Decarbonization During Predevelopment of Modular Building Solutions

Noah Klammer, Zoe Kaufman, Ankur Podder, Shanti Pless, David Celano, and Stacey Rothgeb

National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
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List of Acronyms

BAU	business-as-usual
CLF	Carbon Leadership Forum
EPD	Environmental Product Declaration
GEB	grid-interactive efficient building
GHG	greenhouse gas(es)
GWP	global warming potential
HSS	hollow structural sections
HVAC+R	heating, ventilating, air conditioning, and refrigeration
IBC	International Building Code
IN^2	Wells Fargo Foundation Innovation Incubator program
ISO	International Organization for Standardization
kWdc	kilowatts of D.C. current power
kWh	kilowatt-hour
LCA	life cycle assessment
LCI	life cycle inventory
lbmCO_2e	pounds-mass of carbon dioxide equivalent greenhouse gas
NREL	National Renewable Energy Laboratory
NZE	net zero energy
PV	photovoltaic(s)
SAM	System Advisor Model

Executive Summary

Affordable, zero carbon emissions is an important climate-performance target for the future of multifamily housing, and the multifamily construction industry holds an essential position in achieving this goal in the United States. Building construction and operation accounts for 37% of global energy-related carbon emissions (UN Environment Programme 2021). Meanwhile, an additional 3.8 million housing units are needed to address the shortage in the United States (Khater et al. 2021).

To date, net zero energy (NZE) has served as a tangible preliminary target for high-performance building in both voluntary certification programs and, now, building energy codes. Industrialized construction is one approach to efficiently achieve affordable housing that implements NZE strategies.[1] These dwelling units are often all-electric and outfitted with rooftop solar arrays, and they produce at least as much energy through on-site renewable resources as they consume each year, enhancing energy affordability. However, the full potential of affordable, NZE housing has not yet been tapped, due in part to incremental costs of NZE strategies surpassing traditional budgets for affordable housing projects. Additionally, as new construction becomes more energy efficient, the greenhouse gas (GHG) emissions from the construction industry play a proportionately larger role in environmental impact and must be considered when evaluating methods of construction. There has been limited investigation into the trade-offs between site-built and industrialized construction buildings from the perspective of reducing the incremental cost of NZE strategies and reducing GHG emissions resulting from upfront and operational emissions that are "embodied" in the building's life. **This report details actionable pathways for the industry to leverage advanced building construction, reduce NZE incremental costs, and achieve significant GHG emissions reduction by 2030.**

This effort demonstrates a pathway to affordability and emissions reduction via specific strategies within the framework of industrialized construction. Various decarbonization strategies were compared in "what-if" scenarios at each development stage, using cost, energy, and emissions modeling, with the most impactful and viable strategies proposed in the resulting pathway. The primary audience, stakeholders, and beneficiaries for this methodology are productized modular builders and associated investors who are interested in (1) NZE incremental cost reduction and (2) GHG emissions reduction. "Productized" here refers to the repeatable, solutions-based, packaged design that a manufacturer commits to developing, evolving, and producing and delivering at scale, over time. The case study is analyzed over the years 2016–2030, where the production builder begins instituting the analysis and intervention 5 years after initial product development.

The unique contributions from this framework are two methodologies:

1. **Methodology I** is focused on cost reduction through learning effects and experience curves applied to NZE productized modular construction.

[1] More information on NREL's industrialized construction research can be found at https://www.nrel.gov/buildings/industrialized-construction.html.

2. **Methodology II** is focused on reducing GHG emissions per unit of housing, evaluated via a life cycle assessment (LCA). The reductions come from a variety of strategies, including: the bill of materials, learning effects on production waste, learning effects on logistics, decarbonization of the electrical grid, and energy demand management.

As 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. This framework introduces three development phases that modular builders can plan to 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). **Following the proposed development road map could uniquely position high-performance modular builders to achieve significant reduction in both NZE incremental costs (Figure ES-1) and total GHG emissions from their dwelling units (Figure ES-2).**

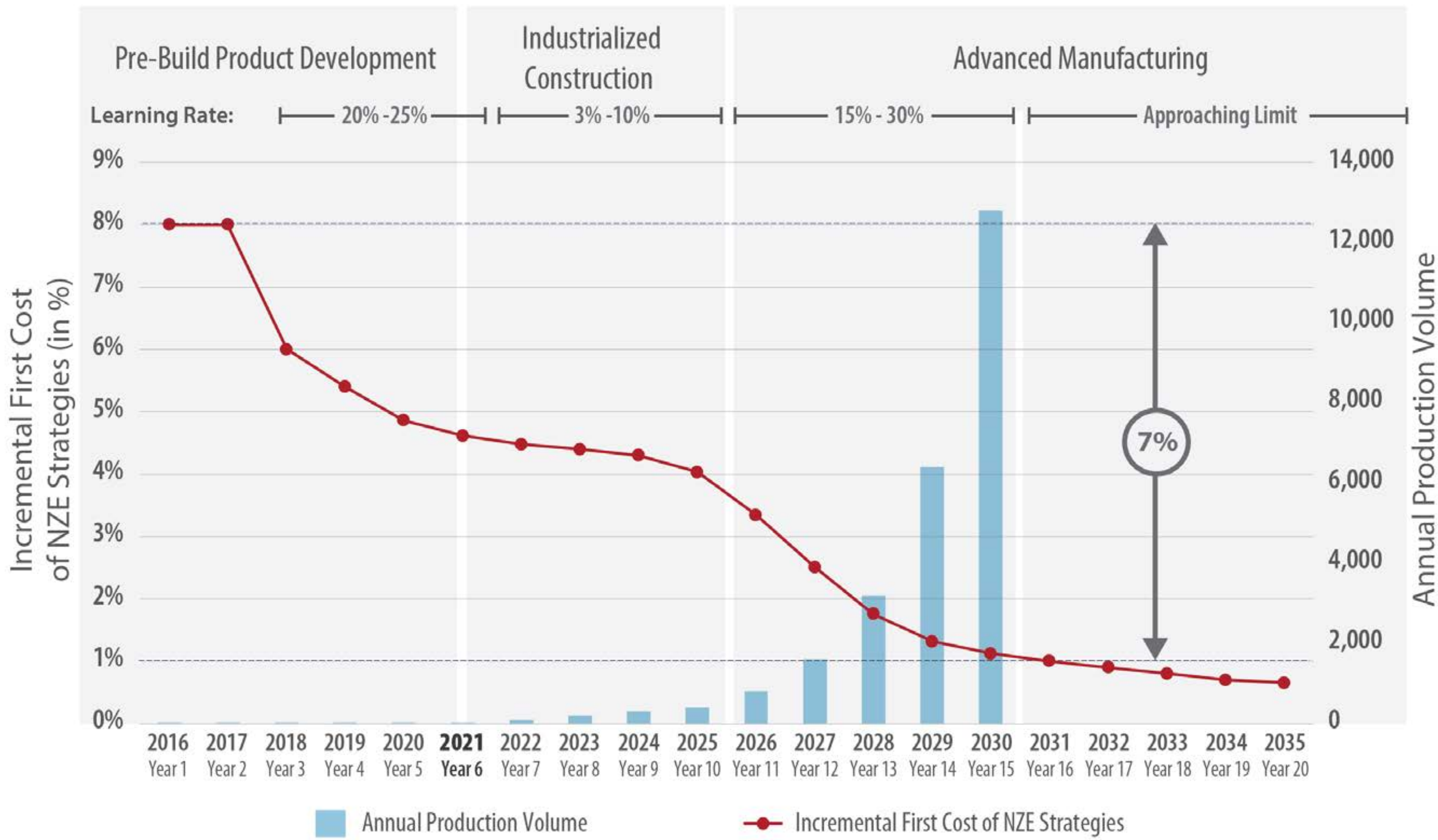

Figure ES-1. Projected cost curve for NZE strategies across the development road map. Case study analysis and intervention begins in 2021, 5 years after initial product development.

Figure by NREL

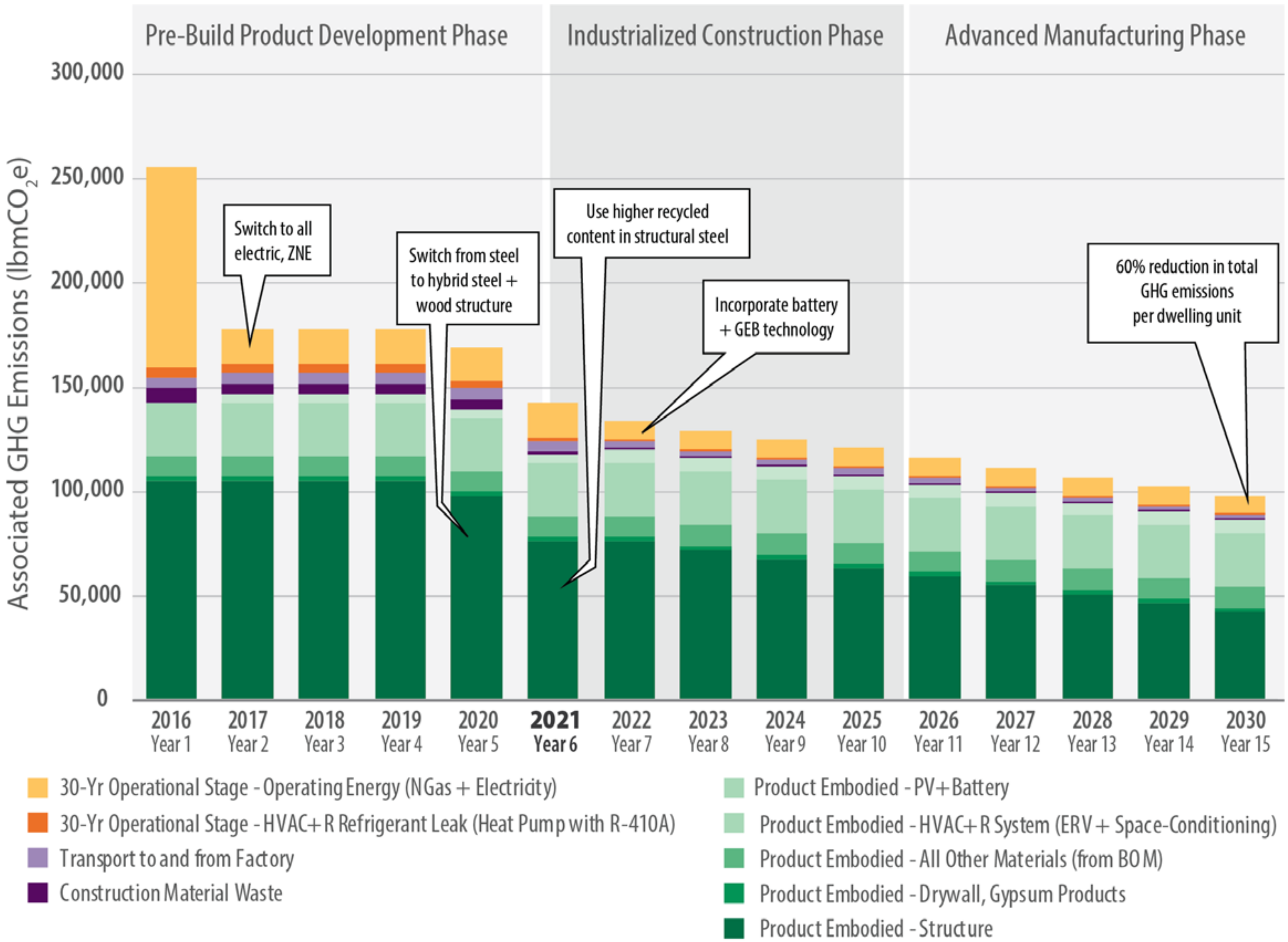

Figure ES-2. Road map for 30-year life cycle GHG reduction over three phases from 2016 to 2030. Case study analysis and intervention begins in 2021, 5 years after initial product development.

Figure by NREL

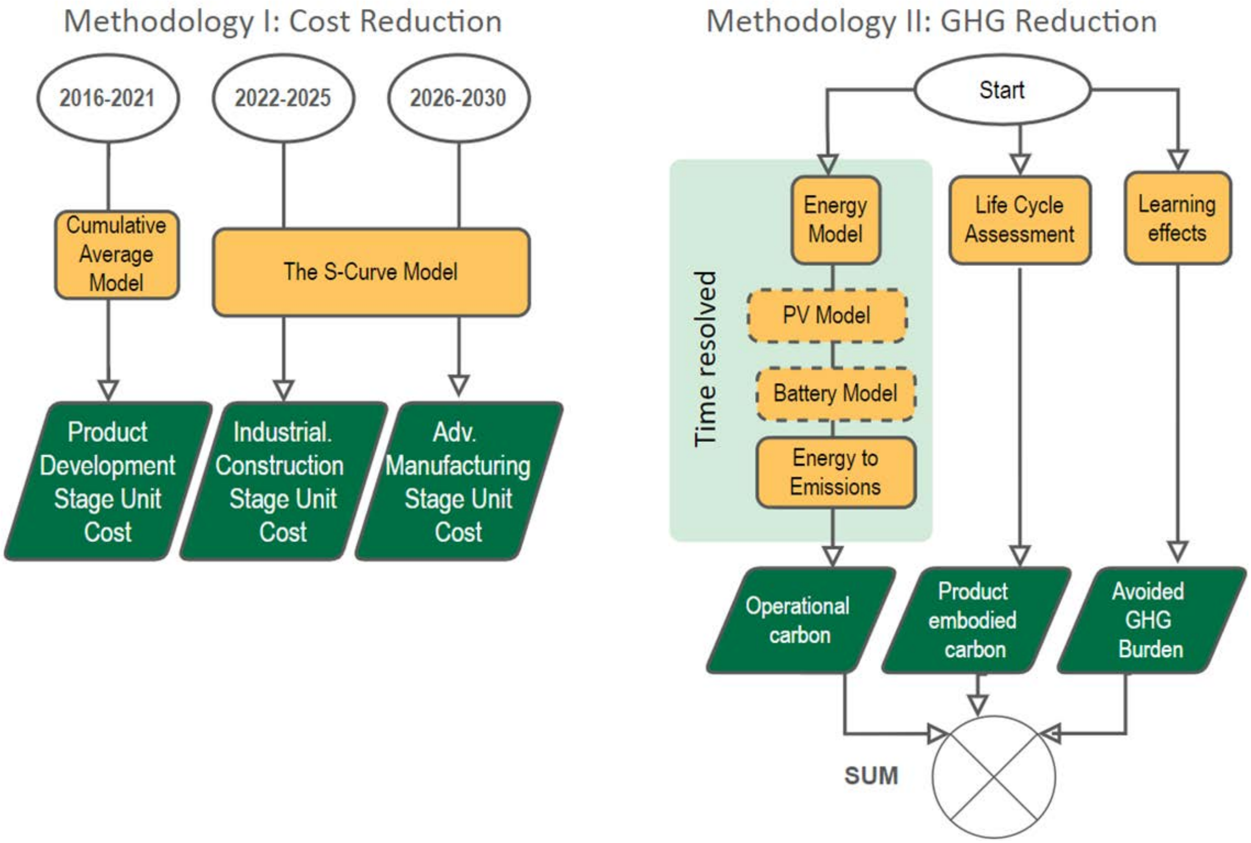

Figure ES-3. Unique contributions of two methodologies that could lead to significant NZE incremental cost reduction (left) and significant GHG emissions reduction (right).

Figure by NREL

As shown in Figure ES-3, Methodology I brings together two widely used learning- and experience-curve models, the Cumulative Average Model and the S-Curve Model, into a sequential cost-reduction methodology for NZE strategies. The Cumulative Average Model is applied to the Product Development stage, and the cost-reduction opportunity depends upon the number of product development iterations or attempts (full cycles), the starting incremental cost of NZE strategies, end-of-year target incremental cost of NZE strategies, and the maximum annual learning rate opportunity. The Cumulative Average Model stipulates that the greater the number of attempts made to perform a task on a standardized unit, the time taken to complete that task and the unit cost will decrease. The model lends itself to this phase as the task of product development recurs as the same unit goes through multiple design iterations or attempts over a period. The S-Curve Model is applied to the Industrialized Construction Phase and Advanced Manufacturing Phase. The cost-reduction opportunity in these two phases depends upon the annual production volume and the end-of-year target incremental cost of NZE strategies. Based on a set of underlying assumptions for Methodology I (see Appendix A), **if the modular builder successfully produces and delivers on the order of 10,000 NZE dwelling units annually by 2030 (year 15) following the proposed development road map across three phases, it could reduce the approximately 8% incremental costs associated with achieving NZE to 1% incremental costs** for its product, owing to learning and experience curves. At this point in time, 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.

Another major outcome of this framework is a quantitative estimate of the life cycle (upfront and operational) building embodied carbon saved through the execution of the road map, under Methodology II. Embodied carbon refers to the measure of environmental impacts related to global warming potential of the building's materials, construction, maintenance, and end of life (termed embodied impacts). For a modular builder, the key lies in translating road maps already laid out in terms of energy efficiency and incorporating carbon-responsive GEB technology, factory efficiency, waste reduction, and low-embodied-carbon materials. A major opportunity ahead of modular builders gearing up to design, produce, and deliver 10,000 dwelling units built from structural-steel components, such as those of the case-study example, is embodied-carbon reduction of steel. In order to be well-positioned to leverage this opportunity, modular builders should first minimize the quantity of steel used and wasted, and then specify structural-steel components with greater percentage of recycled content (as per Buy Clean acts) during the Pre-Build Product Development Phase. To benefit from learning effects during the Pre-Build Product Development Phase to reduce construction material waste, modular builders should focus on materials with high waste factor such as drywall. Other opportunities, while smaller in impact compared to steel, include switching to low-GWP or natural refrigerants and/or reducing HVAC+R refrigerant-leakage embodied carbon through mechanical design focusing on minimizing refrigerant lines and aggressive quality assurance/quality control. Overall, the productized modular builder that achieves the road map milestones could expect to **achieve a roughly 60% reduction in total GHG emissions.**

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. Readers are encouraged to provide feedback to the authors[2] for future revisions and an expansion of the framework's scope and content.

[2] The corresponding author can be reached at Ankur.Podder@nrel.gov.

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1 Introduction

1.1 Targeting Affordable Decarbonization

Affordable, zero carbon emissions is an important climate-performance target for the future of multifamily housing, and the multifamily construction industry holds an essential position in achieving this goal in the United States. To date, NZE has served as a tangible preliminary target for high-performance building in both voluntary certification programs and, now, building energy codes. The availability of housing in urban areas is not only a market convenience, but also a basic need upon which many people and families depend. The financial feasibility of affordable housing projects is highly subject to the costs of construction—a major barrier for the construction industry to achieve an NZE target has been the high incremental costs of NZE strategies added to the total construction cost of affordable housing projects, which can be a deal-breaker in traditional development structures where first-cost drives feasibility.

Affordable housing with NZE strategies is not being designed, constructed, and delivered across the United States as quickly as needed, and greenhouse gas (GHG) emissions from the construction industry continue to contribute substantially to climate change. There has been limited investigation on trade-offs between site-built and industrialized construction from the perspective of reducing the incremental cost of NZE strategies and reducing GHG emissions during production and operational stages (Simonen et al. 2020; Johnstone et al. 2020). Therefore, we present this "decarbonization proforma" with actionable pathways for the industry to reduce NZE incremental costs and achieve significant GHG emissions reduction by 2030.

The primary audience, stakeholders, and beneficiaries for this report are high-performance, productized modular builders such as Blokable, LLC, a modular manufacturing research partner developing affordable housing and focusing on energy affordability. (This research collaboration between the National Renewable Energy Laboratory [NREL] and Blokable is supported by the Wells Fargo's Innovation Incubator, or "IN^2," program.) Blokable has a vertically integrated model, in which it designs, builds, and often owns and operates the apartment units it produces. Because Blokable has interest in the long-term performance of its buildings, it is also able to invest in the productization (both product and process) of its NZE commodity. Other paths toward productized or high-performance modular housing include a larger market demanding NZE performance, or more long-term partnerships with organizations that specify this type of performance.

The primary metrics of interest for this study are (1) NZE incremental-cost reduction and (2) GHG emissions reduction. Forecasting is projected over the period of 2016–2030, with Blokable's actual completed projects informing the assumptions for 2016–2020 and hypothetical production making up the subsequent 10 years. This report contributes two methodologies. The first is focused on learning effects and experience curves applied to modular construction and NZE incremental cost reduction. The second focuses on evidence-based reductions to GHG emissions possible with an integrated modular building process. The reductions come from a variety of strategies having to do with the process of construction, the building materials included therein, and the operational life of the produced module.

We are calling this report a "proforma," a term that is borrowed from other industries to mean a specific type of business analysis or financial report. Real estate economist Wayne Lemmon described a real estate proforma as "the basic financial analysis that developers do in deciding whether to move forward with a project. A proforma analysis looks at the financial return that a proposed real estate development is likely to create. It begins by describing the proposed project in quantifiable terms, then estimates revenues likely to be obtained, costs that will have to be incurred, and the net financial return the developer expects to achieve" (Senville 2007). Lemmon also mentions that it can be used to test "what-if" scenarios.

This approach is directly applied to this paper, with a focus on reducing up-front costs while striving toward life cycle decarbonization. As the primary stakeholders, modular builders can leverage this proforma 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. Following such a development road map could uniquely position modular builders like Blokable to achieve significant reduction in both NZE incremental costs and total GHG emissions from their dwelling units.

1.2 Driving Forces and Emerging Contexts for Decarbonization

A net zero energy performance target is not merely a means of zeroing out a building's energy consumption or reducing GHG emissions; the use of energy efficiency strategies combined with demand response and storage can alleviate grid stress, decrease instances of brownouts and blackouts, foster community resilience, and enable energy affordability. Passive survivability, which has been shown to be a critical need in protecting the residents and structures, is an ancillary benefit of most of the NZE strategies that can provide stacked value on top of GHG reduction.

This performance target is also a verified pathway toward complying with local regulations, such as those in California and New York City. California's Title 24 energy code already requires new single-family and low-rise residential buildings to be designed to net zero standards and will require all remaining commercial and high-rise residential buildings to do the same by 2030 (NORESCO 2017). New York City has taken a different approach by setting operational, rather than design, requirements: Local Law 97 requires energy usage reporting (and calculated carbon emissions), with staged thresholds enforced by fines beginning in 2024 and scaling to 2034, with stricter emissions thresholds over time. The law aims to achieve a 40% GHG reduction from covered buildings by 2030, and an 80% reduction in citywide emissions by 2050—equivalent to 0.0014 tCO_2e/sf/yr (NYC Buildings 2019). Thresholds vary by occupancy group and year, but the penalty is to be paid proportionate to the amount by which reported emissions exceed the threshold allowance. Whether in California, New York City, or elsewhere, it pays to be ahead of the regulatory curve in the following ways:

1. Get ahead of the curve by implementing solutions in select projects that reduce energy-related emissions, with enough time to verify strategies that work well in different contexts.

2. Build in the time to implement building operations techniques that enable net zero performance.

3. Scale the solution to repeatable effectiveness to reduce or eliminate the performance cost premium by the time the codes and laws require all buildings to meet the standard.

Another key aspect of building decarbonization is the full electrification of building systems, including heating and domestic hot water. Especially as the electrical grid lessens its dependence on fossil fuels (i.e., decarbonizes), emissions from electric energy usage (as opposed to fuel usage) are more easily offset by on-site and off-site renewables. This will likely be reflected in upcoming Local Law 97 rulings in 2023 that set emissions multipliers for 2030 and beyond, with lower CO_2e/ft^2-yr coefficients expected over time. Therefore, a building that is planned to have truly zero emissions over time must be “all electric” in its fuels use. Thus, the study at hand considers a road map in which the prototype buildings begin with a mix of natural gas and electricity fuels, but soon transition to being “all electric” energy consumers—as was the trajectory for Blokable.

Additional advantages to building without natural gas or other fossil fuels include avoided costs of building out gas infrastructure—both new hookups and right-of-way distribution—as well as avoiding delays and costs of often unpredictable gas moratoriums, as was the case in New York City during the debate over the Williams Pipeline.

Beyond operational carbon, this study considers embodied carbon in the “upfront” and “use” stages (see the Glossary for term-specific definitions). The authors ask the question, “In a highly energy-efficient modular apartment unit, how do embodied emissions compare to lifetime operational emissions, and what key aspects of the building can be addressed in order to significantly decrease life cycle carbon while simultaneously decreasing production cost and increasing affordability?”

2 Modular Product Evaluation

2.1 Functional Unit of Study: One Volumetric Modular Dwelling Unit

This report combines aspects of a scaling proforma (which considers financial impact) and a life cycle assessment (LCA), (which considers whole-life building emissions impact). The purpose of combining the two is to demonstrate the financial and environmental benefits that justify the upfront investments needed to achieve the necessary scaling. The case example considers the modular construction method, whereby volumetric “closed” modules are first finished in a facility before later being erected at the project site. The subject of study, when speaking with respect to LCA, is known as the functional unit. A functional unit should be defined in a physical quantity and functional quality. A typical one-bedroom apartment unit made from factory-finished modules provides a convenient and interpretable functional unit of study per ISO 14044 “Environmental Management: Life Cycle Assessment: Requirements and Guidelines.”

The functional unit is a fully “amenitized” one-bedroom apartment with a floor area of 720 ft^2, consisting of one-and-a-half closed volume modules constructed by Blokable. The functional unit serves an occupancy of two and conforms to the design requirements of a Type III residential construction in the case location of Sacramento, California. The analysis period is 30 years, although many of the building components will have a much longer service life. In the case example construction method, many systems and equipment are unitary, and allocation is not necessary. When a building system (e.g., a rooftop solar PV array) could not be enclosed by the functional unit, allocation was used accordingly. In those cases, allocation distributed the embodied and operational impacts to units evenly based on the number of identical units that would use that building system.

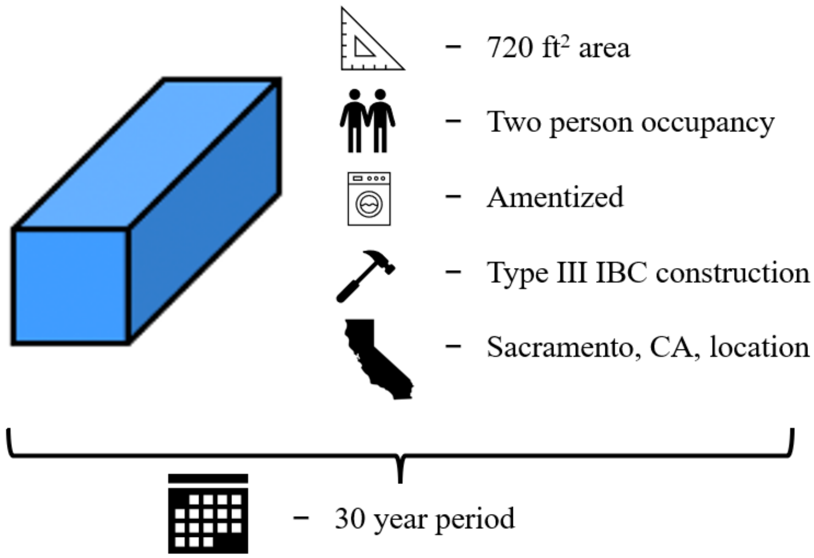


Figure 1. Details and description on the functional unit of study

Figure by NREL

2.2 Modular Product Evolution

Modular builders and developers providing a specific building product as their business model must scale their efforts over time, with prototypes, testing, and refinement throughout the process. As a startup, Blokable has focused on delivering smaller-scale, single-story apartment complexes via a small-scale prototype modular factory. The company's plan to scale includes using full-scale factories, increasing throughput, and building bigger/taller in order to efficiently increase impact. The three planned phases of development and their timelines are shown in Table 1 and Figure 2. They include the initial Product Development Phase, the Industrialized Construction Phase implementing a larger prototyping facility, and, finally, the large-scale, Advanced Manufacturing Phase, which will include multiple facilities and automated construction techniques.

As a company evolves, so will its construction "means and methods." One of the goals of this study is to inform the growth of a modular builder/developer with energy, carbon, and cost savings in mind.

With the original goal being net zero performance, we modeled a net zero source-energy scenario using ASHRAE's Multifamily Zero Energy Design Guide draft energy model (ASHRAE 2019); however, additional scenarios are presented that account for life cycle carbon, which is more aligned with emerging definitions of "net zero" (Canada Green Building Council 2021; Architecture2030 2016). Strategies to get closer to life cycle net zero include reducing emissions associated with the life cycle of materials, as well as further reducing operational carbon emissions by accounting for electrical-grid emissions factors and the use of energy storage such as home batteries. The modular product's transition to all-electric design during the first prototyping phase is seen as a necessary step toward decarbonization; although the electric grid has opportunities to reduce emissions over time, fossil fuels, like natural gas, remain relatively static in terms of their projected emissions.

Grid emissions and projections will be discussed further in Section 4. Table 1 outlines some of the basic actions proposed to achieve lower life cycle emissions over time. The original/baseline structure is made of steel, using hollow structural sections (HSS) for the structural frame and light-gauge joists/studs for walls, floors, and ceilings. While the HSS frame is important for maintaining low tolerances, high precision, and structural flexibility, the steel studs and joists are not as crucial to the design. After an initial embodied carbon analysis of the structure, it became clear that steel was the most important material to focus on because it contributes the most to upfront embodied emissions (A1–A3). Appendix B details the boundaries of the life cycle analysis. Later discussion will dive further into each component's associated emissions. Table 1 reflects the planned reduction of steel usage, as well as the strategies used to reduce operational emissions within the three planned phases.

Table 1. Construction and Operations Strategies Across Product Stages

Stage	Year	Description: Construction	Description: Structure	Description: Operational
Product Development	2016–2020	Prototype Factory	Steel-structure (CFS studs 24” o.c., HSS column-beam)	Natural gas for water heating at first, then transition to all-electric; no PV
Industrialized Construction	2021–2025	Factory-Built/ Modular	Hybrid-structure (wood studs 16” o.c. 2x4s, HSS column-beam)	All-electric, NZE, using energy efficiency and solar PV
Advanced Manufacturing	2026–2030	Factory-Built/ Modular	Hybrid-structure (wood studs 16” o.c. 2x4s, HSS column-beam)	All-electric, NZE+GEB, grid-responsive, solar-plus-storage, advanced controls

In the context of locally available benefits, Blokable has already made headway by transitioning to all-electric building systems as California decarbonizes its grid. Blokable began working with NREL to optimize energy efficiency, building process optimization, and materials efficiency, with a large focus on minimizing waste and tenant utility bills to promote affordability. *By comparing projected contributions of upfront and operational GHG emissions in its buildings over time, Blokable can create a road map toward its core goals and set interim and final targets specific to materials and building systems.*

2.3 Development of Volumetric Modular Dwelling Units Across Three Phases

Based on the manufacturing industry’s widely used standard models for scaling and recent developments in the modular construction industry, we developed three phases of a proposed development road map for volumetric modular dwelling units (Figure 2). The development road map was developed with NREL’s industrialized construction partners such as Blokable and other modular builders who own and operate off-site factories. As primary stakeholders, modular builders can leverage this road map for future strategy planning to invest and allocate necessary resources in their large manufacturing facilities or off-site factories in a way that (1) encourages labor learning and increased productivity and (2) doubles the annual production of dwelling units to reach an annual production volume of roughly 10,000 dwelling units by 2030.

- **Pre-Build Product Development Phase (2016–2020):** In this early pre-build design and prototyping phase, a modular builder’s dwelling unit (with novel products and systems) undergoes iterative product development in a smaller prototype factory.

- **Industrialized Construction Phase (2021–2025):** In this phase of development, the pre-designed standardized dwelling unit will be produced at scale in a large manufacturing facility or off-site factory.

- **Advanced Manufacturing Phase (2026–2030, and beyond):** With higher productivity gains, increases in integrated project delivery, data-driven supply-chain optimization, increases in adoption of automation and manufacturing tools, and investment in multiple large manufacturing facilities, the annual production volume of dwelling units could double every year over the prior year's volume.

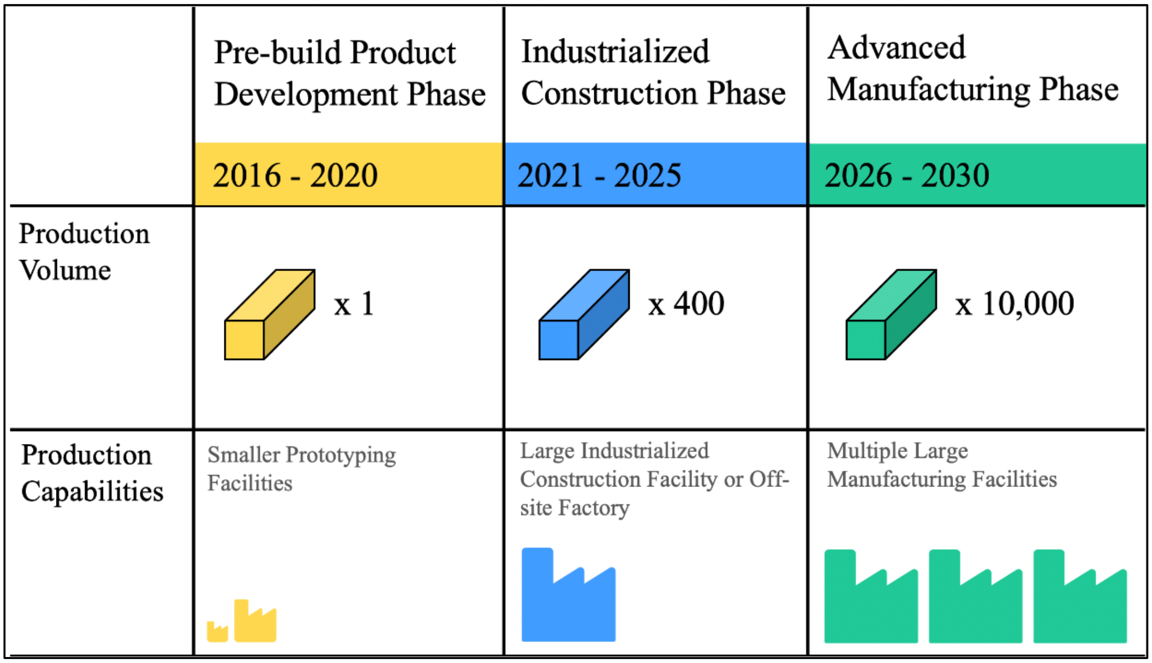


Figure 2. Three phases in development road map for dwelling units

Figure by NREL

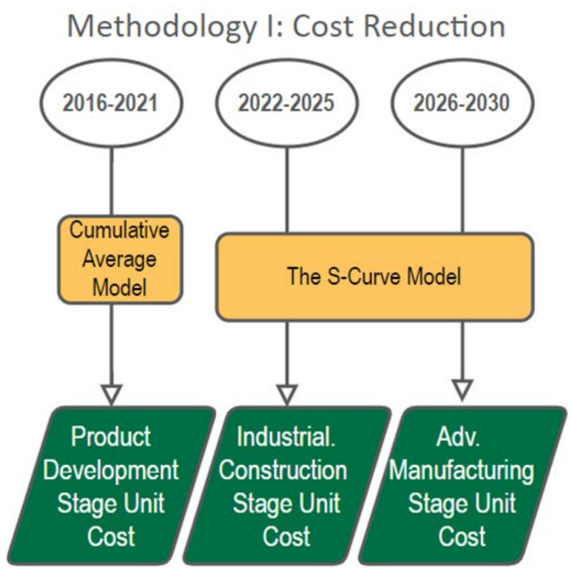
2.4 Parameters Considered

This report is intended to be useful to locations across the United States, but we use the single case example of Sacramento, California, for illustration. The location is relevant when considering important parameters of the road map, namely (1) climate, (2) solar resource, (3) supply chain and logistics, (4) grid mix, (5) building construction type, (6) occupancy, (7) building design requirements, and (8) construction cost premium for NZE strategies. The choice of case example reflects Blokable's specifications. Other U.S. locations may draw conclusions by analogy to the case example presented herein.

Table 2. Parameters Considered in the Case Example of a Modular Dwelling Unit in Sacramento

Parameter Name	Value
Climate	ASHRAE Climate Zone 3B "warm-dry," typical year
Solar Resource	Sacramento, CA, typical year
Supply Chain and Logistics	Sacramento, CA
Grid Mix	California state-wide average forecasts, 2020–2050
Building Construction Type	IBC Residential Type III, volumetric modules
Occupancy	Two people, residential
Building Design Requirements	Sacramento, CA, 2016
NZE Construction Cost Premium	Northern California market, 2015

- For the Methodology I section, pertaining to cost compression of NZE strategies, we considered the following learning models (as visualized in the figure below) and their relevant parameters:
    - The Cumulative Average Model:
        - Number of product development iterations or attempts (full cycles)
        - Starting incremental cost of NZE strategies
        - End-of-year target incremental cost of NZE strategies
        - Maximum annual learning rate opportunity.
    - The S-Curve Model:
        - Annual production volume
        - End-of-year target incremental cost of NZE strategies.



- Two widely used learning effect models also applied to incremental cost of NZE strategies; see Appendix A. For the Methodology II section, pertaining to LCA, the following is a nonexhaustive list of embodied impact parameters that we considered (as visualized in Figure 3):
    - Embodied emissions of products (ISO 14044: modules A1–A3)
    - Emissions associated with vehicle miles traveled during the construction process (module A4)
    - Emissions associated with construction material waste (module A5).

- Operational impact parameters:
    - Refrigerant R-410a leakage from 30-year service operation (module B1)
    - Emissions from 30-year electricity and gas consumption (module B6).

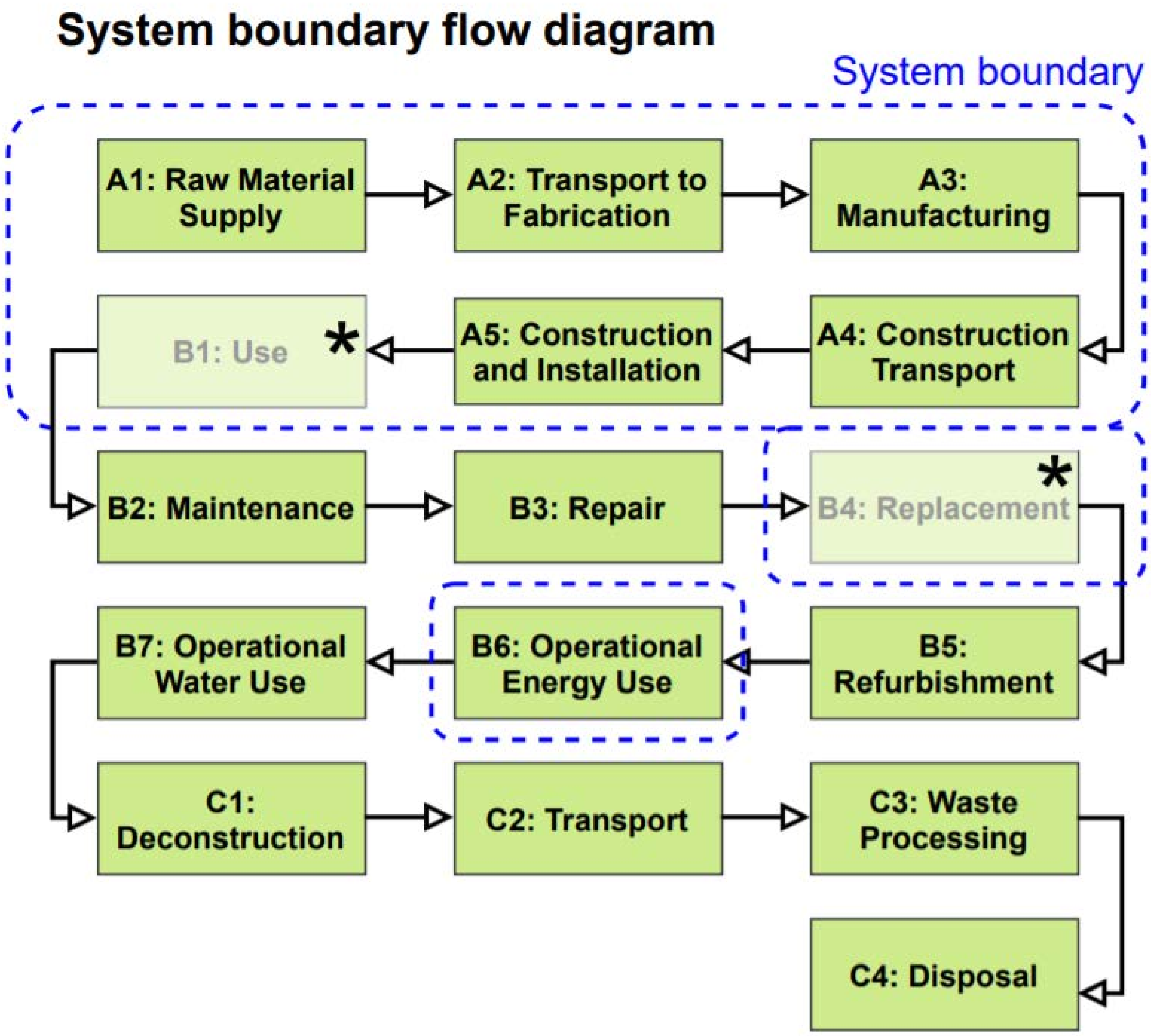


Figure 3. LCA system boundary flow diagram

* Modules B1 and B4 had selective exclusions in scope; see Appendix B

The system boundary of the LCA was aligned with "whole-building carbon" impact assessment, including both embodied GHG emissions from products and emissions from building energy use during a 30-year service period. The system boundary can be thought of as "cradle-to-site," plus operational energy. "Cradle-to-site" means that in addition to product data (available through means like an environmental product declaration, or EPD), we include emissions relating to the efficiency of construction for industrialized construction. A complete list of assumptions and modules included can be found in Appendix B.

3 Methodology I: Applying Learning and Experience Curves to Predict Future Cost Reduction of NZE Strategies

3.1 Applying to Products and Systems With Advanced Manufacturing

Learning and experience curves have been around since the early 1900s and have been used to model productivity, efficiency improvement, and per-unit cost reduction based on learning experience. T.P. Wright studied the variation of cost with quantity beginning in 1922 and described a basic theory for obtaining cost estimates based on repetitive production of airplane assemblies (Wong 2013). The Wright model shows that each time the production volume annually doubles, the cost per unit is reduced by 5%–30%. For example, in 1936, the aircraft industry had already demonstrated 20% cost reduction per unit per year by employing highly efficient advanced manufacturing tools and optimizing the supply chain (Wright 1936). More recently, studies by Our World in Data have validated that learning and experience curves have been fundamental in driving down the price of solar photovoltaics (PV) modules (Roser 2020). As shown in Figure 4, with each doubling of installed capacity, the price of solar modules dropped on average by 20.2%. This is the “learning rate” for solar modules. The applicability of the learning and experience curves to predict future costs of solar energy technologies was predicted in a 1980 NREL study, *An Investigation of Learning and Experience Curves* (Krawiec et al. 1980). We benefit from two major takeaways from that report:

1. Learning rates vary substantially among industries, products, and types of work.
2. In most industries (in addition to direct labor learning), tooling changes, adopting advanced manufacturing approaches with redesign of production methods, and improved management techniques contribute to cost reduction.

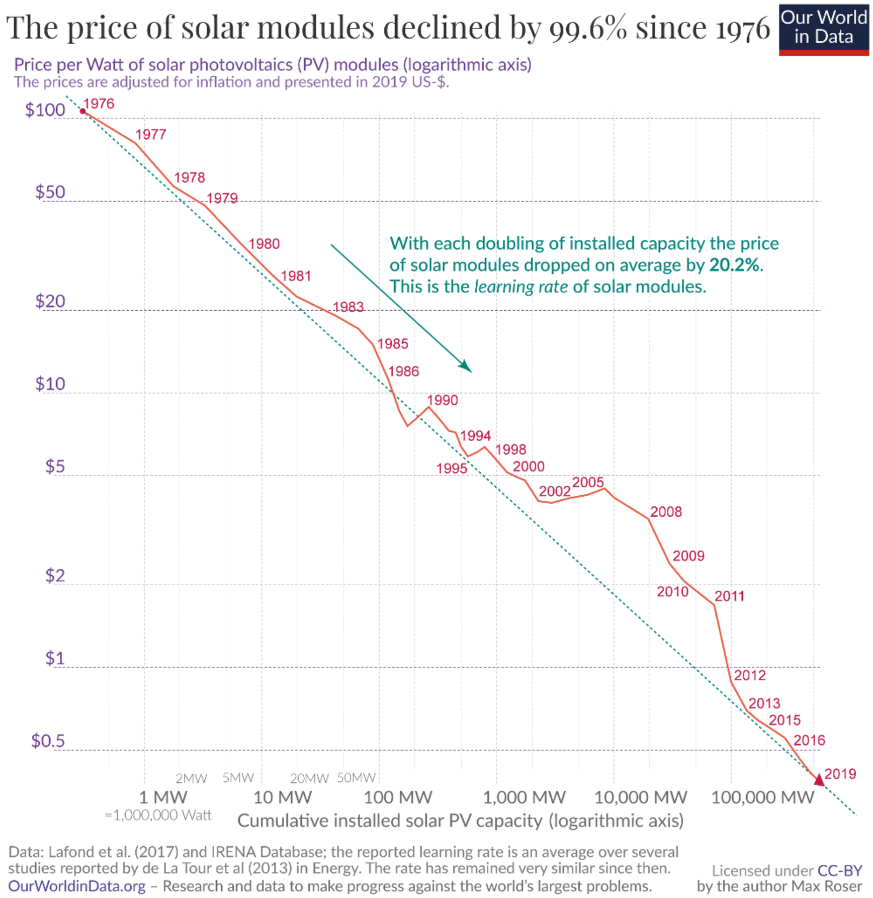


Figure 4. The price of solar modules has declined by 99.6% since 1976

Figure from OurWorldinData.org

3.2 Applying to Products and Systems With Industrialized Construction

The principles of a learning curve, which have been used effectively in manufacturing, can also be used in construction (Sundaram 2015). A recent seminal paper, "Learning curves in construction: A critical review and new model," provides a point of departure from the widely used Wright model to put forth a model that is suitable for the modern construction industry as it accommodates for complexities, inefficiencies, lower productivity, and forgetting (Srour et al. 2016). In the traditional site-built construction industry, the learning rate has historically been 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 (Barbosa et al. 2017), industrialized construction approaches such as producing modular building units in off-site factories have proven to maximize efficiencies and quality while reducing cost and speeding construction. A recent McKinsey report highlights that industrialized construction approaches lead to economies of scale—one of the key drivers of cost savings. This requires large-enough factories as well as sufficient output to ensure repeatability and learning to achieve a rapid and substantial step-up in productivity to allow an off-site factory to produce and deliver approximately 1,000 dwelling units per year. As shown in Figure 5, it takes a 5-fold increase in dwelling units from 1,000 to 5,000 to achieve a 5% boost in productivity. We see two major takeaways from Figure 5:

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

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

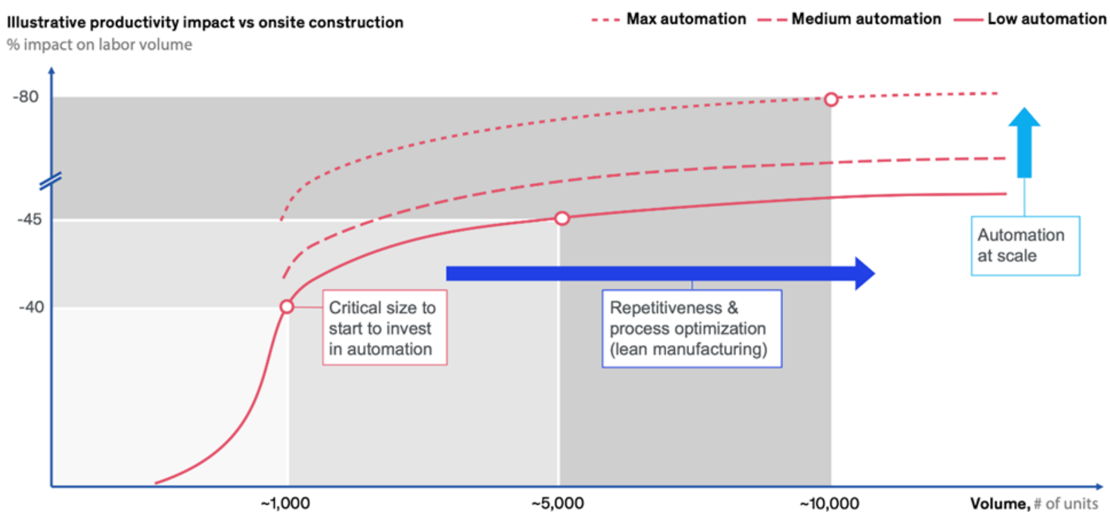


Figure 5. Productivity impact from economies of scale implementing industrialized construction as the production volume increases from 1 dwelling unit to 1,000 dwelling units to 10,000 dwelling units, catalyzed by learning

Figure from McKinsey Global Institute

3.3 Applying to Volumetric Modular Dwelling Units Across Three Phases

Based on (1) the manufacturing industry's widely used standard models for learning and experience such as the Wright model, (2) recent model developments in the construction industry, and (3) the cost reduction opportunities from industrialized construction, we have applied appropriate learning rates for three phases of a proposed development road map for volumetric modular dwelling units. The development road map has been developed with NREL's industrialized construction partners such as modular builders who own and operate large manufacturing facilities or off-site factories. As primary stakeholders, modular builders can leverage this road map for future strategy planning to invest and allocate necessary resources in their large manufacturing facilities or off-site factories in a way that encourages labor learning and increased productivity, doubles the annual production of dwelling units to reach an annual production volume of 10,000 dwelling units by year 15, and achieves significant per-unit cost reduction with higher learning rates in the downstream phases. The three phases are as follows:

- **Pre-Build Product Development Phase (2016–2020):** In this early pre-build design and prototyping phase, a modular builder's dwelling unit (with novel products and systems) undergoes iterative product development prior to commencing production at scale in a large, industrialized construction facility or off-site factory. We use the Cumulative Average Model, which stipulates that the greater the number of attempts made to perform a task on a standardized unit, the time taken to complete that task and the unit cost will decrease. The model lends itself to this phase as the task of product development recurs as the same unit goes through multiple design iterations or attempts over a period. *The learning rates applied for this phase is in the range of 20%–25%.* The factors determining the exact learning rate in this phase include integrated product delivery principles such as design for manufacturing, assembly, and installation (DfMAI), pilot testing in smaller prototyping facilities, optimizing the design to incorporate plug-and-play strategies that can further reduce on-site labor, and making informed design decisions to increase standardization by installing solar PV, battery, and mechanical equipment as prepackaged systems. It should be noted that this phase's high learning rates are influenced by nonproduction factors. There is an opportunity to achieve significant cost reduction by simplifying the design, lightweighting the dwelling unit, reducing number of unique or redundant parts, reducing variability in components, and optimizing system selection. See Appendix A for details on major assumptions, learning rates, and per unit annual cost reduction opportunities.

- **Industrialized Construction Phase (2021–2025):** In this phase of development, the predesigned standardized dwelling unit will be produced at scale in a large, industrialized construction facility or off-site factory. We use the S-Curve Model that assumes a gradual build-up in the early stages of production. This build-up is typically attributed to personnel and procedural changes as well as time needed for new machinery set-ups that occur early in the production process. The top of the curve indicates the cost reduction behavior in this phase. There is a slow build-up period before the worker or organization can be fully proficient in accomplishing the task. *The learning rates applied for this phase is in the range of 3%–10%.* The factors determining the exact learning rate in this phase include industrialized construction innovation through off-site methods such as prefabrication and modularization as well as opportunity for continuous improvement and quality assessment just by building the dwelling units in a controlled factory environment. The ability to achieve a higher learning rate in this phase is inhibited by the fact that industrialized construction is not advanced manufacturing yet, especially held back by minimal productivity gains and low automation. Due to the same reasons, we assume that the production volume will double over a span of four years in this phase, instead of doubling annually. More precisely, the factory would need to produce and deliver a minimum of 400 dwelling units annually by 2025 to benefit from this phase's learning rates. See Appendix A for details on major assumptions, learning rates, and per-unit annual cost reduction opportunities.

- **Advanced Manufacturing Phase (2026–2030, and beyond):** With higher productivity gains, increases in integrated project delivery, data-driven supply chain optimization, increases in adoption of automation and manufacturing tools, and investment in multiple large manufacturing facilities, the annual production volume of dwelling units could annually double for the entire duration of this phase. We use the S-Curve Model that assumes a period of peak performance in the latter stages. The bottom half of the curve indicates the cost reduction behavior of this phase. There is a significant improvement in production time in this phase due to repetition of the process. The trailing-off effect is referred to as the slope of diminishing returns after a worker or organization has reached maximum efficiency. *The learning rates applied for this phase is in the range of 15%–30%.* Multiple large manufacturing facilities would need to produce and deliver a minimum of 10,000 dwelling units by 2030 annually to benefit from this phase's learning rates. However, the productivity increase and cost reduction benefits would begin to approach the limit even if the annual production volume continues to double beyond 2030. See Appendix A for details on major assumptions, learning rates, and per unit annual cost reduction opportunities.

3.4 Incremental Costs of Novel NZE Building Products and Systems

As an emerging affordable housing solution, Vermont Energy Investment Corporation (VEIC) assessed market readiness for "zero-energy modular" buildings and trends across many U.S. states. A trend in affordable housing with NZE strategies has been seen for residential, mainly in accessory dwelling units and single-family detached homes (Juliette and Donovan 2019). According to a recent VEIC report, affordable housing with NZE strategies combine the benefits of no to low energy costs with the efficiencies of modular construction. All-electric and highly efficient, affordable housing with NZE strategies is often outfitted with rooftop solar arrays and use about as much energy as they produce each year. However, as mentioned previously, there is untapped potential for affordable, NZE housing to expand and grow in the United States. There has been limited investigation of trade-offs between site-built and industrialized construction from the perspective of reducing the incremental cost of NZE strategies.

Numerous collaborative efforts between local and state governments, nonprofit organizations, and industry entities in the United States are failing to deliver the 1.8 million housing units per year needed to meet the housing demand (Khater et al. 2018). More precisely, the annual average U.S. supply deficit of 370,000 housing units has led to the cumulative need of 3.8 million units to match long-run demand (Khater et al. 2021). Furthermore, only a small fraction of the 1.8 million housing units per year are produced and delivered to be NZE. According to Team Zero's 2019–2020 *Zero Energy Residential Buildings Inventory* for the United States and Canada, there are only 27,965 NZE dwelling units (including single and multifamily units) (Team Zero 2021). Therefore, the supply deficit is even larger for NZE dwelling units. With the growing push for decarbonization and electrification of households in the United States (Billimoria et al. 2018) and the need to achieve an overall goal of 50% reduction in U.S. GHG pollution by 2030 (Fakhry and Yeh 2021), the only path forward is for all new 1.8 million units per year to employ NZE strategies, and for all of today's aggregated supply deficit of 3.8 million units to be produced and supplied as grid-responsive, low-carbon dwelling units.

A major barrier for the construction industry to deliver on this target has been the incremental costs of NZE strategies added to the total construction cost of housing projects. A recent report on an NZE site-built rental housing community in Spring Lake, California shows that the incremental cost to achieve NZE was 8% of the total construction costs. The incremental cost in this case study was found consistent with passive house projects in the United States, which typically cost about 2%–10% more than conventional homes, depending on project size, location, and furnishings (Passive House Institute U.S. 2015). As shown in Figure 6, NZE strategies that make up this incremental cost include an energy-efficient and airtight envelope with quality insulation, high-efficiency HVAC and water heating equipment, ENERGY STAR® appliances and LED lighting package, and solar PV system.

Measure	2008 Title-24 Basecase	Spring Lake Specifications	Base Cost	Actual Project Cost	Incremental Cost
Envelope					
Exterior Wall Construction & Insulation	2x6 R-19 16"oc	2x6 R-21 16"oc	$21,435	$28,121	$6,686
Foundation Type & Insulation	Slab, uninsulated	Slab, uninsulated	Same	Same	$0
Attic Insulation	R-38 attic insulation	R-49	$22,580	$28,276	$5,969
Roofing Material	Comp shingles, CRRC-certified, w/ radiant barrier	Comp shingles, CRRC-certified, w/ radiant barrier	Same	Same	$0
House Infiltration – Blower Door Test	7 ACH50	4 ACH50	$0	$22,994	$22,994
Glazing	U-value = 0.40, SHGC = 0.40	U-value = 0.29, SHGC = 0.19	$0	$8,600	$8,600
Thermal Enclosure Checklist / Quality Insulation Installation	No	Yes (sealing at top/bottom plates, quality insulation, etc.)	$0	$3,400	$3,400
HVAC Equipment					
Heating Type & Efficiency	Single-speed heat pump: SEER 13, HSPF 7.7	Altherma inverter-driven heat pump: SEER 13, HSPF 11	$141,196	$405,304	$264,108
AC Type & Efficiency					
Heating & Cooling Distribution	Ducted	Ducted	$349,816	$349,816	$0
Hot Water Production		HW storage tank	$0	$86,956	$86,956
Duct Location & Insulation	R-6 ducts located in attic	Conditioned space: Dropped soffits (flats), buried ducts (townhomes)	$0	No change with Daikin system	$0
Mechanical Ventilation	Exhaust fans per ASHRAE 62.2	ENERGY STAR exhaust fans per ASHRAE 62.2	$17,136	$29,084	$11,948
ENERGYSTAR HVAC Contractor Checklist	No	Yes	$0	$21,867	$21,867
Return Air Pathway Vents at Bedrooms	No	Yes	$0	$28,508	$28,508
Water Heating Equipment					
Water Heater Type & Efficiency	Gas storage: 0.575 Energy Factor. Includes gas line	Altherma heat pump: 2.4 Energy Factor	$67,300	$0	-$67,300
Evolve Shower Heads	No	Yes	$0	$5,464	$5,464
Appliances & Lighting					
ENERGYSTAR Appliances	None	Dishwasher & Refrigerator	$0	$6,200	$6,200
Lighting Package	~1/2 fluorescent, ~1/2 incandescent	~1/3 fluorescent fixtures, ~2/3 LED A-lamp bulbs	$81,600	$187,800	$106,200
PV System					
PV System 209 kW DC	None		$0	$973,351	$973,351
		Subtotals:	$701,063	$2,185,741	$1,484,678
		Incentives/Rebates:	$0	-$408,516	-$408,516
		Estimated Total Hard Cost Premium:	$701,063	$1,777,224	$1,076,161
				Total Construction Cost:	$13,970,997
				Cost Increases:	8%

Figure 6. Incremental cost for NZE strategies for Mutual Housing California's Spring Lake project

Table values from Mutual Housing California (2018)

3.5 Predicting Future Costs of NZE Strategies Across Three Stages of Development

We applied appropriate learning rates and models (following Methodology I) for each phase (from Section 3.3) to a range of novel building products and systems to be integrated into the predesigned dwelling units, such as subassemblies of components, pods, and panels, especially those associated with NZE strategies listed in Figure 6 (see Section 3.4). *Based on our assumptions, a modular builder who successfully produces and delivers on the order of 10,000 NZE dwelling units annually by 2030 following the proposed development road map across three phases could reduce the 8% incremental costs of NZE strategies (compared to code minimum) to 1% incremental costs by 2030 owing to learning and experience curves alone.* At this point in time, the 1% incremental cost can actually be seen as a 7% cost advantage over code-minimum construction, as some codes will require net zero design at this date. For a full description of the results from Methodology I/Proforma I, see the "Results" section, Section 5, and Appendix A.

[3] California currently requires NZE design for low-rise residential new construction, and has set a goal to require NZE for new construction commercial buildings (including high-rise residential) by 2030, meaning that Title 24 2028 would require NZE for all residential buildings (California Energy Commission 2019; NORESCO 2017).

4 Methodology II: GHG Emissions Reduction

GHGs are emitted at various stages of a building's life cycle, from the production of materials to the end-of-life disposal of those same materials as described by ISO Standard 14044 for LCA. This report considered "embodied" emissions (those that come from the production, construction, and maintenance of building components, see Glossary) and operational emissions during a building's occupancy. A novel approach of this report is that operational electricity use and its associated grid emissions are considered with a high temporal resolution. This allows for the operational emission savings of technologies to be weighed against the incremental embodied emissions of those same technologies.

The assessment of emissions from the production and operation of the functional unit should be clear and transparent according to best LCA practice. Thus, information about the goals and methods of the LCA as well as the data used within the LCA will be declared next.

4.1 Carbon by Scenario

We used different scenarios for energy performance to associate emissions from energy consumption and from embodied carbon. The analysis period was 30 years, from 2020 to 2050. More details about the methodology can be found on page 18. We investigated a range of energy performance scenarios for the assembly of the scaling road map. The purpose of the energy performance scenarios is to assess the GHG impact of potential product development options for the Blokable product. Table 3 gives the description of each scenario.

Table 3. Energy Performance Scenarios

Scenario Name	Description
Prototype	A modular-built apartment based off a 2016 Blokable prototype design, hypothetically sited and completed for occupancy in the 2016 calendar year. Energy performance and components are to minimum code requirements of Sacramento. Energy consumption is a mix of two fuels: natural gas for domestic water heating and electricity for all other building uses.
ZED	Zero energy design only, no generation. All-electric building loads match the net zero energy scenario, but there is no energy generator such as PV.
NZE	Net zero energy scenario. All-electric building annual energy consumption matches annual energy generation of a 3.4-kW_{dc} PV system.
NZE+GEB5	Net zero energy plus grid-efficient 5-kWh battery scenario. The building load of the "ZED" and "NZE" scenario but with a coupled PV-battery system. The 5-kWh battery is grid-efficient and maximizes "self-consumption" of PV power while minimizing carbon during grid charging.
NZE+GEB10	A replica of the previous scenario but with a 10-kWh battery.

4.2 Goal and Scope

The primary goal of this LCA was to evaluate the carbon emission tradeoffs of NZE strategies and the cumulative effect of implementing those strategies in the mass production of building modules. A secondary goal was to benchmark an existing modular construction product (see “Functional Unit of Study” on page 3) and provide design recommendations for reducing the global warming impact of the modular product. This LCA represents Methodology II in the decarbonization road map for Blokable. The transparency of the data and method of this LCA means that it can also be adapted for other modular manufacturers. This LCA was not appropriate for comparative assertion with other builders and has not been designed as such.

The subject of study, when speaking with respect to LCA, is known as the functional unit. The functional unit was previously defined in Section 2.1 and is a 720 ft^2, one-bedroom dwelling unit. The scope of this LCA defined which building components were included in the assessment (Table 4). If components were excluded, a justifying reason was given that supports the goal statement above. The included components were: (1) structure system (superstructure), (2) envelope system excluding roofing system, (3) interior walls and partitions, (4) HVAC system, (5) other mechanical/electrical systems, and (6) the PV system. The excluded components were: (1) foundation system (substructure), (2) roofing system, (3) interior finishes beyond gypsum board, and (4) interior furnishings inclusive of home appliances.

Table 4. Scope of the LCA

The corresponding CSI MasterFormat number is given for each building system.

✔ Included	✖ Excluded
Structural system (superstructure) (Divs. 05 and 06)	Foundation system (substructure) (Divs. 03 and 31)
Envelope system (Div. 07), except roof system	Roof system (Divs. 07 10, 07 22, and 07 50)
Interior walls and partitions (Divs. 05 and 06)	Interior finishes (Div. 09)
HVAC system (Div. 23)	Furnishings including home appliances (Div. 11 30 and 12)
Other mechanical and electrical (Div. 26)	
PV system (Div. 48)	

Four categories of building components were excluded from the scope of the assessment in Table 4. We acknowledge that foundation and site work can be associated with significant upfront carbon emissions; however, site work and foundation design vary greatly by site conditions and are often not reported in embodied-carbon benchmark studies (Simonen et al. 2017). Excluding them from the modular scope of the LCA study made the LCA results more interpretable and applicable to wider circumstances. The roofing system was excluded from the scope because the roofing components could not be enclosed within the functional unit—not every dwelling module would have roofing components (i.e., middle floor modules). In this case, the authors did not deem allocation appropriate because the unit area of roofing per apartment would vary based on the building massing. Interior finishes and furnishings are commonly excluded in “core and shell” LCAs as these components contribute little on a mass basis. A concluding justification for the exclusion of the above components is that none of the studied NZE strategies involved the excluded components.

The system boundary of this LCA includes the "product" stages of the building life cycle supplemented with the emissions from the operation of the HVAC system. The LCA necessitated many methodological assumptions to treat biogenic carbon, grid electricity use, vehicle miles traveled, refrigerant leakage, and others. The system boundary is shown graphically in Figure 3. A full description of the system boundary and methodology is in Appendix B. The only environmental impact considered in this LCA was global warming potential (GWP), expressed in pound mass equivalent units to carbon dioxide (lbmCO_2e).

Because the LCA portion of this report included emissions during building operation, it was necessary to declare a period of operation; we chose 30 years. This length of time roughly matches the expected service lifetime for many building components, with two exceptions: lithium-ion (Li-ion) batteries and the HVAC+R components. These two systems are replaced every 15 years in the LCA. Additionally, a 30-year period started in present day is near the time horizon (year 2050) for the electrical grid forecasts from the Cambium data set.

4.3 Data Quality and Inventory

Most of the life cycle inventory (LCI) data come from Athena Impact Estimator for Buildings Version 5.4 (May 2019) database. The Athena LCI database comprises ISO 14040/14044-compliant unit process LCI data related to basic materials, building products and components, fuel use, and transportation. Most of these data are less than 10 years old. Athena LCI data were supplemented or updated with other transparent sources as needed. Details on the sources for LCI data are found in Appendix B under "Underlaying LCI Data." LCI data on the production of Li-ion batteries was added from a review of contemporary publications. Evidently, battery embodied emissions did not converge to a single value and a special approach was needed; see Appendix B.

4.4 Upfront Embodied Emissions

Upfront embodied emissions are those that arise in the "infancy" of the building's life cycle and come from sources such as product raw material supply, product transport, and product manufacturing. Mindful design and procurement of these products has been shown to yield meaningful carbon emission avoidance. There are active research themes about the advantages of industrialized construction over traditional construction regarding embodied emissions (Kamali and Hewage 2015). Rather than comment on this research activity, this road map is focused on providing guidance to modular builders on how to reduce embodied impacts of their existing product; see "Goal and Scope" section on page 18. A bill of quantities provided by Blokable for the functional unit informed the "upfront" emissions from material use in construction. The relevant bill of quantities is in Table 12 of Appendix B, and the material-related assumptions, including material waste, are under the heading "Methodology" of Appendix B.

4.5 Operational Energy Emissions Modeling

The combination of upfront embodied emissions and operational emissions make up nearly all of a building's life cycle emissions. Many LCAs conducted to date considered only how to achieve emissions savings through reducing material embodied carbon. An important research question in this road map was, "what emissions savings are possible through building demand-side management?" To answer this question, we undertook a detailed building energy model to simulate realistic hourly end loads on an electrical grid. In some case scenarios, a distributed energy resource in the form of a PV array offset carbon emissions from grid electricity consumption. In a few cases, a dispatchable battery was selected as a demand-side management strategy to further minimize grid carbon consumed.[4] Most importantly, the temporal forecasting of the Cambium data set allows the time of energy use to be a parameter in estimating emissions. This method demonstrated that load-shifting technologies led to notable carbon emissions savings, even if they had no net energy benefit (as is the case of a battery).

4.5.1 Building Energy Model

The objective of modeling operational energy was to quantitatively estimate the emissions savings possible over a 30-year period for NZE strategies. The first step in achieving this objective was to develop hourly building energy consumption data for the functional unit—a 720 ft^2, one-bedroom apartment. Because direct measurement is preferred over allocation (ISO 14044), our modular LCA scope required that an apartment inside the larger energy model be selected as typical for the group and have its energy use submetered. Free and open source, we selected the OpenStudio® building energy modeling software for this implementation. We modeled two building energy performance scenarios with the help of the public, corollary OpenStudio Standards. One model scenario, "Prototype Reference," was informed by business-as-usual energy design requirements in the appropriate Sacramento, CA, location for the hypothetical year 2016 (see Table 3). The other model scenario was heightened to "net zero design" and followed the recommendations of the forthcoming Zero Energy Design Guide for Multifamily (see Table 3). The single apartment was selected on a temporally sensitive definition of statistical "typicalness." The selected apartment was chosen by cluster center analysis on the 8760-dimensional space of hourly energy consumption. Greater methodology is provided in Appendix C.

[4] Additional demand-side management strategies such as building-integrated thermal energy storage and appliance load control could have similar impact reduction but were not included in the modeling due to the conceptual nature of the design.

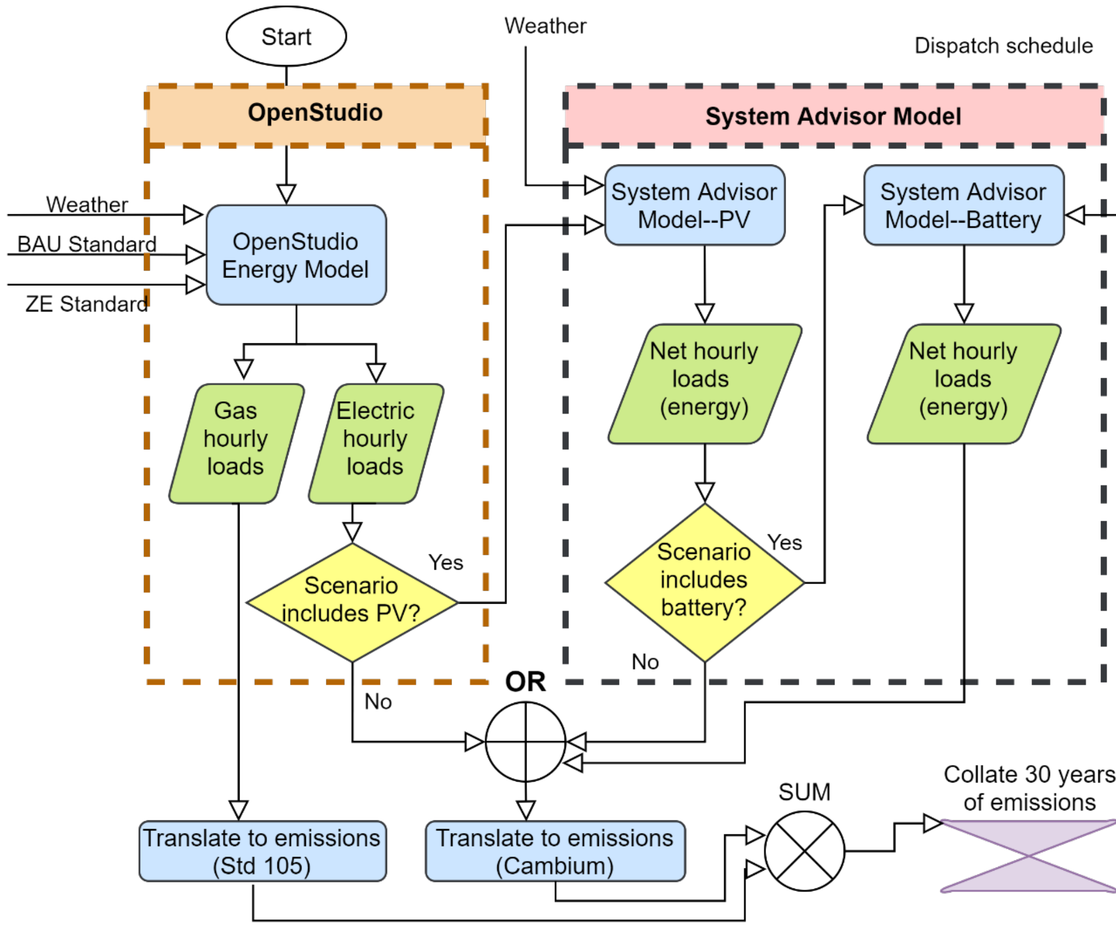


Figure 7. Analysis workflow used for operational energy emissions calculation

"ZE" refers to zero energy, "BAU" refers to business-as-usual, "Std 105" refers to ASHRAE Standard 105 (2014), and "Cambium" refers to the Cambium dataset from the 2020 Standard Scenarios (Gagnon et al. 2020). Figure by NREL.

4.5.2 PV and Storage System Model

After the hourly energy loads of the functional unit were generated as output from OpenStudio, the next step involved simulating a PV and storage system with this connected electrical load (Figure 7). The publicly available System Advisor Model (SAM) emulated the integration of PV and battery systems. In case scenarios that included PV, a 3.4-kW$_{dc}$ array provided sufficient annual energy output to offset the annual consumption of the "net zero design" building loads.

Case scenarios that included battery storage with PV were programmed to dispatch battery energy to minimize carbon emissions through energy arbitrage (Figure 7). This presented a technical challenge, because most dispatch applications intend to lower energy demand charges ("time of use" rates) or power demand charges (peak charges). Here, a heuristic "shortcut" method was used whereby the time-dependent carbon emission rates were recreated in a custom utility pricing scheme given as input to the objective cost function. The full details of this shortcut method for carbon-saving battery dispatch are given in Appendix D. The net result of this step was hourly grid end loads for each grid-efficient building case scenario.

4.5.3 Transforming Energy Use Into Emissions

The third step was to estimate carbon emissions attributable to the connected end load of the modular apartment functional unit. The Cambium data set represents standard scenarios of forecasts of grid operation from 2020 through 2050 with spatial granularity by U.S. state and temporal granularity of 1 hour. These forecasts include various GHG emission metrics. The "long-run marginal carbon emission rate" seen in Figure 8 was identified as the most appropriate metric for comparing carbon opportunity costs for the theoretical grid loads. To determine the annual carbon emissions of the given grid load, a product sum operation was performed, $\sum_{i=1}^{8760} L_i \cdot e_{i,z}$, where L_i is the end load for hour i and $e_{i,z}$ is the emission rate for hour i in year z. In our case example of a Sacramento location, we calculated this annual operational emissions value every five years from 2020 to 2050. This accounts for the fact that U.S. grids such as those in California are forecast to decarbonize with time as seen in the series "2020," "2030," and "2040" in Figure 8.

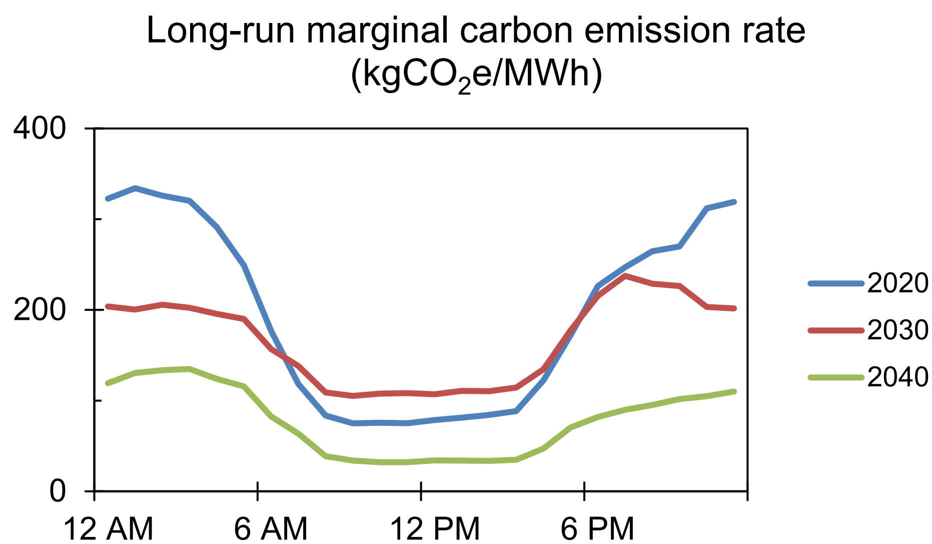


Figure 8. Annual profile of carbon emissions factors for statewide California averages

Data from Cambium

One case scenario, "Prototype Reference," includes a domestic hot water system heated by natural gas. It is important to note that whereas the emissions of electricity consumption vary dynamically (hourly and long-term), emissions of fossil fuel consumption are static. A site-to-source factor for natural gas of 1.09 was used and the emissions per source energy unit used was 147 lbmCO_2e/MMBtu per Table K2 of ASHRAE Standard 105-2014 (ASHRAE 2014). When considering a 30-year period of operation, the emissions from natural gas make up most of the cumulative emissions from operation. In fact, if these natural gas emissions were a category of their own, they would be the second highest contributor in the scope considered for the functional unit (steel superstructure included, foundation substructure excluded). While electricity decarbonizes in the Sacramento case, fossil fuel emissions remain stuck in place, widening the emissions gap. The temporal nature of emission factors emphasizes the importance of constructing all-electric buildings for a modular builder.

5 Results

The primary deliverable of this study is the carbon proforma road map for Blokable's product development. Outlined in the road map is a timeline for implementing recommended carbon reduction strategies, framed within three phases of product scaling. The road map achieves the cost-reduction goal described in Section 3 and the carbon-reduction goal described in Section 4. The recommended implementation reaches cost and carbon goals effectively by (1) prioritizing changes with the greatest return on effort and (2) taking advantage of efficiency curves from learning effects. The road map, if followed by a productized modular builder leveraging learning effects, leads to increasingly low-cost, low-energy, and low-carbon housing. In the case of Blokable's vertically integrated business model, the value generated from advanced housing performance and production efficiency may be reinvested in the company's R&D.

5.1 Results From Methodology I/Proforma I

Methodology I sequentially brought together two widely used learning and experience curve models. Using Methodology I, we found that a high-performance modular builder may reduce the incremental costs of NZE strategies from +8% to +1% by meeting the road map's conditions. The first road map condition is that a minimum of 10,000 annual NZE dwelling units are produced and delivered by 2030. The second road map condition is that the sequence of actions in the proposed development are followed.

Such a significant cost reduction for a set of NZE strategies could be possible by maximizing the learning rates for each phase and leveraging prototyping and repetition. The incremental costs of NZE strategies will continue to decrease as it approaches a limit in Figure 10. On the horizontal axis is Blokable's year of housing production. On the left vertical axis is the incremental first costs of NZE strategies as percentages, and on the right vertical axis is the annual production volume in number of dwelling units. Soon, some new residential construction will be required to be NZE, and the incremental NZE costs will become rolled into baseline building costs. Thus, the +1% incremental cost today could be seen as a 7% cost advantage over future typical construction. Additionally, government initiatives that incentivize peak energy savings via efficiency measures and installation of batteries, renewables, and electric vehicle chargers in the interest of reducing strain on the electric grid—California's Market Access program (Simon 2021), for example—are expected to become more widespread over time and further reduce the cost premium of these NZE technologies.

Appropriate learning rates applied to each phase influence the behavior of the cost curve in Figure 10. In the Advanced Manufacturing Phase at the right of Figure 10, marginal cost is reduced from +4% to +1% through economies of scale where the annual production volume of the dwelling units with NZE strategies annually doubles. The cost reduction made possible by industrialized construction and advanced manufacturing is a crucial strategy to transition into a decarbonized, energy-efficient, and fully electrified new building stock by 2030.

5.2 Results From Methodology II/Proforma II

A rigorous carbon accounting in Methodology II revealed the carbon-reduction benefits of following the proposed development road map. The conventional assessment of upfront embodied carbon from raw extraction, manufacturing, and transportation was combined with a high-granularity emissions model for operational carbon. This allowed a comparative assessment of the effectiveness of carbon reduction strategies that were recommended in the road map. The standalone comparison of building performance cases is presented next, followed by the decarbonization road map.

5.2.1 Building Performance Comparison

Multiple building performance cases were compared for their life cycle GHG emissions in Figure 9. Assessing each performance case for its technical difficulty and benefit to GHG reduction helped inform the sequence of the carbon proforma road map. The greatest absolute difference in carbon was between the "Prototype Reference" case and the zero energy design "ZED" case (Figure 9). Electrifying hot water heating systems proved to be a strong leverage point because the on-site combustion of natural gas represented 62% of all energy consumption emissions in the "Prototype Reference" performance case (Figure 9).

The introduction of PV generation in the net zero energy "NZE" case to offset the annual energy consumption of the "ZED" case further reduced carbon emissions between "ZED" and "NZE" in Figure 9. Notably, the nearly 20,000 equivalent pounds of CO_2 produced over the life cycle of the "NZE" case confirmed that NZE did not necessarily equate to net zero carbon. Further emissions reductions were possible with the introduction of a grid-interactive battery in the "NZE+GEB5" and "NZE+GEB10" cases. We submit, backed by data, that electrification of building loads together with energy efficiency is one of the most effective strategies for reducing building life cycle carbon.

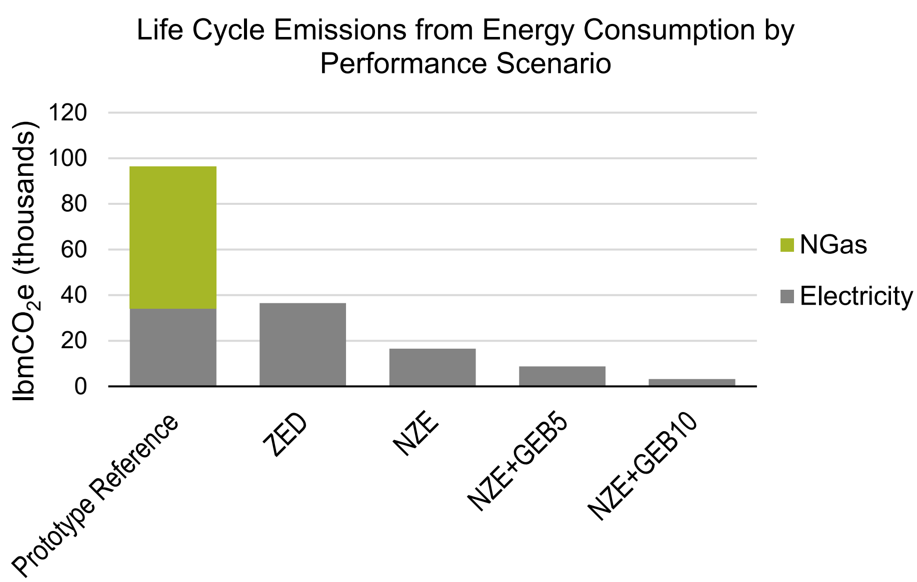


Figure 9. Carbon emissions from building energy use over 30 years across five performance scenarios considered: "prototype," "zero energy design," "net zero energy," "net zero energy plus grid-efficient battery 5 kWh," and "net zero energy plus grid-efficient battery 10 kWh"

5.2.2 Decarbonization Road Map

Life cycle emissions decrease year-over-year in the production years in the decarbonization road map in Figure 11. Like before, the horizontal axis shows year of housing production. On the vertical axis is the GWP of life cycle GHG emissions expressed as equivalent mass units of carbon dioxide. The overall emissions are broken down by the contributing category with operational emissions in orange and embodied emissions in shades of green and purple. As technologies and experiential learning mature onward from 2016, the life cycle carbon savings compound as production scales up. The cost and carbon benefits from a 15-year learning period is maximally leveraged in the 2030 production year when the greatest number of apartment units are produced. Ultimately, these compounded benefits lead to approximately a 60% reduction of emissions in the 2030 product life cycle over the prototype reference life cycle. The sequence of proposed NZE strategies follows.

Reference Production Year 2016

Each production year's life cycle GWP can be seen in Figure 11. To maximize the cost benefits from learning effects, the proposed volume of housing production is staggered into three phases: (1) "product development," (2) "industrialized construction," and (3) "advanced manufacturing" in Table 5. The initial prototype (production year 2016 in Figure 11) is provided as a reference and had life cycle carbon emissions of about 240,000 equivalent pounds of CO_2. In the next year, 2017, the road map enters the "product development" phase, during which the proposed strategies are independent of external technological development or market influence.

Production Year 2017

The first major emissions-mitigating action is to switch the housing product to all-electric, zero energy performance with installed PV in the production year 2017. This is prioritized over all other reduction strategies because of the compounding effect of 30 years of operation. In the reference prototype, nearly 40% of life cycle emissions, about 96,000 equivalent pounds of CO_2, come from the operational energy use. By the 2030 production year, after operational carbon has been minimized in the building design, life cycle emissions from operation are less than one-tenth of those of the 2016 production year. A comparison of life cycle carbon by different building-performance cases is given next.

Production Year 2020

The second action of the first phase is the "dematerialization" of the structural design starting in the production year 2020 in Figure 11. Dematerialization refers to the reduction in the mass quantity of a designed structure without sacrificing structural performance or safety. This change is next in sequence because after the reduction in operational energy in year 2017, the steel superstructure becomes the primary life cycle GHG contributor, even with its associated uncertainty.[5] The implementation of dematerialization, in Blokable's case, means that secondary steel structural elements such as joists and studs be replaced by their engineered-wood counterparts in a "hybrid structure" in the year 2020 in Figure 11. Wood structural elements serve the carbon goal in two ways: (1) they weigh less than steel elements, and (2) they have much less embodied emissions on a per mass basis than steel. These benefits were conservatively estimated because carbon sequestration, or the ability of plant-based materials to photosynthesize CO_2, was not included in the methodology of this study (see Section B.6 of Appendix B).

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[5] See Section B.4 in Appendix B and Appendix E.

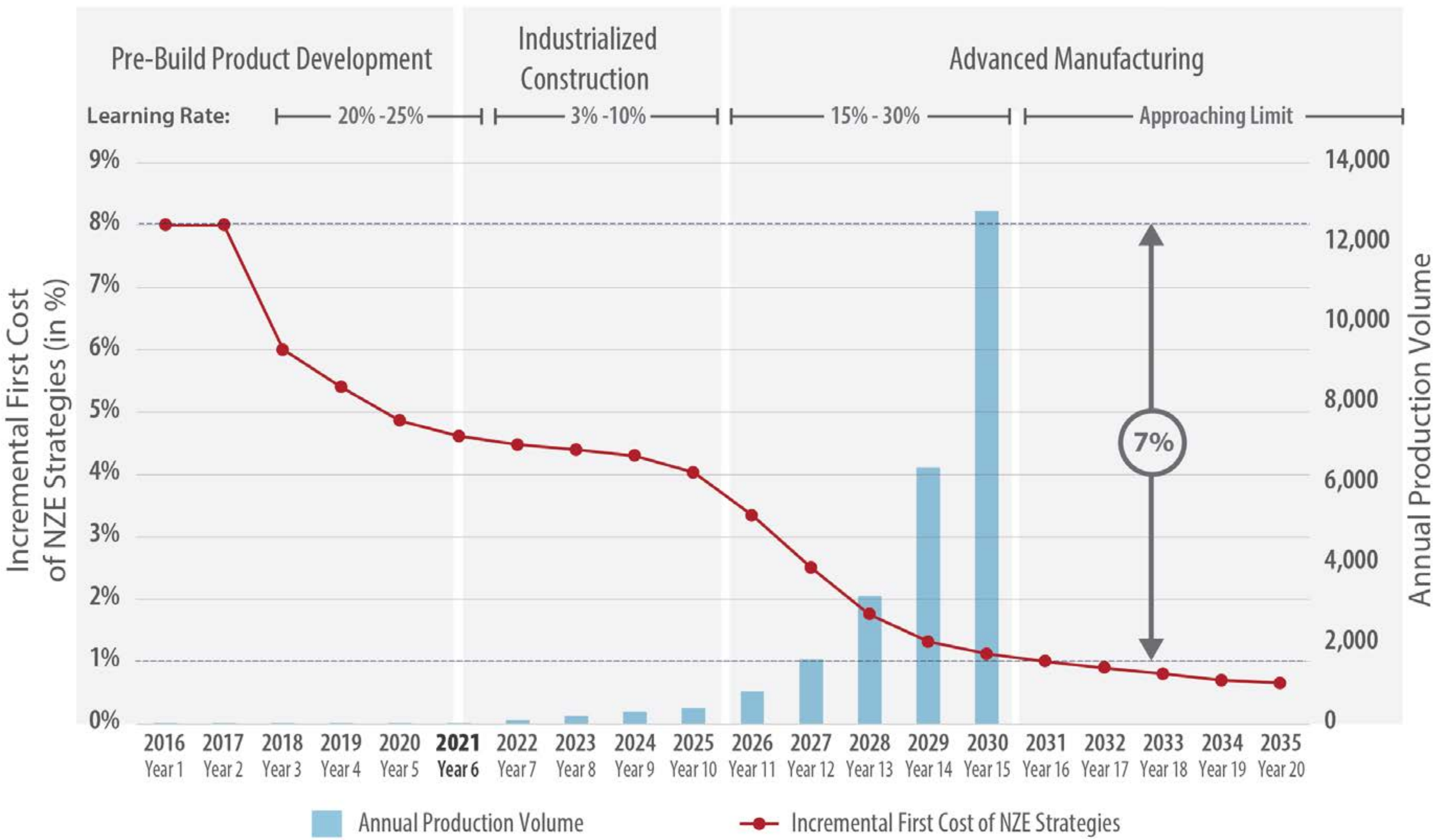

Figure 10. Projected cost curve for NZE strategies across the development road map. Case study analysis and intervention begins in 2021, 5 years after initial product development.

Figure by NREL

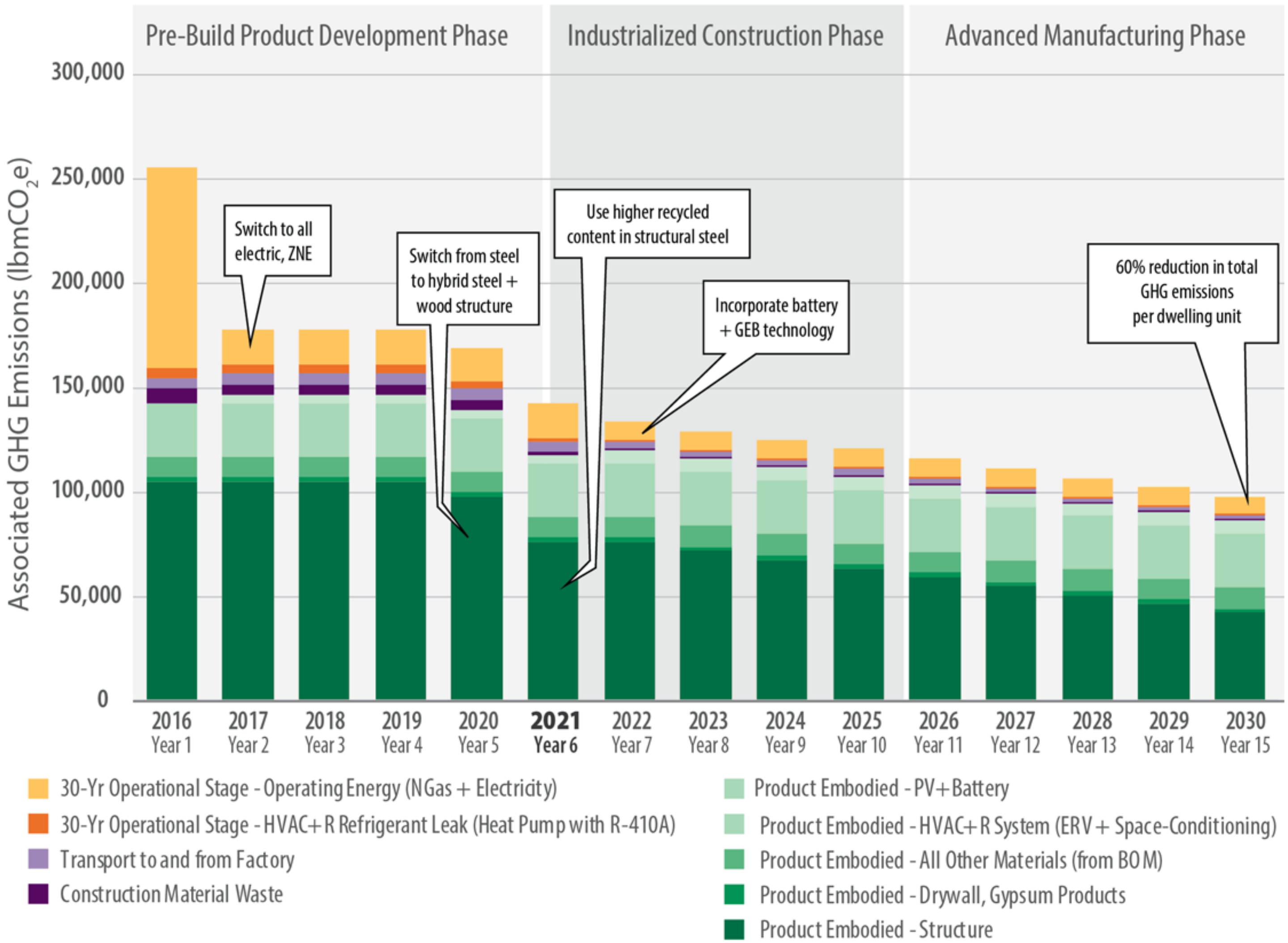

Figure 11. Decarbonization road map for 30-year life cycle + GHG reduction over three phases from 2016–2030, including “Pre-Build Product Development Phase,” “Industrialized Construction Phase,” and “Advanced Manufacturing Phase.” Case study analysis and intervention begins in 2021, 5 years after initial product development.

Figure by NREL

Table 5. Production Scaling by Production Year With Learning Rates

The road map for decarbonization assumes this timeline for production scaling corresponding to these learning rates.

Phase	Year	Annual Production Volume (Dwelling Units)	Learning Rates (Per-Unit Annual Cost Reduction Opportunity)
Product Development Phase in a Smaller Prototyping Facility	2016	1	NA
	2017	1	Up to 25%
	2018	1	Up to 21%
	2019	1	Up to 21%
	2020	1	Up to 21%
Industrialized Construction in a Larger Prototyping Facility	2021	1	Up to 20%
	2022	100	3%
	2023	200	10%
	2024	300	
	2025	400	
Advanced Manufacturing in Multiple Large Manufacturing Facilities	2026	800	17%
	2027	1,600	25%
	2028	3,200	30%
	2029	6,400	25%
	2030	12,800	15%

Production Year 2021

In the production year 2021 the road map enters the "Industrialized Construction" phase. In this phase, greater learning effects take hold as production ramps up exponentially year over year (Table 5). The challenges and benefits of mass producing the completed product design are the main concerns in this phase. This phase signifies a change in fabrication practices from prototyping to manufacturing at varying capacity.

The first recommendation of this phase is the procurement of low-GWP steel. At the time of writing, a differentiated market for low-GWP steel is emerging, brought on by regulatory influences[6] and market influences. EPDs, which are third-party-verified, can be used to compare a difference in the embodied emissions between manufacturers and even between mill locations. Blokable can achieve incremental GHG reduction by procuring steel from supply chains with the lowest documented emissions. The recommended implementation year of 2021 coincides with a greater individual buying power and synergistic market forces. From the production year 2021 and onward, Blokable will be increasing its volume of production and strengthening its relative

[6] The Buy Clean California Act was passed in July of 2021. The Act only applies to materials purchased for projects where a public California entity is the client. For materials purchased such as steel structural sections, it must be proven that their GWP falls below the established threshold as documented by a valid EPD.

bargaining power. Simultaneously, steelmakers will be increasing scrap input and consuming electricity from a cleaner grid mix.

Production Year 2022

In production year 2022 an integrated PV-battery system with dispatch is recommended. By this time, home battery technology will have improved, as will have supplier efficiency. The electric grid mix will likely undergo its largest transition around the year 2030 (see Figure 8). Around this time, grid resource rebalancing to accommodate new online renewables will mean a temporary spike in carbon emissions. A dispatchable PV-battery system will provide a GEB solution during this time of variability. Having a battery system included in every apartment unit produced will contribute significantly to life cycle carbon reduction in the years leading to and following 2030.

Production Year 2026

In 2026 the road map enters the "advanced manufacturing" phase where production and material process efficiencies are the main concerns. Learning benefits reaped from the previous 10 years of production continue to be further enhanced. GHG reduction comes from high material and labor efficiency with reductions to construction material waste as well as reductions to associated emissions from vehicle miles traveled due to regionalization of supply chain and electrification of fleet. External forces like the decarbonization of electrical grids in the supply chain translate to incrementally lower embodied carbon approaching the production year 2030.

5.2.3 Temporal Aspects of Embodied and Operational Carbon

The design decisions we make today have lasting effects on global climate change. The temporal nature of embodied versus operational carbon can be difficult to conceptualize. The upfront difference in embodied carbon between the "Prototype Reference" case and the "NZE+GEB5" is a lesser fraction of the total embodied carbon in Figure 12. However, during operation, the net GHG emissions diverge, and the "Prototype Reference" emissions become almost two-fold the "NZE+GEB5" case by the 30th year. By the 30th year, the life cycle carbon for the "Prototype Reference" has almost doubled its starting value while the life cycle carbon of the "NZE+GEB5" has remained almost steady. Therefore, the year of implementation of the suggested strategies has both immediate (year 0) and lasting impact (years greater than 0) on GHG reduction in Figure 12.

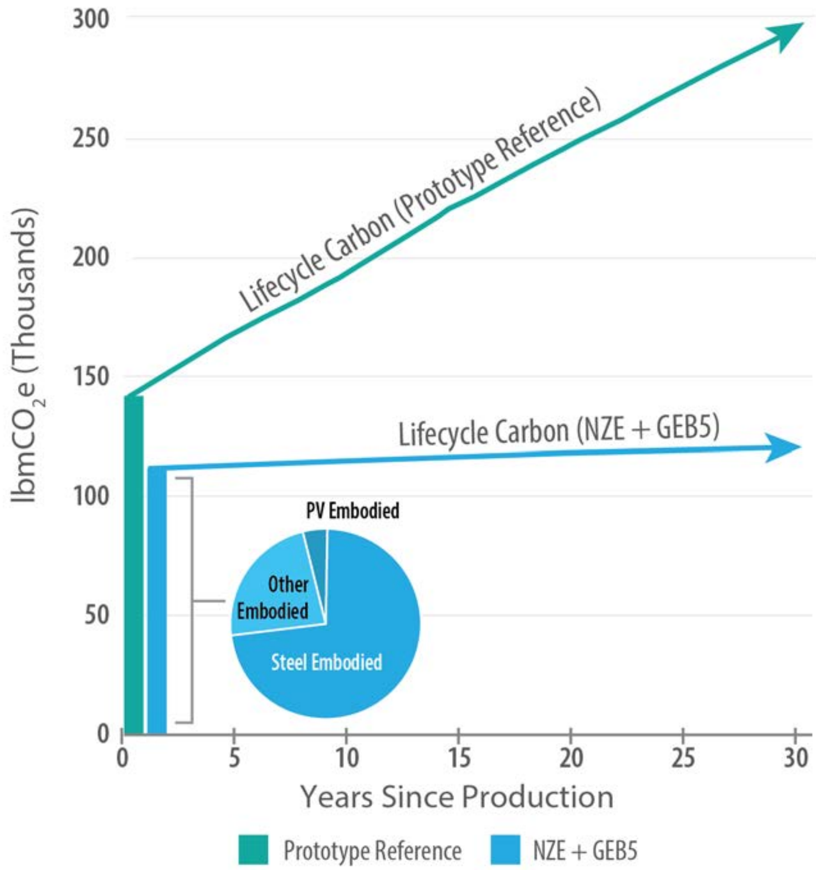

Figure 12. Temporal aspects of life cycle carbon emission for two case scenarios, "prototype" and "zero energy plus grid-efficient 5 kWh-battery"

Figure by NREL

5.2.4 Zero Carbon Balance Exercise

Renewable energy generation to offset grid-electricity carbon is an essential strategy to decarbonize buildings. In visiting each of the impact categories of Figure 11, it became apparent that the steel structure contributed the most of any material. As a conceptual exercise, the carbon surplus of the steel was compared to the carbon offsets of renewable and grid-interactive energy systems. This "zero carbon balance" exercise helps designers consider the relative weight of decisions regarding material systems and operational systems.

In order to put this into perspective, the relative emissions contributions of the steel structure versus the avoided emissions due to the use of solar PV and battery, Figure 13 directly compares the two at three snapshots during the road map period. The 2016 production year has no 30-year operational savings over the code-required baseline performance, and steel embodied carbon reflects the most recent decade of steelmaking. The 2025 production year sees reductions in steel GWP and quantity, and there are significant operational savings from a PV-battery system. Finally, in the 2030 production year, similar energy performance is achieved, but internal builder efficiencies and external forces have lowered the total GWP impact from steel to an even greater extent.

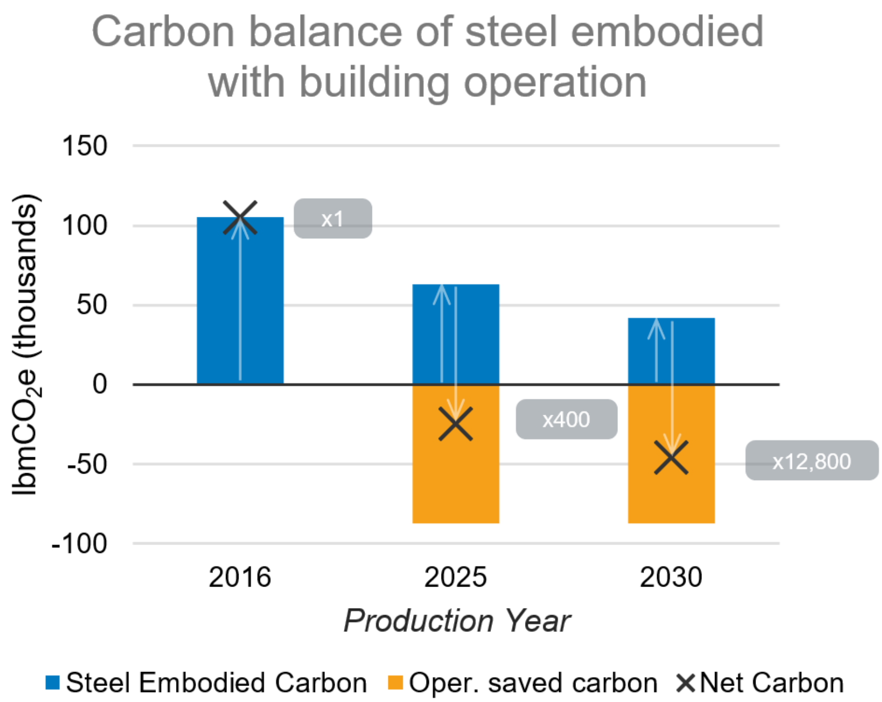

Figure 13. Projected steel embodied emissions versus operational energy emissions savings

To an even greater extreme, a sufficient capacity of renewable energy generation could offset all the embodied carbon of a dwelling unit. As we discovered, the quantity of carbon embodied in each unit necessitates a larger horizontal exposed surface area for PV than what is feasible for even low-rise multifamily buildings. For a 2017 dwelling unit, 26 kWdc of PV and 10 kWh of battery storage would be needed to "zero out" the total embodied carbon over 30 years with feasible generation for the Sacramento, CA, location. For the more conscientious 2030 dwelling unit, 16.5 kWdc of PV and 20 kWh of battery storage would be needed. For achievable solar cell and inverter efficiencies, this translates to 1,860 ft^2 and 1,180 ft^2 of solar panel area per dwelling unit, respectively—far too much for a 720 ft^2 dwelling unit. Again, the quantification of embodied carbon does not include foundation or site work, which would be expected to increase these figures significantly further. Thus, the authors determined that offsetting life cycle carbon would not be feasible to incorporate into the typical site area of a multifamily modular building. Additional emissions-reduction methodologies and/or carbon-capture strategies must be explored to compensate for the remaining (mostly building structure related) embodied carbon.

6 Discussion

As the electric grid decarbonizes, it becomes more and more environmentally effective to electrify all building systems. This is exemplified by the increasing difference in operational emissions projected for the "Prototype Reference" case versus the proposed "NZE" and "NZE + GEB" cases over time. **This proforma report could serve as a strategy guide for high-performance, productized modular builders. These builders can leverage the development road map for future strategy planning to invest and allocate necessary resources in their large manufacturing facilities or off-site factories.** In order to be well-positioned to achieve GHG emissions reduction, the modular builder should produce a consistent product and use lessons learned to adjust both its product and the off-site factory process. In planning future operations for a modular builder, developing a plan that considers improvement in product impacts over time is critical to the company's long-term environmental impact, and this process is made easier by homing in on the business's most impactful materials and processes.

Many companies are taking the plunge to commit to zero carbon—some by purchasing carbon offsets, and others by a combination of drastically changing their operations, manufacturing, practices, and business models. **For a modular builder, the key lies in translating road maps already laid out in terms of energy efficiency, and incorporating carbon-responsive GEB technology, factory efficiency and waste reduction, as well as low-embodied-carbon materials over time.** We have applied appropriate influencers to each phase of the proposed development road map to both embodied carbon and operational carbon.

As previous LCA studies have found, a building's structure usually contributes significantly to the overall carbon emissions—both upfront and total life cycle emissions. This case study's results are in line with that pattern—even without factoring in substructure—which led to the focus on steel embodied carbon. Upcoming and future carbon-emissions legislation will likely have significant impact on the timeline of steel's associated emissions reductions. For instance, "Buy Clean" acts across the country have begun to set emissions limits on various products, including steel, such that the purchase of materials with emissions outside these limits are not considered to be in compliance for certain project types. Colorado's House Bill 1303 (passed in 2021 and effective July 2022) requires EPDs provided for building materials (cement and concrete mixtures, glass, post tension steel, reinforcing steel, structural steel, and wood structural elements) on all public projects (Bill Track 50 2021). California, which seeks to implement its Buy Clean California Act by July 1, 2022 (CA.gov 2021), holds significant influence due to its vast size and population. The limits outlined in January 2022 could set the stage for the speed at which structural-steel-associated emissions ramp down both locally and, perhaps, nationally.

Therefore, a major opportunity ahead of modular builders gearing up to design, produce, and deliver 10,000 dwelling units built from structural-steel components is embodied-carbon reduction of steel. In order to be well-positioned to leverage this opportunity, these builders should specify HSS with higher percentage of recycled content (as per Buy Clean CA) during the Pre-Build Product Development Phase. Although this specification could be reflected in the product's bill of materials, there would be a need to actively engage with the regional or national steel supply chain to ensure these specifications are met as part of the procurement or purchase orders. **A commitment toward constant vigilance on the amount of recycled content in the steel components and/or their secondary production source can help modular builders with**

steel-framed dwelling units achieve significant embodied carbon reduction. As steelmaking moves in the direction of 100% recycled, 100% renewable-powered electric arc furnace (EAF) production, and as emerging production methods such as molten oxide electrolysis become widely adopted, such builders would be uniquely positioned to reach the lowest possible embodied carbon from their steel-framed products.

It is also important to note that the location of extraction and manufacturing, as well as the type of fuel/power used for transport fleets, has a significant effect on a particular product's embodied emissions, so the information in Appendix E should be considered when interpreting results and outlook. An additional opportunity that could be realized during the Advanced Manufacturing Phase is to plan a regional network of suppliers and factories with local workforce and optimized supply chain. This work also emphasizes the importance of choosing particular products wisely, including those used for structure and mechanical systems, while other products may not be as influential (e.g., wood framing). **To benefit from learning effects during the Pre-Build Product Development Phase to reduce construction material waste, modular builders should focus on materials with high waste factor such as drywall.**

Other opportunities, while smaller in impact compared to steel, include **reducing HVAC+R leakage embodied carbon through aggressive quality assurance/quality control, continuous improvement, continuous monitoring, easy access/maintenance, and reduction of refrigerant-line length**. The emissions impact of refrigerant leakage contributed to about 2% of life cycle carbon (and 5% of operational emissions); however, a centralized variable refrigerant flow system could contribute between 4% and 20% of total life cycle carbon, according to Hamot et al. (2020). After unitizing the space-conditioning system, refrigerant leaks contribute to less than 1% of total life cycle carbon. First of all, this points to the **use of unitized, rather than centralized, space-conditioning systems due to a lower relative length and amount of refrigerant piping when compared with centralized refrigerant distribution systems.** Although variable refrigerant flow systems can have low operational energy use when properly designed, their refrigerant usage and leakage potential tend to be outsized when compared to that of other high-performance systems, especially if high-GWP refrigerant is specified. **The opportunity to reduce refrigerant impact can be leveraged by builders with mechanical systems currently using high-GWP refrigerants (such as R410a) with a switch to a system that utilizes a lower-GWP refrigerant** (such as R32), although variable refrigerant flow technologies using refrigerants with near-zero GWP have yet to hit the market. Because this study considered a unitized minisplit heat pump system, further action could be taken by specifying future-looking unitized mechanical and plumbing systems with natural refrigerants (with supercritical CO_2 as a major contender).

Leveraging one demand-side management and GEB opportunity—adding a battery—allowed the builder to further reduce operational carbon. The battery-control logic was set to minimize emissions by maximizing "self-consumption" of site-generated energy and timing the dispatch of stored energy into high-carbon grid periods. The control logic was accomplished through a carbon heuristic described in Section 4.5.2, assuming that the algorithm aligned with grid emissions factors. Whereas actual electricity cost of production is correlated with grid emissions at a conceptual level, the realities of the regulated energy market complicate the correlation. For instance, battery charging at night is cost-optimal even though less of the nighttime supply comes from renewable generation. If only cost benefits alone of demand-side management are weighed, carbon benefits are missed in studies such as Buro Happold's "Battery Storage Study" (Buro Happold 2021).

Moreover, demand-side management and GEB opportunities expand to other technologies beyond the home battery considered here. Grid-interactive appliances, such as heat pump water heaters, washers, dryers, dishwashers, and others, can augment the ability of the dwelling unit to respond to electricity-grid characteristics. The study at hand used the example of a dwelling unit located in Sacramento. Because California's electrical grid already experiences high renewable penetration (solar, primarily), the impact of renewables and battery storage on-site would likely have lower GHG impact compared to if the unit were located in a state without much renewable energy on its grid. In relation to impacting marginal carbon, Clearloop, a cleantech startup, finds that "a watt of new solar displaces more carbon on a dirtier grid than it would on a cleaner one […] In California, where solar power already supplies a large and growing share of the state's electricity, 'a metric ton of carbon is avoided by building something between 50 to 80 watts of solar,' Zapata explained. 'In Tennessee or other more fossil-fuel-heavy regions, it's 30 to 40 watts of solar'" (St. John 2021).

Finally, in regard to significance of this study's findings, the roughly 60% carbon emissions reduction shown in Figure 11 is greater than the assumed 15% uncertainty of the LCI data (Appendix E). Hence, a manufacturer that successfully achieves the milestones of the road map could have strong confidence that the emissions avoided are significant.

6.1 Contextualizing Embodied Carbon

The goal of reducing the embodied carbon in this study fits into the larger context of rising concerns over the "locked in" global warming impact of newly constructed buildings. By nature of taking place upfront, the "upfront" embodied emissions have the most immediate impact on the environment and on climate change. Upfront embodied emissions make up a significant and immediate spike in GHG emissions, as seen in Figure 12, and are locked in the atmosphere for decades. Therefore, they are the most effective lever for meeting short-term climate goals in the context of new construction. Readers may wish to understand the context of a given embodied carbon value compared to the rest of the building field. At the time of writing, data on the embodied carbon of existing buildings were severely lacking compared to, for example, data on energy consumption. Nevertheless, recent efforts to benchmark upfront embodied carbon were made in the United States (Simonen et al. 2020) and in the United Kingdom (Johnstone et al. 2020).

Simonen et al.'s (2020) benchmark study included 61 multifamily building LCAs of various locations, forms, and scope. Some buildings were as high as 200 $lbmCO_2e/ft^2$ but, "the initial embodied carbon (LCA stage A) of low-rise (less than 7 story) residential building's structure, foundation and enclosure is typically less than [100 $lbmCO_2e/ft^2$]." Within the multifamily building type, all LCAs included "structure" in scope but some excluded "enclosure," "interior," and/or "foundation." With many inconsistencies inside the category the study's authors added, "...there is not sufficient data to state ranges with confidence" (Simonen et al. 2020).

Across the Atlantic, the Royal Institute for British Architects Climate Challenge enumerated benchmarks for current U.K. residential building practice at 250 $lbmCO_2e/ft^2$, with 2021 best practices at 200 $lbmCO_2e/ft^2$. The aspirational goal of 130 $lbmCO_2e/ft^2$ was set for the year 2030

(Johnstone et al. 2020). These numbers were for a 60-year lifetime and did not include operational carbon. The London Energy Transformation Initiative was more ambitious and instead marked 200 lbmCO_2e/ft^2 as the business-as-usual practice and 120 lbmCO_2e/ft^2 as aspirational for the year 2020 (Johnstone et al. 2020).

For the sake of comparison, the embodied carbon in this study for the appropriate comparative scope was 170 lbmCO_2e/ft^2 for the 2016 prototype and 80 lbmCO_2e/ft^2 for the aspirational 2030 production year. At the time of writing, there is no universal consensus for LCA scope, so readers are encouraged to read the documentation for each respective benchmarking source to identify scope gaps or to extrapolate results.

6.2 Limitations

We made every concerted effort to overcome limitations encountered in preparing this report. However, some limitations remain and should be noted. Conceptually, building operational performance is nondeterministic, and there is a wide range of available building products and materials. Thus, there are many limitations to projecting carbon emissions, carbon impact, energy use, and building productivity with respect to looking toward future building rather than a particular planned building.

For ease and interpretability, we simplified some of the temporal aspects of global warming potential through the emission of GHGs. We followed the convention of using a "static" global warming potential based on the 100-year climate horizon of 1 kg of CO_2 (GWP100). This convention collapses the time-sensitivity of global warming into a single value in a base year. We assume that all embodied carbon, whether from "upfront" or "use" stages, is "point" emitted in the same base year when, in reality, emissions from different building stages would be staggered. For example, we assume that for a dwelling unit produced in 2022, all embodied carbon emissions are emitted as a single point in the base year of 2022.

Many building products' data were sourced through Environmental Product Declarations (EPDs), a subtype of an LCA. EPDs rely on LCI data, which are continuously updated for temporal and regional representativeness. The temporal and regional applicability of the LCI data is listed in Table 13 of Appendix B. Some LCI data for developing technologies are expected to change in a matter of years. As a result, the LCI data in this report should be considered valid only for a finite period after publication—for reference, five years is the period of validity for some EPDs. Some building components and technologies mentioned do not have EPDs available, and their associated emissions must be presumed to be like products with similar material composition and function. For instance, home battery EPDs are not available, so electric car batteries were used as a stand-in. See Appendix B.5 for further discussion.

As with any enterprise growth plan, assumptions and market conditions can vary widely from the present to the future. Predicting the scaled development track of the modular builder must be revisited year-after-year, as production and waste targets may vary from original plans. The builder's location(s), level of automation, growth rate, and market context will also influence the company's ability to remain on track to meet specified targets.

Electric grid decarbonization scenarios, such as those presented in the Cambium data set, are expected to be updated and amended as infrastructure and markets change over time. Indeed, there have been yearly updates to the original 2015 publication of the standard grid scenarios. The forecasts are based off least-cost models for regional energy deployment; values closer to the year of publication have higher confidence than those further in the future. For additional information on Cambium's sources and uncertainties, see Gagnon et al. (2020).

This study extrapolated future GWP impacts for some influential building products into the future (see Table 14 in Appendix B.6). The level of decarbonization of many products, including that of steel, is dependent on both internal processes and external factors like the mix of renewable generators in the electrical grid. For steel products sourced from electric arc furnaces, manufacturing energy input is very high, so its manufacturing emissions depend highly on grid resources. Additional steel-associated limitations include the unknowns of future extraction and steelmaking technologies, as well as the availability and quality of recycled steel scrap throughout the upcoming decades.

LCA Boundaries and Scope

We deemed the LCA system boundary and scope to be appropriate for the stated goal of the LCA in Section 4.2. We would also like to reemphasize some of the limitations relating to the LCA boundaries used in this report—refer to Figure 3 for a graphical representation of the system boundaries. The embodied carbon tally did not include all "Use" stages in the building life cycle: "Maintenance," "Repair," and "Refurbishment" were excluded. "Use" and "Replacement" stages were partially included as is discussed in Appendix B. The embodied carbon tally excluded "End-of-Life" stages, including recycling. Some nontraditional materials require energy-intensive recycling or disposal at end of life—e.g., battery recycling on the order of 33 $lbmCO_2e/kWh_{cap}$ (Emilsson and Dahlhöf 2019).

The upfront emissions associated with building foundations are often significant, and the large quantity of cement in foundations is largely responsible. However, foundation design is difficult to control for in a comparison because it is extremely influenced by site conditions and location-specific lateral load design requirements. Because this study is focused on modular building methods, and particularly strategies that can be accomplished within the factory, structural foundations are excluded.

Still, concrete remains a significant contributor to GHG emissions in essentially any structure it is used in, and the following two strategies should be utilized to minimize the environmental impact: (1) specify low-carbon concrete design mixes, and (2) ensure that the structural engineer works with the integrated design team to minimize the amount of concrete required and ensure that all concrete design strengths are up to date. Interested readers will note that Senate Bill 596 in California, enacted in September 2021, laid out requirements to achieve net zero carbon emissions from cement production by 2045, with implementation by the California Air Resources Board (Jackson 2021). Considering that interim goals included a 40% reduction in carbon emissions by 2035, new foundation work in California is likely to decrease to much lower embodied emissions throughout the timeline of this study.

Occupant behavior and energy consumption modeled using the methods described in Appendix C did not explore the full range of potential occupant behavior; therefore, building energy consumption would vary significantly under different operational and occupant conditions. This propagated to the algorithms that governed battery storage and dispatch; carbon savings from battery storage may vary under different operational conditions. The uncertainties of the building energy systems are presented in Table 22 of Appendix E.

6.3 Future Work

Although this effort was able to employ the defined methodologies to explore one business case for which steps toward building decarbonization could generate profit and an economy of scale, there are several additional situations and details that could be explored further and updated in the future. Included in this list is applying the proforma to a range of examples of productized, prefabricated builders—perhaps builders using stick-built modular construction methods or panelized methods, and builders in different locations throughout the country. We would also like to delve into details of factory operation, identifying main drivers of GHG emissions—e.g., location of factory, organization of factory line, tools required for assembly both inside and outside the factory, worker proximity to factory vs. factory proximity to jobsite, number of production facilities, and proximity of factories to main construction materials sources. Because many of these variables relate to vehicle miles traveled, future study could include different scenarios for fleet electrification and decarbonization to better understand comparative long-term impact of each measure.

Projections of future electrical grid mix should also be explored and updated as time reveals trends in the production of local electrical power and the presence of grid-scale energy storage. Updated predictions can also be implemented as local, state, and federal regulations are introduced, as product EPDs become more widely available, and as patterns of electricity usage evolve due to grid-interactive appliances, usage of batteries, updating of electricity rate structures, and prevalence and charging patterns of electric vehicles. Building location is also expected to change the overall impact of implementing renewable and battery technologies, with these technologies contributing more significantly in locations with lower renewable penetration in the electric grid.

In the interest of reducing life cycle GHG emissions and planning for longer-term improvement, future study could explore beyond the typical 30-year study period, as well as incorporate end-of-life scenarios. These scenarios could consider design for disassembly, reuse and recycling of parts and materials, and rehabilitation at the end of the building's useful life.

Finally, in order to easily implement the proposed decarbonization proforma, the calculation and optimization tools should become more integrated. This would mean integration of LCA software and building energy modeling software—perhaps similar to the prototype for architectural firm EHDD's "Early Phase Carbon Assessment Tool," or EPIC, which outputs projected embodied and operational carbon side-by-side, albeit using high-level assumptions and relatively crude calculations to date. This type of tool could integrate the available information within Cambium and SAM to provide grid-interactive outputs and dynamic electric-grid scenarios without the need for external postprocessing. Overall, the proposed methodology can act as a useful tool for productized modular builders to plan their operations and evolving product, and it could be leveraged more widely and more easily with the proposed technological augmentations.

Glossary

Term	Definition
Biogenic carbon	Biogenic carbon is the material that living organisms produce through direct physiologic activities (e.g., wood, agricultural crops and wastes, wool, animal manure, algal residue). For the intent of this work, biogenic carbon principally deals with Harvested Wood Products and Engineered Wood Products used as building materials.
Embodied carbon (def. per Carbon Leadership Forum)	In the building industry, this refers to the GHG emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials.
Grid-interactive efficient building (GEB)	A GEB is an energy-efficient building that uses smart technologies and on-site renewables to provide demand flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences, in a continuous and integrated way.
Operational carbon (def. per Carbon Leadership Forum)	In contrast to embodied carbon, this refers to the GHG emissions due to building energy consumption.
Proforma	A real estate proforma is the basic financial analysis that developers perform in deciding whether to move forward with a project. A proforma analysis looks at the financial return that a proposed real estate development is likely to create. It begins by describing the proposed project in quantifiable terms, then estimates revenues likely to be obtained, costs that will have to be incurred, and the net financial return the developer expects to achieve. It can be used to test "what-if" scenarios.
Upfront carbon	Upfront carbon is the GHG emissions that are released in the early phases of a life cycle (i.e., life cycle "A" stages as defined in ISO 14040), arising from materials production and construction/installation. These emissions are released before the object of interest (e.g., building or infrastructure) starts being used.
"Use" stage carbon	GHG emissions arising from the maintenance, replacement, and refurbishment of building materials. This emissions are primarily scoped to life cycle "B" stages (per ISO 14040), with the exclusion of operational energy use (B6). See "operational carbon" definition above.

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Appendix A. Application of Appropriate Learning Rate Ranges Based on Past Empirical Studies and Assumptions

As explained in Section 3.3, we applied appropriate learning rate ranges for three phases of a proposed development road map toward producing and delivering 10,000 volumetric modular dwelling units annually by 2030. The three phases, their respective learning rate ranges, factors of influence, and major assumptions are as follows:

Table 6. Learning Rates Ranges, Factors of Influence, and Major Assumptions for Each Phase

Phase	Learning Rate Range	Factors of Influence	Major Assumptions
Pre-Build Product Development Phase (2016–2020)	20%–25%	The extent to which the modular builder successfully adopts, and practices integrated product delivery principles such as design for manufacturing, assembly, and installation (DfMA+I), pilot testing in smaller prototyping facilities, optimizing the design to incorporate plug-and-play strategies that can further reduce on-site labor, and making informed design decisions to increase standardization by installing solar PV, battery, and mechanical equipment as prepackaged systems.	(1) In this early pre-build design and prototyping phase, a modular builder's dwelling unit (with novel products and systems) undergoes iterative product development prior to commencing production at scale in a large industrialized construction facility or off-site factory. There is no production or build at this phase. (2) High learning rates are influenced by nonproduction factors such as design and prototyping. There is an opportunity to achieve significant cost reduction by simplifying design by lightweighting the dwelling unit and by reducing number of unique or redundant parts, reducing variability in components, and optimizing system selection.
Industrialized Construction Phase (2021–2025)	3%–10%	The extent to which the modular builder successfully introduces and implements industrialized construction innovation through off-site methods such as prefabrication and modularization as well as opportunity for continuous improvement and quality assessment just by building the	(1) The predesigned standardized dwelling unit will be produced at scale in a large industrialized construction facility or off-site factory. (2) The ability to achieve a higher learning rate in this phase is inhibited by the fact that industrialized construction is not advanced manufacturing yet, especially held back by minimal productivity gains and low

Phase	Learning Rate Range	Factors of Influence	Major Assumptions
		dwelling units in a controlled factory environment.	automation. (3) We assume that the total production volume will reach 400 dwelling units over a span of 4 years in this phase, instead of doubling annually. More precisely, the factory would need to produce and deliver minimum 400 dwelling units by 2025 to benefit from this phase's average learning rates.
Advanced Manufacturing Phase (2026–2030, and beyond)	15%–30%	The extent to which the modular builder successfully operates multiple large manufacturing facilities to produce and deliver minimum 10,000 dwelling units by 2030 (annually)	(1) The Advanced Manufacturing Phase will involve higher productivity gains, increases in integrated project delivery, data-driven supply chain optimization, increases in adoption of automation and manufacturing tools, and investment in multiple large manufacturing facilities. (2) Cost reduction benefits would begin to approach the limit even if the annual production volume continues to double beyond 2030.

We arrived at these learning rate ranges by following a three-step analysis:

<u>Step 1:</u> Selecting a case study of a novel product or system that combines multiple NZE strategies (as listed in Section 3) and that could be designed, produced, and delivered by modular builders as 10,000 unitized pods—one in each of the 10,000 dwelling units.

The selected case study of a novel product or system is an integrated mechanical pod. The term "pod" refers to one-room modules; the most common applications today are bathroom pods for site-built high-rises (Schoenborn 2012). More precisely, a pod is a turnkey prefabricated subassembly of multiple equipment (like mechanical/electrical/plumbing, HVAC, fixtures, ducts) along with all structural and functional components that can be preinstalled in an off-site factory. Pods can be applied to both new construction and retrofits, designed to be multifunctional, and chunked into different form factors and scales such as bathroom pods, integrated mechanical pods, energy pods, and kitchen pods. As seen in the United Kingdom with "utility cupboards," 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 (AlternativeHeat N.D.). According to Modular Building Institute's report on bathroom pods, the pod approach lowers construction costs by reducing construction time, improving quality, and eliminating the defects list (Modular Building Institute 2016). An "energy pod" is comparable to those used in Energiesprong projects[7] where a building's key mechanical, electrical, and plumbing systems are cost-effectively consolidated in a single, compact shape serving a multifamily dwelling unit (NYSERDA N.D.). A recent American Council for an Energy-Efficient Economy (ACEEE) paper by NREL identified integrated mechanical pods as an NZE strategy that lends itself to be built in an off-site factory and integrated into volumetric modular dwelling units (Podder et al. 2020). *We assume that modular builders could design, produce, and deliver a minimum of 10,000 integrated mechanical pods—one in each of the 10,000 dwelling units—by 2030. In doing so, they could benefit from learning and experience curves that significantly reduce the incremental cost from products and systems associated with relevant NZE strategies.*

For this report, as shown in Figure 14, each integrated mechanical pod would have multiple equipment associated with two NZE strategies (from Section 3.4): HVAC equipment and water heating equipment. In addition, such a unitized pod could contain a home battery, which further adds to the incremental cost of NZE strategies.

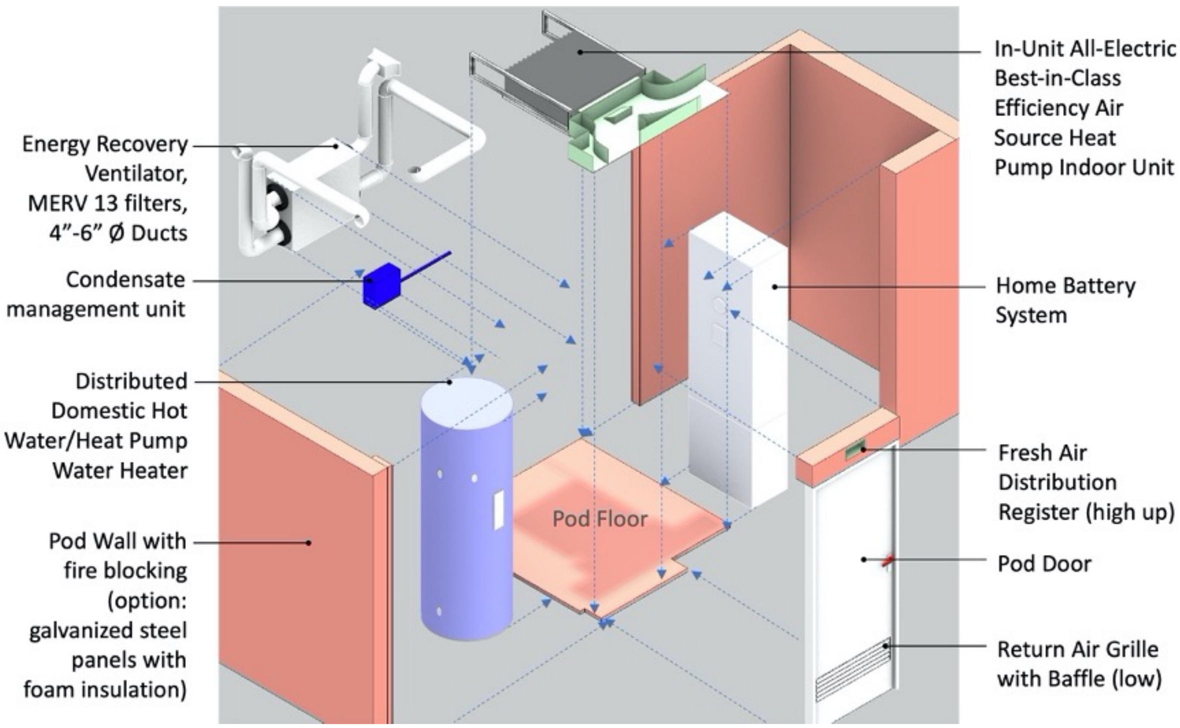

Figure 14. Axonometric exploded visualization of an integrated mechanical pod

Figure by NREL

[7] More information about Energiesprong available at: https://energiesprong.org/about/.

<u>Step 2:</u> Identifying and applying specific equations or learning curve models from past empirical studies to each phase, starting with the Advanced Manufacturing Phase as the best-case scenario.

Learning curve models were empirically developed by Wright in 1936 for unit production cost reduction of airplanes. Over the years, variants of the Wright model and applications have been reported widely in many industries and disciplines. We benefit from the seminal paper "Learning curve models and applications: Literature review and research directions," which provides the state of the art in the literature on learning and forgetting curves, describing the existing models, their limitations, and reported applications. According to the paper, in the Wright model as well its multiple variant modes, the dependent variables usually include (1) time to produce a single unit, (2) number of units produced per time interval, (3) costs to produce a single unit, and (4) percent of nonconforming units (Anzanello and Fogliatto 2011). Table 7 enlists the learning curve model applied to each phase, provides justification for the choice, and describes the learning curve model as per our case study.

Table 7. Standard Learning Curve Models Applied to Each Phase for the Case Study of an Integrated Mechanical Pod

Phase	Learning Curve Model Applied	Choice Justification Based on Past Empirical Study	Description as per Case Study of an Integrated Mechanical Pod
Pre-Build Product Development Phase (2016–2020)	The Cumulative Average Model presents a commonly used formula: $Y = aX^b$. Here, *Y* is the average unit cost over the measured duration, *a* represents the unit cost when performing a task on the unit for the first time, *X* represents the total number of attempts at the task for the same unit (cumulative), *b* is the slope of the function. Here, $b = ln\ (p)\ /\ ln\ (2)$ and *p* represent the maximum annual learning rate opportunity (in percentage).[8]	The formula stipulates that the greater the number of attempts made to perform a task on a standardized unit, the further the time taken to complete that task and the unit cost will decrease. Note that Y-axis can be “average time spent per unit” or “average cost per unit.” The formula lends itself to this phase as the task of product development recurs as the same unit goes through multiple design iterations or attempts over a period.	We consider the unit to be designed and prototyped in this phase to be an integrated mechanical pod. The task to be performed by the modular builder is product development. There would be multiple attempts at designing the pod over a measured duration of 4 years owing to the iterative nature of the integrated design process. Blokable has performed a similar iterative product development for its entire dwelling unit (“Blok”), leading to significant cost reduction of the overall dwelling unit. Their cost reduction trend since 2018 follows similar curve behavior in this phase as seen in the Cumulative Average Model. The same factors that maximized cost reduction at the Blok-level can be applied to novel products and systems associated with NZE strategies.
Industrialized Construction Phase (2021–2025)	The S-Curve Model assumes a gradual build up in the early stages of production followed by a period of peak performance. This build up is typically attributed to personnel and procedural changes as well as time needed for new machinery set-ups that occur early in the production process (Carr 1946).	At the top of the curve there is a slow build up period before the worker or organization can be fully proficient in accomplishing the task.	We have adjusted this model to evaluate the effects of forgetting and product modifications in the construction segment that is widely observed in industrialized construction. Even as the worker is progressing along the learning curve, forgetting will eventually take place (Srour et al. 2016). We consider that a total of 400 integrated mechanical pods would be produced in this phase—as part of 400 dwelling units. The task to be performed by the modular builder is industrialized construction in a large manufacturing facility or off-site factory. The production volume doubles over 2 years and not annually.
Advanced Manufacturing Phase (2026–2030, and beyond)		At the bottom half of the curve, there is a gradual improvement in production time due to repetition of the process. The trailing off effect is referred to as the slope of diminishing returns after a worker or organization has reached maximum efficiency.	

[8] See https://www.yourarticlelibrary.com/how-to/how-to-calculate-learning-curve-with-example/45136

<u>Step 3:</u> Quantify per unit annual cost reduction opportunity for each phase.

We use the Cumulative Average Model formula from Table 7. In $Y = aX^{[ln(p)/ln(2)]}$, a = 8% as the assumed the incremental cost of NZE strategies in 2016–2017. We assume that one full cycle iteration or attempt at product development is completed each year. As shown in Table 8 below, solving for p or the maximum annual learning rate opportunity, we get values for p in the range 0.75–0.80 or 75%–80% based on predefined end-of-year targets for incremental cost of NZE strategies. In other words, 20%–25% of per-unit annual cost reduction is practical in this phase. This learning rate is consistent with the Wright's 80% learning curve example presented in the paper "A Comparative Study of Learning Curve Models in Defense Airframe Cost Estimating," which notes that Wright observed a learning rate of 80% meant a 20% per unit annual cost reduction (Moore 2015). It should be noted that increasing the number of iterations or attempts over the same period opens the opportunity to reduce costs further and could lead to more than 25% per-unit annual cost reduction. Similarly, we have applied the S-Curve Model to the Industrialized Construction Phase and Advanced Manufacturing Phase to quantify per-unit annual cost reduction opportunities. *It is important to note that this exercise can benefit the modular builder at an early product development phase to set a realistic target of cost reduction over a measured period and then allocate the necessary resources to maximize the factors influencing learning rates to achieve the set target.* Based on factors and major assumptions from Table 6 and models and formulas from Table 7, we arrived at the per-unit annual cost reduction for each phase as shown in Table 8, Table 9, and Table 10.

Table 8. The Cumulative Average Model Applied to Pre-Build Product Development Phase, Including Tail-End Cost Reduction Opportunities in 2021

Year	X= Number of Product Development Iterations/Attempts (Full Cycles)	Starting Incremental Cost of NZE Strategies	Y= End of Year Target Incremental Cost of NZE Strategies	p = Maximum Annual Learning Rate Opportunity	Learning Rates (Per-Unit Annual Cost Reduction Opportunity)
2016	1	8% (=a)	8%	NA	NA
2017	2	8%	6%	75%	Up to 25%
2018	3	6%	5.4%	78%	Up to 21%
2019	4	5.4%	4.9%	78%	Up to 21%
2020	5	4.9%	4.6%	79%	Up to 21%
2021	6	4.6%	4.5%	80%	Up to 20%

Table 9. Industrialized Construction Phase, With Production Starting 2022

Year	End of Year Target Incremental Cost of NZE Strategies	Annual Production Volume	Learning Rates (Per-Unit Annual Cost Reduction Opportunity)
2022	4.5%	100	3%
2023	4.4%	200	10%
2024	4.3%	300	
2025	4.0%	400	

Table 10. Advanced Manufacturing Phase

Year	End-of-Year Target Incremental Cost of NZE Strategies	Annual Production Volume	Learning Rates (Per-Unit Annual Cost Reduction Opportunity)
2026	3.3%	800	17%
2027	2.5%	1,600	25%
2028	1.8%	3,200	30%
2029	1.3%	6,400	25%
2030	1.1%	12,800	15%

Appendix B. Life Cycle Assessment

This appendix goes into further detail about system boundary, LCI, and methodology of the LCA portion of the report starting in Section 4. The goal and scope of the LCA are already stated in Section 4.2. The functional unit was a one-bedroom apartment and is fully described in the Section 2.1. The system boundary of the LCA and special exceptions are noted in Table 11. Generally, the modules pertained to the "product" stage of the building, but there were exceptions. GHG leakage from refrigerants was the only inclusion in the B1 "use" module, and the B6 "operational energy use" module was fully included.

B.1 Energy Performance Scenarios

The energy performance was used to associate emissions from energy consumption by scenario. The information in Table 3 on page 17 is repeated here for ease of reference.

Table 3. Energy Performance Scenarios

Scenario Name	Description
Prototype	A modular-built apartment based off a 2016 Blokable design. Energy performance and components are to minimum code requirements of Sacramento. Energy consumption is a mix of two fuels: natural gas for domestic water heating and electricity for all other building uses.
ZED	Zero energy design only, no generation. All-electric building loads match the net zero energy scenario, but there is no energy generator such as PV.
NZE	Net zero energy scenario. All-electric building annual energy consumption matches annual energy generation of a 3.4-kWhdc PV system.
NZE+GEB5	Net zero energy plus grid-efficient 5-kWh battery scenario. The building load of the "ZED" and "NZE" scenario but with a coupled PV-battery system. The 5-kWh battery is grid-efficient and maximizes "self-consumption" of PV power while minimizing carbon during grid charging.
NZE+GEB10	A replica of the previous scenario but with a 10-kWh battery.

B.2 System Boundary

Table 11. System Boundary of the LCA Scaffolded by the ISO 14044 Modules

Module	Module Name	Incl.?	Notes
A1	Product raw material supply	✔	
A2	Product transport	✔	
A3	Product manufacturing	✔	
A4	Construction transport	✔	
A5	Construction and installation	✔	Includes the product stage emissions from wasted materials during construction.
B1	Use	*	Only inclusion is refrigerant leakage during HVAC operation.
B2	Maintenance	MND	
B3	Repair	MND	
B4	Replacement	*	Only inclusion is the replacement of batteries and HVAC system at 15 years out of 30-year analysis period.
B5	Refurbishment	MND	
B6	Operational energy use	✔	
B7	Operational water use	MND	
C1	End-of-life demolition	MND	
C2	End-of-life transport	MND	
C3	End-of-life waste processing	MND	
C4	End-of-life disposal	MND	
D	Benefits and loads beyond system boundary	MND	

MND: Module not declared. LCA modules per ISO 14044: A1: product raw material supply; A2: product transport; A3: product manufacturing; A4: construction transport; A5: construction and installation; B1: use; B2: maintenance; B3: repair; B4 replacement; B5: refurbishment; B6: operational energy use; B7: operational water use; C1: end-of-life demolition; C2: end-of-life transport; C3: end-of-life waste processing; C4: end-of-life disposal; D: benefits and loads beyond system boundary.

B.3 Functional Unit Bill of Quantities

Table 12. Bill of Quantities Used in the LCA Portion of the Report

Material	Unit	Total Unit Quantity	Mass Value (Short Tons)
#15 Organic Felt	sf	1170	0.087
1/2" Regular Gypsum Board	sf	4975	4.11
5/8" Glass Mat Gypsum Panel	sf	817	1.053
Air Barrier	sf	290	0.0018
Aluminum Window Frame	lbm	52	0.026
Double Glazed Hard Coated Argon	sf	201	0.332
Extruded Polystyrene	sf (1")	570	0.072
Fiber Cement	sf	451	0.647
Galvanized Sheet	Tons (short)	0.061484	0.061
Galvanized Studs	Tons (short)	1.225797	1.226
Hollow Structural Steel	Tons (short)	11.74975	11.75
Joint Compound	Tons (short)	0.508537	0.509
Metal Wall Cladding—Commercial (26 Ga.)	sf	445	0.222
Nails	Tons (short)	0.048864	0.049
Oriented Strand Board	sf (3/8")	3741	2.237
Paper Tape	Tons (short)	0.005825	0.006
Polyiso Foam Board	sf (1")	2145	0.165
Screws, Nuts, and Bolts	Tons (short)	0.0193	0.0193
Small Dimension Softwood Lumber, Kiln-Dried	bfm,* small dimension	1502	1.085
Softwood Plywood	sf (3/8")	212	0.098
Water-Based Latex Paint	Gallons (US)	97	0.302
HVAC+R	lbm	3800	1.900
Solar Panels (Includes Balance of System)	kWdc	3.4	Approx. 0.1
Home Battery	kWh	Varies	Approx. 0.08

* “bfm” is board feet measure, a unit of volume equal to 1/12 of a cubic foot (ft^3).

B.4 Underlying LCI Data

The underlaying LCI data used throughout the report are presented here. The LCI data for building products and materials came from the publicly available Athena Impact Estimator for Buildings v5.4, updated in May 2019. These Athena data comply with ISO 14040/14044 for data quality and temporal/spatial applicability. The Athena data were supplemented by additional data sources as needed with special care paid to the largest GHG contributors in the system. Data were updated or added for: (1) steel hollow structural sections, (2) cold formed steel studs used in wall construction, (3) emissions from vehicle miles traveled, (4) embodied emissions of HVAC+R, (5) embodied emissions of solar panels, and (6) embodied emissions of a Li-ion battery pack. The quality of battery production data was provisional and uncertain. This is discussed further below in this appendix.

Table 13. Life Cycle Inventory (LCI) Data

ISO 14040/14044-compliant LCI data from the Athena user manual page 15. All LCI data is from Athena Impact Estimator for Buildings unless noted otherwise.

Product	Vintage	Comments
Cement and concrete products		Not included in the scope of this study.
Steel products	North America, 2010	• Unless stated otherwise, all profiles updated for steel construction products based on the worldsteel LCA methodology approach. Data have been regionalized to reflect North American steel production technologies (BOF/EAF) and market virgin/scrap rates.
Nails		
Screws, nuts, bolts		
Hollow structural sections (not from Athena)	North America, 2021	• Background structural steel data for the last decade come from EPA Waste Reduction Model (WARM; EPA 2020) model for structural steel. Contemporary and forecast data come from the methodology of the Steel Tube Institute (2021) and Nucor Tubular Products (2021) for Hollow Structural Sections.
Galvanized sheet		
Galvanized studs (not from Athena)	WA state 2019	• SCAFCO (2019) EPD
Wood products		
Softwood lumber (kiln dried)	U.S. 2012, CDN 2018	• Canadian regional data updated in 2018. • 2012 CORRIM data for U.S. represents PNW, Inland West, NC and SE production. See CORRIM.org for reports.
Plywood		• Canadian regional data originally developed in 1993 updated in 2006, 2012, and 2018.
Oriented strand board		

Product	Vintage	Comments
		• Resource harvesting profile updated in 2012. • CORRIM data for U.S. represents PNW and SE production in 2012.
Wood I-joists		• Composite product of softwood lumber, laminated veneer lumber, oriented strand board, or plywood with fabrication process. Canadian manufacturing data updated in 2018. U.S. manufacturing data updated in 2012.
Cladding products		• Roll forming data from 2011. Base steel sheet values updated in 2013. • Fiber cement data originally developed in 2009 from unit process data.
Metal wall cladding	2013	
Fiber cement siding	2009	
Insulation and barrier products		• Air barrier based on American Chemistry Council polypropylene profiles (updated in 2010). • See U.S. LCI database (www.nrel.gov/lci). • Polyiso reflects 2011 Polyisocyanurate Insulation Manufacturers Association data. • Polyiso foam board is assumed to be equivalent on a unit mass basis to closed cell spray foam because of the production similarities.
Air barrier	2010	
Polystyrene XPS and EPS	2007	
Polyisocyanurate foam board (foil faced)	2011	
Paint products		• Originally developed in 1998 and updated in 1999. Athena report available; due to be updated.
Basic latex paint, solvent based	1999	
Gypsum board products		• Originally developed in 1997 • Regular and fire-rated GWB updated in 2012 • Original Athena report available. Gypsum Association report also available; see https://www.gypsum.org/stewardship/life-cycle-assessment-tools/ • Glass mat industry-wide EPD commissioned by the Gypsum Association see https://www.astm.org/CERTIFICATION/DOCS/313.EPD_for_Glass_Mat_Gypsum_Panels_-_Industry_Wide_EPD.pdf
Regular	2012	
Fire rated		
Joint compound and paper tape		
Glass mat gypsum panels	2015	
Roofing products		Not included in the scope of study.
Windows	North America	• Frame and insulating glazing unit data and quantity take offs updated in 2013 • US LCI database (www.nrel.gov/lci) for data
Aluminum frame (double- and triple-paned)	2002	

Product	Vintage	Comments
Double and triple pane glazing, hard (tin) and soft (silver or tin) coated, air and argon filled	2013	
Vehicle miles traveled *(not from Athena)*	North America, 2012	• See Quale et al. (2012) for emissions per unit distance traveled. Learning effects are considered for actual distance units of miles. This accounts for associated GHG emissions from material transport (building materials: 16 metric ton truck, building materials: 28 metric ton truck, modules to site: 28 metric ton truck) and worker transport (to factory: car/light duty truck, and to site: car/light duty truck).
HVAC+R *(not from Athena)*	Pacific Northwest, 2019	• Uses Tables 7.1 and 7.2 of dissertation "Embodied Carbon of Heating, Ventilation, Air Conditioning and Refrigerants (HVAC+R) Systems" • Assumes 5.3 lbm of system equipment per ft^2 conditioned floor area (Rodriguez 2019). 3,800 lbm of mechanical, electrical, and plumbing equipment in the 720-ft^2 functional unit. Embodied carbon scaling factor of 3.4. • Commercial office values are equated to residential apartment.
Solar panels, 3.4-kWdc, si-C, roof-mounted with balance of system (not from Athena)	Europe, 2020	• See Krebs et al. (2020) • Emissions assumed to be linear with unit capacity of PV system: 1,070 $lbmCO_2e$/kWdc unit PV system
Li-ion (type NMC111, approx. 5-kWh capacity), includes battery management system and battery case (not from Athena)	East Asia supply chain, 2020	• Data are allocated according to battery capacity. Most data come from electric vehicle battery packs (approx. 27 kWh capacity). • Chosen emissions value per unit capacity ($lbmCO_2e$/kWh) is the average of seven contemporary published values. See Figure 15. • Ni-Co-Mn and Li-Fe-PO_4 batteries have similar GWP for equivalent capacity (kWh) (Krebs et al. 2020). • Due to battery cycling behavior and depth of discharge, it is assumed 2 battery packs will be needed in the 30-year analysis period (Krebs et al. 2020). • Battery weighs approx. 70 kg

B.5 Li-Ion Battery Production Emissions

As a relatively new technology, large-scale Li-ion batteries present a challenge in determining the embodied GHG emissions from their production. Values from contemporary publications vary widely and new, primary data sourced from manufacturing facilities show that production efficiency is increasing as battery technology matures. Consequently, there should be appropriately low confidence in any singular, discrete value for a residential battery pack. Instead, we reviewed a selection of contemporary publications on the embodied emissions from production of Li-ion batteries. In Figure 15, the ranges of embodied carbon per unit capacity of Li-ion, NMC111 batteries are compared from seven selected publications.

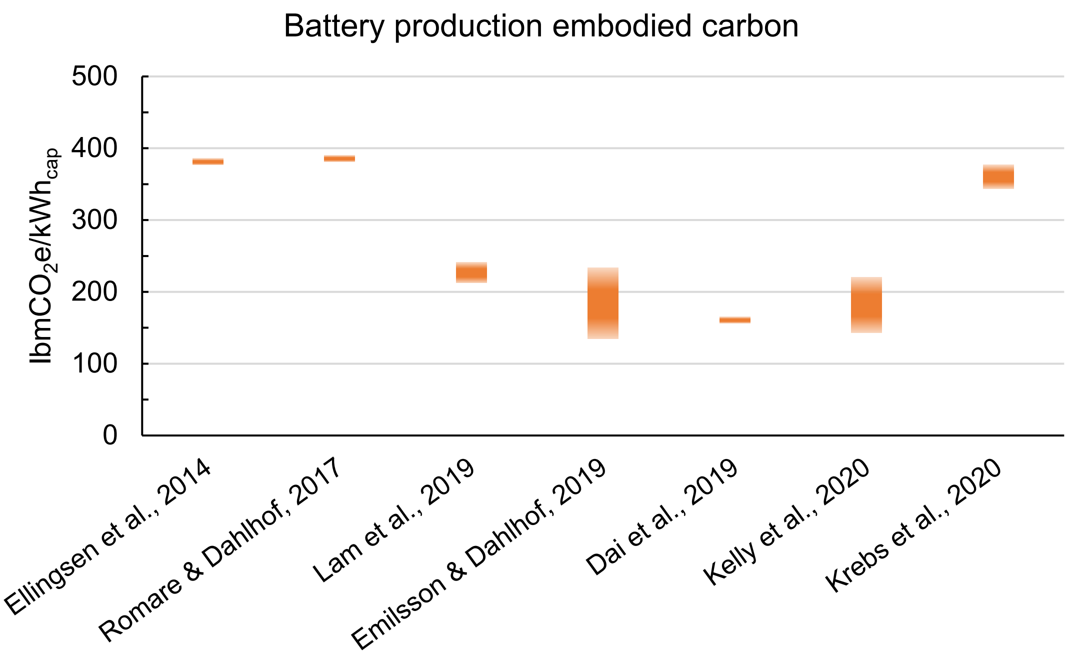

Figure 15. Range of production GHG emissions per unit capacity of Li-ion battery from seven select LCI sources

The unit processes considered, as well as the energy use and electricity mix, vary from source to source. Consequently, the embodied emissions are presented with low confidence in any singular, discrete value. Figure by NREL.

Two discrete groups emerged from the LCI data in Figure 15, one centered around 350 lbmCO_2e/kWh and another around 200 lbmCO_2e/kWh. Each of the seven sources was reviewed for data transparency and none were found to be unqualified. Ultimately, we took the average of the range midpoints (270 lbmCO_2e/kWh_{cap}) as the embodied carbon value. Rather than nominate a "best" embodied carbon value, we recommend that purchasing agents for batteries use the framework herein to choose a battery that can provide as much carbon benefit from operation with as little carbon cost from production as possible.

B.6 Methodology

- **Refrigerant leak model:** Basic calculation method of TM65-2021 assuming 2 kg charge of R-410a refrigerant leaking 4% each year for 30-year service period. The refrigerant charge (kg) was based off an engineering manual for a 2-ton minisplit heat pump unit in the U.S. market. The leak rate was based off the 2020 report "Refrigerants & Environmental Impacts: A Best Practice Guide" (Hamot et al. 2020).

- **Electric grid energy consumption and grid mix:** See Appendix C and Appendix D.

- **Vehicle miles traveled:** Although operational carbon is assumed to reduce as the electrical grid decarbonizes over time, we did not venture to make assumptions about electrification and decarbonization of vehicles used for transporting construction materials and workers. Therefore, vehicle miles traveled and associated emissions do not change over time with regard to any projected vehicle-electrification timeline.

- **Treatment of metal recycling and scrap:** Regarding end-of-life recycling, the "avoided burden" approach for metal recycling was not necessary as the system boundary did not include end-of-life stages. For steel products using the worldsteel 2010 data in Table 13, scrap rates reflected global steel production data from that time. Steel production data that was apart from the worldsteel data in Table 13 reflected regional, contemporary steel production. Using simple algebra and data contained in EPDs for steel products, we modeled decreasing carbon emissions per unit steel by year (Table 14) based on the assumption that a regional, differentiated steel market would emerge for low emission ("clean") steelmaking. This assumption does not include new steelmaking technologies; instead, it we assumed that the scrap input for the hollow structural section products would increase and/or the regional electric grid emissions would continue to decrease on their current trajectory.

Table 14. Assumed GWP per Mass Unit Steel by Year

Year	Steel GWP Assumed (lbmCO_2e/lbm Steel)
2016–2021	3.05
2022	2.89
2023	2.72
2024	2.56
2025	2.40
2026	2.24
2027	2.08
2028	1.92
2029	1.76
2030	1.60

- **Treatment of biogenic carbon:** The treatment of biogenic carbon follows established protocols for harvested wood products in the "product" stages, whereby the emissions of planting, maintaining, cutting, milling, transporting, and processing the wood product are counted in the product stages. The system boundary of this study does not include End-of-Life or Beyond Life stages, so the negative carbon emissions that are associated with the growth of biogenic products in some carbon accounting methods were not included.

- **Construction waste:** The emissions burden of construction waste was calculated by adding a waste factor (WF) percentage to "billed" quantities in the bill of quantities in Table 12. Structural steel WF is 1%; wood products WF is 13%; and gypsum board products WF is 20%. All other materials WF is 36%. After the waste factor was applied, an additional factor of 30% was applied for packaging waste and purchase order inefficiencies.

Appendix C. Energy Modeling Methodology

To add fidelity to the analysis of GHG emissions, we considered the emissions resulting from operational energy consumption with a great deal of granularity. To this end, building end loads were modeled and validated hour-by-hour for a typical weather year before anticipating any emissions savings from energy generation and storage. We used the freely available OpenStudio software (v3.0.1) to create a white-box building energy model for each of two cases. The "Prototype Reference" was a business-as-usual case of an apartment unit built from modules but otherwise excluding efficiency measures. The second "Zero Energy Design" modeled case was for the same apartment but with the energy features to achieve NZE performance over the course of a year.

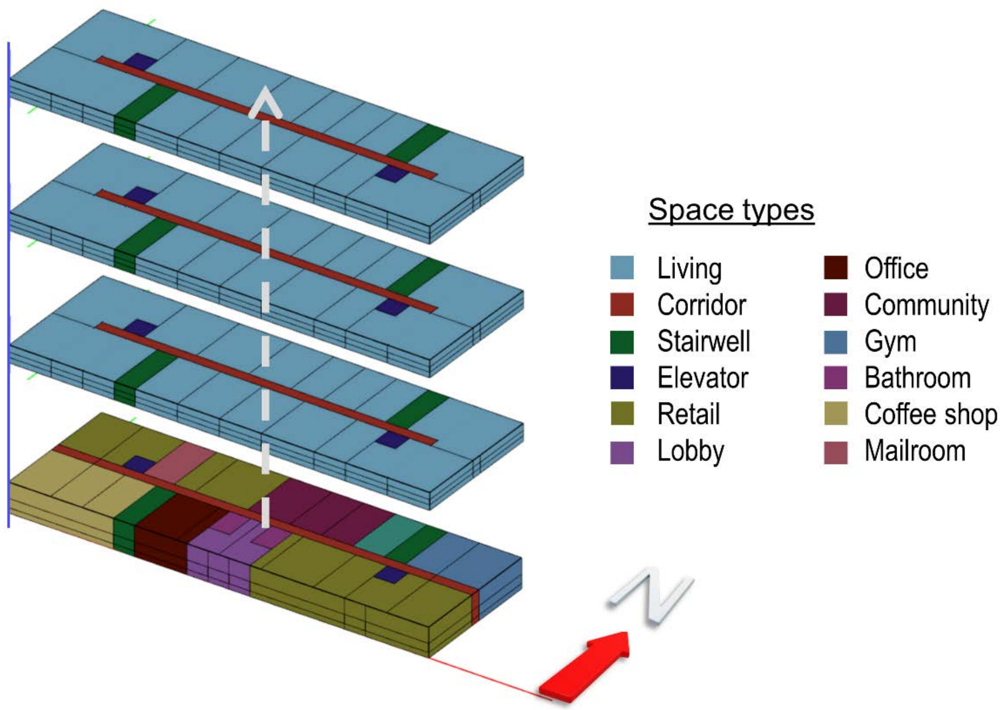

Figure 16. Prototype multifamily model geometry by floor

There were three residential-only floors of apartment units above a mixed-use commercial floor. Each space type has its own respective internal loads corresponding to its use. The dwelling units represent a typical mix of unit sizes on each floor: four studio units, seven 1-bedroom units, three 2-bedroom units, and one 3-bedroom unit.

The modeled cases were a "typical" apartment unit from within a multifamily building previously developed by the Zero Energy Design Guide series for general modeling use (Langner et al. 2020). The advantages of selecting a single typical apartment unit for analysis are two-fold. Firstly, the functional unit in the embodied-carbon and cost areas of the scaling analysis was one apartment unit. Secondly, the discrete energy loads of one apartment unit were a more appropriate assumption for battery-storage and dispatch modeling than were the blended, continuous loads of the whole building. A single apartment unit was selected as statistically typical by cluster analysis using the affinity propagation method (Frey and Dueck 2007). The 45 cluster points were the apartment unit thermal zones in the model, and the 8,760 cluster parameters were all hourly observations of the apartment unit energy consumption. The typical unit "2_Bdrm_2_3" was decided by the cluster center of the largest cluster of the apartment thermal zones.

The geometry of the model represented a 2-bedroom apartment from inside a 52,000-ft^2, market-rate, 4-story mixed-use residential building in Figure 16 with the breakdown of space type in Table 15. The model case overview is given in Table 16. This model configuration represented the input of a technical advisory group with the goal of creating a more granular, complex prototype model for newly constructed multifamily buildings. To differentiate the two modeled energy performance cases, five building systems were given special attention: (1) envelope, (2) plug loads, (3) lighting, (4) domestic hot water, and (5) HVAC. These five systems for the "Prototype Reference" case corresponded to the minimum prescriptive requirements of the jurisdiction's building energy codes. In the "Zero Energy Design" case these five systems were instead optimized to achieve zero energy performance in the location without "overdesigning" any one system.

Table 15. Space Type Breakdown by Floor of Multifamily Model Case

Model from Zero Energy Design Guide for Multifamily (forthcoming)

Space Type	Commercial Floor		Residential Floor*	
	Area (ft^2)	Percentage of Total	Area (ft^2)	Percentage of Total
Stairs	600	5%	600	5%
Elevator	200	2%	200	2%
Corridor	1,000	8%	800	6%
Retail	4,600	35%	-	-
Coffee Shop	1,500	12%	-	-
Mail/Shipping	450	3%	-	-
Lobby	600	5%	-	-
Bathroom	300	2%	-	-
Garbage	450	3%	-	-
Office	750	6%	-	-
Gym	1,050	8%	-	-
Community Room	1,500	11%	-	-
Studio Apartment (4 units/floor)	-	-	1,800	14%
1-Bedroom Apartment (7 units/floor)	-	-	4,650	36%
2-Bedroom Apartment (3 units/floor)	-	-	3,450	26%
3-Bedroom Apartment (1 unit/floor)	-	-	1,500	11%
Total	13,000	100%	13,000	100%

* Note that the simulation models included three residential floors and one commercial floor. The data provided here represent one residential floor.

Table 16. Model Parameters for the Studied 2-Bedroom Apartment Unit

Model Parameter	Prototype Reference	Zero Energy Design
Geometry and Occupancy		
Floor Area	1200 ft^2 *	1200 ft^2 *
Height	10 ft	10 ft
Story	3 of 4	3 of 4
Exposed Wall Area	750 ft^2	750 ft^2
Internal Wall Area	750 ft^2	750 ft^2
Window Area	225 ft^2	225 ft^2
Number of Occupants (# of Bedrooms)	2.5 (2)	2.5 (2)
Occupant Equivalent Full Load Hour	0.69	0.69
Envelope		
Wall R-Value	R-20.4	R-34
Window U-Value and SHGC	U 0.35, SHGC 0.22	U 0.25, SHGC 0.22
Infiltration Rates	28 CFM (0.14 ACH)	14 CFM (0.07 ACH)
Infiltration Schedule	Linear w/ wind speed	Linear w/ wind speed
Plug Loads		
Equipment Power Density	66.3 W/ft^2	66.3 W/ft^2
Equipment Equivalent Full Load Hour	0.0042	0.0042
Lighting		
Lighting Power Density	0.14 W/ft^2	0.14 W/ft^2
Lighting Equivalent Full Load Hour	0.38	0.38
Domestic Hot Water		
Water Equipment Power Density	9.8 W/ft^2 gas	7.5 W/ft^2 electric
Water Equipment Equivalent Full Load Hour	0.037	0.037
Gallons per Day of Hot Water	50.9 GPD	50.9 GPD
HVAC System		
Cooling Design Air Flow	572 CFM	422 CFM
Capacity	23 kBtu/h	19 kBtu/h
Cooling Coil SEER/Heating Coil HSPF	13.0/8.2	19.0/14.0
ERV Flow Rate at Maximum Cooling	82 CFM	82 CFM
ERV Sensible Recovery Efficiency	50%	76%
Average Ventilation Rate	84 CFM	84 CFM

Note 1: In the Advanced Energy Design Guide (2019) from which this was model was taken, the occupancy level of the apartment had greater effect on energy use than the floor area. Thus, the energy use profile of a market-typical, 2-bedroom unit was deemed to be closest to Blokable's 720-ft^2, 2-bedroom apartment prototype.
Note 2: CFM: Cubic-foot per minute flow rate. SHGC: Solar Heat Gain Coefficient. SEER: Seasonal Energy Efficiency Ratio. HSPF: Heating Season Performance Factor. ERV: Energy Recovery Ventilator.
Note 3: The building parameters of the above table, on a holistic basis, were deemed to be energy performance equivalent to the location's governing energy code, Title-24 2013, even though some individual parameters may not meet the minimum prescriptive requirements.

C.1 Custom Energy Meters by Apartment Unit

To localize energy consumption to the apartment-unit level, virtual energy submeters were implemented via the "MeterCustom" object in OpenStudio. This implementation involved custom scripting in the OpenStudio environment.

Table 17 shows how multiple energy model report variables are rolled into a virtual submeter for the whole apartment unit. The readings on the custom submeters were sum-checked against the whole-building values to validate that no end uses escaped consideration.

Table 17. Apartment Unit-Level Variables That Constitute a Virtual Submeter for Each Unit

The syntax rules for variable names in EnergyPlus are given in the Input Output Reference.

For All Thermal Zones	
	"Electricity:Zone:*ZONE_NAME*"*
Only for Conditioned Zones	
	"*ASHP*:Fan Electric Energy," "*ASHP_SUPPLEMENTAL*:Heating Coil Electric Energy," "*ASHP*:Unitary System Heating Ancillary Electric Energy," "*ERV_SUPPLY*:Fan Electric Energy," "*ERV_EXHAUST*:Fan Electric Energy," "*ERV*:Heat Exchanger Electric Energy," "*ASHP*:Cooling Coil Electric Energy," "*ASHP*:Heating Coil Electric Energy," "*ASHP*:Heating Coil Defrost Electric Energy," "*ASHP*:Heating Coil Crankcase Heater Electric Energy"
Only for Zones With Water Heating (Heat Pump Water Heater)	
	"*HPWH*:Cooling Coil Crankcase Heater Electric Energy," "*HPWH*:Cooling Coil Water Heating Electric Energy," "*HPWH*:Fan Electric Energy," "*HPWH*:Water Heater Off Cycle Ancillary Electric Energy," "*HPWH*:Water Heater Electric Energy," "*HPWH*:Water Heater Off Cycle Parasitic Electric Energy," "*HPWH*:Water Heater On Cycle Parasitic Electric Energy"
OR (Gas-Fired Water Heater)	
	"*APT_NAME*:WaterSystems:Gas"

* Includes lights, equipment, and all home appliances.
Characters in all capital letters represent the variable key name (e.g., "1_Bdrm_1_3").

C.2 Climatic Data Used

The building weather file selected for representativeness was "USA_CA_Sacramento.Metro.AP.724839_TMY3.epw" with design days contained in a .DDY file extension with the same prefix. Later in the System Advisor Model simulation (see Appendix D), the PSM3 solar radiation profiles from 2009–2020 were used in the actual meteorological year (AMY) hourly format, e.g., "sacramento_38.582087_-121.500120_psm3_60.csv."

C.3 Building Load Results

Using the model method described herein, the whole-building energy load by end use is shown in Figure 17. The annual profile of the building energy load for the typical apartment unit is shown in Figure 18. The large midmorning peak is explained by the hot water use schedule of the occupants.

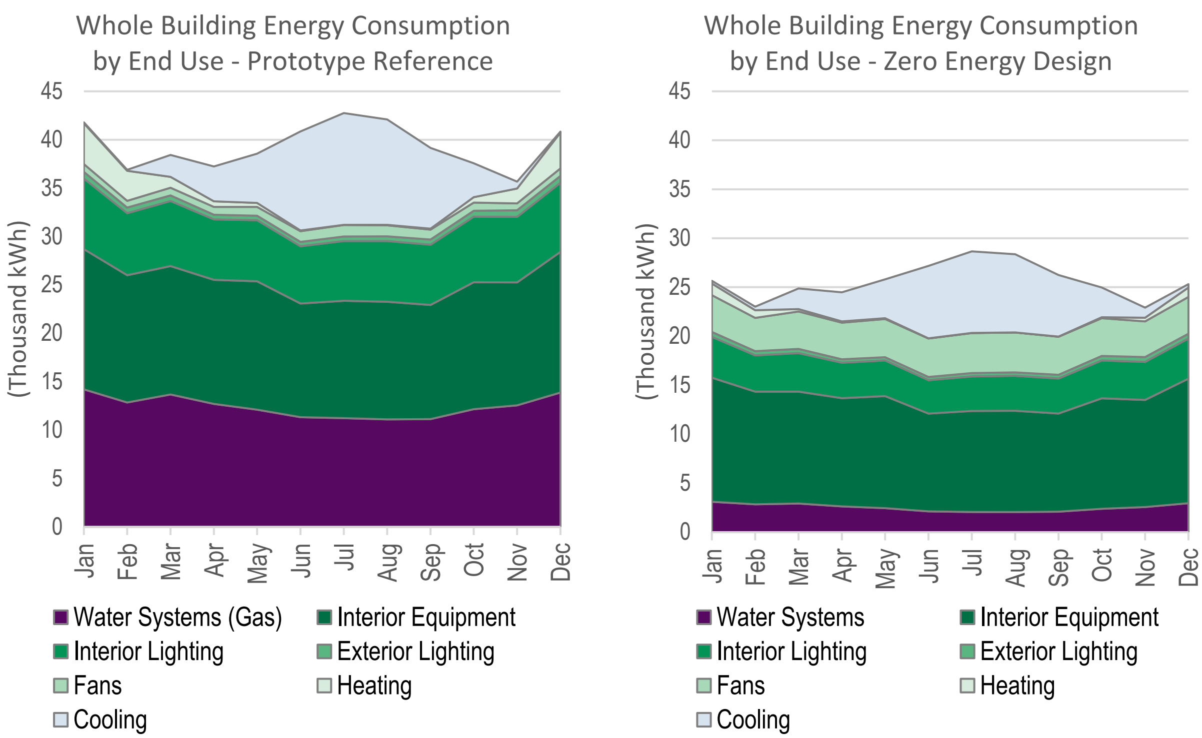

Figure 17. Whole-building site energy consumption by end use for two performance cases

All end uses are electric energy unless otherwise noted

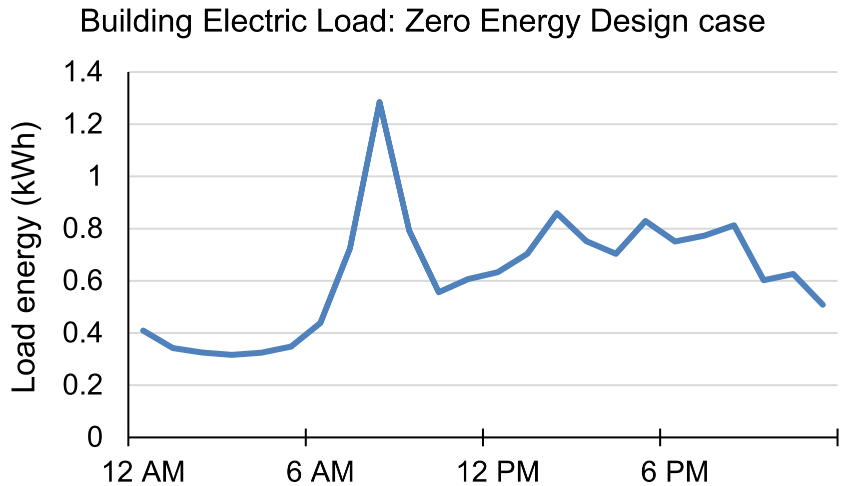

Figure 18. Building energy load annual profile for the "zero energy design" model case

C.4 Replication

The modeling process was based off the publicly available Zero Energy Multifamily standard of the OpenStudio Standards library published with new releases of OpenStudio. Other modeling resources may be available upon request to the corresponding author.[9] The subsequent methodology of converting building electricity consumption to carbon emissions used simple spreadsheet-based calculations. Further carbon emission conversion methodology is given in Appendix B.

[9] Ankur.Podder@nrel.gov

Appendix D. PV-Battery System Methodology

Using the building electricity loads previously obtained (Appendix A), we quantified the effective carbon emissions attributable to a typical modular apartment unit with the help of both the System Advisor Model (SAM) and the Cambium data set (both freely available). We used a two-step process to determine the attribution of carbon emissions through electricity consumption. First, in the scenarios with PV generation, the simplified "PVWatts" model of SAM was used to predict solar energy generation given a typical meteorological file for the area of study. Second, the hourly energy exchange with the grid was multiplied by the carbon emission rates forecast by the 2020 Standard Scenarios (made available in the Cambium data set). The apartment load annual profile and the emission rate annual profile are plotted side-by-side in Figure 19.

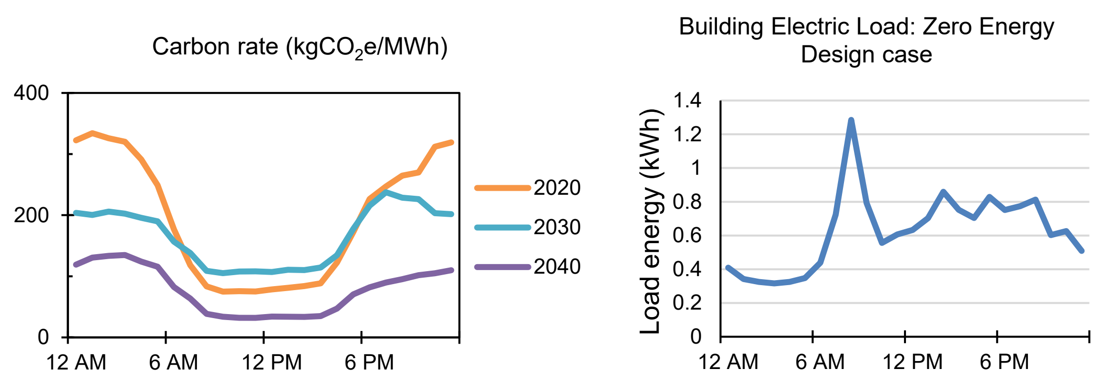

Figure 19. The average daily profile of the grid-carbon-emission rate compared to the average daily profile of the typical apartment energy consumption

For the case scenarios that included rooftop PV, we used SAM to forecast power generation from a typical meteorological year. The PV system was modeled as 3.4 kWdc capacity of standard crystalline Silicon panels (approximately 17% nominal efficiency). This capacity was chosen because (1) the annual AC power generation was approximately equal to the apartment's annual AC power consumption, and (2) the required rooftop area for such a system would be available given a low- to mid-rise multifamily building configuration. Further assumptions about the PV system are given in Table 18.

Table 18. Modeled PV System Parameters

Parameter	Value
System type	Fixed, roof-mounted
System size (kWdc)	3.4
Photovoltaic type	Crystalline Silicon
Nominal cell efficiency	17%
Tilt	20°
Azimuth	180°
Ground coverage ratio	0.4
Shading	No shading considered
DC-to-AC ratio	1.2
Inverter efficiency	96%
System losses	14%

In the scenarios with PV generation that also included battery storage, the "PVWatts-Battery" model method of SAM was used. For the purposes of this report, a behind-the-meter AC-coupled battery bank reduces the residential building's net emissions by minimizing grid power consumption. The battery bank was modeled as a Li-NMC type (an abbreviation for Lithium ion with a Nickel-Manganese-Cobalt oxide anode), having capacities ranging from 2.5 kWh to 10.0 kWh. A schematic of a PV-battery coupled system is shown in Figure 20. Similar to the inverter efficiency of the PV array, the conversion of AC power to battery DC power back to AC power has energy losses in Figure 20. The so-called "roundtrip efficiency" of this conversion ranged from 89% to 91%.

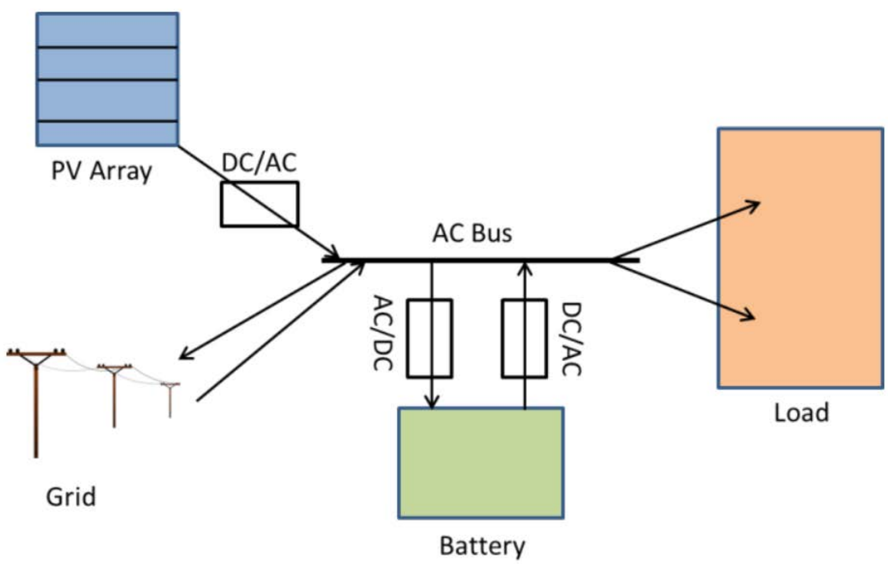

Figure 20. Modeled PV-battery configuration. The roundtrip efficiency of energy transfer to and from the battery was in the range from 89% to 91% for the scenarios modeled.

Figure from DiOrio et al. (2015)

D.1 Carbon Emissions From Energy Consumption

To quantify the building's net emissions from electricity consumption, data from the 2020 Standard Scenarios was used to forecast the carbon emissions produced per unit energy consumed. The emissions-related metric used was "End Use Long Run Marginal Emission Rate" in the Cambium data set, containing the 2020 Standard Scenarios. The CO_2-equivalent emissions per MWh unit of energy can be seen in Figure 21. In the "Prototype Reference" case that included gas-fired water heaters, the emission factor used for the burning of site natural gas was 0.228 $kgCO_2e/kWh$ and taken from Table K2-B of ASHRAE Standard 105-2014. Additionally, a site-to-source energy factor of 1.09 was applied to the natural gas consumption. This analysis assumed that while the effective carbon emissions per energy unit of electricity would be dynamic in time, the emissions per energy unit of natural gas would remain static.

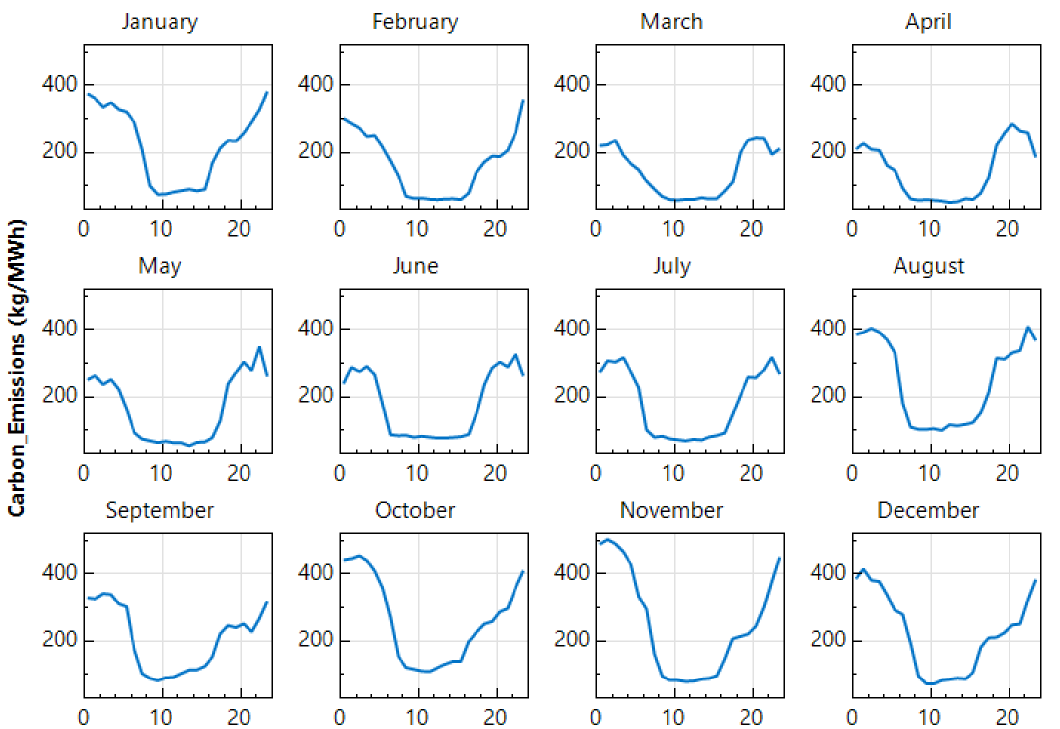

Figure 21. Monthly profile of long-run carbon emission rates for end use loads ($kgCO_2e/MWh$), by month, for the 2020 California Standard Scenario

The temporal resolution of the Cambium data allowed us to analyze the emissions savings from a PV-only system or a coupled PV-battery system. The desired goal of a coupled PV-battery system was to (1) maximize energy self-consumption and reduce reliance on the grid, and (2) store excess solar energy to return to the grid later in the day for a higher emissions credit.

To achieve a relative minimization of net emissions, the carbon emission rate needed to be given a monetary cost in order to be accounted for in the objective function (discussed later). Based off the data in Figure 21, a primitive pricing schedule for energy demand was developed in Table 19. Carbon emission rates for electricity are lowest during the grid-wide production of solar energy in the midday. The exact hours of the trough and transition periods vary slightly month-to-month.

Table 19. Contrived Cost Pricing Given to Energy Demand and Energy Generation to be Included in the Algorithm That Generated the Carbon-Minimal Battery Dispatch Schedule

The carbon emission rates of the 2020 California Standard Scenario above were simplified into a discrete time-of-use utility schedule to maximize self-consumption.

	Low Carbon Period	Shoulder Period	High Carbon Period
Pricing			
Buy Rate	Varies; Starts at $0.15/kWh	Varies; Starts at $0.30/kWh	Varies; Starts at $0.45/kWh
Sell Rate	$0.00/kWh	Varies; Starts at $0.30/kWh	Varies; Starts at $0.45/kWh
Monthly Periods			
January, February, March	07:00–15:00	04:00–06:00, 16:00–22:00	23:00–03:00
April, May, June, July	06:00–16:00	04:00–05:00, 17:00–19:00	20:00–3:00
August, September, October	06:00–15:00	03:00–05:00, 16:00–21:00	22:00–02:00
November	07:00–15:00	04:00–06:00, 16:00–22:00	23:00–03:00
December	07:00–14:00	04:00–06:00, 15:00–22:00	23:00–03:00

D.2 Battery Operation

The PV-coupled battery was made to charge and discharge to minimize net emissions from electricity consumption. Specifically, the battery handled the excess of solar power during the midday period and the variability when combining the load profile and the PV generation profile. For this purpose, a dispatch algorithm was needed to instruct the battery in the model when to accept energy from the system or grid and when to deliver it to the apartment load or the grid connection. An application programming interface (API) connection between SAM and the REopt Lite® API allowed for the minimization of an objective cost function that included battery dispatch. Thus, the REopt Lite API generated optimal dispatch algorithms from the minimization of the objective function that considered a penalty for energy use and a benefit from energy supply. The objective function took arguments of cost c and incentive I, and minimized the sum of (1) capital costs, (2) variable operation and maintenance costs, (3) demand costs, (4) battery costs, and (5) fuel costs, minus (6) production incentives.

$$\min \sum_{fixed} c + \sum_{opex,time} c + \sum_{demand,time} c + \sum_{battery,time} c + \sum_{fuel,time} c - \sum_{prod,time} I$$

It is important to note that the battery must be operated within physical constraints so as not to degrade the service life of the battery. The objective cost function did not consider these constraints when generating battery dispatch schedules. Instead, the battery model inside of SAM processed the dispatch schedule as a data input to the following control scheme evaluated at each time step (Figure 22).

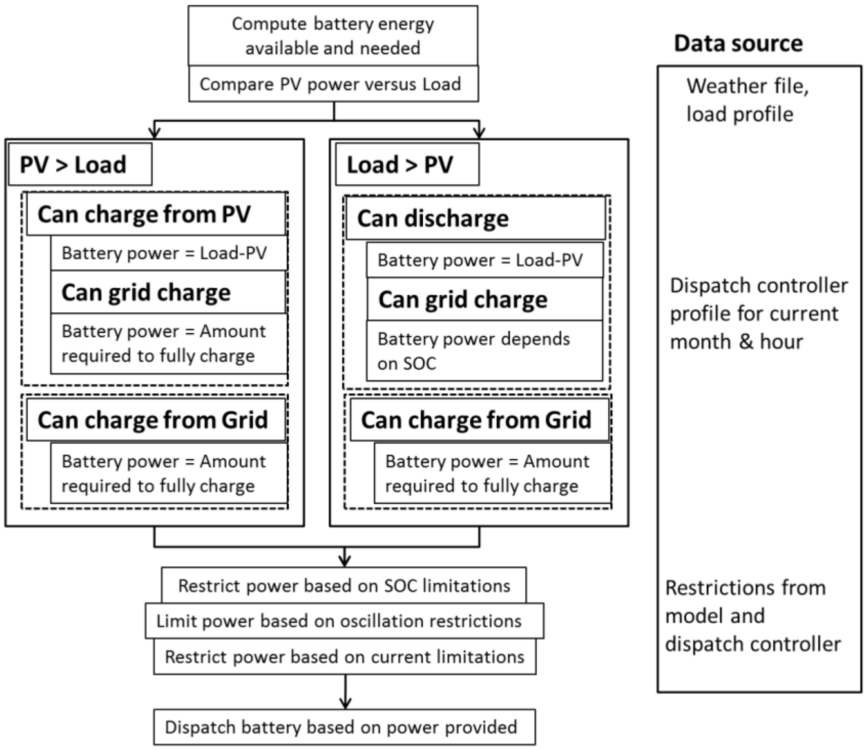

Figure 22. Dispatch control logic flow

Note that SOC stands for battery state of charge. Figure from DiOrio et al. (2015)

D.3 System Advisor Model Outputs

For illustration, select outputs from SAM are presented here. Figure 23 shows the monthly energy generation of a 3.4-kWdc system and the consumption by the NZE apartment unit. There is a monthly excess of solar energy in the months of March, April, May, June, July, August, and September.

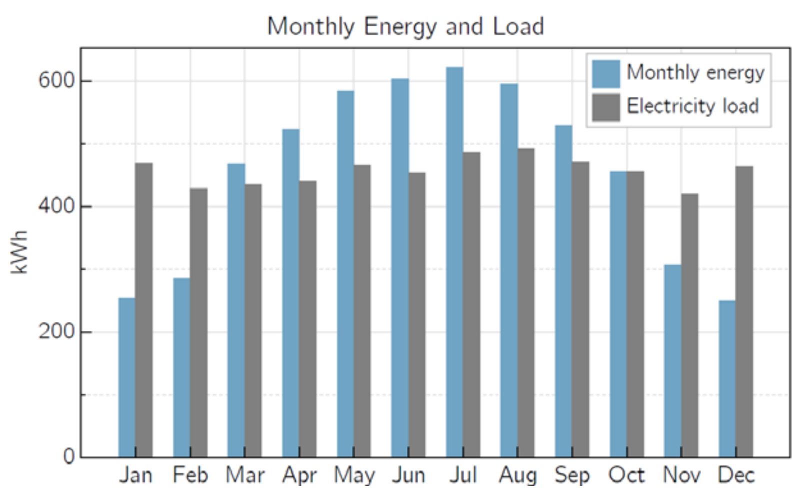

Figure 23. Monthly energy consumption and energy generation of the apartment unit with 3.4-kWdc photovoltaic system. The excess energy generated by solar in the summer months balances the difference in energy consumption throughout the year.

The annual system performance of the six case scenarios is shown in Table 20. Annual AC load (kWh) was the same for all but the "Prototype Reference" case. The "Prototype Reference" case energy consumption (25 kBtu/ft^2) was higher than the "Zero Energy Design" case energy consumption (16 kBtu/ft^2). However, the electricity consumption was lower in the "Prototype Reference" case because hot water heating was not electrified. For the case scenarios with PV systems, the 3.4-kWdc system generated 5,476 kWh of AC energy for a typical meteorological year.

Table 20. PV Battery System Specifications by Case Scenario

	Energy Use Intensity (kBtu/ft^2)	Annual AC Load (kWh)	Annual AC Output From PV (kWh)	Battery Capacity (kWh)	Battery Annual Energy Discharged (kWh)
Prototype, Excl. Natural Gas	25	5,048*	0	0	0
ZE Design, No PV	16	5,483	0	0	0
ZE Design, PV Only	16	5,483	5,476	0	0
ZE Design, 2.5-kWh Battery	16	5,483	5,476	2.5	670
ZE Design, 5.0-kWh Battery	16	5,483	5,476	5.0	1,338
ZE Design, 10.0-kWh Battery	16	5,483	5,476	10.0	2,509

* Excludes natural-gas consumption in the Prototype case

The result of the carbon-optimal battery dispatch was the altered grid load profile seen in the green line in Figure 24, right. The left side of Figure 24 shows the annual profile of the carbon emission rate per unit electricity for comparison. The annual load profile for the cases with no system (red line in Figure 24, right) had a midmorning peak when there was repeated domestic hot water use. In terms of the carbon emission rate, this peak occurred when solar generators began coming online, while the carbon emission rate was decreasing from high to low values. In contrast, the green line on the right side of Figure 24 shows the net load on the grid with a 3.4-kWdc PV system coupled with a 5.0-kWh battery. While the carbon rate is high at the early and late hours of the day, the system is giving carbon-free energy to the grid for a "carbon offset." During the midday, when the carbon rate is at its lowest, the system is taking energy from the grid to (1) charge the battery, and (2) meet building loads.

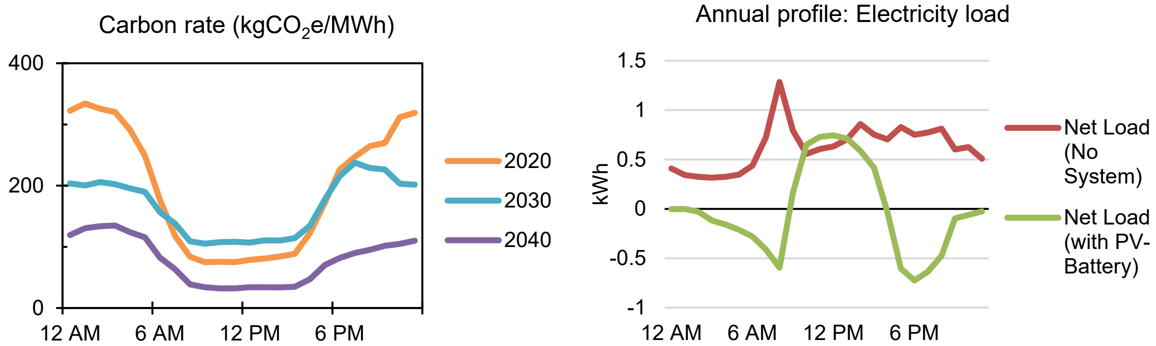

Figure 24. Annual profile of carbon emissions per unit electricity (left) and annual load profiles of apartment with and without PV-battery system (right)

On the right side the red line shows the annual load profile of a NZE apartment without any generation or storage. The green line shows that same apartment but with 3.4-kWdc photovoltaics and a 5.0-kWh battery optimized to reduce net carbon emissions.

D.4 Cambium Emissions Outputs

The central objective of the methodology presented herein is to assess the GHG emissions resulting from 30 years of operating one typical apartment unit. The 30-year emissions of three case scenarios are presented in Table 21.

Table 21. Cumulative GHG Emissions (Simple, Static CO_2-Equivalent Method) of 30 Years of Apartment Unit Operation for Three Selected Scenarios

	30-Year Emissions (lbmCO_2e)		
	from Natural Gas	from Electricity	Total
Prototype	62,250	36,258	**98,508**
Net Zero Energy (NZE)	0	17,202	**17,202**
Grid-Efficient, NZE building (NZE+GEB5)	0	8,989	**8,989**

In the “Prototype Reference” case, emissions from natural gas use in hot water heating accounted for about two-thirds of the total carbon emissions. Emissions for the “NZE” case were, unsurprisingly, lower. Notably, the net emissions of a NZE apartment were not zero, and were in fact about half the emissions from electricity use in the “Prototype Reference” case. Furthermore, in the “Grid-Interactive NZE” case, the emissions were reduced by about half compared to the “NZE” case. This is intriguing because these two cases were otherwise equivalent in terms of net annual energy use.

Appendix E. Uncertainty Propagation

It is not possible to directly measure GHG emissions from every emitter related to a building LCA. Instead, "wholesale" emissions data from an inventory of processes and material inputs are apportioned according to the functional unit. Thus, LCA results depend greatly on the inventory data and on the processes and materials included. These contribute to the uncertainty inherent in any LCA. Best practice for LCA dictates that methods and data be transparent to the reader to understand how the assessment was completed. This appendix voluntarily covers the topic of uncertainty in the LCA we used.

The results of the LCA were an apportionment of inventory data to the functional unit. Mathematically, the global warming potential impact GWP was a summation of the product of a quantity of material or process x_i with the associated unit emissions β_i:

(Eq. 1) $$GWP = \sum_{i=1} \beta_i \cdot x_i = \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \cdots$$

The uncertainty of the impact result $\delta(GWP)$ came from the uncertainty of the terms $\delta(\beta_i \cdot x_i)$:

(Eq. 2) $$\delta(GWP) = \sqrt{\big(\delta(\beta_1 \cdot x_1)\big)^2 + \big(\delta(\beta_2 \cdot x_2)\big)^2 + \cdots}$$

which took into account the "balancing" effects of adding uncertain terms. In turn, the uncertainty of a term $\delta(\beta_i \cdot x_i)$ depended on the uncertainty of the quantity of material or process δx_i and on the unit emissions data for that quantity $\delta\beta_i$:

(Eq. 3) $$\delta(\beta \cdot x) = \sqrt{\left(\frac{\delta\beta_i}{\beta_i}\right)^2 + \left(\frac{\delta x_i}{x_i}\right)^2}$$

because it was assumed that both the values x_i and β_i followed a normal distribution. Using the Embodied Carbon in Construction Calculator (EC3),[10] we can confirm that this is a valid approximation for most construction materials. We assumed that for large uncertainty terms $\delta(\beta_i \cdot x_i)$, the relative uncertainty in the quantity was much less than the relative uncertainty in the unit emissions, $\frac{\delta x}{x} \ll \frac{\delta\beta}{\beta}$, and the uncertainty term became $\delta(\beta \cdot x) \approx \delta\beta$. With this simplification the uncertainty of the impact result became:

(Eq. 4) $$\delta(GWP) = \sqrt{(\delta\beta_1)^2 + (\delta\beta_2)^2 + \cdots} \quad .$$

The significance of the above Equation 4 is that the overall uncertainty of the impact results mostly depended on the biggest uncertainties in terms of absolute units (e.g., lbmCO_2e). Hence, special attention was paid to terms where the contribution term $\beta_n \cdot x_n$ is large when compared to the average contribution. The following items were declared significant contributors to

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[10] https://www.buildingtransparency.org/.

uncertainty of the LCA impact and ranked in Table 22. Overall, absolute uncertainty in the LCA should be no more than 30,000 lbmCO_2e.

Table 22. Ranked Uncertainties by Absolute Uncertainty in the LCA

Item	Relative GWP Uncertainty (%)	Absolute Life Cycle GWP Uncertainty (lbmCO_2e)	Notes
Steel hollow structural section	± 20%	20,000	Department of General Services of California estimates a 20% tolerance for Buy Clean California compliance (Department of General Services 2021). A recent mill-specific EPD affirmed that values from five U.S. mills varied by about ±20% of the average (Nucor 2021).
Operational energy consumption, energy basis	± 5%	2,500	Declared uncertainty by the authors.
Electrical grid futures mix	± 5%	2,500	Systemic uncertainty (bias) in the calculation method of the chosen carbon per energy unit metric, see Section 4.5. Uncertainty in future economic conditions, see Figure 25.
Li-ion battery bank	± 40%	500	Many sources, spread of values for GHG emissions per unit battery capacity. See Section B.5.
Solar energy generation	± 3%	120	Uncertainty in year-to-year climate variations. See Figure 25.

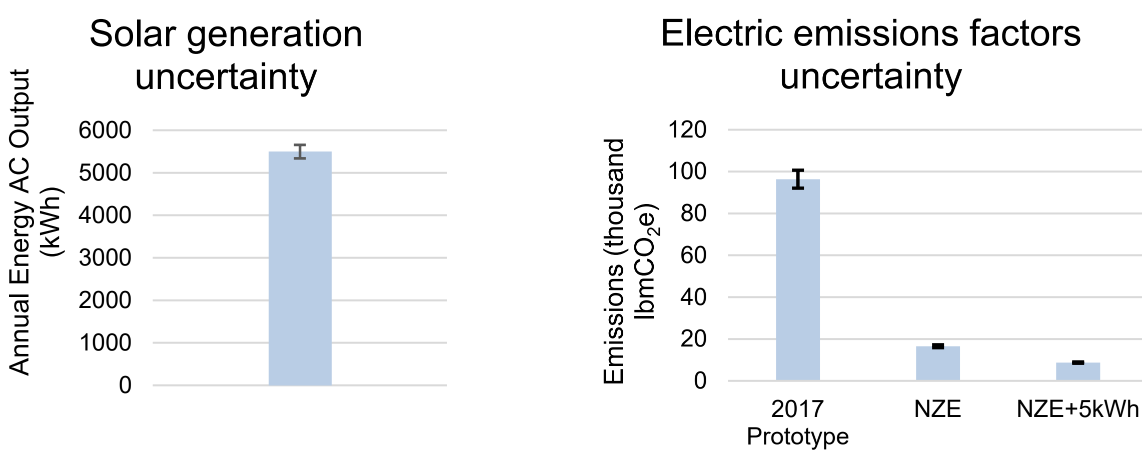

Figure 25. Uncertainty relative to expectation value of solar generation (left) and electrical grid future mix (right)

Left shows average annual energy AC output of 11 years of climate data, 2008–2019.
Right shows electricity emissions factors for three select techno-economic scenarios (pessimistic, mid-case, and optimistic).