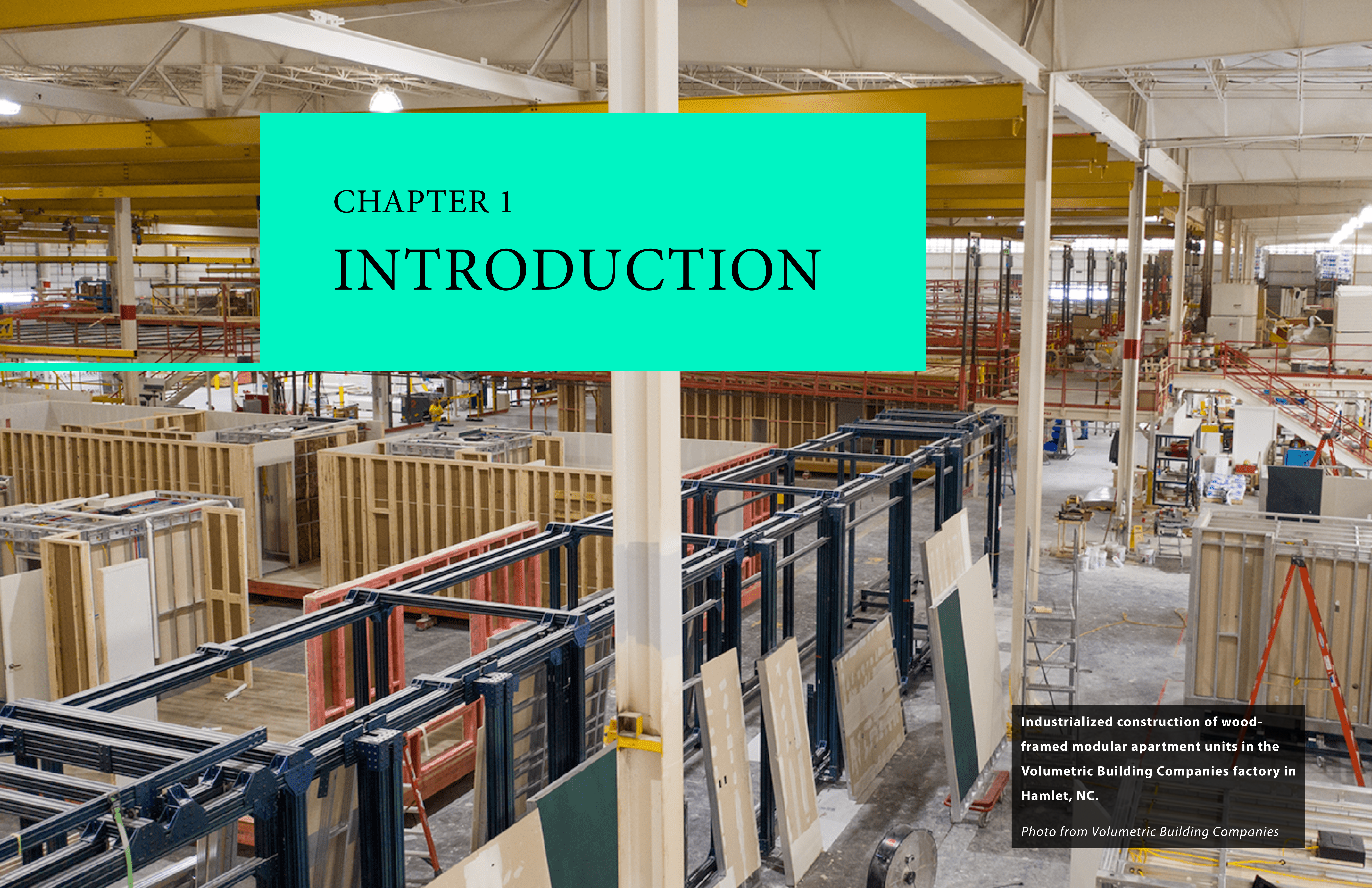
ABOUT THIS GUIDE

This guide 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. This guide is intended to serve as a framework for housing developers, housing agencies, architects, energy experts, and process engineers or factory operator personnel who are critical to today's modular builder teams. **Chapters 1 and 2 present background, proposed methodology, and processes. Chapters 3-7 discuss a select set of energy efficiency strategies, how we applied the EMOD method to each, and the implementation efforts with partners.** This guide focuses on specific energy efficiency strategies, decarbonization pathways, and associated processes as part of NREL's research efforts. Stakeholders may substitute other means, methods, and technologies for the ones evaluated in this study.

1 https://www.osti.gov/biblio/1668862-integrating-energy-efficiency-strategies-industrialized-construction-our-clean-energy-future-preprint
2 www.nrel.gov/buildings/industrialized-construction.html

CHAPTER 1

INTRODUCTION



Industrialized construction of wood-framed modular apartment units in the Volumetric Building Companies factory in Hamlet, NC.

Photo from Volumetric Building Companies

Research question: **"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 guide is the result of a 3-year project funded by the U.S. Department of Energy's (DOE'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 wood-framed and steel-framed modular construction partners and developers in the United States, such as the iUnit (as shown in Figure 2).

As a result, we identified five key energy efficiency strategies to integrate in industrialized construction. In addition, we leveraged intentional design, streamlined workflows, modeling, and cost reduction through process improvement and prototyping.

Key benefits of the EMOD method:

- 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.**
- High-volume production means **reduced cost, time, and complexity from off-site construction and eliminated site work.**

The following energy efficiency strategies were part of the scope of the project (corresponding to chapters 3-7 of this guide):

1. **Envelope thermal control**
2. **Envelope infiltration control**
3. **Mechanical, electrical, and plumbing systems**
4. **Smart controls**
5. **Solar plus storage**

FIGURE 2 An iUnit apartment is tested at the Outdoor Research Block at NREL in Golden, CO. This research area accommodates research, development, and testing on energy efficiency in modular apartment units. Source: NREL.

Our EMOD method allows modular builders to maximize the cost-effectiveness of these energy efficiency strategies and low-carbon solutions and leverage industrial engineering and advanced manufacturing approaches to increase productivity and reduce the first cost of construction.

We 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 and low-carbon 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.[1]

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 by increasing costs and labor and lead time. Instead, the project aimed to optimize and maximize off-site processes and minimize on-site tasks.

1 https://www.osti.gov/biblio/1668862-integrating-energy-efficiency-strategies-industrialized-construction-our-clean-energy-future-preprint

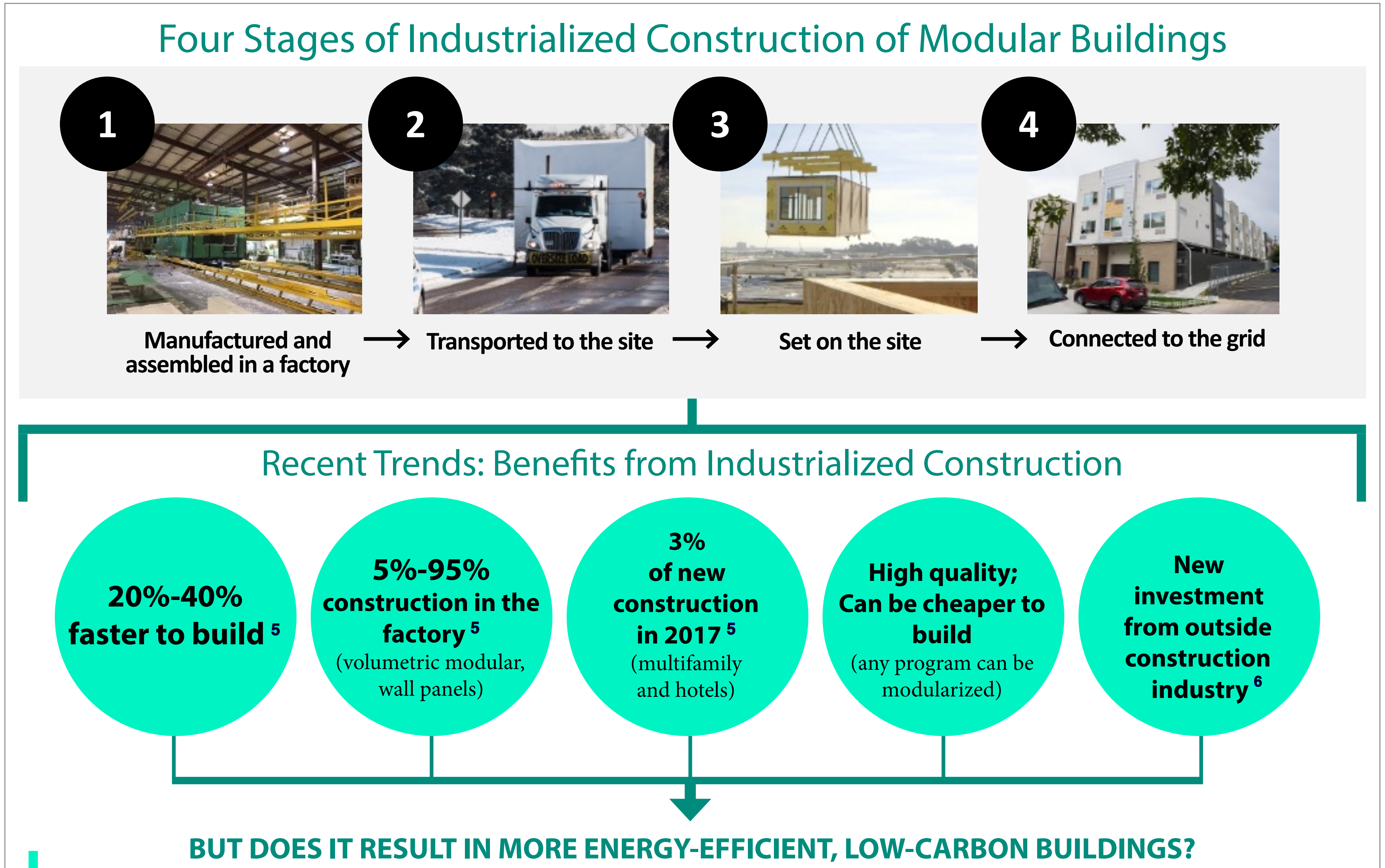


FIGURE 3 Illustrates the four stages of industrialized construction of modular buildings, from the factory to the site. The units are built out in a factory without exposure to weather before being transported to the site and stacked onto prepared foundations to form buildings.[7] According to Modular Building Institute, "Modular construction is a process that constructs a building off-site, under controlled plant conditions using the same materials and designed to the same codes and standards as conventionally built facilities but in about half the time."[8] Modular construction involves 75% to 95% completion of modular apartment units in factories.[9] Source: NREL.

THE NEED FOR INDUSTRIALIZED CONSTRUCTION FOR AFFORDABLE HOUSING DELIVERY

In recent years, the U.S. building construction industry has begun using modular construction to overcome barriers of labor expertise, cost, quality, safety, and speed of construction. The persisting challenges are partly due to the lack of innovation in how we have attempted to improve the highly standardized processes entrenched in the U.S. construction marketplace. According to a recent McKinsey & Company report on productivity in the U.S. construction market,[2] a global effort is needed to modernize and upgrade the construction industry across broad areas. The lack of innovation across the U.S. construction industry has also resulted in increased costs due to inefficiencies in our construction processes.

Because roughly 21 million, or one in six, households in the U.S. are apartments and condos,[3] the initial focus of employing industrialized construction in the United States must be to produce and deliver affordable multifamily housing. According to the U.S. National Institute of Building Sciences' Off-Site Construction Council, off-site construction is "the planning, design, fabrication and assembly of building elements at a location other than their final point of assembly onsite".[4]

As a subset of offsite construction, modular construction is a method to construct a building using three-dimensional or modular units assembled and produced in a factory. **While recent trends indicate benefits from industrialized construction, the question is whether industrialized construction results in more energy-efficient, low-carbon buildings (as shown in Figure 3).**

2 www.mckinsey.com/business-functions/operations/our-insights/reinventing-construction-through-a-productivity-revolution
3 https://www.energyefficiencyforall.org/resources/more-savings-for-more-residents-progress-in-multifamily-housing-energy/
4 https://www.nibs.org/oscc
5 https://www.modular.org/industry-analysis/
6 https://www.mckinsey.com/~/media/mckinsey/business%20functions/operations/our%20insights/voices%20on%20infrastructure%20scaling%20modular%20construction/gii-voices-sept-2019.pdf
7 https://www.modular.org/what-is-modular-construction/
8 www.researchgate.net/publication/305550264_Towards_the_adoption_of_modular_construction_and_prefabrication_in_the_construction_environment_A_case_study_in_Malaysia
9 www.meehleis.com/wp-content/uploads/2015/05/2015_Off-Site_PMC_Report-Ryan-Smith.pdf

The Off-Site Construction Council recognizes the potential of modular construction to improve productivity and efficiency via further digitalization, innovative technologies, and new construction techniques.[10] Modular builders may also **economize on costs by reducing total production and delivery time**. To support the growing modular industry, **many rural and industrial areas in the United States are increasingly becoming manufacturing sites**. Overall, modular builders have successfully proven the delivery of affordable multifamily buildings through **faster construction timelines, improved productivity, and labor cost savings.**

EFFICIENCY BENEFITS FROM INDUSTRIALIZED CONSTRUCTION

Recent studies report that modular construction can save up to 20% on hard costs, reduce construction time up to 50%,[11] and deliver buildings of various typologies, including high-rise luxury hotels (as shown in Figure 4). Thus, many U.S. contractors view modular construction as an opportunity to remain competitive. According to CoStar, in 2017, 45% of all new construction floor area in the United States was multifamily typology.[12] As cities look to expand their affordable housing and apartment options, the demand for cost-effective permanent modular housing is growing. The Terner Center's report Building Affordability by Building Affordably recognizes that modular construction facilitates rapid production of an affordably built supply of housing.[13] Because the apartment units can be constructed while the site and foundation are being prepared, instead of after, there are significant time and cost savings.[14]

Despite additional unintended or secondary energy efficiency benefits and decarbonization opportunities—such as a tighter envelope due to higher construction quality in a controlled factory environment—industrialized construction has not been leveraged to enhance energy efficiency and achieve decarbonization.[15]

FIGURE 4 A crane lifts a volumetric modular hotel room unit onto the AC Hotel New York NoMad at 842 Sixth Avenue. Source: Skystone.

Until now, there has been minimal work to combine the intrinsic benefits of industrialized construction methods with the installation of cost-effective energy efficiency strategies, low-carbon strategies, advanced controls, distributed energy, and grid-friendly design strategies. As a result, there is a need to prove that industrialized construction can address housing affordability challenges for multifamily buildings by lowering the cost of construction and reducing the energy burden.

10 https://www.nibs.org/oscc
11 https://ternercenter.berkeley.edu/research-and-policy/disruptive-development-modular-manufacturing-in-multifamily-housing/
12 https://www.nmhc.org/research-insight/research-report/US-apartment-demand-a-forward-look/
13 ternercenter.berkeley.edu/research-and-policy/offsite-construction/
14 www.researchgate.net/publication/239769075_Construction_Matters_Comparing_Environmental_Impacts_of_Building_Modular_and_Conventional_Homes_in_the_United_States
15 https://www.osti.gov/biblio/1668862-integrating-energy-efficiency-strategies-industrialized-construction-our-clean-energy-future-preprint

A net-zero energy (NZE) building is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied by renewable technologies.[16] According to a recent report by VEIC, "NZE modular" housing **combines the benefits of no to low energy costs with the efficiencies of modular construction**.[17] All-electric, low-carbon, and highly efficient NZE modular housing units are often outfitted with rooftop solar arrays and use about as much energy as they produce each year (as shown in Figure 5).

NET-ZERO ENERGY, LOW-CARBON MODULAR HOUSING

A NZE building should first encourage energy efficiency, and then use renewable energy sources available on-site. In addition, grid-interactive efficient buildings (GEBs) offer fourfold benefits: increased energy savings, decreased carbon emissions (lower marginal emissions), relief for grid congestion, and increased grid resilience.

> NZE buildings, particularly housing, are not being designed, constructed, and delivered across the United States at the rate needed to meet energy efficiency and decarbonization goals.

Numerous efforts by state governments, non-profit organizations, and the private sector have been unable to deliver the 1.8 million housing units per year needed to meet the U.S. housing demand. More precisely, the annual supply deficit of 370,000 housing units on average has led to the cumulative need of 3.8 million units to match long-run demand.[18] Furthermore, only a fraction of the 1.4 million housing units per year are produced and delivered to be NZE. According to the 2019-2020 Zero Energy Residential Buildings Inventory for the United States and Canada, there are only 27,965 NZE housing units (including single and multifamily units).[19] This extreme supply deficit is becoming larger with the growing push for decarbonization and electrification of households[20] and the need to reduce U.S. GHG emissions by 50% by 2030.[21] **To achieve these goals, all 1.8 million new units per year must be NZE, and all of today's aggregated supply deficit of 3.8 million units must be produced and supplied as NZE housing units.**

Now, NREL is bringing its expertise to this problem: examples of NREL's leadership in bridging energy efficiency research with prefabricated and modular housing include seminal projects on weatherization savings for mobile homes,[22] and testing of modular offices[23] and manufactured homes.[24]

FIGURE 5 NZE modular units with factory-installed rooftop solar PV at the Solar Home Factory at Geneva, NY. Source: Solar Home Factory.

16 https://www.osti.gov/biblio/883663
17 https://www.veic.org/clients-results/reports/zero-energy-modular-factory-initiative
18 https://www.freddiemac.com/research/insight/20210507-housing-supply
19 https://teamzero.org/2021/02/01/team-zero-2019-2020-residential-buildings-inventory-released/
20 https://rmi.org/insight/the-economics-of-electrifying-buildings/
21 www.nrdc.org/resources/biden-administration-must-swiftly-commit-cutting-climate-pollution-least-50-percent-2030
22 https://www.sciencedirect.com/science/article/pii/037877889390035S?via%3Dihub
23 https://www.osti.gov/biblio/775894
24 https://www.osti.gov/biblio/5170743

ADVANCED ENERGY DESIGN GUIDES AND OTHER LITERATURE

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provides resources and professional continuing education on design and construction of NZE building service systems for its members (building services engineers, architects, mechanical contractors, building owners, and equipment manufacturers' employees). ASHRAE's Advanced Energy Design Guide (AEDG)—Achieving Zero Energy series serves as a seminal design guide for the industry to set pathways toward delivering NZE buildings (as shown in Figure 6).[25] NREL also played a vital role in development of the AEDGs.[26] Since the first design guide was released in 2004, AEDGs have provided inspiration for the industry to go beyond minimum codes and standards. Overall, AEDGs provide guidance on subsystems such as all-electric best-in-class high-efficiency air-source minisplit heat pumps, heat pump water heaters, energy recovery ventilators, and centralized battery energy storage systems to design and deliver NZE housing projects to ensure a comfortable, healthy, and resilient built environment.[27]

> AEDGs have been instrumental in providing energy-efficient design guidance organized by building type and climate zone. The guides are supported by case studies and energy modeling, developed by leading industry experts and national labs, and referred to for beyond code recommendations.

> AEDGs provide comprehensive **design guidance, case studies and building energy modeling by building type and climate zone**. More importantly, AEDGs provide **a broad range of pathways to design and build residential and commercial zero energy buildings.**

FIGURE 6 Cover pages of the Advanced Energy Design Guides, including the guide for multifamily buildings, which was referenced extensively as part of this project. Source: ASHRAE.

Apart from AEDGs, other literature in building science highlights several pathways including energy efficiency benefits by maximizing unit compartmentalization. For housing projects, research has shown that good unit compartmentalization is vital for fire, smoke, odor, contaminant, and sound control.

Unit compartmentalization can ensure more reliable fresh air ventilation, and when done well, can reduce HVAC loads[28] (as shown in Figure 7). In cold climates, moisture problems occur because of flow from inside to outside. In warm humid climates, the flow is reversed. Therefore, the key to moisture control in modular units in all climates is airtight construction, climate appropriate wall sections, and air-to-air ventilation heat exchange in each module.

25 www.ashrae.org/File%20Library/About/Strategic%20Plan/ASHRAE---Vision-2020-Report.pdf
26 https://www.osti.gov/biblio/1047961
27 https://www.ashrae.org/technical-resources/aedgs/zero-energy-aedg-free-download
28 https://energyproexchange.com/wp-content/uploads/2021/03/Unit-Compartmentalization-How-and-Why-to-Address-a-Difficult-Detail-by-EnergyPro-Exchange-EPX.pdf

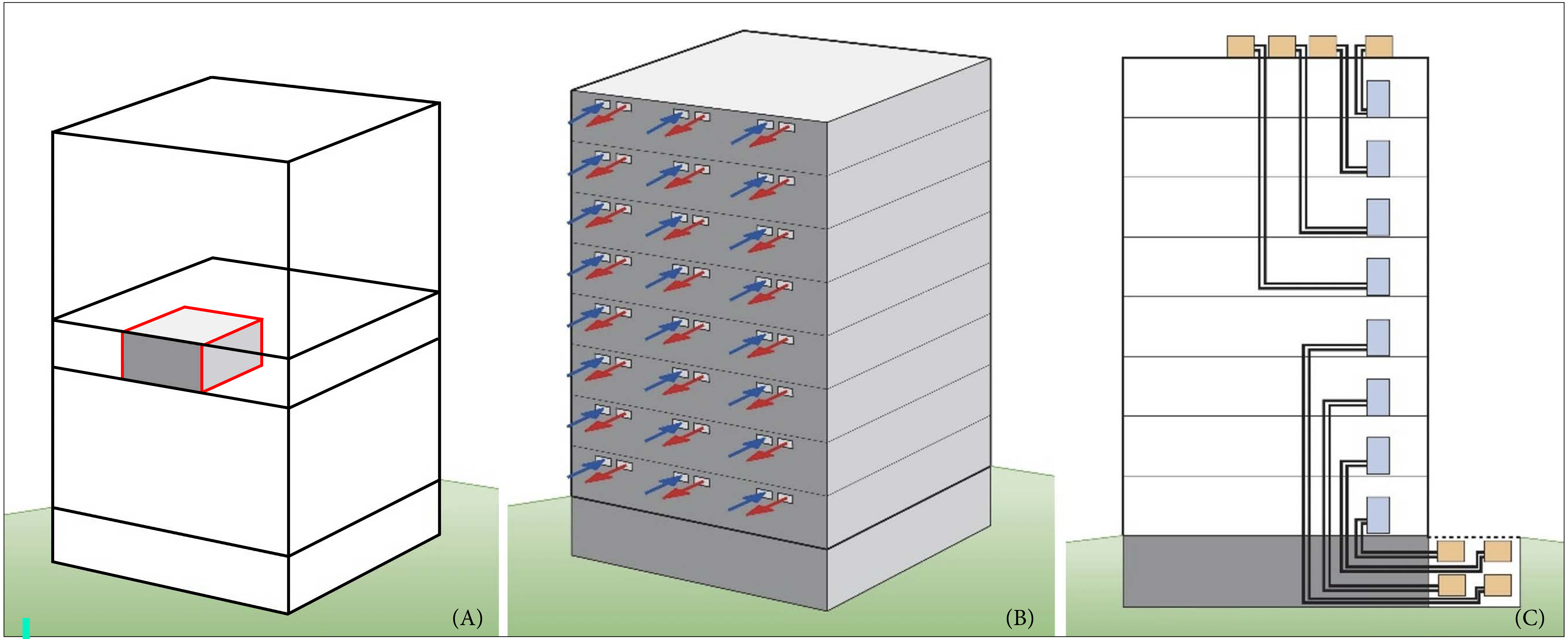


FIGURE 7 (A) Unit compartmentalization: It is necessary to control stack effect air pressures and limit airflow from adjacent units and cross contamination.

(B) Unit ventilation: Avoid vertical shafts and ducts and central systems; keep ducts within each compartment and vent directly to the exterior.

(C) Space conditioning and hot water: The unit compartmentalization principle can also be extended to heating, cooling, and domestic hot water. Unit space heating, cooling, and hot water is provided by individual mechanical systems located in each unit.

Source: "BSI-108: Are We Sealing The Right Walls In Buildings?" by Building Science Corporation.

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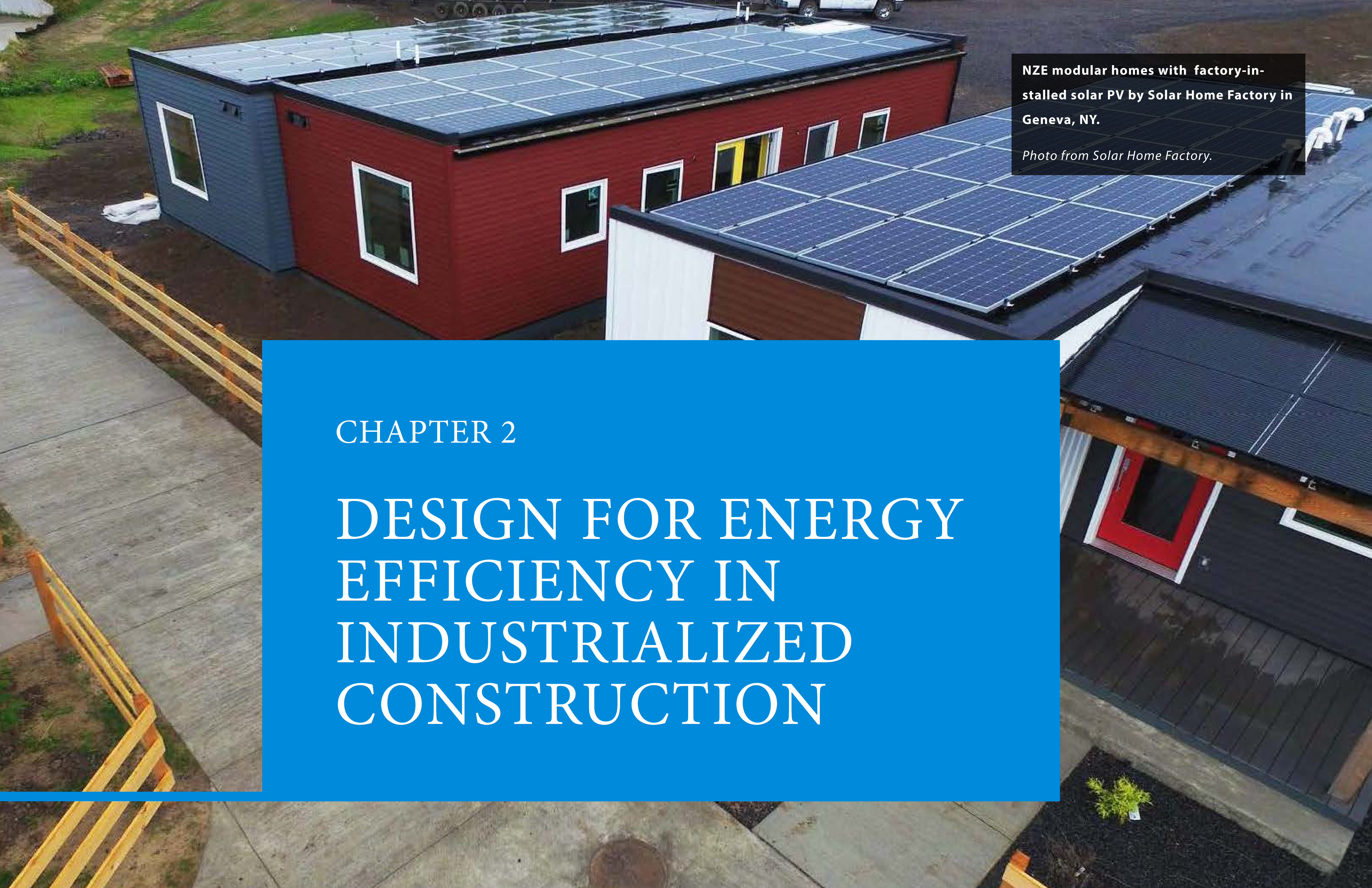


NZE modular homes with factory-installed solar PV by Solar Home Factory in Geneva, NY.

Photo from Solar Home Factory.

CHAPTER 2

DESIGN FOR ENERGY EFFICIENCY IN INDUSTRIALIZED CONSTRUCTION

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 AEDGs and other significant literature from the field. **We now propose DfEE for the industrialized construction of modular buildings.**

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, low-carbon modular housing solution.

Energy efficiency strategies include envelope thermal control, envelope infiltration control, modularization of MEP systems, smart control integration and commissioning, and solar plus storage. In terms of DfMA of energy efficiency strategies, we performed a subassembly design that optimizes workforce productivity. Our efforts led to a standardized catalog of subassemblies of building components, pods, panels, and volumetric modules.

Design for X (DfX) is a systematic methodology to achieve targeted design objectives, where X represents targeted 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).[1]

DfMA is an emerging approach in the architecture, engineering, and construction sector. Many studies have investigated the DfMA principles suitable for different types of construction projects and advocated a wide implementation of DfMA in construction. In 2013, the Royal Institute of British Architects (RIBA) published the RIBA Plan of Work for DfMA implementation.[2] In this report, RIBA focuses on DfMA applications in the construction industry and defines it as an approach that facilitates greater off-site manufacturing, thereby minimizing on-site construction (as shown in Figure 8). The RIBA report also explains that DfMA allows buildings to be constructed more quickly and safely, and more resource-efficiently and cost-effectively.

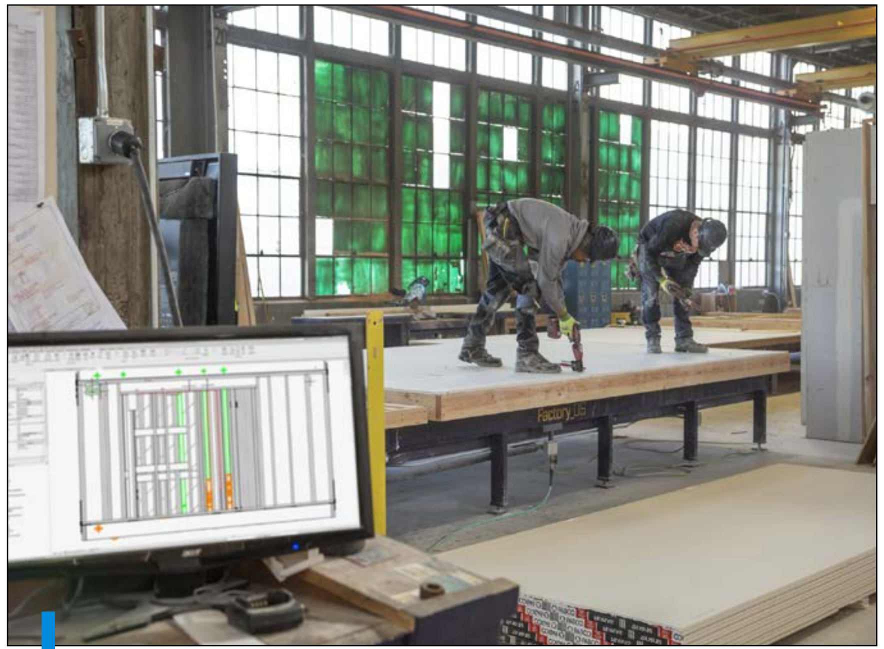


FIGURE 8 Modular construction by Factory_OS with streamlined workflow from design to manufacturing and assembly. Source: Factory_OS.

The proposed EMOD method:

1. **Applies to components and systems** associated with energy efficiency strategies
2. **Focuses on design objectives** that include 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 the following three stages of design-centric evaluation and investigation:

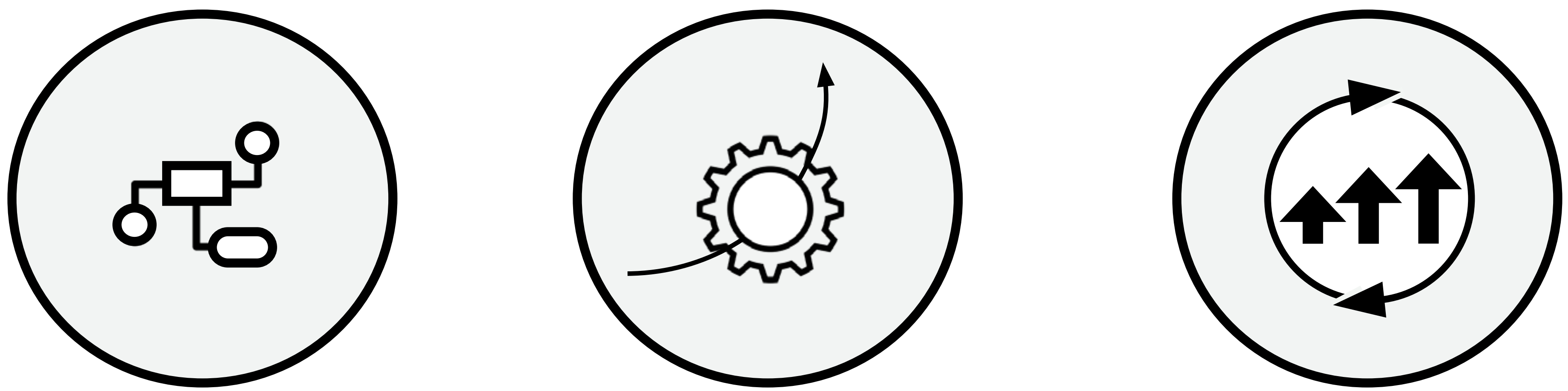
1. **Identify existing components and systems** associated with energy efficiency strategies
2. **Make decisions** based on pre-determined design objectives
3. **Perform design evaluation and pilot studies.**

1 https://link.springer.com/chapter/10.1007/978-94-011-3985-4_1
2 http://consig.org/wp-content/uploads/2018/10/RIBAPlanofWorkDfMAOverlaypdf.pdf

KEY TAKEAWAYS: APPROACHES, TOOLS, AND STRATEGIES

We are leveraging and applying three advanced manufacturing approaches, tools, and strategies to perform the EMOD method effectively (as shown in Figure 9).

The 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 10). Then, others can leverage these approaches to implement their versions.



1 — Streamline workflows through integrated product design to manufacturing

- Virtual design and construction tools, integrated building information modeling tools, generative design
- Automation in construction methods

2 — Building energy modeling and process productivity modeling - DfMA

- Time and motion studies to optimize process efficiency
- Digital twin of product processes and discrete event simulation (DES) modeling to evaluate proposed improvements

3 — Cost compression through prototyping and process improvement

- Test new assembly methods of energy efficiency strategies near or on the factory production line
- Continuous improvement, leverage Six Sigma strategies

FIGURE 9 Illustrates key approaches, tools, and strategies to effectively perform the EMOD method so that factories and others could leverage and implement their own versions. Source: NREL.

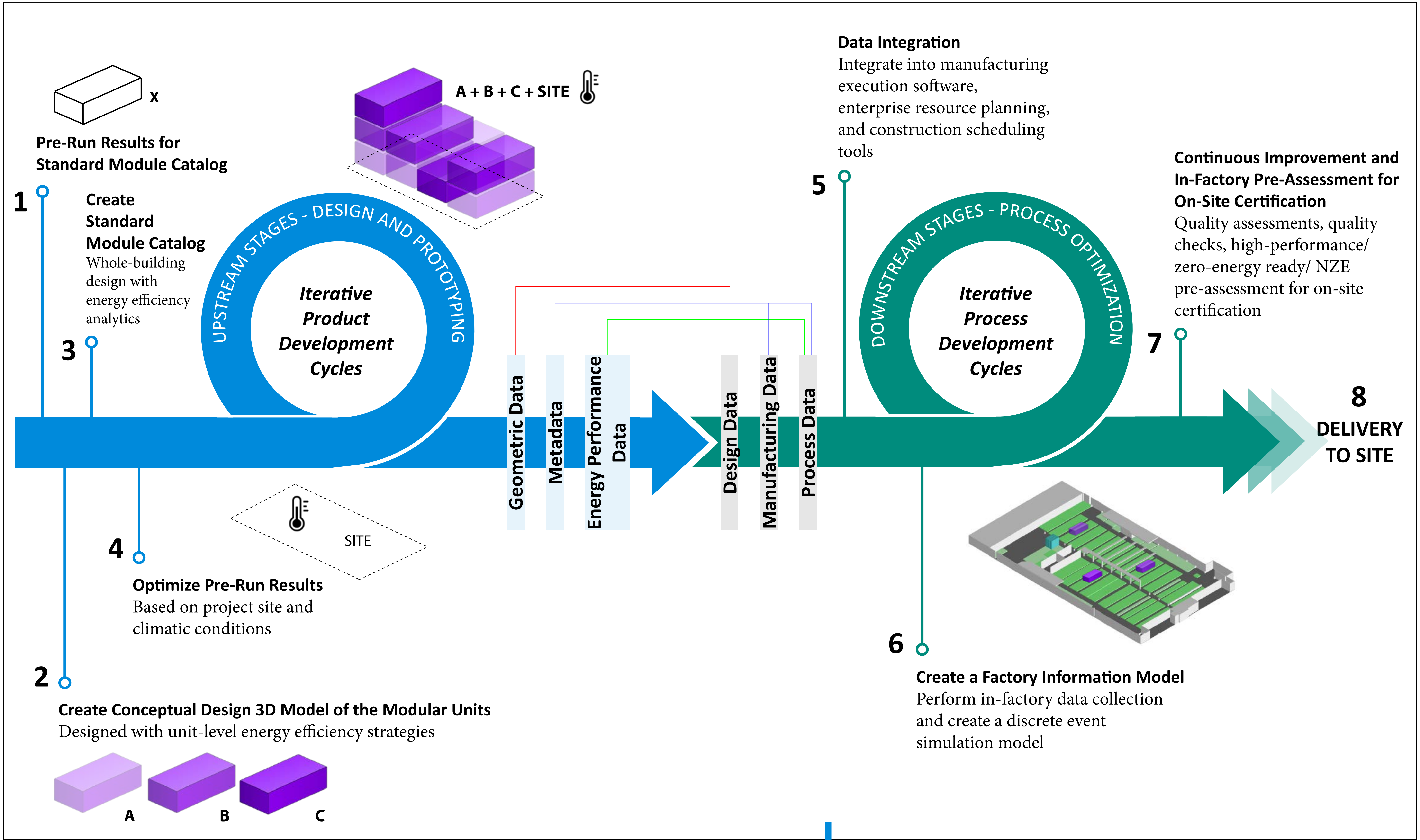


FIGURE 10 Illustrates the integrated design-production process centered around the EMOD method, involving iterative development cycles in both upstream and downstream stages. Source: NREL.

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.**

SELECTING ENERGY EFFICIENCY STRATEGIES

We developed a decision checklist that allows teams to evaluate energy efficiency strategies' components or systems based on pre-determined design objectives (as shown in 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 AEDGs.

> 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 towards identifying the realistic targets for these objectives.

While this was an internal checklist developed by the project team, we envision process engineers and factory managers utilizing this checklist in their factories (as shown in Figure 11). The checklist could help evaluate opportunities associated with staging, construction scheduling, assembly, and commissioning in order to achieve specific design objectives.

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?
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?

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

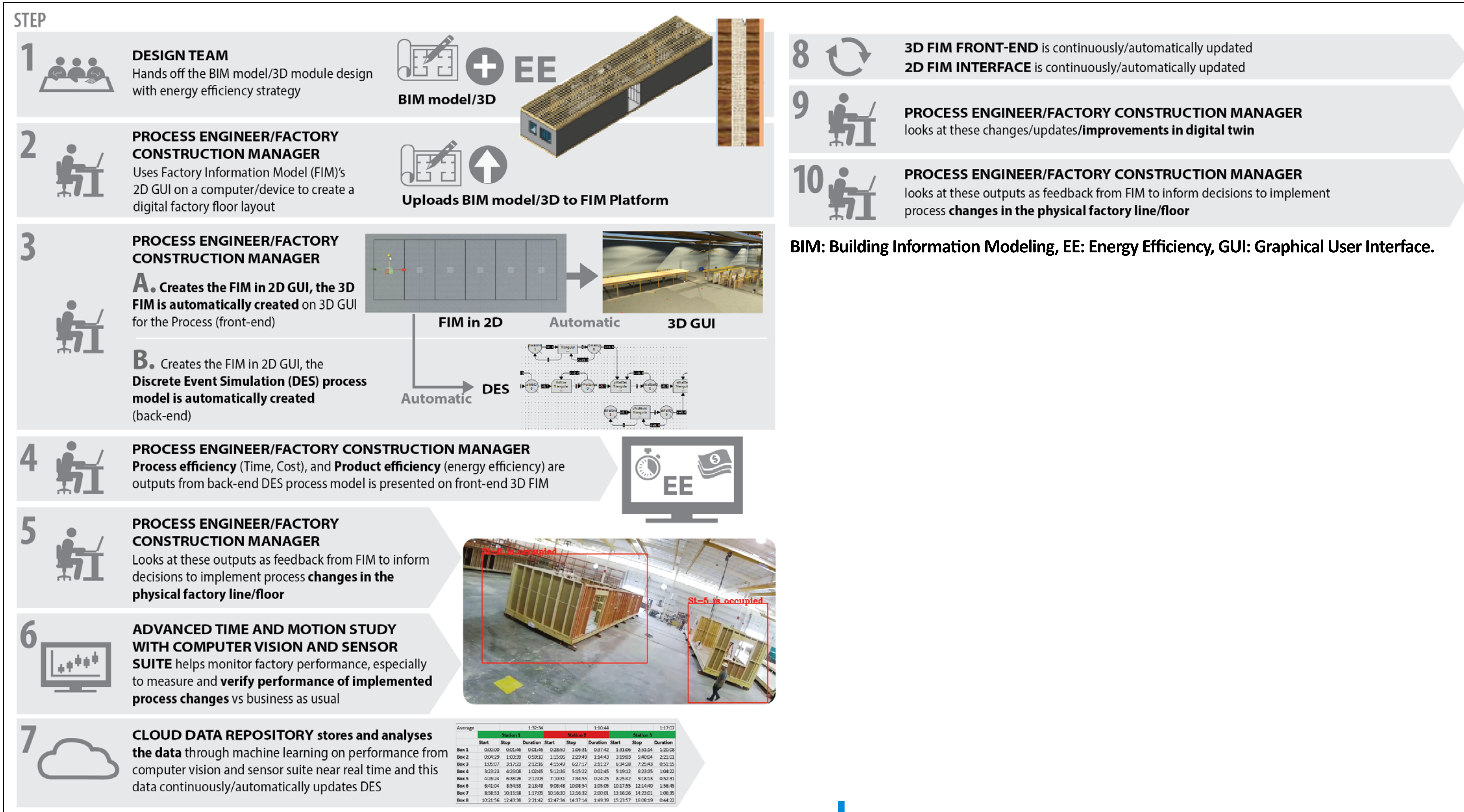


FIGURE 11 Illustrates the 10-step end-to-end workflow with a selected energy efficiency strategy to be integrated during industrialized construction, with the design team and the process engineer or factory construction manager involved. Source: NREL, in partnership with Oregon State University.

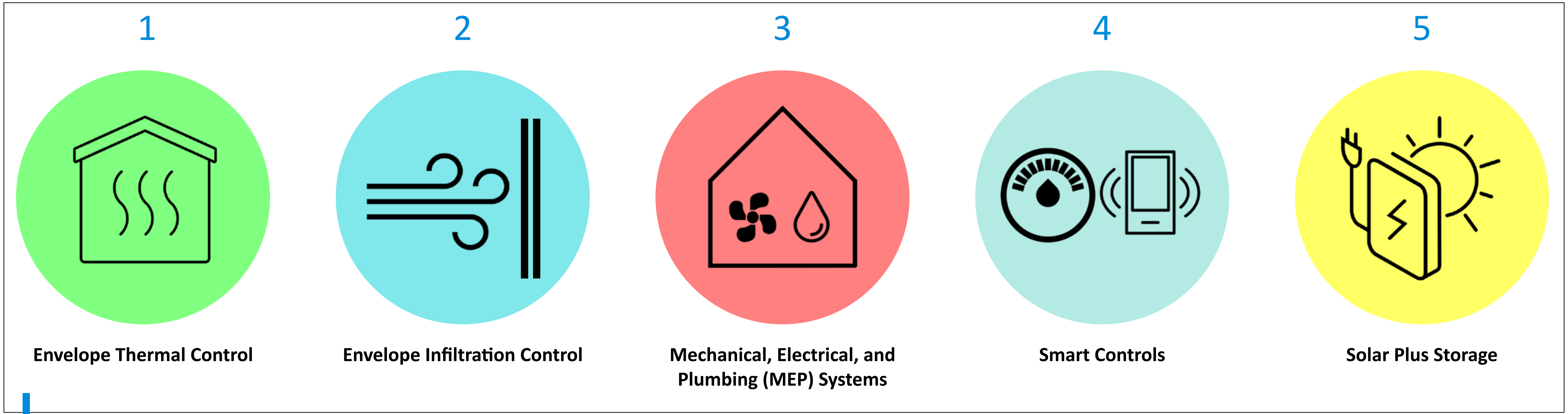


FIGURE 12 Down-selected set of energy efficiency strategies for integration during industrialized construction following the decision checklist. Source: NREL.

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 (as shown in Figure 12) are:

1. **Envelope Thermal Control:** The primary objective is improving thermal and moisture performance. The key strategies are eliminating thermal bridging and optimized insulation.
2. **Envelope Infiltration Control**: The primary objective is improving airtightness. 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 (MEP) Systems:** The primary objectives are space conditioning, fresh air ventilation, domestic hot water, other services from high-efficiency appliances, and power distribution. The key building components associated with this energy efficiency strategy are air-source mini-split heat pump (indoor and outdoor unit), heat recovery ventilator or energy recovery ventilator (with MERV 13 filters), combined conditioned air distribution system and fresh air distribution system (including ducts), heat pump water heater, water distribution system (including pipes and refrigerant lines), washers and dryers, kitchen and bathroom equipment for exhaust and heat or energy recovery, plug load management, and power distribution systems.

   An in-unit best-in-class high-efficiency air-source mini-split heat pump eliminates the need for rooftop site-installed equipment and on-site installation of refrigerant lines. Energy recovery ventilators are in-unit systems with no vertical ducts or chassis with fire blocking. There is no need for dampers or rooftop site work. Heat pump water heaters are single-pipe domestic cold plumbing system with reduced hot water distribution. There is no site-installed rooftop boiler with a domestic hot water circulation system.
4. **Smart Controls:** The primary objective is providing communication and controls. The key components are advanced controls for submetering, occupant engagement platform, grid-integrated HVAC and hot water controls, and utility price signaling. Advanced controls are smart apartment controls hardware that can be installed and programmed in the factory. Services can include access control, leak sensors, submetering for both electricity and water, property management feedback and thermostat control.
5. **Solar Plus Storage:** The primary objective is providing solar plus storage services. The key components are rooftop solar PV, small distributed battery energy storage system, along with the electrical distribution. The scope also includes discussion on fair billing for multifamily tenants and benefits of submetering for each unit.

To build and deliver NZE modular housing units at scale, we need to address the challenges with performing energy efficiency work off-site. Our research efforts demonstrate **how the completion of all work related to energy efficiency strategies in factories can significantly reduce the cost, time, and labor effort** associated with delivering NZE modular housing units.

DESIGN OF IDEAL NZE, LOW-CARBON MODULAR HOUSING

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.[3]

The scope of work included research and prototyping informed by design objectives such as maximizing work related to integrating energy efficiency strategies (staging, construction scheduling, assembly, and commissioning) in factories, **eliminating rework, increasing efficiencies, enhancing overall energy efficiency, and reducing GHG emissions.**

Overall, these design objectives could inform the decisions made in the early design stage of NZE, low-carbon modular housing. 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 as shown in Figure 13) to achieve NZE goals.

The EMOD method workflow, as illustrated in Figure 8, forms the core of approaches and tools that we followed during the project to arrive at a design for an ideal NZE, low-carbon modular housing solution (see Figures 14 and 15).

FIGURE 13 NZE modular housing unit, with rooftop solar PV, fully completed in the factory. Source: Solar Home Factory.

NEED FOR A NATIONAL-SCALE SHARED RESEARCH PLATFORM USING THE EMOD METHOD

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 has 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[4] 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.

3 www.eere.energy.gov/buildings/publications/pdfs/rsf/netzero_energy_buildings_and_homes.pdf
4 www.nrel.gov/docs/fy21osti/77114.pdf

FIGURE 14 Whole-building design, comprising the ideal NZE, low-carbon modular housing unit.
Source: NREL.

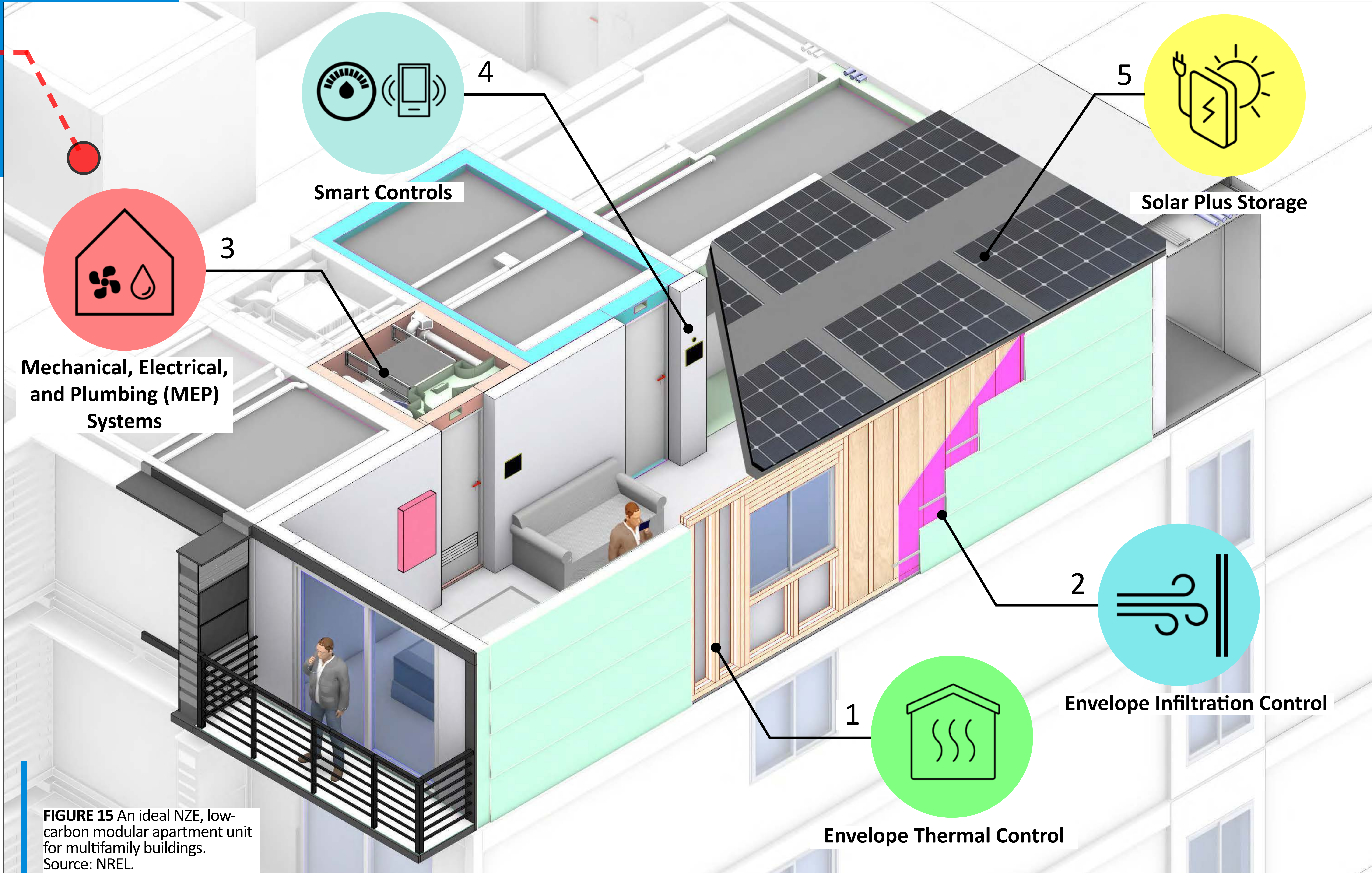


FIGURE 15 An ideal NZE, low-carbon modular apartment unit for multifamily buildings. Source: NREL.

BUILDING ENERGY MODELING

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.[5] 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 (as shown in Figure 16). 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.

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.

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.

MOISTURE MANAGEMENT MODELING

Innovative envelope assemblies for thermal energy management often require moisture management studies. As highlighted in the AEDG 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.[6] A hygrothermic analysis is recommended to confirm proper placement of the air, vapor, and thermal control layers. In many cases, vapor retarders are coincident or coplanar with the other controlling layers of the envelope.[7] It is important to understand the vapor-permeability properties of each material used so as not to accidentally introduce a vapor barrier where it would trap moisture or prevent assembly drying.

Equally important is identifying thermal-bridging details and performing thermal-bridging calculations to mitigate risk of condensation. As per the design caution highlighted in the AEDG for large hospitals (50%), the design of building envelopes for durability, indoor environmental quality, and energy conservation should not create conditions of accelerated deterioration or reduced thermal performance or problems associated with moisture, air infiltration, or termites.[8] In the same report, EN16 Moisture Control (all climate zones) highlights that building envelope assemblies should be designed to prevent wetting, high moisture content, liquid water intrusion, and condensation caused by diffusion of water vapor. For more information, see Chapter 25 of the ASHRAE Handbook—Fundamentals 2017.[9]

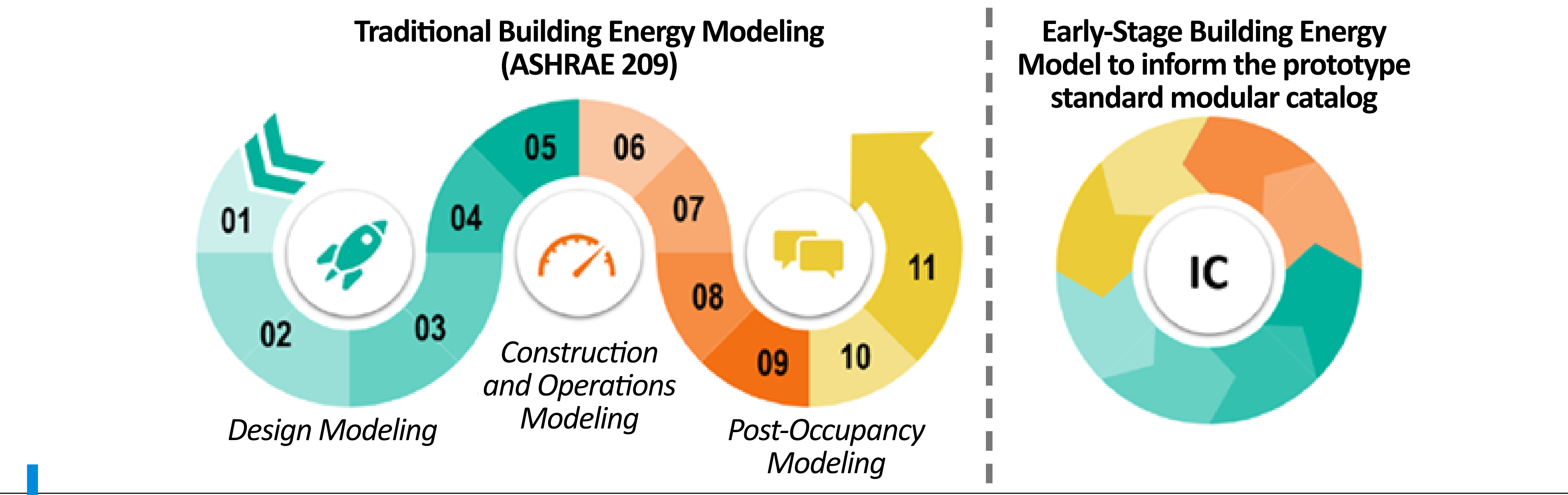


FIGURE 16 Illustrates traditional building energy modeling workflow and stages (left) and early-stage building energy model to inform the design of a prototype standard modular catalog (right). Note that while both are similar, there an opportunity in industrialized construction to create a "unit-level energy model" and then multiply it to the whole-building level energy model. Source: NREL.

5 https://www.ashrae.org/about/news/2018/ashrae-publishes-energy-simulation-aided-design-standard
6 https://wufi.de/literatur/Karagiozis,%20Künzel%20et%20al%202001%20-%20WUFI-ORNL%20IBPA%20North%20American%20Hygrothermal%20Model.pdf
7 https://www.ashrae.org/about/news/2018/new-advanced-energy-design-guide-available-to-help-k-12-schools-achieve-zero-energy
8 https://www.ashrae.org/technical-resources/aedgs/50-percent-aedg-free-download
9 https://www.worldcat.org/title/2017-ashrae-handbook-fundamentals/oclc/989056692

PROCESS SIMULATION MODELING

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 (as shown in Figure 17). 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. Because of the high integration between the simulated factory layout, the resources, and the process, the result of any of those changes will be in the factory performance metric as part of an integrated enterprise resource planning tool or manufacturing execution software.

NREL, Louisiana State University and VEIC 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.[10]

PRODUCTIVITY MODELING FROM DESIGN THROUGH MANUFACTURING

Working towards advanced time and motion studies to optimize process efficiency, we have carried out machine learning-based data analytics on collected real-world data to develop productivity modeling from DfMA, and to create digital twins of processes that evaluate proposed improvements.

Purpose-built manufacturing execution software for industrialized construction is needed to create process simulation models of production line and on-site activities, representing all resources and workforces in varying fidelities for both retrofits and new construction.

Today, myriad commercially available software options exist to support the creation of building information models and factory information models. A factory information model is a fly-through virtual representation of the factory, enabling direct interaction with a wide range of assessments.

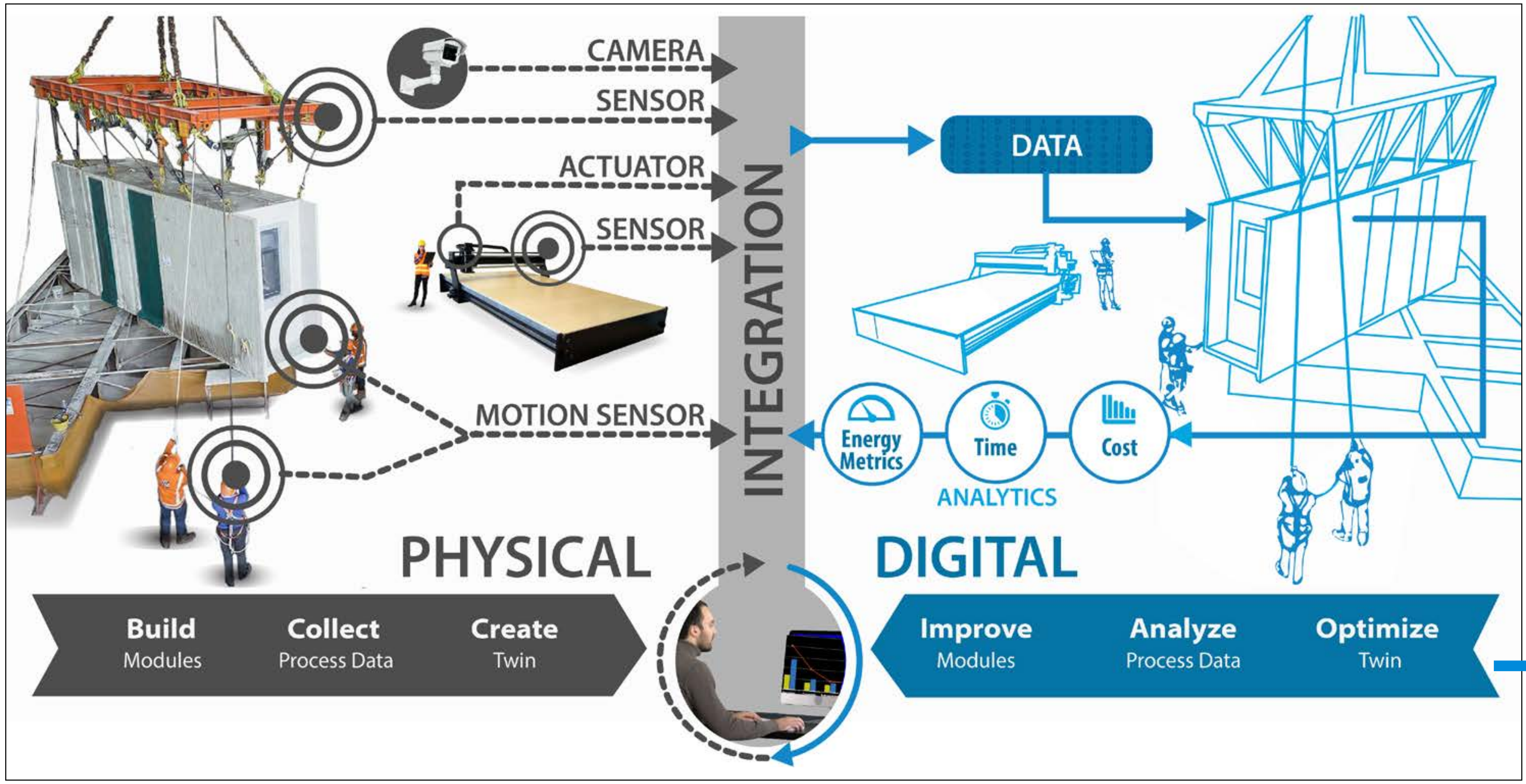


FIGURE 17 Illustrates conceptual representation of construction process modeling, with data integration between physical and digital worlds. Source: NREL.

10 https://www.huduser.gov/portal/periodicals/cityscpe/vol24num1/article15.html

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.**[11]

COST COMPRESSION THROUGH PROTOTYPING AND PROCESS IMPROVEMENT

In the traditional site-built construction industry, the learning rate has been historically considered lower than what other industries employing more matured advanced manufacturing approaches (such as aircraft and solar modules production) have already achieved. While 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.

As shown in Figure 18:

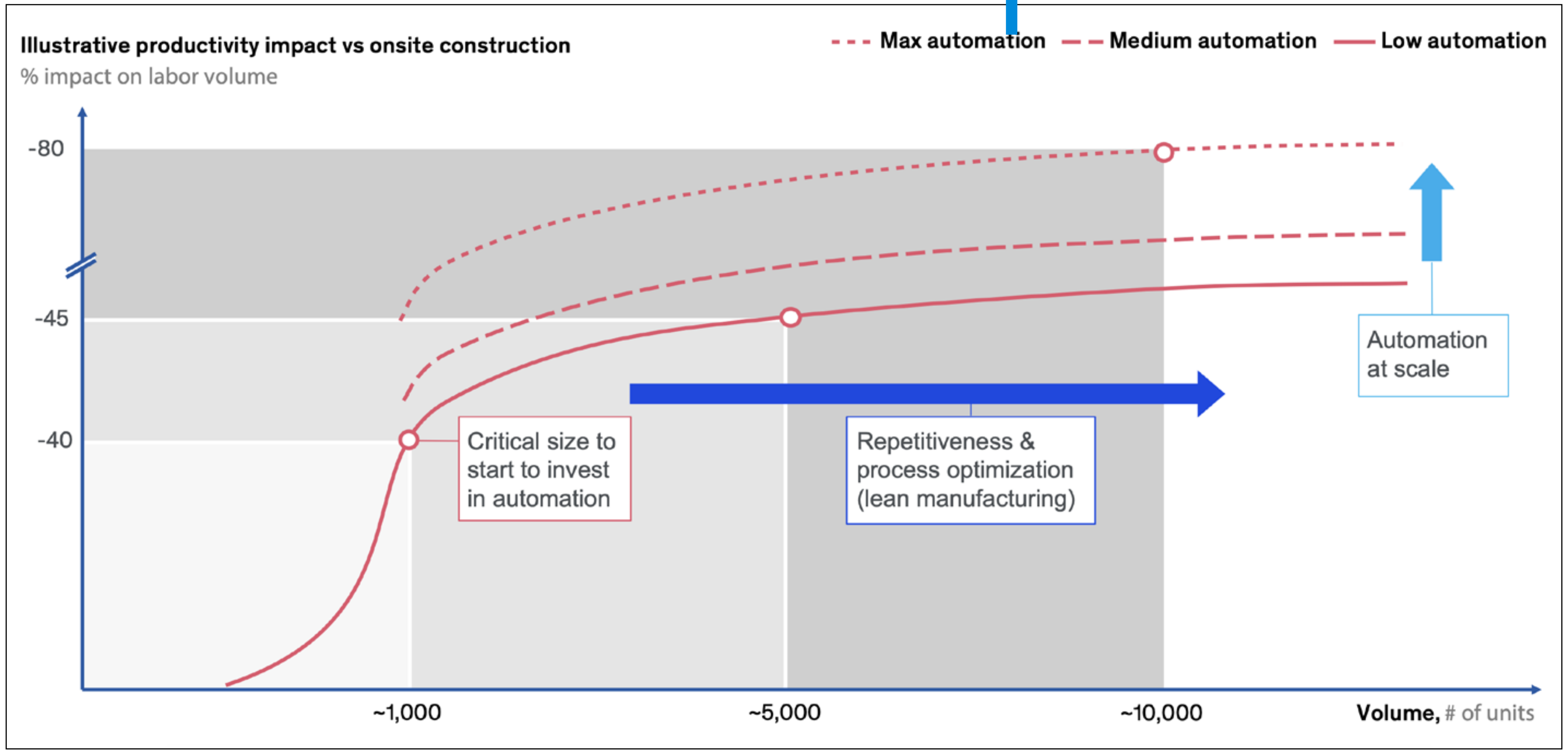
1. Even with low learning rates, there are cost-reduction opportunities with industrialized construction (compared to site-built)

2. After an exponential increase with the first 5,000 units built, the productivity gains drop beyond 10,000 units, indicating that construction cost reduction for each dwelling unit from learning and experience would also approach the limit simultaneously.

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.

Our proposed EMOD method strongly positions modular teams to benefit from learning rates and lower per-unit cost.

FIGURE 18 Productivity impact from industrialized construction economies of scale as the production volume increases from 1 dwelling unit to 1,000 dwelling units to 10,000 dwelling units. Source: Expert Interviews by McKinsey Global Institute.



11 www.mckinsey.com/business-functions/operations/our-insights/reinventing-construction-through-a-productivity-revolution

SCALING DECARBONIZATION

As a companion to this guide, the 2021 NREL technical report Decarbonization During Predevelopment of Modular Building Solutions details cost compression opportunities for NZE buildings using industrialized construction.[12] **The primary stakeholders, productized modular builders, can leverage this framework as a development road map for strategic planning to invest and allocate necessary resources in their facilities that (1) encourage labor learning and increased productivity, and (2) continuously increase the annual production of dwelling units to reach a goal of 10,000 dwelling units annually by 2030.** Modular builders; project developers; architecture, engineering, and construction firms; building energy modeling professionals; utility companies; system operators; energy suppliers; financial investors; organizations involved in modular construction planning and managing; and others involved in modular-construction development should find this framework to be a valuable resource in establishing corporate carbon-reduction goals and laying out stepping stones to reach those goals.

The report introduces **three development phases that modular builders can follow to achieve financially viable high-performance projects**: **Pre-Build Product Development Phase** (years 1-5), **Industrialized Construction Phase** (years 6–10), and **Advanced Manufacturing Phase** (years 11–15 and beyond).

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 as shown in Figure 19, **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.

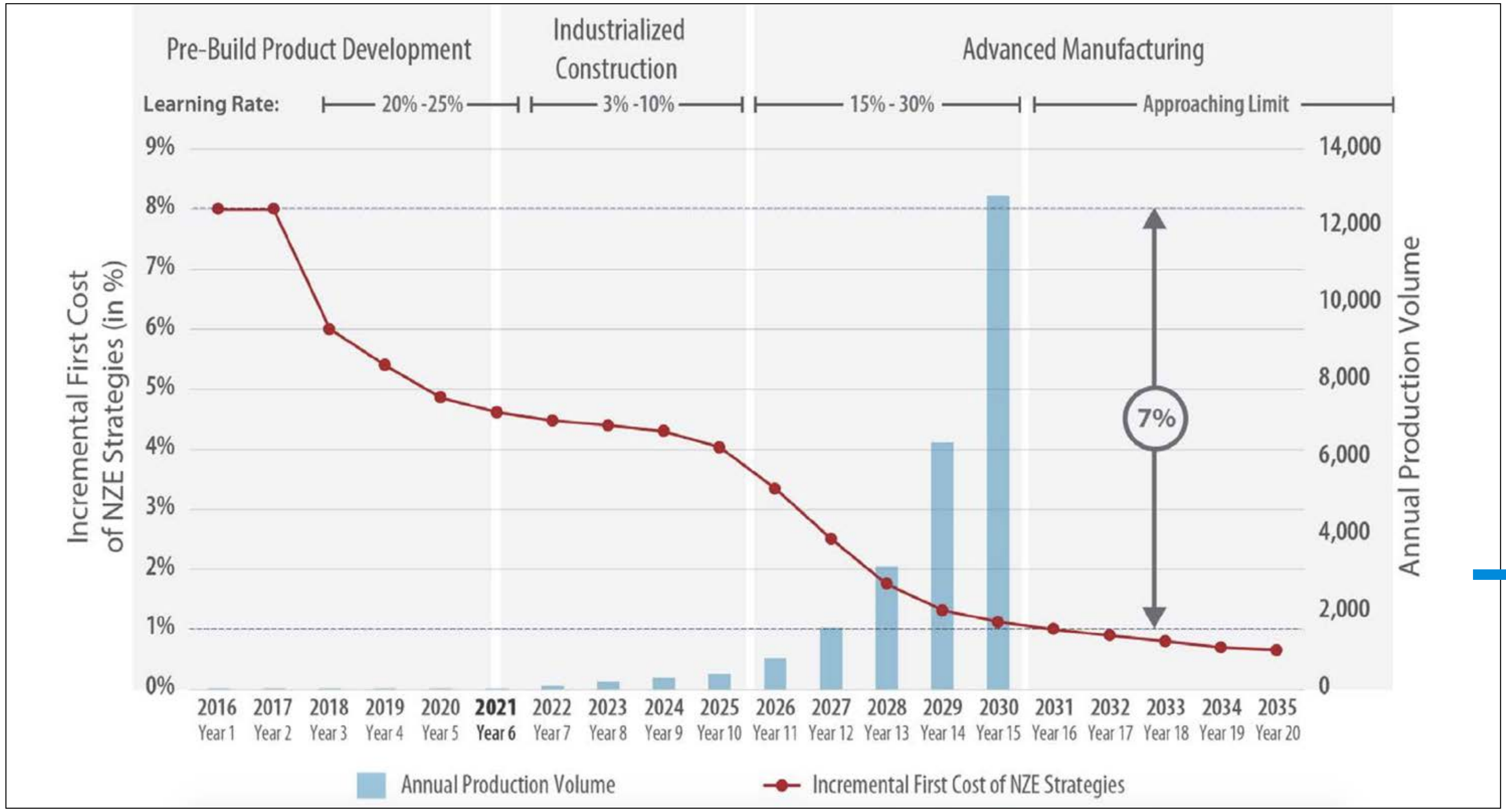


FIGURE 19 Illustrates projected cost curve for NZE strategies across the development road map. Case study analysis and intervention begins in 2021, 5 years after initial product development. Source: NREL and Blokable Inc.

12 https://www.osti.gov/biblio/1837021

CHAPTER 3

ENVELOPE THERMAL CONTROL

Blokable Inc.'s modular apartment unit at the NREL campus in Golden, CO.

Photo from NREL

KEY TAKEAWAYS

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.

KEY BENEFITS

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).

Removing the need for continuous insulation on-site r**educes 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.

CASE STUDY: INSULATED TRUSS STUDS

Using insulated truss studs (ITSs) such as Tstuds[1] in place of standard wood studs, along with advanced framing techniques, could cost-justify overhauling the typical 2x6 business-as-usual wall framing in the factory. Integration of ITSs addresses major construction woes with building envelopes that continue to concern modular builders, such as thermal breaks, structural strength, wind loads, sound transmission, and fire safety (as shown in Figure 20).

The primary energy efficiency advantage of ITSs is that they are cost-effective and reduce thermal bypasses or bridges. Current site-built best-practice is the high-R-value exterior wall system: 2x6 wood framing with R-21 batt insulation with 1" or 2" continuous exterior insulation board.

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. A new alternative product is ITSs with R-19 insulated structural 2x6 wall framing is under consideration. For the purposes of this research, we referred to ITSs as the component along with the foam-in-place insulation.

FIGURE 20 Variations of BareNaked Tstud, pre-assembled and designed to be used as a direct replacement of solid sawn lumber as wall studs, top plates, and bottom plates. Source: Tstud.

1 www.Tstud.com

PROCESS MODELING RESULTS

The preliminary results from comparative analysis of discrete stations show a range of potential process optimization (for cost, time, and material savings) as well as energy efficiency benefits from integrating the novel product. In this way, discrete event simulation can help:

1. Compare all four options with specific focus on processes taking place off-site and on-site
2. Compare scenarios related to multiple iterative pathways during off-site integration of the most cost-effective option. Discrete event simulation modeling can help demonstrate the cost-effectiveness of all four options.

Creating a process-based digital twin for the wall-framing station in a modular construction factory can enable builders to identify bottlenecks in the process before they arise in the factory, and thus optimize the factory layout and resource allocation. The discrete event simulation model includes each unique step necessary to frame with ITSs, such as increased use of more nail guns for a longer 4" nail. It also analyzes alternative methods enabling 24" o.c. framing, as well as the use of thermally broken C.i. attachments (e.g., GreenGirt) and pin fasteners.

It is important to note that **an ITS is stronger than a traditional 2x6 stud and thus enables advanced framing, especially for volumetric modular units that are stacked and require greater load-bearing capacity than a typical advanced-framing single-family project.** However, design loads should be checked by a qualified professional and should not exceed the allowable capacities set forth by the construction manual for commercially available ITSs. A baseline 3D model (as shown in Figure 21) was created based on typical wood-framed modular unit design from project partner VBC.[2]

2 www.vbc.co/

The primary research question is: **"How can optimal integration of ITSs (such as Tstuds) and advanced wall-framing techniques be achieved with modular construction for envelope thermal control with little or no additional cost, labor, or lead time?"** To address this question, we performed a set of comparison analyses for different framing strategies. To effectively compare the proposed strategies to the baseline, we created **a discrete event simulation model, using existing construction process simulation modeling tools.**

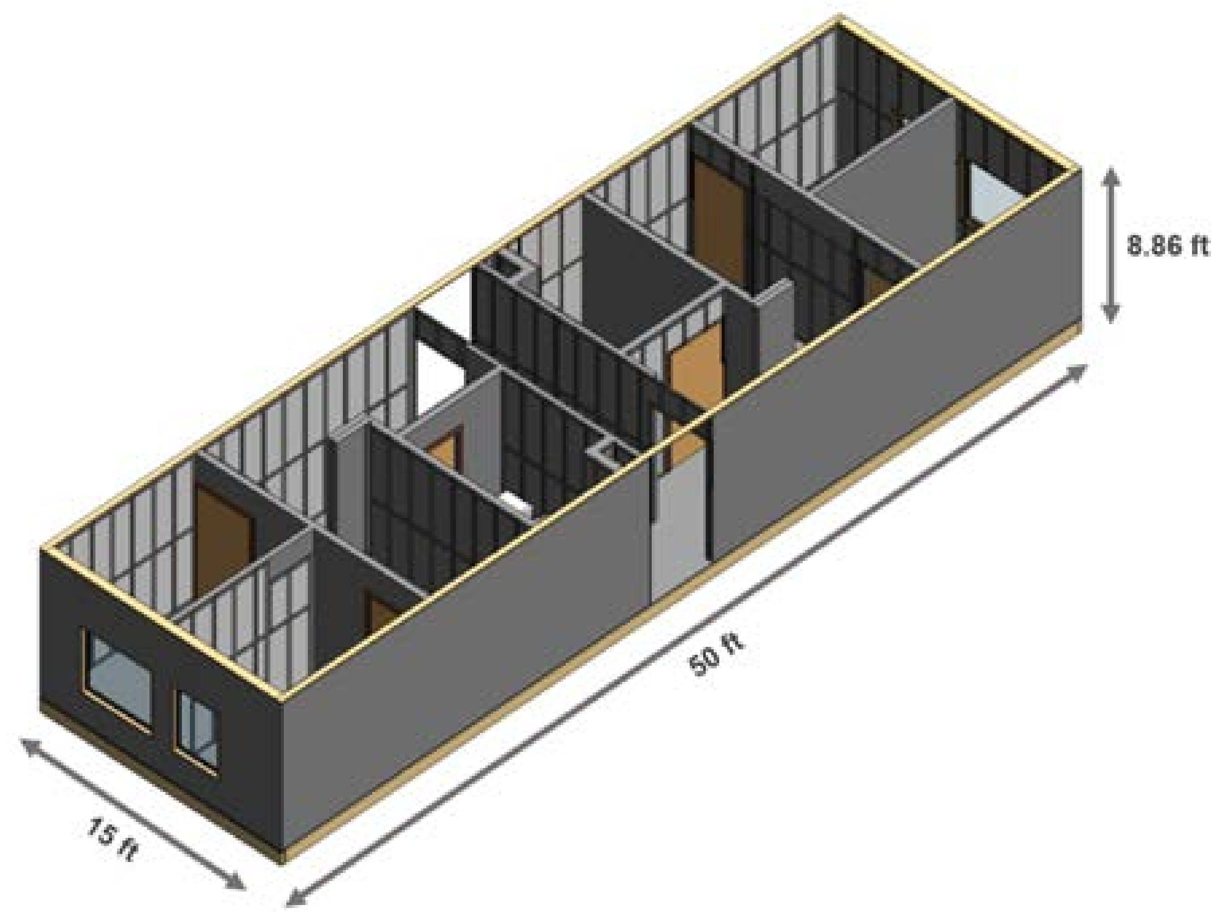


FIGURE 21 Baseline 3D model of modular unit showing wall framed with traditional 2x6 studs at 16" o.c., framed in the factory. After the modular unit gets shipped to site and stacked along with others, C.i. is installed. Source: Oregon State University.

Options	(A) Baseline Framing	(B) ITS Framing	(C) Advanced Framing	(D) ITS + Optional C.i.
Envelope Assembly Description*	Traditional framing with 2x6 studs at 16” o.c. in factory, with C.i. installed on site using GreenGirt and exterior sheathing	ITS framing at 24” o.c. in factory, with no requirement for C.i. and exterior sheathing installed on-site	Traditional framing with 2x6 studs at 24” o.c. in factory, with C.i. installed on-site using traditional fasteners and exterior sheathing	ITS framing at 24” o.c. in factory, with the option of C.i. installed on-site using traditional fasteners
Effective R-Value*	22.05	22.91	23.9	24
Time	0.119 labor hr/ sq.ft.	0.059 labor hr/ sq.ft.	0.116 labor hr/ sq.ft.	0.156 labor hr/ sq.ft.
Cost	$13.31/sq.ft.	$4.92/sq.ft.	$7.95/sq.ft.	$10.63/sq.ft.

ITSs: insulated truss studs, C.i.: continuous insulation, o.c.: on center
* Potential future study: (1) Could use nominal insulation R-factory with assembly U-factory as per common reference and code suggestions. (2) Could consider including cost and time associated with installing vapor retarders for moisture management.

TABLE 2 Results from comparative analysis using discrete event simulation model followed by detailed calculation and assumptions. Note that Advanced Framing (C) is a favorable option considering trade-offs between upfront costs, labor costs, and enhancing energy efficiency. As part of the modeling exercise, we validated and calibrated the model through various data inputs from factory processes, advanced time and motion study, and a pilot demonstration.

Key takeaways from the results summary in Table 2:

1. ITSs Framing (B) in factory without need for C.i. takes ~ 50% less labor hours per sq. ft. and ~ 63% less cost per sq. ft. than Baseline Framing (A) in factory with C.i. installed on-site.
2. In certain climate zones where the optional C.i. might be used to achieve required effective R-value on top of ITSs walls, the cost per sq. ft. of such ITSs + Optional C.i. (D) is **still lower than the cost per sq. ft.** of Baseline Framing (B).
3. While labor hours per sq. ft. for Advanced Framing (C) is almost same as that of Baseline Framing (A), framing with ITSs at 24” o.c. is **faster and still much cheaper** than advanced framing with traditional 2x6 studs. However, **considering trade-offs of upfront cost, labor cost, and most energy-efficient benefits, (C) Advanced Framing is a highly recommended option.**

CHAPTER 4

ENVELOPE INFILTRATION CONTROL

The Factory_OS Factory Floor Learning Center is dedicated to education and research on industrialized construction.

Photo from Factory_OS

KEY TAKEAWAYS

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 non-destructive testing)** to achieve a factory-installed airtight envelope. The key steps are:
   i. Plan for a QA/QC envelope design review
   ii. 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
   iii. 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:**
   i. Identify the optimal station or bay after drywall install station before the tasks associated with interior finishing installs
   ii. Develop reusable seals and simple prep methods for quick covering of openings.

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. We propose **in-factory airtightness improvement** for envelope infiltration control.

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 unit airtightness testing in the factory for quality control of air barrier measures and QA/QC using standardized and repeatable air barrier installation, training, and verification (as shown in Figure 22). As part of this project, along with partners Momentum Innovation Group and AeroBarrier Inc., 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 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 multi-family projects.

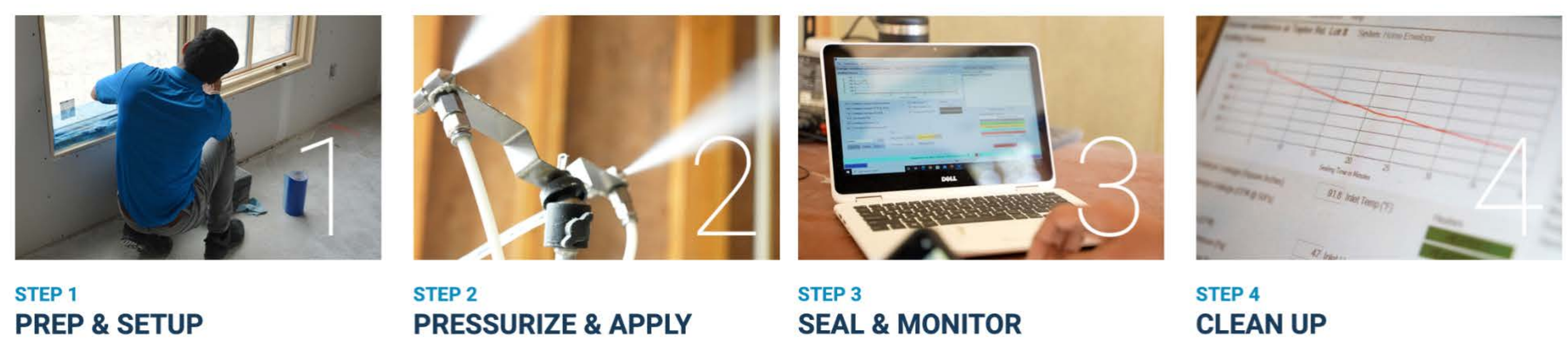


FIGURE 22 The five-step process of AeroBarrier[1] using ionized sealants. Source: AeroBarrier.

1 https://aeroseal.com/aerobarrier/how-aerobarrier-works/

CASE STUDY: VOLUMETRIC BUILDING COMPANIES

As part of this project, we leveraged AeroBarrier's ionized sealing process as an airtightness improvement strategy to perform pilots that show how off-site sealing reduces labor cost due to reduced cycle time. As part of the project, we performed a series of pilots with Momentum Innovation Group and AeroBarrier at 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.
    - i. Ionized sealing for 100+ site-built apartments shows average unsealed tightness of 6-8 ACH50
    - ii. 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:**
    - i. Opportunities: We demonstrated we can quickly seal compartmentalized apartments so they are airtight to the 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.
    - ii. 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 in the line just after drywall is installed to eliminate cleanup and finished surface prep (as shown in Figure 23).

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.**

FIGURE 23 (1) Blower door test equipment; (2) Module wrapped before leaving the factory; (3) Prep stage before ionized sealing showing covered openings at VBC's Hamlet, NC factory (Pilot 1).

KEY TAKEAWAYS FROM PILOT 1 (JULY 2019)

Key takeaways from VBC Pilot 1 (based on test data in Table 3) are:

1. It took about 2-2.5 hours per unit to do the entire process: pretest blower door (10 min), prep unit (60 min), air seal (15 min), and breakdown and cleanup (45 min)
2. All three units tested (3020 A, 3020 C, 3020 D) were nearly identical, except 3020 D had a rubber membrane roof (top box of building).

To summarize, the results of Pilot 1 (July 2019) were:

1. We identified the ideal location on the factory production line for air sealing: **after station with all drywall complete**
2. We identified a clear case for single modular studio apartment sealing: **minimal setup time**
3. There is a need to prove out the case for multimodule apartments, as openings across modules will need to be prepped.

This suggests **the need to develop a well-trained, repeatable, and reusable system for various-sized openings to streamline prep time for sealing openings.**

S.No.	Unit No.	Starting ACH	Ending ACH	Reduction in Envelope Leakage
1	Model 3020A	5.72	1.55	**72.9%**
2	Model 3020C	3.14	1.68	**46.5%**
3	Model 3020D	3.33	0.99	**70.4%**

TABLE 3 Data from VBC Pilot 1 showing reduction in envelope leakage.

KEY TAKEAWAYS FROM PILOT 2 (MAY 2021)

Our second pilot involved AeroBarrier and Momentum Innovation Group returning for a second round of in-factory air sealing to evaluate an air sealing station on the production line (see Figures 24, 25, and 26). **The goal was to evaluate the in-factory ionized sealant process (targeted 1-2 ACH50) for enhanced building performance (energy, sound, and air quality) and code compliance (when necessary).** During this test, the following observations were made:

1. Modules were approximately two times leakier during Pilot 2 than during Pilot 1. These modules were a different design with corridor and light gauge steel prefab bathroom pods vs. no corridor or light gauge steel in Pilot 1.
2. Bathroom pods were framed using light gauge steel, which appeared to allow "bay to bay leakage" via grommets in the light gauge steel studs.
3. Hollow metal frame entrance doors were leaky. Doors were installed but are not caulked until the field due to required field adjustments.
4. Double wall corridor walls were leaky (could feel air blowing out at all wood/wood joints). Assembly was 2x4 wood outboard and 2x4 light gauge steel bathroom wall inboard.
5. Corridor wall plumbing chase seemed to leak at the shower pan and wall areas.
6. HVAC cabinets did not have a closet door (air handler installed) so we sealed the opening with cardboard and tape, but it was still very leaky. We also taped off the exterior grilles.
7. The operable windows were leaking around the gasket seals; the window closing mechanisms seemed loose and did not create an airtight seal.
8. We caulked corridor leaks and exterior door frame leaks to speed up the sealing time.

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 (as shown in Table 4), 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.

Test #	Starting ACH	Ending ACH	% Reduction	Sealing time
Test 1	9.0	1.8	78%	56 min
Test 2	5.9	1.0	87%	41 min
Test 3	10.7	3.1	65%	40 min
Test 4	6.9	1.8	77%	30 min
Test 5	5.7	1.7	70%	48 min
Test 6	7.4	2.4	66%	23 min
Test 7	6.4	1.1	88%	45 min
Average	7.4	1.8	76%	40 min

TABLE 4 Data from Pilot 2.

FIGURE 24 Prep stage prior to ionized sealing, showing sealing supply register. Source: Photo documentation of VBC Pilot 2.

FIGURE 25 Prep stage prior to ionized sealing, showing covering and taping utility room. Source: Photo documentation of VBC Pilot 2.

FIGURE 26 Photo documentation of Pilot 2. Source: VBC.

Pilot 2 had the following learning outcomes:

1. Prior to air sealing, work with a modular construction design team to recommend air sealing details for a more consistent baseline test of 5 ACH or lower, prior to sealing.
2. Major leakage areas must be sealed prior to treatment otherwise time to seal is lengthy.
3. The AeroBarrier installation (process, resources, and duration of install) could be incorporated into an existing build station with minimal disruption.
4. Most of the major leakage areas during this testing can be remedied when units are envelope tested at the start of a project's production. The following observations were made:
    - Include employees in demonstration so they understand why air sealing is important (VBC employees were inquisitive about what we were doing)
    - Visually showing the air sealing process (AeroBarrier) is good but best to add smoke to highlight leakage pathways that are not easily seen.

NEXT STEPS AND FUTURE WORK

As part of future work, we hope to:

1. Perform envelope leakage testing after transport, but prior to on-site assembly
2. Test immediately after on-site "set" (assembly and site work)
3. Test finished unit prior to move-in.

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 (as shown in Figure 27).

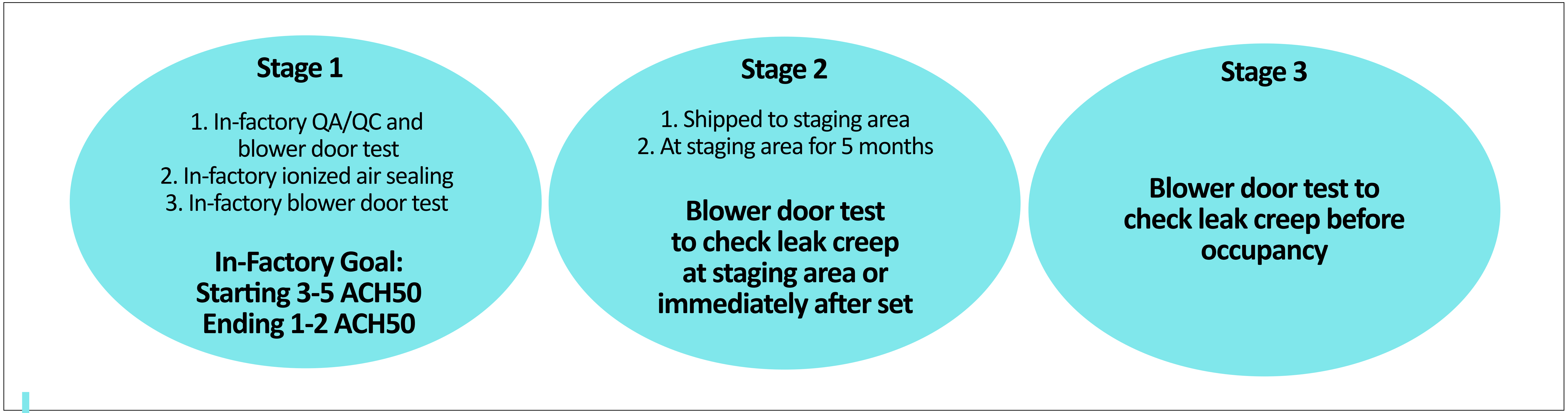
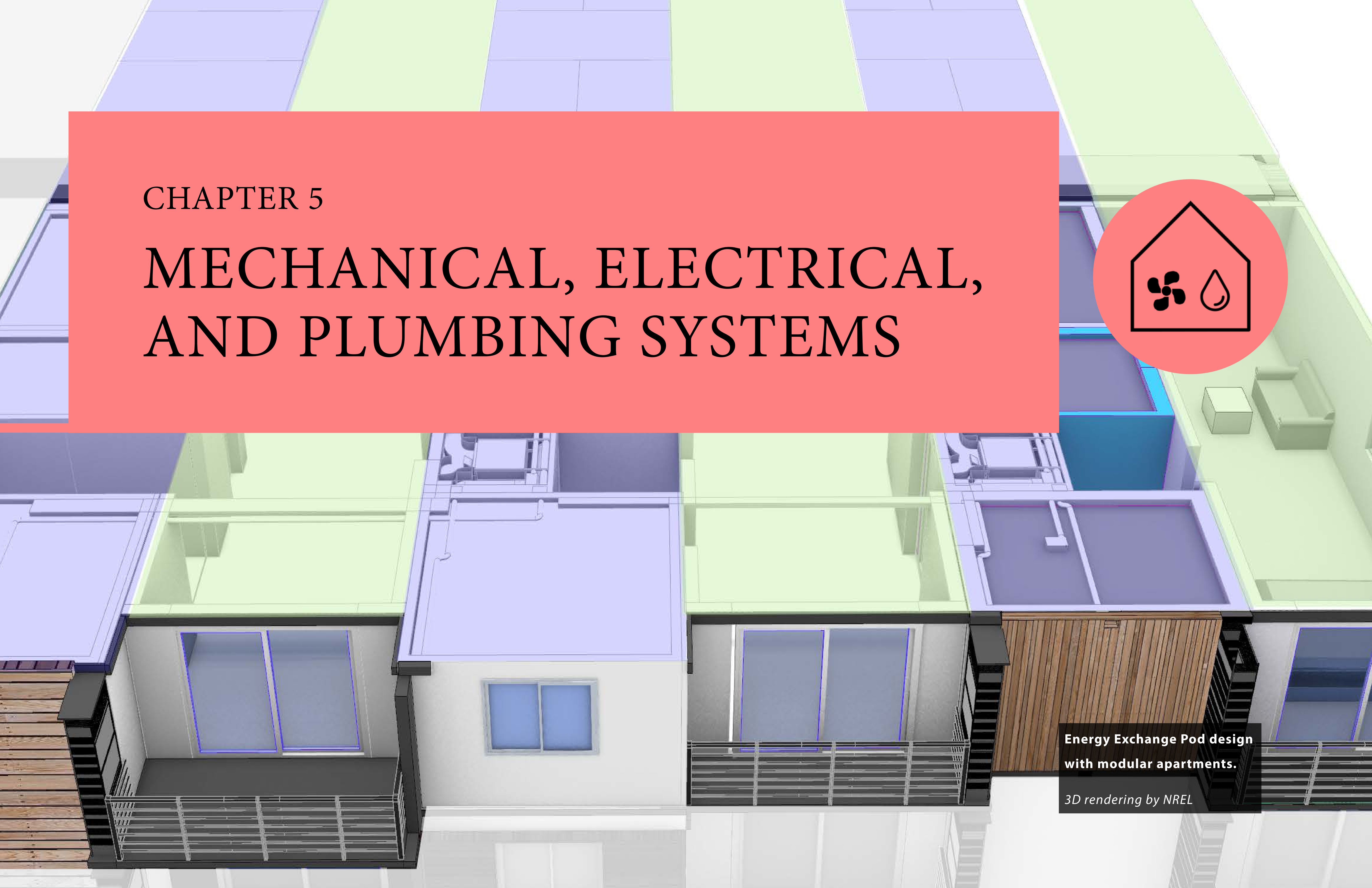


FIGURE 27 Illustration of end-to-end workflow to identify "leak creep" through pre-planned blower door tests.

CHAPTER 5

MECHANICAL, ELECTRICAL, AND PLUMBING SYSTEMS



Energy Exchange Pod design with modular apartments.

3D rendering by NREL

KEY TAKEAWAYS

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 MEP systems is a unitized Energy Exchange Pod. 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:**
   i. Site-installed with outdoor unit on roof
   ii. In-unit equipment in ceiling and closets
   iii. Partially decentralized shared systems.

We propose an EMOD optimization of mechanical, electrical, and plumbing (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.**

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.[1] 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 multi-functional, and chunked into different form factors and scales such as bathroom pods, energy exchange pods, and kitchen pods. According to Modular Building Institute's report on bathroom pods, using pods lowers construction costs by reducing construction time, improving quality, and eliminating the defects list.[2]

As seen in the Battersea Power Station site redevelopment project in the United Kingdom, where 540 "utility cupboards" were manufactured in a small-scale temporary factory, a pod could also take the form of a complete packaged solution that is fully fitted, pretested, and ready to install on-site, complete with all equipment and all associated piping, manifolds, and electrical installed to specification (as shown in Figure 28).[3]

Manufacturing and delivering utility cupboards at scale in the United Kingdom was a first-of-its-kind attempt and has not been demonstrated in the United States at the same scale to the best of our knowledge. Documentation on these utility cupboards shows that there were no explicit predetermined NZE targets for the project, and that the cupboards were not fully built in the factories, as there were pending connections for centralized systems that had to be made on-site.[4]

FIGURE 28 The Battersea project involved producing 540 utility cupboards for apartments in a major real estate development in the United Kingdom. Source: RIBA 2013.

1 https://vtechworks.lib.vt.edu/handle/10919/32397
2 https://www.nibs.org/files/pdfs/MI_OSCC_BathroomPods_2017.pdf
3 https://openresearch.lsbu.ac.uk/item/889zw
4 https://www.diva-portal.org/smash/record.jsf?pid=diva2:1025851

We collaborated with multiple industry partners to **design, develop, and prototype a novel fully functional, full scale Energy Exchange Pod**, transitioning away from a centralized system (as shown in Figure 29). The pod consists of **a set of all-electric heat pump mechanical equipment with integrated functionalities through built-in controls, with heating, cooling, hot water, ventilation (including energy recovery), electrical management, and battery storage within a single package** (see Figure 30).

CASE STUDY: FACTORY_OS

We leveraged installation manuals and expert guidance from original equipment manufacturers for three-dimensional (3D) geometric data, constraints, and code compliance of modules and components. Optimizing the Energy Exchange Pod design in 3D using computer-aided design (CAD) tools allowed us to identify new interfaces and develop new modules that could boost productivity and enhance energy efficiency.

The design objectives from DfMA of energy efficiency methodology informed the design. As a reminder, the design objectives are (1) maximizing work in factories (e.g., activities related to storage, construction scheduling, assembly, and commissioning), (2) eliminating rework, and (3) increasing labor efficiencies.

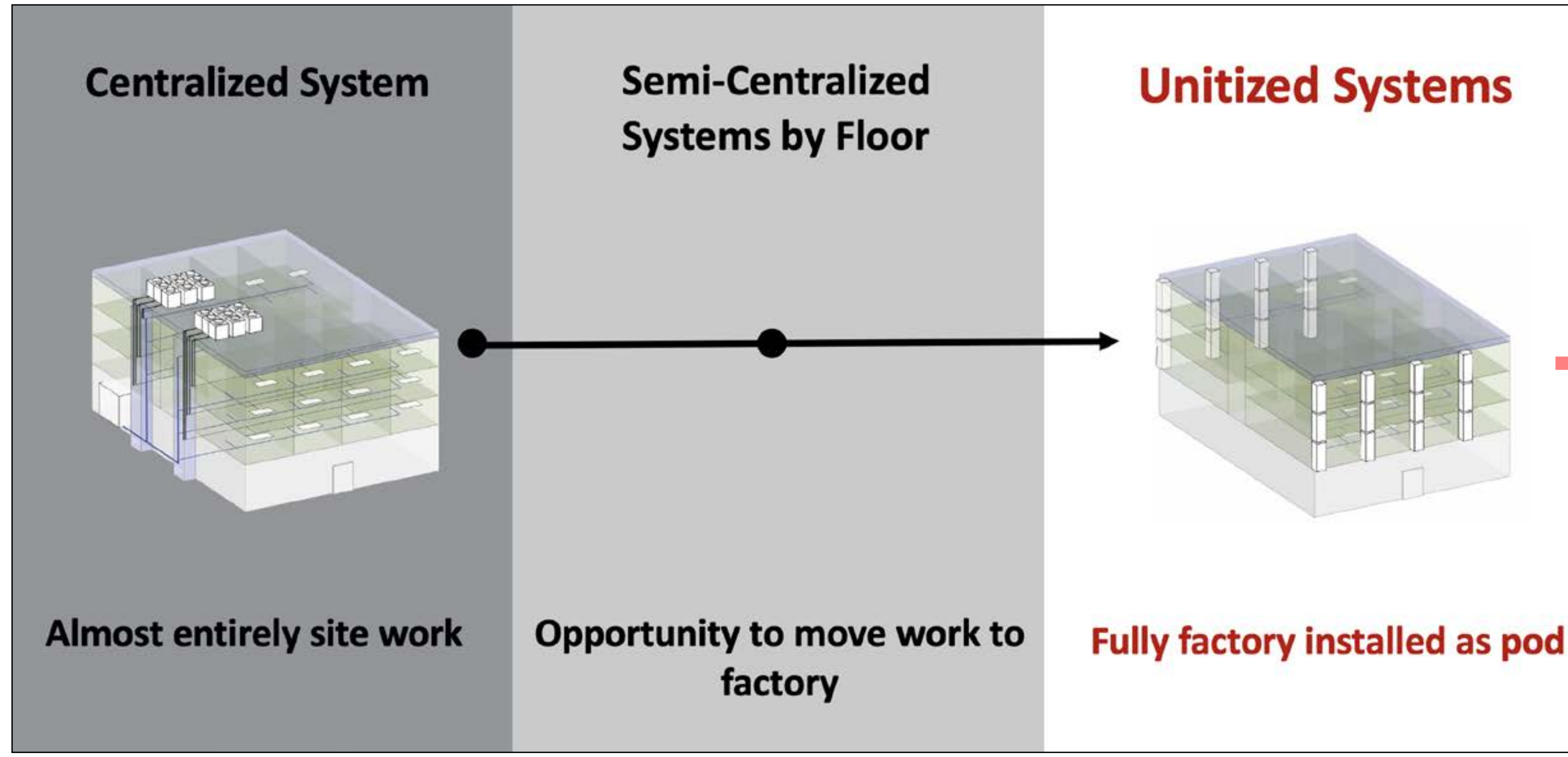
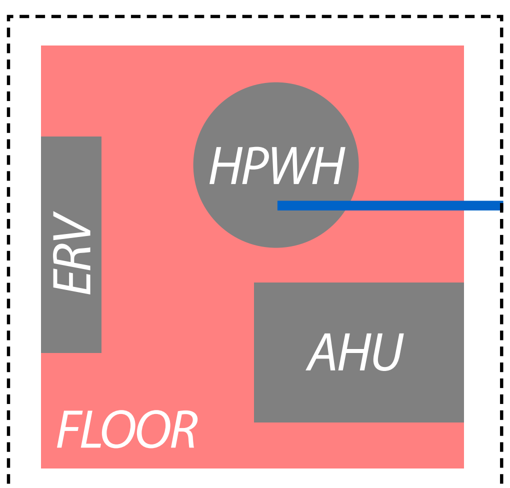


FIGURE 29 Design variations of the Energy Exchange Pod's fully implemented and partially implemented options. Source: NREL.

1. Fully implemented idealized Energy Exchange Pod solution



Pod's Top View

2. Partially implemented pod solution

i. HVAC + domestic hot water pod with outdoor unit on roof (site-installed)

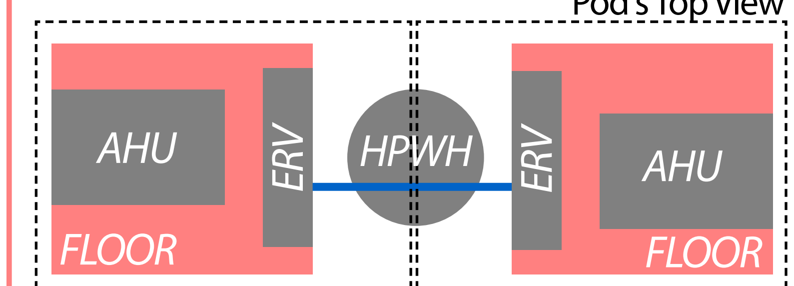
ii. HVAC + domestic hot water located in unit ceiling and closets

   a. Enables factory installation, but not as a prefab component

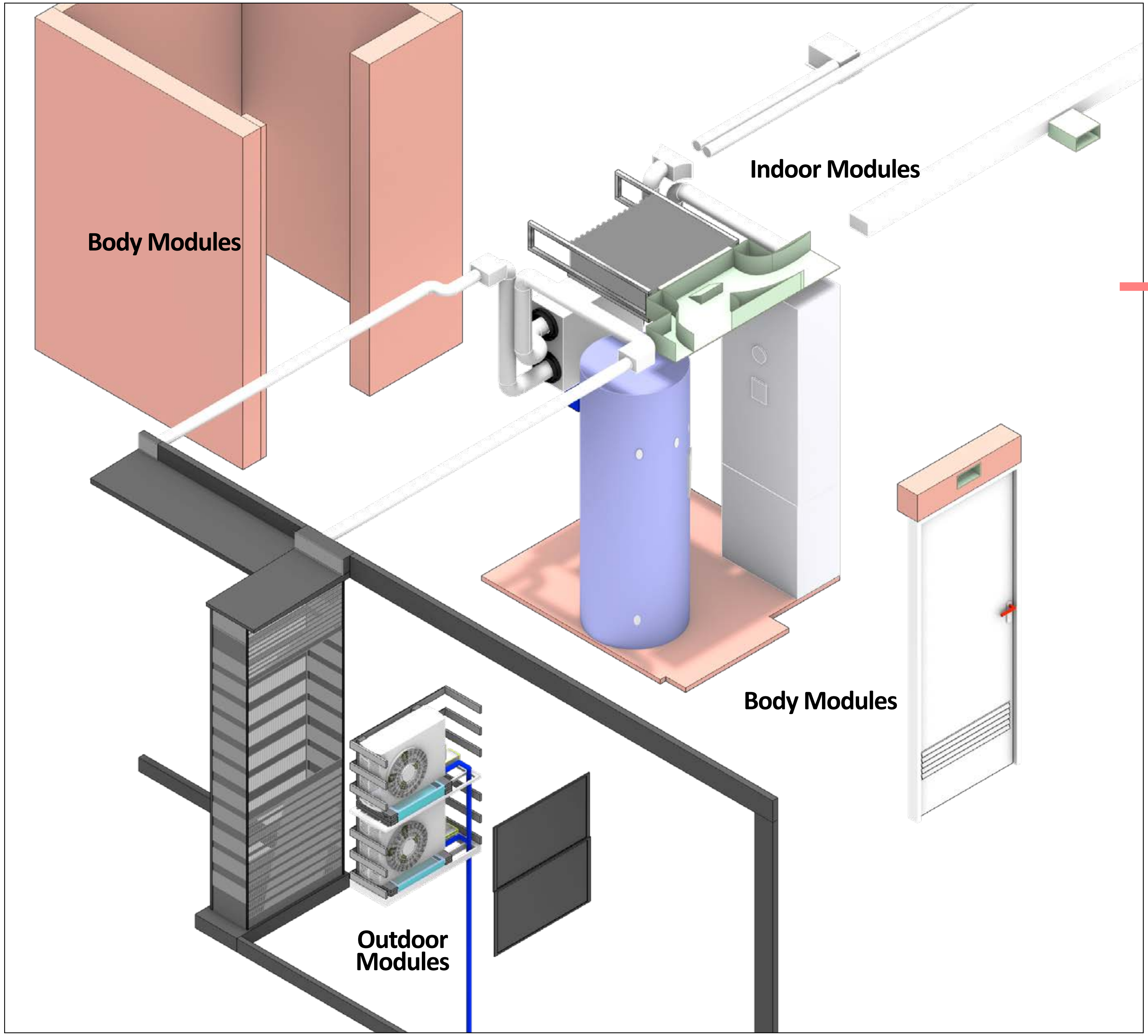
   b. Allows design options with PTHP as the air system

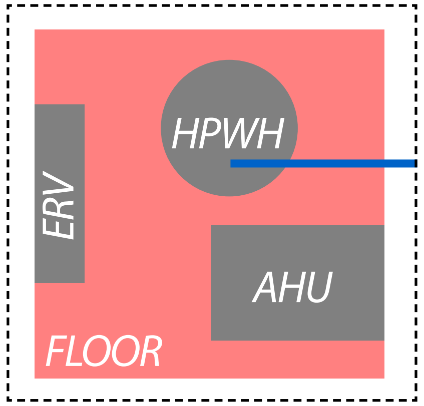
iii. Partially decentralized shared systems, such as shared hot water system across 3-5 apartments.

Pod's Top View



ERV: energy recovery ventilator, HPWH: heat pump water heater, AHU: air handling unit (indoor), PTHP: packaged terminal heat pump





Pod's Top View

FIGURE 30 Designing with the dimensions of the Energy Exchange Pod (25 ft^2) led to the development of “body modules” that can be insulated walls, galvanized metal chassis, or just the structural framework on which the indoor modules are mounted or installed.

Body modules facilitate the creation of the pod and boost productivity as they allow all subsystem modules to be assembled at-scale on a parallel production line in the factory before being integrated into each modular housing unit as turnkey packaged solutions.

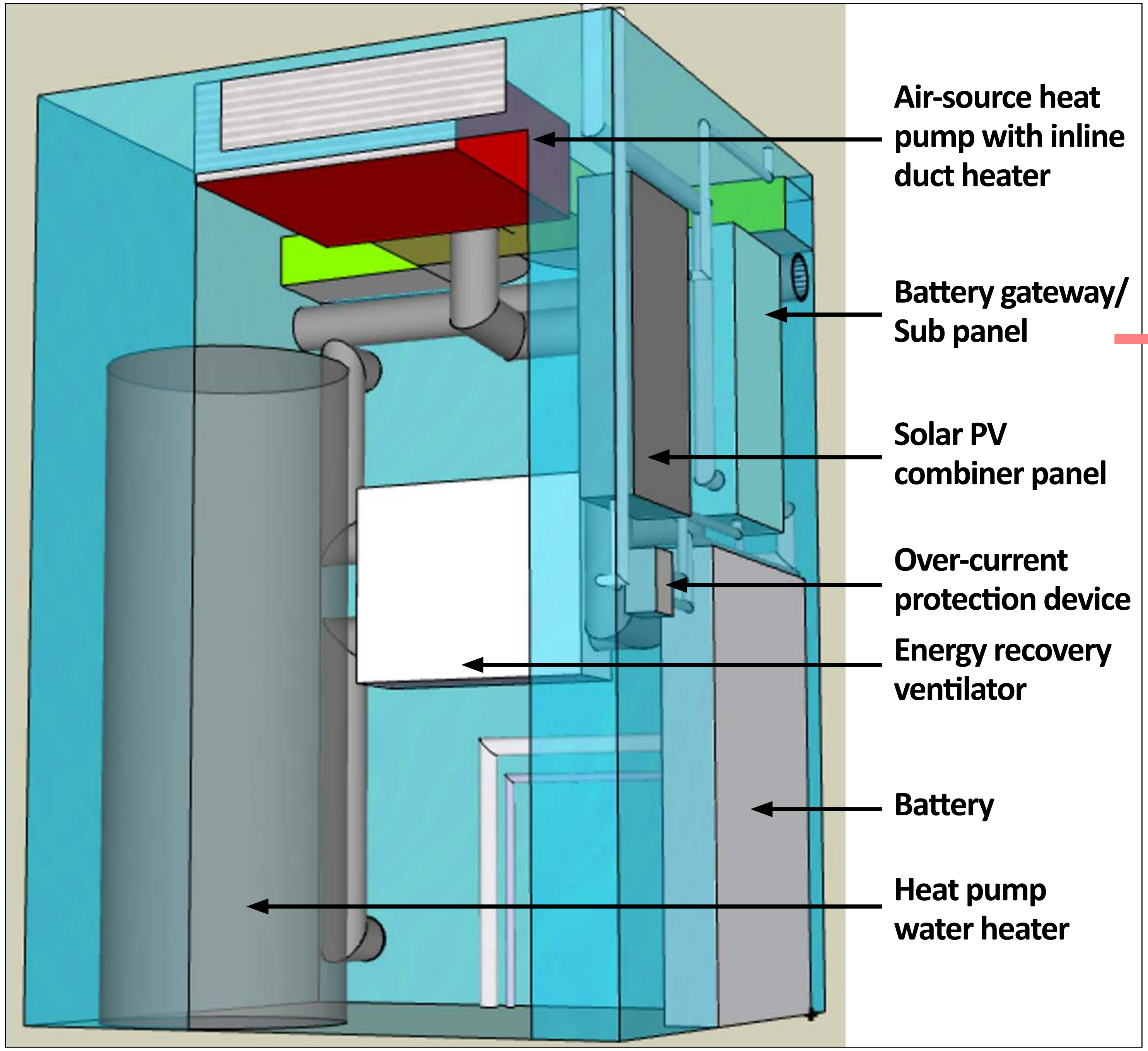
Source: NREL.

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 (as shown in Figure 31).** The typical zero-energy modular 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 (see Figure 32).

CASE STUDY: VEIC

We supported VEIC and KBS Builders in piloting a demonstration of an Energy Exchange Pod as part of their zero-energy modular home project. VEIC's zero-energy modular project helps make zero-energy, resilient, and healthy homes affordable. **VEIC's Mobile Home Replacement project is focused on delivering 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 following key stages were part of the pilot to ensure factory installation and maximizing work in the factory:

- Install distribution at framing stage; gypsum wall board will run behind ductwork on walls and ceiling
- Plenum with integrated sweep delivers air to both sides of the home and reduces resistance to airflow
- Coordinate equipment delivery to factory
- Tie HVAC equipment into distribution
- Ensure proper space for install and future service
- Use injection port for fresh air via ERV
- Use CO2 on-demand control and condensate integration
- Use transfer grille for AHU return air
- Carefully plan around plumbing and electric
- Install heat pump compressor; gable-end install so it can travel down the road
- Deliver house and set with HVAC already commissioned at the factory.



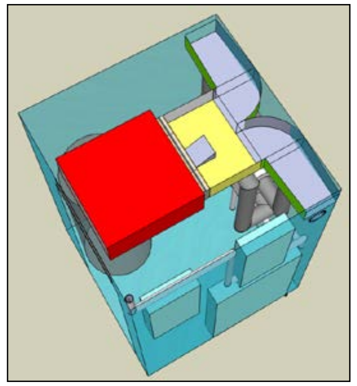


FIGURE 31 Design of VEIC's Energy Exchange Pod for zero-energy modular homes: Perspective (left) and Top view (above).

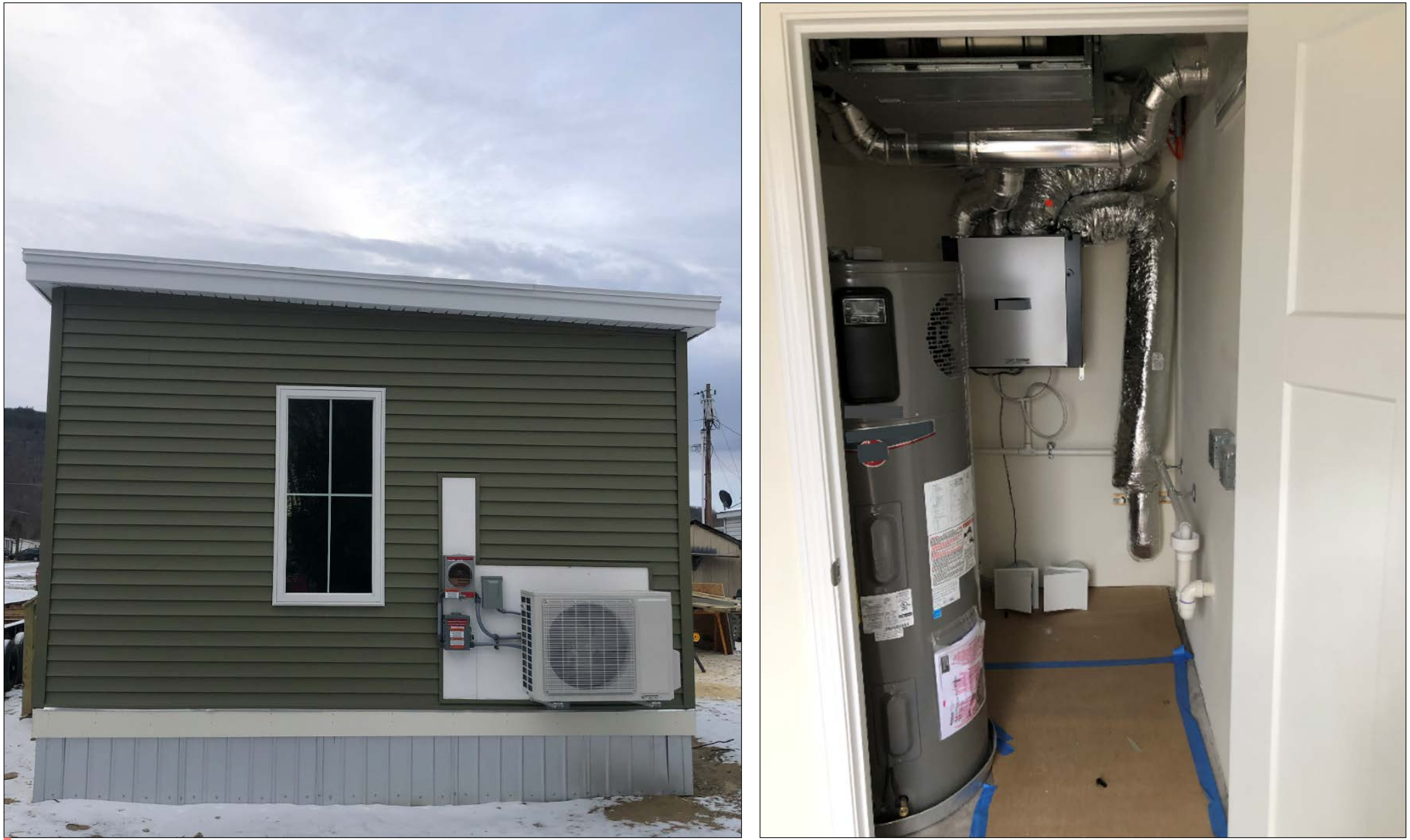


FIGURE 32 Photo documentation of VEIC's Energy Exchange Pod for zero-energy modular homes (partially implemented design option). Source: VEIC.

DUCTING STRATEGY

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. **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 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.

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 (as shown in Figure 33).

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.**

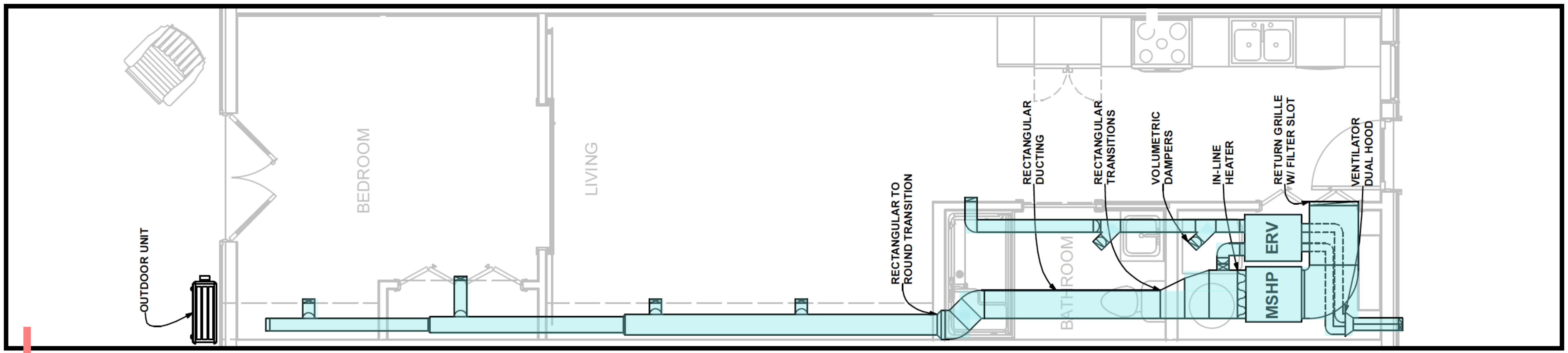
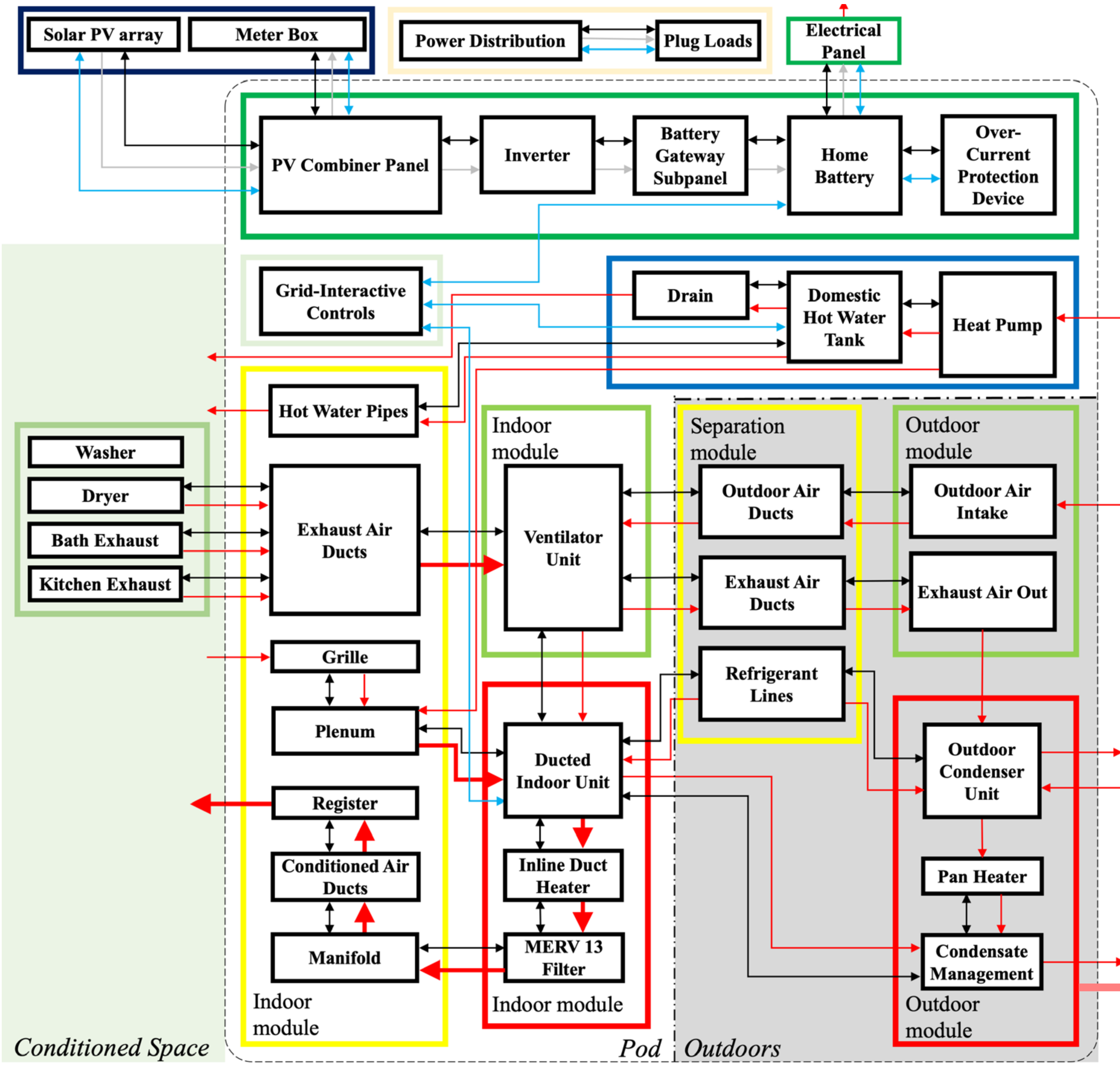


FIGURE 33 Floor plan layout demonstrating the ducting strategy as developed in collaboration with VEIC and Solar Home Factory. Source: NREL.

PRODUCT ARCHITECTURE

Product architecture is the organization (or chunking) of a product's functional elements. It is the ways these elements, or chunks, interact.[5] We propose chunking as a key approach to realize the EMOD method for Energy Exchange Pods. The proposed product architecture should consider the pod's interactions with conditioned space and outdoors (as shown in Figure 34).



KEY (FIGURE 34)

FIGURE 34 Proposed product architecture for Energy Exchange Pods, following the key approach of chunking. Source: NREL.

5 https://www.sciencedirect.com/science/article/abs/pii/S0166497218308162

CHAPTER 6

SMART CONTROLS

Smart Apartments Intelligent Buildings: STRATIS focuses on a "Sidewalk to Sofa" solution for both property managers and residents.

Photo from STRATIS

KEY TAKEAWAYS

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.

NEED, CHALLENGES, AND BENEFITS

The "smart home" has evolved since its conception in the 1980s. With tenant-engagement platforms, apartments and hotels can now provide electronic and remote access, security, and maintenance; control lighting and thermostats remotely; detect faults and leaks with connected sensors; hibernate vacant units; and sub-meter energy and water usage.

Water-leak sensor systems have been found to save between 14% and 40% annually. Energy savings from building commissioning across the commercial building sector have previously been documented at 5%-15%, with an additional 5%-15% savings possible for building control systems that work properly.

Add to this the ability to control building loads based on grid signals and trends, and the result is fourfold: **increased energy savings, decreased carbon emissions (lower marginal emissions), relief for grid congestion, and increased grid resilience.**

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.**

GEBs, the next generation of smart buildings, employ a wide range of technologies (as shown in Figure 35) to respond to predicted loads, energy pricing, or demand response signals.[1]

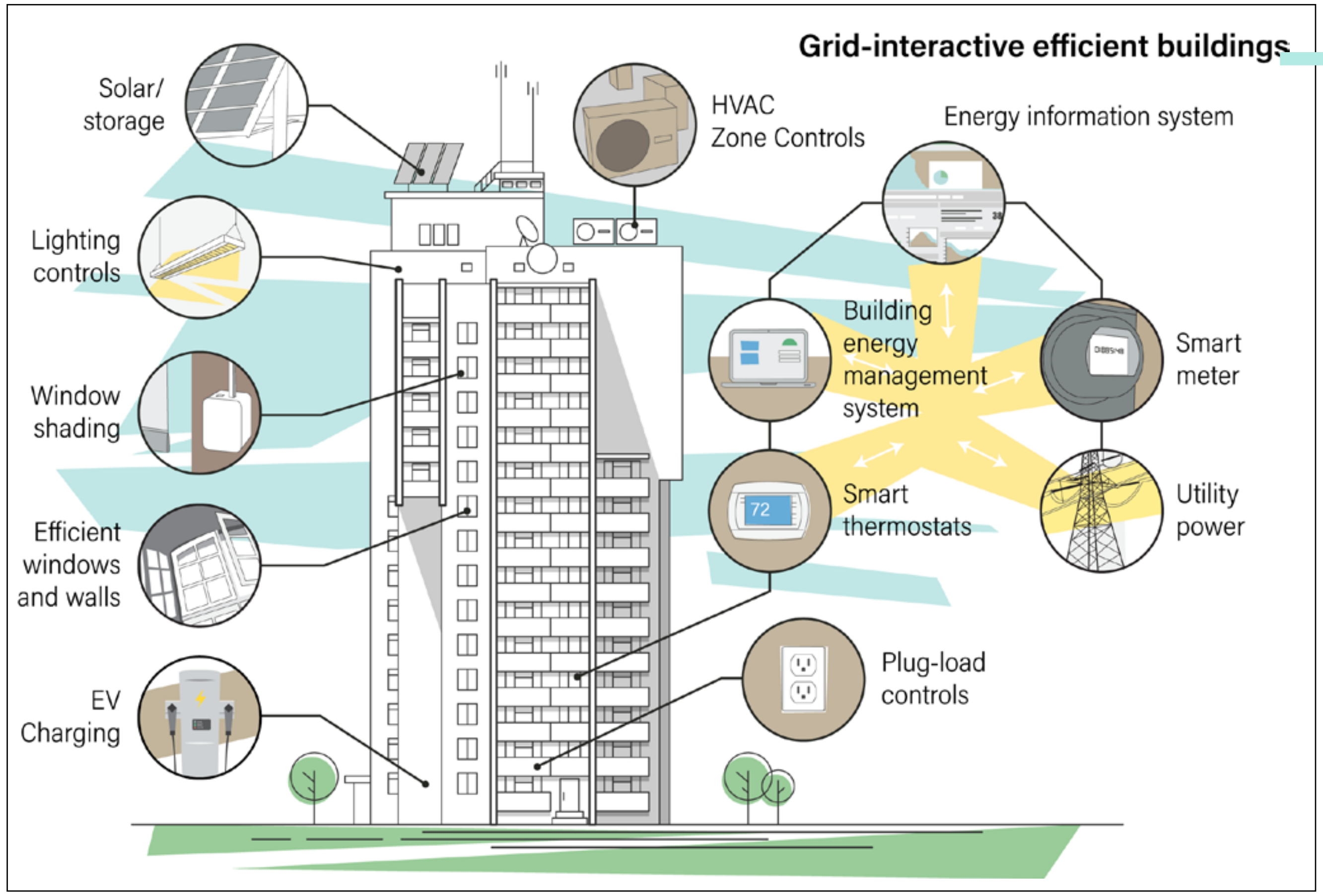


FIGURE 35 GEBs employ the following to respond to predicted loads, energy pricing, or demand response signals: (1) dynamic shading for solar gain management; (2) smart outlets and fan controllers for load shaving and prioritization; (3) electric water heaters for setpoint control and load shifting; (4) lighting for occupancy sensing and daylighting; (5) thermostats for setpoint control and pre-heating/cooling; (6) ventilation for control based on indoor air quality indicators; (7) smart on indoor air quality indicators; (8) smart appliances for MEL delay and scheduling; and (9) PV and home batteries for optimal charging and dispatch. Source: DOE.

1 https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings

GEB technologies in any building require integration to achieve a smart- apartment control system and usable platform. Platforms like STRATIS 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.**

CASE STUDY: STRATIS

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 precommissioning can all be done within the factory setting.

FIGURE 36 Controllable thermostat and sensors. Source: NREL.

The pilot project in this effort is in partnership with the Wells Fargo Innovation Incubator (IN2) program,[2] where vertically integrated modular builder/developer, Blokable Inc., partnered with STRATIS[3] to test integrated smart controls for energy efficiency, comfort, and demand-side management. Technologies in this project include thermostat floating, light dimming (as shown in Figure 36), plug-load reduction, dynamic shading (see Figure 37 and 38), and heat-pump-water-heater floating. STRATIS plans to incentivize higher participation in demand response in order to maximize the offset load. One of the project aims was to determine how to estimate the incentive amount that would correspond to the amount of power/energy reduced during a demand response event, which is influenced by the devices controlled, as well as the utility rate structure. Initial functional testing using the OpenADR communication protocol and GridFabric virtual terminal node simulated demand response events has proven successful, and follow-on energy modeling using OpenStudio has demonstrated peak-price savings, especially in cases with significant load flexibility. STRATIS continues to develop a GEB platform as part of its suite.

2 https://in2ecosystem.com
3 https://stratisiot.com

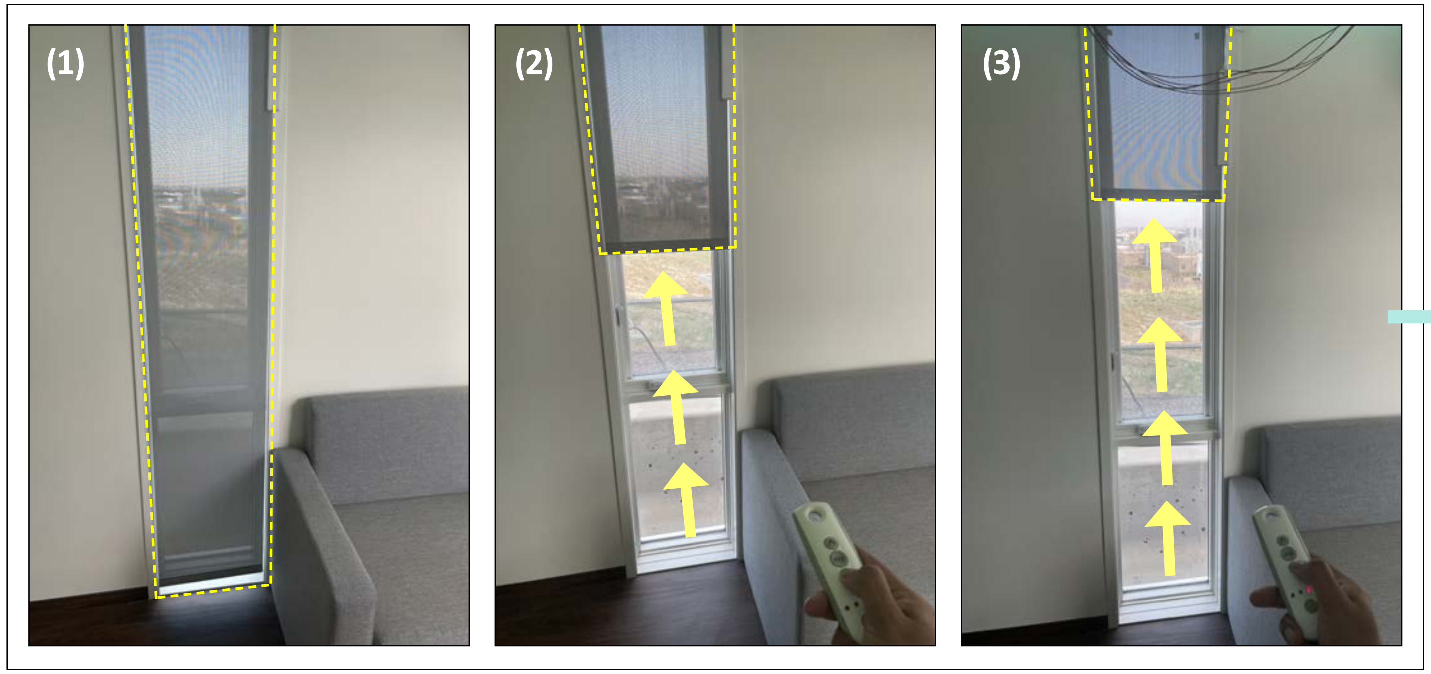


FIGURE 37 Smart controls for shading, controlled by the occupant, in Blokable Inc.'s modular unit at the NREL campus in Golden, CO. Source: NREL.

FIGURE 38 Dynamically controlled shading, triggered by DR events. Source: NREL.

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 up-front cost, **as an affordable-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.**

In approaching modular GEB integration, important considerations for implementing these internet-connected solutions include:

- **Security –** There are many security implications that come with a cloud-based internet-connected platform.
- **Scalability –** The "smart apartment" market has drastically increased in competition in 2018 and 2019. Many "startups" exist that have less than 10k apartments total. Focus on providers that have proven scale.
- **Future-proofing –** Utilizing a provider that focuses on a single wireless protocol or deployment strategy can be
- **Efficiency –** Does the provider focus on the standard bells and whistles of single-family smart homes, or do they focus on security, energy management, asset protection, and operational efficiencies?
- **Thermal or electrical storage –** The ability to schedule or put off mechanical loads is determined by storage capabilities: battery storage and/or a means of thermal storage, such as thermal mass or water tanks. Without energy storage, apartments opting-in to demand-side management are subject to reduced comfort during high-demand events, as well as potential energy penalties due to ramping of equipment upon conclusion of an event.
- **Precommissioning –** Ensure modular building QA/QC techniques are leveraged by coordinating and precommissioning installation in the factory.
- **Standardization –** By building apartments and modules with standardized features and appliances, modular GEB solutions are more easily implemented and managed.
- **Occupant engagement –** Educate and continuously engage occupants and operations staff through well designed platforms in strategically located positions in the building (as shown in Figure 39). Informed building operation can mean the difference between working with and working against the intended design.

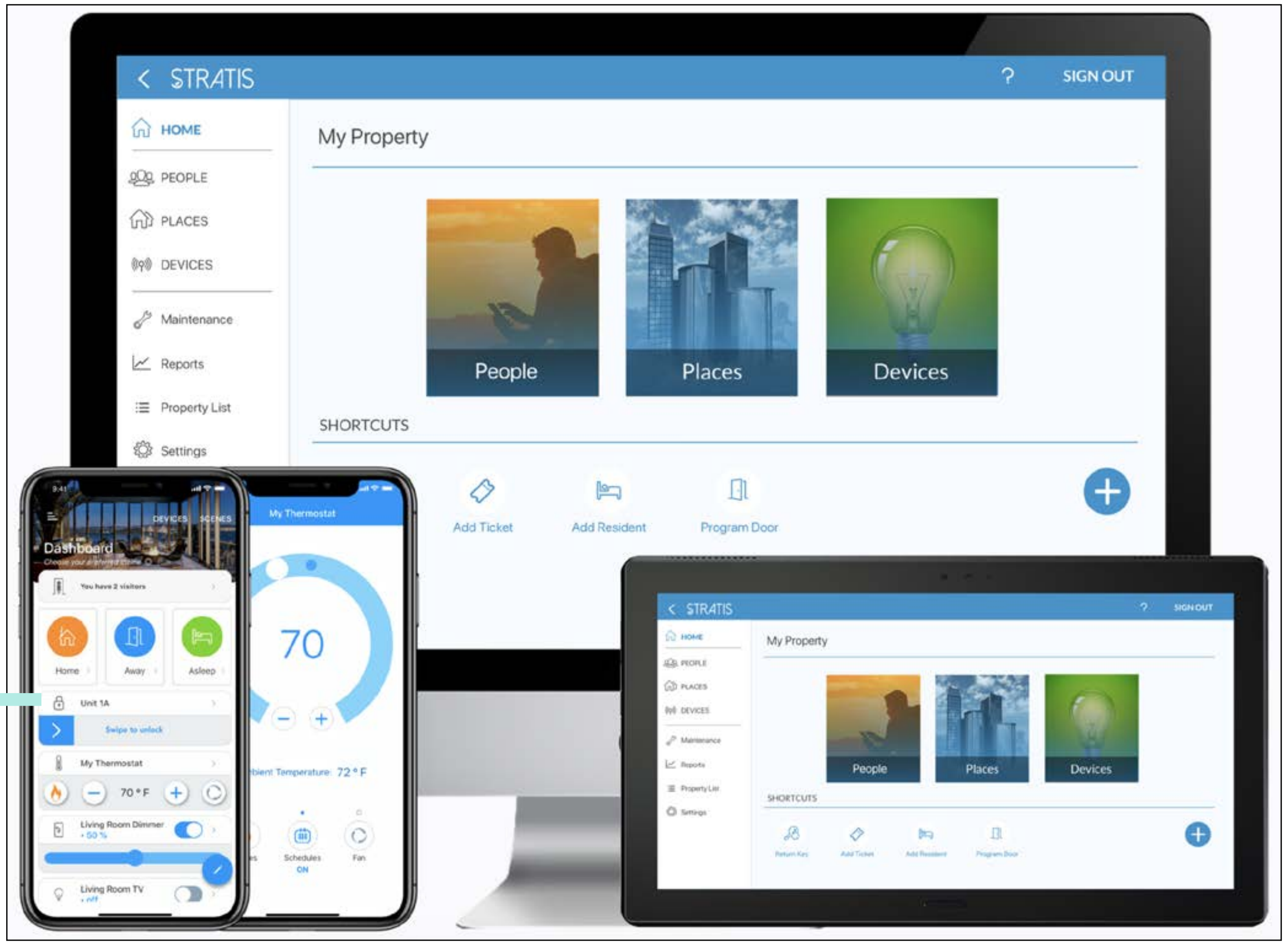


FIGURE 39 Tenant Engagement Platform through user-friendly mobile interface. Source: STRATIS.

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At the Lake Tunnel Solar Village in Geneva, New York, each home has solar panels and is net-zero.

Photo from Solar Home Factory

CHAPTER 7

SOLAR PLUS STORAGE

KEY TAKEAWAYS

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.

The key EMOD method for solar plus storage is to **maximize solar PV panels and balance-of-systems (BOS) installation in the factory**. Our proposed approach also includes **using standardized components that do not require custom design, engineering, product customization, or approval processes.**

NEED, CHALLENGES, AND BENEFITS

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 (as shown in Figure 40). Factory-installed solar plus storage and its lean benefits of reduced soft costs and lower installation time is 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 construction of affordable housing units. Along with rooftop solar PV, residential batteries make a clean grid vastly more affordable. Including distributed storage will also allow more realistic comparison between utility-scale and building-scale solar PV. By investing in a distribution grid that can support high levels of DERs and offer grid controlled or load shape incentives for tenant or owner control, we can free up modern infrastructure that would need to be upgraded eventually. This would further enable more grid-scale renewables to be added faster. Higher adoption and deployment of residential batteries become exceedingly achievable by leveraging benefits from off-site construction of new and upcoming housing. 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%.[1]

FIGURE 40 Solar Home Factory's volumetric modular units with factory-installed rooftop solar PV being set on-site. Source: Solar Home Factory.

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.

1 www.mckinsey.com/business-functions/operations/our-insights/modular-construction-from-projects-to-products

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.

SITE-INSTALLED CENTRALIZED VS. FACTORY-INSTALLED DECENTRALIZED BATTERY SYSTEMS

As more residential battery products hit the market, wider adoption by affordable housing developers can be facilitated by addressing challenges associated with higher first costs and growing fire safety concerns. Supported by DOE's Advanced Building Construction (ABC) Initiative, we developed an ambitious plan to accelerate the integration of energy efficiency measures and distributed energy resources, including residential batteries, during the off-site construction of affordable housing. The research shows optimal integration of residential batteries (along with associated electrical infrastructure and control systems) is possible with little or no additional cost.

FIGURE 41 Ease of installation and maintenance of small, distributed home batteries. Tesla Powerwall Certified Installer (left). Source: Tesla Inc., sonnen Inc.'s U.S. factory (right). Source: sonnen Inc.

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** (as shown in Figure 41), 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.

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/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 back-up of house/life safety loads like egress lighting and elevators	Decentralized storage can more easily be wired to provide backup power in apartments
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/ code officials on design and inspection	Questions on "who does what" on approvals with design and inspection when work is on-site	Contiguous/sequential/integrated approval process in the factory on design and inspection

CASE STUDY: SOLAR HOME FACTORY

Along with partners Solar Home Factory[2] (see Figure 42) and VEIC, we developed a "vertical tower design and delivery strategy" for the modules by incorporating factory-installed solar plus storage (see Figure 43). This optimized design would make it possible to manufacture affordable, 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 are 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 (as discussed in Table 5). 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.

TABLE 5 The project team 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.

2 www.solarhomefactory.com/

FIGURE 42 Solar Home Factory's dwellings are pre-assembled in the factory and shipped to the site, reducing on-site construction to civil, foundations, and exterior finish. Source: Solar Home Factory.

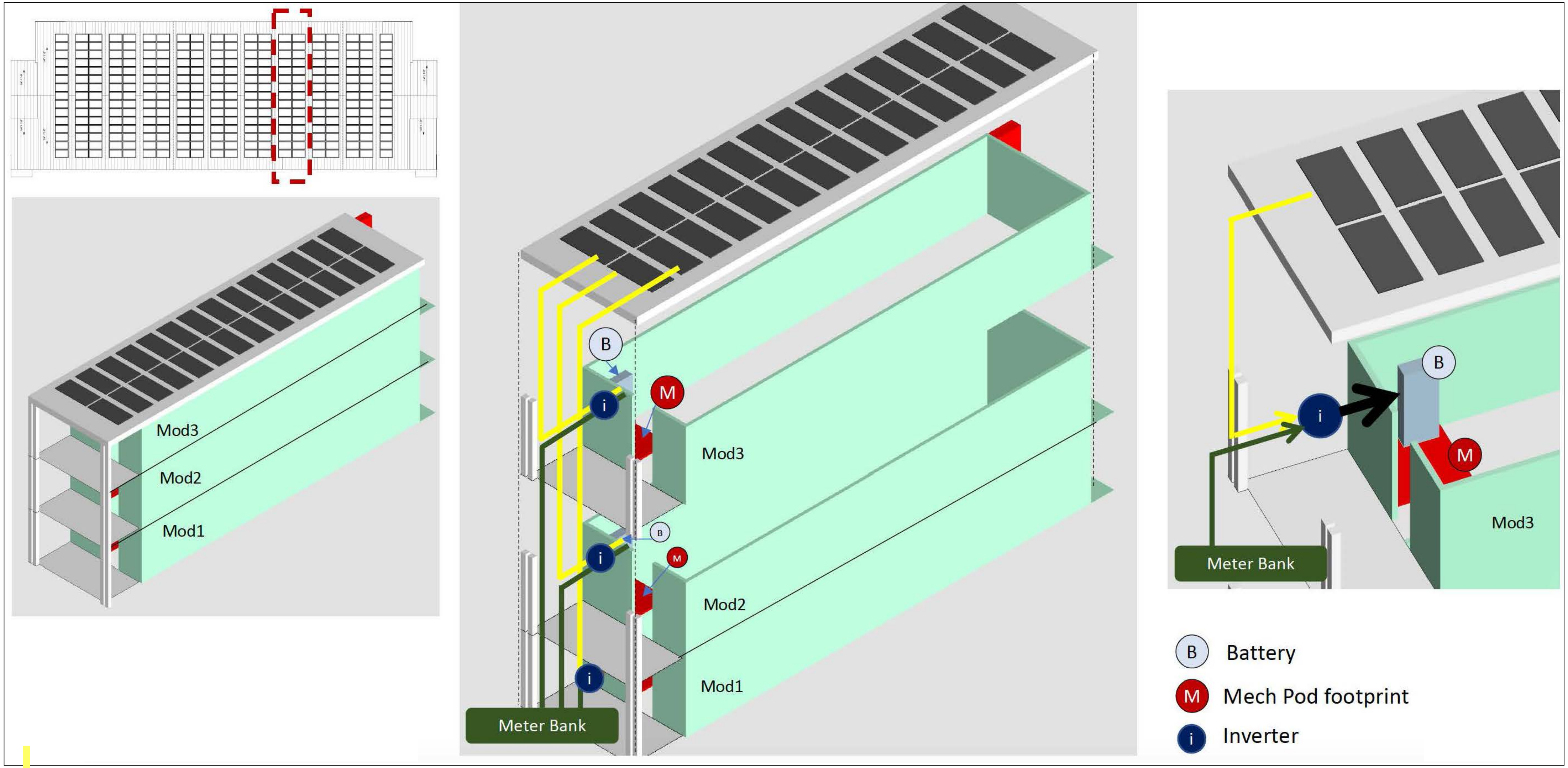

FIGURE 43 The proposed solar plus storage modular tower strategy is a three-module vertical tower. The design proves effective in streamlining solar plus storage and distribution integration in the factory with minimal need for work on-site. Here, the topmost module is fitted with rooftop solar PV arrays, serving the three modules stacked vertically. The electrical distribution system is routed vertically down without the need to run horizontally into adjacent modules and the need for minimal tie-ins on-site. Small decentralized battery systems (installed in the factory) are located in each apartment, along with the inverters. Source: NREL.

CONCLUSION

This project, and the work by NREL and our industrialized housing partners, shows great potential for delivering affordable housing at scale, decarbonizing and electrifying buildings, 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, high construction costs with affordability, and GHG emissions with low carbon buildings. As these codes become ever more stringent, there is a unique opportunity for high-performing modular builders (such as Blokable Inc., as shown in Figure 44) 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.

This guide 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 decarbonization of the built environment**
- **Invest in the U.S. construction workforce by improving productivity and increasing employment opportunities in underserved communities**
- **Meet national goals of energy efficiency and decarbonization.**

The industrialized construction of NZE, low-carbon modular buildings is an essential step for developing a transformational pathway for our clean energy future. The future construction workforce is also an energy efficiency workforce. Our overall goal is to address the affordable housing crisis by lowering construction costs, solving the energy burden, and mitigating GHG emissions.

*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, low-carbon modular buildings**, both nationally and globally.*

FIGURE 44 Phoenix Rising project by Blokable Inc. Source: Blokable Inc.

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Steel-framed modular apartment unit being set on-site, as part of a modular multifamily building.

Photo from FullStack Modular

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