Decarbonizing Multi-Family Housing Development: Actionable Pathways to GHG Emission and Building Cost Reduction with Industrialized Construction

Shanti Pless
National Renewable Energy Lab
May 16, 2023
Innovate on Process to Install EE

Better Product
Affordable, net-zero energy, low-carbon, and healthier

Better Process
Improving productivity, quality, carbon emissions, and affordability of building construction
U.S. DOE “Advanced Building Construction”

Net-Zero Energy | Low-Carbon | Affordable | Appealing

Mission:

– Help deliver affordable, appealing, high-performance, low-carbon new buildings and retrofits at scale

– Help integrate energy efficiency solutions into highly productive U.S. construction practices for new buildings and retrofits
Advanced Building Construction (ABC) offers a powerful solution.

In short, ABC refers to retrofit and new construction approaches that combine:

- **Energy-efficient decarbonization**
- **Scalable, streamlined industrialized construction**
 DOE’s Advanced Building Construction (ABC) Initiative is focused on accelerating the decarbonization of the U.S. buildings sector through industrialized construction innovations that deliver efficient, affordable, and appealing new buildings and retrofits at scale.

**Development & Demonstration**
Innovate & validate appealing solutions that can achieve carbon neutrality for common and high-impact building types.

**Market Transformation**
Use the ABC Collaborative to communicate consumer interests and inform product design; aggregate demand; reduce risks; and establish competitive business models.

ABC Initiative Investments Focus on Technologies, Manufacturing, & Markets

[www.buildings.energy.gov/abc](http://www.buildings.energy.gov/abc)
Zero Energy Mixed Use and Multifamily: Site Built Examples

Boulder Commons
http://bouldercommons.com/

UC Davis Student Housing at Net Zero
https://www.ucdavis.edu/news/west-village-expansion-start-construction
Near Passive House levels of insulation
  – Enhanced air tightness
Triple pane windows
  – Electrochromic, automated shades
Mechanical ventilation with heat recovery
100% LEDs
Electric heating and hot water
  – Heat pump hot water heating
  – VRF, Air Source, Ground Source Heat Pumps
High efficiency appliances
Technology, tenant monitoring, and control integration
  – Smart home technology
Unit level façade and rooftop PV
  – Battery storage and grid coordinated controls

But all struggle with cost effectiveness and affordability...
Parts of the industry could move toward a manufacturing-inspired mass-production system, in which the bulk of a construction project is built from prefabricated standardized components off-site in a factory. Adoption of this approach has been limited thus far, although it’s increasing. Examples of firms that are moving in this direction suggest that a productivity boost of five to ten times is possible.


The report calls for a global effort to modernize and upgrade the construction industry across seven broad areas:
• Reshape regulation and raise transparency
• Rewire the contractual framework
• Rethink design and engineering processes
• Improve procurement and supply-chain management
• Improve on-site execution
• Infuse digital technology, new materials, and advanced automation
• Reskill the workforce

“America’s construction industry productivity is lower today than it was in 1968.”
Productivity in manufacturing has nearly doubled, whereas in construction it has remained flat.

**Overview of productivity improvement over time**

Productivity (value added per worker), real, $2005

$ thousand per worker

Source: Expert interviews; IHS Global Insight (Belgium, France, Germany, Italy, Spain, United Kingdom, United States); World Input-Output Database
“Off-site construction of housing, which leverages the efficiencies of factory production to achieve significant cost savings, represents a much needed solution to this problem. It has the potential to revolutionize the way homes and apartments are built.”

“Inefficiencies in traditional construction have hampered productivity and driven costs up for decades, resulting in increasingly costly development. Today, in many regions in the United States, the production of housing - especially infill multifamily housing – has become so costly to produce it demands rents or sale prices that are unaffordable for most people.”
Four Stages of Industrialized Construction of Modular Buildings

1. Manufactured and assembled in a factory
2. Transported to the site
3. Set on the site
4. Connected to the grid

Recent Trends: Benefits from Industrialized Construction

- 20%-40% faster to build
- 5%-95% of construction in the factory (Volumetric modular, wall panels)
- 3% of new construction in 2017 (Multifamily and hotels)
- High Quality, Can be cheaper to build (Any program can be modularized)
- New investment from outside construction industry

BUT DOES IT RESULT IN MORE ENERGY-EFFICIENT, LOW-CARBON BUILDINGS?
“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 question was addressed by NREL’s ICI Team along with project partners as part of the 3-year DOE funded project “Energy Efficiency in Permanent Modular Construction (EEPMC).”
Design for Manufacturing and Assembly for Energy Efficiency Strategies

• Factory installed EE strategies can simplify installation, better control scope and scheduling, enhance quality, standardize means and methods, increase construction productivity, and reduce overall construction timelines
• Quantify trade-offs for strategies that increase cost of module but reduce construction cost/time/complexity and/or eliminate on-site scope

This allows modular solutions to maximize cost effectiveness of EE solutions and leverage industrial engineering and advanced manufacturing approaches to increase productivity and reduce first cost of construction
Selected Energy Efficiency Strategies

1. Envelope Thermal Control
2. Envelope Infiltration Control
3. Modularization of MEP Systems
4. Smart Controls Integration and Commissioning
5. Solar plus Storage, Distribution Design and Integration
Whole-Building Design with unit-level EE integration
Permanent Volumetric Modular Construction

Ideal NZE, low-carbon modular housing unit

Source: NREL
Key Takeaways:

To optimally integrate the energy efficiency strategy of advanced thermal envelope, **we propose that a superior quality insulation system is installed in the factory, as opposed to on-site insulation systems.** Towards this end, it is critical to design an EMOD-optimized factory-installed envelope system that also achieves similar thermal performance as on-site continuous exterior systems.

- Insulated studs
- SIPs
- Exterior insulation installed in factory with simple module to module detailing planned
EE Strategy 1: Case Study

Benefits from Off-site wall framing with Insulated Truss Studs (ITSs) [B]:
- Reduced labor-minutes by 63%
- Reduced total material used by 38%
- Reduced cost (material + labor) by 78%

A- Baseline: Off-Site Wall framing with standard 2x6 studs followed by on-site continuous insulation
B - Strategy: Off-Site Wall framing with ITSs and no on-site continuous insulation
Key Takeaways:

An example of in-factory airtightness improvement strategies includes the efficient use of ionized sealing. Lessons learnt from ionized sealing pilots could be leveraged to also identify opportunities for in-factory taping and caulking. We propose the following key steps to integrate the energy efficiency strategy of improved airtightness in the factory:

Use construction and manufacturing QA/QC tools and methods (such as non-destructive testing) to achieve factory-installed airtight envelope. The key steps involved are:

- Plan for a QA/QC design review of the envelope
- Test the airtightness on a set of modular units in the factory to evaluate air-barrier installation quality and develop specific strategies to ensure all modules adopt well-known standardized air-barrier details
- Test the airtightness on a representative sample of modular units at end of the factory production line to verify the airtightness value and the installation processes.
EE Strategy 2: AeroBarrier pilots at VBC factory
The key lessons learned are that airtightness starts with design and material selection, and ionized sealing should be used for fine-tuning, with additional focus on set processes, final site installed details, and final testing.

Based on the testing data prototyping and visual factory walkthrough of the station’s activities and processes, there is much room to impact the overall quality of modular units positively.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Starting ACH</th>
<th>Ending ACH</th>
<th>% Reduction</th>
<th>Sealing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>9.0</td>
<td>1.8</td>
<td>78%</td>
<td>56 min</td>
</tr>
<tr>
<td>Test 2</td>
<td>5.9</td>
<td>1.0</td>
<td>87%</td>
<td>41 min</td>
</tr>
<tr>
<td>Test 3</td>
<td>10.7</td>
<td>3.1</td>
<td>65%</td>
<td>40 min</td>
</tr>
<tr>
<td>Test 4</td>
<td>6.9</td>
<td>1.8</td>
<td>77%</td>
<td>30 min</td>
</tr>
<tr>
<td>Test 5</td>
<td>5.7</td>
<td>1.7</td>
<td>70%</td>
<td>48 min</td>
</tr>
<tr>
<td>Test 6</td>
<td>7.4</td>
<td>2.4</td>
<td>66%</td>
<td>23 min</td>
</tr>
<tr>
<td>Test 7</td>
<td>6.4</td>
<td>1.1</td>
<td>88%</td>
<td>45 min</td>
</tr>
<tr>
<td>Average</td>
<td>7.4</td>
<td>1.8</td>
<td>76%</td>
<td>40 min</td>
</tr>
</tbody>
</table>
Can we imitate the bathroom pod approach for mechanical system?

Common for bathroom pods to be:
• Prefabricated
• installed on-site or on volumetric modular factory line

‘Utility cupboards’ in the UK

• Prefabricated 540 ‘utility cupboards’ by Skanska UK for Battersea Project
• Took 18 man-hours to build vs 42 hours for those constructed on-site
• 44% cheaper, including factory overheads; 73% fewer defects
EE Strategy 3: Energy Exchange Pod

Key Takeaways:
A unitized Energy Exchange Pod enables:
1. Build-to-Stock of subsystems through chunking and prefabrication for volume production in production lines
2. A unitized air system for each apartment.

By following the proposed methodology, the subassembly "pod" design (fully-implemented or partially-implemented) leads to the following benefits:
1. Ensures proper ventilation that is hard to ensure with central ventilation systems and variable pressure across the height of a building
2. Limits unit to unit air cross contamination, reducing odor and acoustic pollution.
EE Strategy 3: Energy Exchange Pod

Source: VEIC
Solar Home Factory

Modular Factory Installed Solar reduces install costs
EE Strategy 5: Solar plus Storage

Each Modular Tower with 3 modules (each LVL) and rooftop PV array
ENERGY IN MODULAR METHOD
[ EMOD METHOD ]

A GUIDE TO DESIGN FOR ENERGY EFFICIENCY IN INDUSTRIALIZED CONSTRUCTION OF MODULAR BUILDINGS

Shanti Pless
Ankur Podder
Zoe Kaufman
Noah Klammer
Conor Dennehy
Dr. Naveen Kumar Muthumanickam
Stacey Rothgeb
National Renewable Energy Laboratory

Dr. Joseph Louis
Oregon State University

Colby Swanson
Heather Wallace
Momentum Innovation Group

Cedar Blazek
U.S. Department of Energy

https://www.nrel.gov/docs/fy22osti/82447.pdf
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER 1: INTRODUCTION</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Need For Industrialized</td>
<td>8</td>
</tr>
<tr>
<td>Construction In The U.S. For Affordable Housing Delivery</td>
<td></td>
</tr>
<tr>
<td>Efficiency Benefits</td>
<td>9</td>
</tr>
<tr>
<td>From Industrialized Construction</td>
<td></td>
</tr>
<tr>
<td>Towards Net-Zero Energy, Low-Carbon Modular Housing</td>
<td>10</td>
</tr>
<tr>
<td>Leveraging The Advanced Energy Design Guides And Other Literature</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 2: DESIGN FOR ENERGY EFFICIENCY IN INDUSTRIALIZED CONSTRUCTION</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Takeaways: Approaches, Tools, And Strategies</td>
<td>16</td>
</tr>
<tr>
<td>Selecting A Set Of Energy Efficiency Strategies</td>
<td>18</td>
</tr>
<tr>
<td>Design Of An Ideal NZE Modular Housing Solution</td>
<td>21</td>
</tr>
<tr>
<td>Need For A National-Scale Shared Research Platform On EMOD METHOD</td>
<td>21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 3: ENVELOPE THERMAL CONTROL</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Takeaways</td>
<td>29</td>
</tr>
<tr>
<td>Key Benefits</td>
<td>29</td>
</tr>
<tr>
<td>Case Study: Time Studies And Process Modeling Evaluation With Insulated Truss Studs</td>
<td></td>
</tr>
<tr>
<td>Process Modeling Results</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 4: ENVELOPE INFILTRATION CONTROL</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Takeaways</td>
<td>33</td>
</tr>
<tr>
<td>Case Study: In-Factory Airtightness Improvement Pilots With Volumetric Building Companies (VBC)</td>
<td>35</td>
</tr>
<tr>
<td>Key Takeaways From VBC Pilot 1</td>
<td>36</td>
</tr>
<tr>
<td>Key Takeaways From VBC Pilot 2</td>
<td>37</td>
</tr>
<tr>
<td>Next Steps And Future Work</td>
<td>39</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 5: MODULARIZATION OF MEP SYSTEMS</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Takeaways</td>
<td>41</td>
</tr>
<tr>
<td>Case Study: Design Evolution With Factory_OS</td>
<td>42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 5: MODULARIZATION OF MEP SYSTEMS (CONTD.)</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Study: Zero Energy Modular Pilot With VEIC</td>
<td>44</td>
</tr>
<tr>
<td>Ducting Strategy</td>
<td>46</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 6: SMART CONTROLS INTEGRATION AND COMMISSIONING</th>
<th>48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Takeaways</td>
<td>49</td>
</tr>
<tr>
<td>Needs, Challenges, And Benefits</td>
<td>49</td>
</tr>
<tr>
<td>Case Study: STRATIS IoT</td>
<td>50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 7: SOLAR PLUS STORAGE, DISTRIBUTION DESIGN AND INTEGRATION</th>
<th>54</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Takeaways, Needs, Challenges, And Benefits</td>
<td>55</td>
</tr>
<tr>
<td>Site-Installed Centralized Battery Systems vs. Factory-Installed Decentralized Battery Systems</td>
<td>56</td>
</tr>
<tr>
<td>Case Study: Solar Home Factory</td>
<td>57</td>
</tr>
</tbody>
</table>

| CONCLUSION | 60 |
Project Overview

• **Blokable is developing an integrated multifamily development product that is:**
  – Net-zero energy
  – Affordable AND profitable
  – Comfortable
  – Environmentally forward-thinking
  – Ahead of policy

– How can we utilize their proposed scale up to reduce both operational carbon and embodied carbon?
  • IF we built 400 units a year, what happens to the cost and performance model?
    – 10,000?
Productization, Standardization, & Manufacturing
Methodology

Modeling the product’s roadmap

- Economy of scale
- Learning effects
- Leverage vertical integration for long-term savings & affordability

- LCA model
- Scale up 1 apartment to 10k units
Methodology

Modeling product roadmap 10 years down the line

Cost model
- Productivity increase
- Economy of scale
- Reduced waste
- Operational energy savings

Energy & emissions model
- Material decarbonization
- Learning-affected waste reduction
- Grid-responsive technologies
- Operational energy savings
Apply Learning Curves to Modular scale up
The price of solar modules declined by 99.6% since 1976. With each doubling of installed capacity, the price of solar modules dropped on average by 20.2%. This is the learning rate of solar modules.

Figure 4. The price of solar modules has declined by 99.6% since 1976

Figure from OurWorldinData.org
Embodied Carbon Modeling Methodology

*Modeling up-front carbon of evolving product line involves policy considerations.*

- Buy Clean California Act passed in July 2021 (Bill Track 50 2021)
- Project steel-related emissions:

<table>
<thead>
<tr>
<th>Year</th>
<th>2016-2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel GWP (lbmCO₂e/lbm)</td>
<td>3.05</td>
<td>2.89</td>
<td>2.72</td>
<td>2.56</td>
<td>2.4</td>
<td>2.24</td>
<td>2.08</td>
<td>1.92</td>
<td>1.76</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Emissions change as Cambium emissions-factor projections change over time. Effects of decisions are weighed over the lifetime of the building.
Combined lifecycle emissions across product roadmap

- Switch to all electric, ZNE
- Switch from steel to hybrid steel + wood structure
- Use higher recycled content in structural steel
- Incorporate battery + GEB technology
- 60% reduction in total GHG emissions per dwelling unit
Findings

Path toward decarbonization for vertically integrated developers/builders

- To reduce emissions by 60% by 2030, modular builders should incorporate the following over time:
  - Electrification and carbon-responsive GEB capability well integrated into their standard modular product
  - Factory efficiency to apply learning curves to decarb strategies
  - Waste reduction for materials with high waste factor (e.g., drywall)
  - (Structural) materials with low embodied carbon and high recycled content
  - Design (and commission) for minimal refrigerant and leakage
    - Modular HVAC systems can reduce GHG emissions by up to 20% versus centralized systems
Findings

Backdrop for moving toward building decarbonization

• With the aid of **staged planning for emissions reduction of building materials, components, and operations**, integrated developer-owners can create more accurate roadmaps of their own to stage a path for decarbonization

• Product design with decarbonization **included at the beginning of product development lifecycle** necessary to ensure we can leverage learning curves as production ramps

• **60% lifecycle carbon reduction** on a pathway of cost reduction curves
Decarbonization Roadmap & NREL Technical Report

https://nrel.gov/docs/fy22osti/81037.pdf

Google Search: “decarbonization during predevelopment”
We now have methods that can utilize Advanced Manufacturing and Industry 4.0 Industrial Engineering productivity improvement approaches to better integrate complex and decarbonization strategies into the design and construction process MORE cost effectively

• Requires a design that maximizes off-site and prefab approaches
• Leverages productivity gains and repeatability of processes available in factory-built modular

Next Steps:
• Scaling solutions to different regions/factories/building types
• HVAC Pod in 50 units
• ICC Off-Site MEP and Energy Code (out for first draft public review!)