A Scalable Method for Decarbonizing Modular Building Solutions

Preprint

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National Renewable Energy Laboratory

Presented at the 2022 ACEEE Summer Study on Energy Efficiency in Buildings
Pacific Grove, California
August 21-26, 2022

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5500-82516
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Suggested Citation
Kaufman, Zoe, Noah Klammer, Ankur Podder, and Shanti Pless. 2022. *A Scalable Method for Decarbonizing Modular Building Solutions: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-82516. https://www.nrel.gov/docs/fy22osti/82516.pdf.

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A Scalable Method For Decarbonizing Modular Building Solutions

Zoe Kaufman, Noah Klammer, Ankur Podder, and Shanti Pless, NREL

ABSTRACT

The decarbonization movement emphasizes the shift in focus from energy efficiency to directly reducing global-warming impact. Blokable, LLC, a vertically integrated modular housing developer and manufacturer with an all-electric portfolio, worked with NREL on a roadmap to decarbonize its high-performance building product at a relative cost advantage by utilizing the learning curves of mass production.

Previous decarbonization literature focused on either lifecycle assessments or efficiency measures. These decarbonization exercises were bespoke to individual building projects without considering positive feedback loops of builder experience or process repetition. Vertically integrated, prefab builders possess the unique ability to leverage learning and repetition to decarbonize their design-build-operate process. This collaboration between Blokable and NREL resulted in a decarbonization strategy utilizing the company's scaling and production efficiencies, on-site renewable energy and battery storage, and the projected evolution of building components and materials over time based on trends and emerging legislation.

The method developed here encompasses a growing business model, lifecycle carbon assessment, and projected changes in product and grid emissions over time due to existing trends and emerging legislation. This methodology incorporates learning-curve efficiencies gleaned from scaled manufacturing, along with open-source tools integration for energy and carbon accounting. The output projects and compares cost and carbon savings per modular unit as production increases to 10,000 dwelling units annually over 15 years. The resulting roadmap illustrates a path to roughly 60% carbon savings and beyond-net-zero-energy performance at no incremental cost by 2030. The methodology can be mapped to other integrated or productized builders for methodical decarbonization.

Introduction

Compared to the demand for housing in the United States, there is a supply deficit of 370,000 housing units annually, which has led to a cumulative need for 3.8 million units to match long-run demand (Khater et al. 2021). At the same time, to reach the U.S.'s stated goal of net-zero emissions by 2050 (Whitehouse.gov 2021), an immediate transition to all-electric, net-zero lifecycle carbon must be made for construction at this large scale.

Off-site construction methods can compress construction costs and timelines by leveraging the advantages of a controlled factory setting and parallel site-work and construction activities. "Productized" prefabrication (a standardized, repeatable product, as opposed to one-off) has the added advantage of repeatability and refinement of both process and product, particularly when the development process and the manufactured product are both controlled by the builder. Due to these advantages, a productized builder/developer has the ability to create and implement strategic roadmaps with more concrete means and metrics and clearer incentives for high performance and energy efficiency.

One such integrated modular developer and builder, Blokable, LLC, wanted to quantify how the learning curves of mass production could help them decarbonize their modular housing prototype at a relative cost advantage. To address this question, Blokable would need to understand: (1) the current lifecycle carbon intensity of their existing product; (2) the lifecycle carbon intensity of future construction alternatives; (3) potential process-related carbon reduction stemming from factory production; (4) patterns of waste reduction tied to factory-based, productized building; (5) trends in electrical-grid decarbonization; and (6) projected product and material decarbonization trends.

Additionally, each of these analyses would need to be woven together into a combined product-process analysis for comparing efficacy of different strategies. To this point, lifecycle assessment (LCA) studies, as compiled in both the United States (Simonen et al. 2017) and the United Kingdom (Johnstone et al. 2020), have focused on one-off projects, with the goal of minimizing a project's emissions or making strategic material replacements while remaining within budget. This application, however, sought to explore long-term payoff for a portfolio of modular buildings, which translates to the ability to consider pathways toward means and methods of building with technical and financial feasibility in the long-term and/or at scale, rather than feasibility simply for an individual project in the present day. Additionally, because Blokable both builds and owns/operates the housing as the developer, decisions can more easily be made based on lifecycle cost, rather than primarily up-front cost.

This study finds that, using its 15-year production roadmap, Blokable can reduce its per-unit carbon emissions by around 60% at no incremental cost by implementing advanced-construction technologies, optimizing material selection, and doubling down on zero-energy strategies with renewable energy and storage. Combining methodologies for projecting cost reductions and emissions reductions, various product options can be compared. We find that the regulatory landscape surrounding the industry plays a significant role in the ability to project environmental impact, and to navigate building component and technology options.

Methodology

The methodology developed for this analysis is presented in Figure 1, and consists of two parts: (1) cost-reduction analysis due to scaling and learning curves across Blokable's projected growth path, and (2) GHG reduction analysis considering operational carbon, product embodied carbon, and avoided carbon emissions.

Combined, the two-part methodology allows for cost- and GHG-comparisons for future product roadmaps. By cumulatively adding cost and emissions for buildings erected between the time of study and 2030, Blokable is able to assess the trajectory and 15-year outlook on payback, including incremental changes to production scale, waste factors, electrical grid decarbonization, and product embodied carbon.

The single case example of Sacramento, California, is used in this study for sake of illustration and the ability to compare costs and emissions over time. 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 code design requirements, and (8) construction cost premium for NZE strategies. Table 1 outlines the parameters considered in this case study.

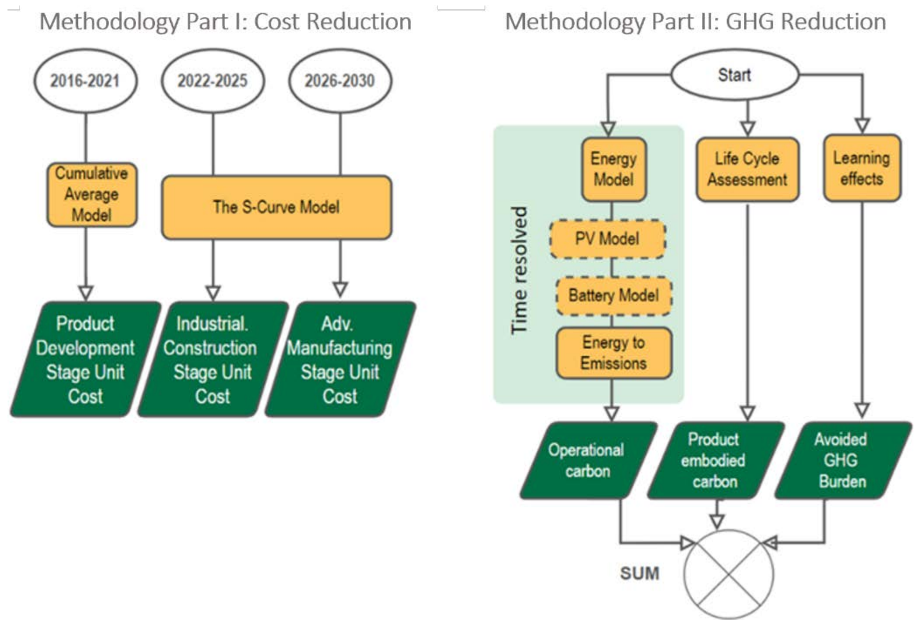

Figure 1. Unique contributions of the two-part methodology assessing NZE incremental cost reduction (left) and GHG emissions reduction (right). Dashed lines indicate steps applicable only to particular scenarios. *Source*: Klammer et al. 2021.

Table 1. Case study context and modeling parameters

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	IBC & Title 24 for Sacramento, CA, 2016
NZE Construction Cost Premium	Northern California market, 2015

Methodology Part 1: Learning Curves for Cost Reduction

A scaling plan, or product-growth roadmap, is crucial to being able to take advantage of learning effects. While not always the same across industries, learning and experience curves are used to model efficiencies in production, leading to greater throughput with reduced effort and reduced per-unit cost. A “learning rate” can be calculated as the cost reduction attained with a doubling of output. This concept dates back to T.P. Wright’s 1922 analysis of airplane production, which compared changes in cost to quantity produced, and found a 5%-30% cost reduction per doubling of production volume (Wong 2013). Between 1922 and 1936, the aircraft industry had achieved a 20% reduction in per-unit cost each year by leveraging increasingly efficient manufacturing tools and supply-chain optimization (Wright 1936). An NREL study from 1980 predicted similar learning rates for solar modules (Krawiec et al.), and recent data has proven this prediction correct: solar photovoltaics (PV) have exhibited similar scaling effects: cost of PV reduces by 20.2%, on average, per doubling of installed capacity (Roser 2020).

In order to incorporate learning-rate equations into a productized builder's cost model, one must acknowledge the mechanisms by which efficiencies are obtained; in addition to human learning, the "learning" is embodied into advanced manufacturing techniques and often reorganized or novel production methods. With this understanding, the product must be "industrialized" in order to benefit from these documented learning rates. Figure 2 outlines Blokable's planned growth over a 15-year period, with an end goal of producing at least 10,000 dwelling units annually by doubling annual production.

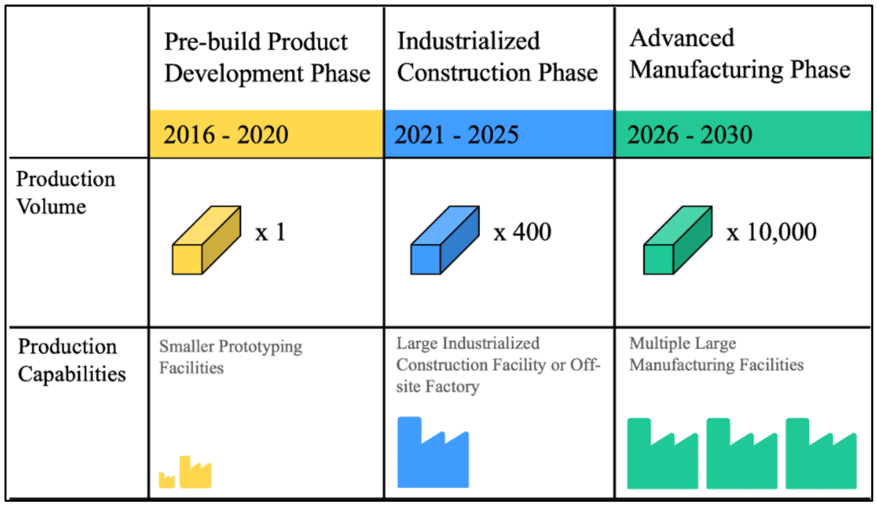

Figure 2. Three phases of product development and production rates. *Source*: Klammer et al. 2021.

Initially, Blokable's production amounted to a few dwelling units each year, with a focus on developing and validating its building product. Next, the company plans to expand production with a dedicated factory, expanded number of projects, and higher-density buildings in its "Industrialized Construction Phase." Finally, having honed the product-specific production process, Blokable will transition into the "Advanced Manufacturing Phase," where automation replaces repetitive processes, and production facilities expand and multiply in response to the growing need for housing.

Using this growth plan, learning rates can be calculated by implementing two models: (1) the Cumulative Average Model, and (2) the S-Curve Model. Wright's Cumulative Average Model uses measurements of initial cost or time reduction versus number of units produced and carries over those percent reductions into future predictions. The S-Curve assumes an evolving learning rate as processes and proficiency change over time. Each phase of product growth may result in a different learning rate.

The Cumulative Average Model applies to the first phase of production, product development, where a single product undergoes multiple iterations with high initial learning rates (20%-25%, or 75-80% "learning curve") influenced in large part by nonproduction factors, including reducing design variability, lightweighting, and incorporating plug-and-play components that reduce on-site labor. The learning rate used here is based on Blokable's reported historical efficiency gains and cost compression.

Once the product has been largely defined, we apply the S-Curve Model, which accounts for procedural changes and repeated processes in the "Industrialized Construction" phase, followed later by increases in automation and data-driven supply-chain optimization in the

“Advanced Manufacturing” phase, as illustrated in Figure 1, and as described previously in more detail by Klammer et al. (2021). This study assumed a moderately low (3%-10%) learning rate for Industrialized Construction, and a steeper (15%-30%) learning rate for Advanced Manufacturing, with rates for individual systems and products depending on those of analogous examples. This cost model can be used to plan for product evolution, and is especially helpful in reducing present-day incremental cost of net-zero-energy (NZE) design over time.

Compressing Marginal NZE Costs

Given the need to significantly increase net-zero construction to meet the housing deficit in a way that aligns with national decarbonization goals, net-zero and electrification strategies, in particular, must undergo cost compression. Available records of cost tracking for high-performance construction suggests that net-zero building carries an incremental cost of around 8%, as detailed in a recent report on an NZE site-built rental-housing community in Spring Lake, California (Mutual Housing California 2018). A range between 2-10% marginal costs for passive-house projects in the U.S. has been reported, depending on project size, location, and furnishings (Passive House Institute U.S. 2015). Of course, the total range can vary widely, but for the purposes of this model, we use the Spring Lake example.

NZE-related costs for this project 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. Applying the cost model to these ZNE incremental costs throughout the 3 construction stages, the originally estimated 8% marginal cost for high performance is projected to decrease over time, and we can follow that identified marginal cost as it reduces.

Methodology Part 2: Lifecycle Greenhouse Gas Emissions Modeling

The second aspect of the methodology for modeling product decarbonization over time involves quantifying GHG emissions over the product lifecycle and accounting for trends in emissions over this time period. Prior to selecting tools to help accomplish this, an LCA boundary must be defined.

Lifecycle Assessment Scope

Blokable was interested in establishing a 15-year roadmap through 2030; however, they and their partners would own and operate all of these projects for many years afterward. Therefore, an operational period of 30 years was used for this LCA, which 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. 30 years also aligns with the end of currently projected grid emissions from NREL.

The only environmental impact considered in this LCA was global warming potential (GWP), expressed in pound-mass-equivalent units to carbon dioxide (lbmCO_2e). This report considered “embodied” emissions (those that come from the production, construction, and maintenance of building components) and operational emissions during building occupancy. Not all buildings or projects will be the same size or configuration, even within a single builder’s portfolio, so this analysis used a single dwelling unit and its associated components (even if these supplementing components are in common areas) as the basic unit for comparison. For the sake of developing a meaningful comparison, the basic unit modeled is a 720-ft^2, one-bedroom dwelling unit. Table 2 details the building components included and excluded from the study. The LCA included: (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. Excluded were: (1) foundation system (substructure), (2) roofing system, (3) interior finishes beyond gypsum board, and (4) interior furnishings, such as home appliances and furniture.

Table 2. LCA scope

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

Corresponding Construction Specifications Institute MasterFormat® (CSI 2021) number for each building system is provided in parentheses. *Source*: NREL.

It is important to note that foundations and site work tend to contribute significantly to embodied carbon; however, they are not included for this analysis because site work and foundation design vary greatly by site conditions, so it would be impossible to include a "representative" value that would change over time due to Blokable's building system and product. We also note that emissions are not calculated for roofs or common areas like lobbies or multipurpose rooms, since the proportion or scale of these attributes compared to the number of dwelling units is variable by building, therefore rendering impossible allocation of associated emissions per dwelling unit.

Table 3 illustrates the LCA modules that were included within this project scope. 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. For more details on LCA methodology and calculations, see Appendix B of Klammer et al. (2021).

Table 3. LCA system boundary scaffolded by ISO 14044 modules. *Source*: Klammer et al. 2021

Module	Stage name	System	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 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	

✓: Included in system boundary. MND: Module not declared. *: Conditionally included (see "Notes" column). 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.

While this LCA framework may be applied to other off-site builders, the analysis performed here is specific to a comparison between Blokable's initial product and future product options; it is not suitable for comparison to other buildings, for several reasons:

1. The excluded components (Table 2) can play a significant role in GHG emissions.
2. Blokable's business model and growth roadmap are unique to the company, and scaling in terms of factory size, number, and location impact metrics such as transportation and waste factor.
3. Blokable's primary market is California. Operation emissions are calculated based on local climate and grid mix, and material/product emissions are based on projected local requirements and availability over time.

A novel contribution of this report's methodology is the granular resolution at which grid-provided-energy emissions are calculated, meaning that energy use, energy production, and battery operation are able to be incorporated with high temporal resolution. This allows for the operational emission savings of technologies to be weighed against the incremental embodied emissions of those same technologies, in the context of an evolving grid.

Embodied Emissions Data

LCI data. Where available, this study drew life cycle inventory (LCI) data from Athena Impact Estimator for Buildings v5.4 database (2019). Most of these data are less than 10 years old. Athena LCI data were supplemented or updated with other transparent, third-party-verified sources wherever more relevant data was applicable. Less straightforward data was available for lithium-ion batteries, where recent publications did not converge to a single value for emissions related to this component. In this case, the average of the range midpoints (270 lbmCO2e/kWh-capacity) was used as the embodied carbon value, although further study of home batteries could reduce uncertainty of this value.

Refrigerant leak model. The TM65-2021 basic calculation method was used to project emissions due to refrigerant leaks, assuming a 2-kg charge of R-410a refrigerant leaking 4% each year for a 30-year service period. The 4% leakage rate applies to more modular, in-unit mechanical systems, as opposed to centralized mechanical systems, which would involve a higher leakage rate due to additional refrigerant-piping and volume charged on site. The leak rate was corroborated by the 2020 report "Refrigerants & Environmental Impacts: A Best Practice Guide" (Hamot et al. 2020).

Vehicle miles traveled. Emissions due to transportation of people and products are assumed to reduce over time, beginning in the Industrialized Construction phase, due exclusively to regionalization of supply chain and distributed factories—not due to assumptions about fleet electrification, although vehicle electrification could be part of future study.

Steel product evolution. Considering the typically large contribution of structural materials to overall embodied carbon in a building, a primary focus of this project was placed on steel—Blokable's original structural material of choice. Hollow structural sections (HSS) allow Blokable's structural frame to maintain low tolerances, high precision, and structural flexibility; however, Blokable's design has shifted to a "hybrid" structure with wood framing amongst steel superstructure due to lightweighting and embodied carbon concerns. Recently, Buy Clean Acts have sprung up across the country, beginning in California, where the Buy Clean California Act passed in July 2021 (Bill Track 50 2021). The Act takes effect in July 2022 and applies only to materials purchased for projects where a public California entity is the client, but this model assumes that, because of Buy Clean CA, compliant products will be regionally available for use. Using data contained in EPDs for local and standard steel products, we modeled decreasing carbon emissions per unit steel by year (Table 4) based on the assumption that a regional, differentiated steel market would emerge for low-emission steelmaking. This assumption does not include new steelmaking technologies; instead, 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 4. Projected GWP per mass unit steel by year (CA)

Year	2016-2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Steel GWP ($lbmCO_2e/lbm$)	3.05	2.89	2.72	2.56	2.4	2.24	2.08	1.92	1.76	1.6

Construction waste: The emissions burden of construction waste was calculated by adding a waste factor (WF) percentage to the calculated quantities of each product, based on Athena's default values for the location. 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. As mentioned in *Methodology Part 1*, waste factor was assumed to reduce over time, based on the relevant learning-curve model.

Modeling Tools and Scenarios

To provide Blokable with an understanding of the relative importance of building materials, systems, and demand-side management, the model had to account for each of these in parallel. In addition, five scenarios were studied:

1. **Prototype reference**: Blokable's initial building typology from inception in 2016, using gas for water heating and no renewable-energy systems.
2. Zero energy design (**ZED**): All-electric, Zero Energy Ready design, without renewable-energy systems.
3. Net zero energy (**NZE**): ZED design, plus photovoltaic rooftop modules, sized to offset 100% of operational energy.
4. Net zero with 5-kW battery storage (**NZE + GEB5**): includes a 5-kW battery per dwelling unit for grid-interactive, efficient (GEB) functionality and demand-side management.
5. Net zero with 10-kW battery storage (**NZE + GEB10**): includes a 5-kW battery per dwelling unit.

Hourly building energy consumption data was modeled in OpenStudio®, an open-source energy-modeling software, for an apartment building in Sacramento, CA. Since the Blokable product is centered around zero energy, the energy model for ASHRAE's Multifamily Zero Energy Design Guide draft (ASHRAE 2019) was used. A single one-bedroom apartment was sub-metered to represent typical energy consumption. The apartment was selected by cluster center analysis on the 8760-dimensional space of hourly energy consumption, with a temporally sensitive definition of statistical "typicalness" (see Klammer et al. 2021, Appendix C for details).

Figure 3 illustrates the pathway from energy modeling, to demand-side-management (energy production and storage) calculations, to operational carbon emissions. The hourly electricity-consumption outputs from OpenStudio were brought into System Advisor Model (SAM) (NREL 2020), another open-source and no-cost tool, to simulate PV and battery storage. Case scenarios that included battery storage with PV were programmed to dispatch battery energy to minimize carbon emissions through energy arbitrage. In order for SAM to "value" carbon emissions, a time-of-use rate was created that reflected the projected relative carbon emissions intensities of grid electricity at different hours of the year. Cambium, a collection of hourly emissions and cost datasets from NREL (Gagnon et al. 2021), was used to identify projected emissions factors between 2020 to 2050 under the "Mid-case" (business-as-usual) scenario, with 5-year granularity. While not always the case, this study assumes that utility time-of-use rates will increasingly align with grid carbon emissions—especially in the absence of projected electric-utility tariffs.

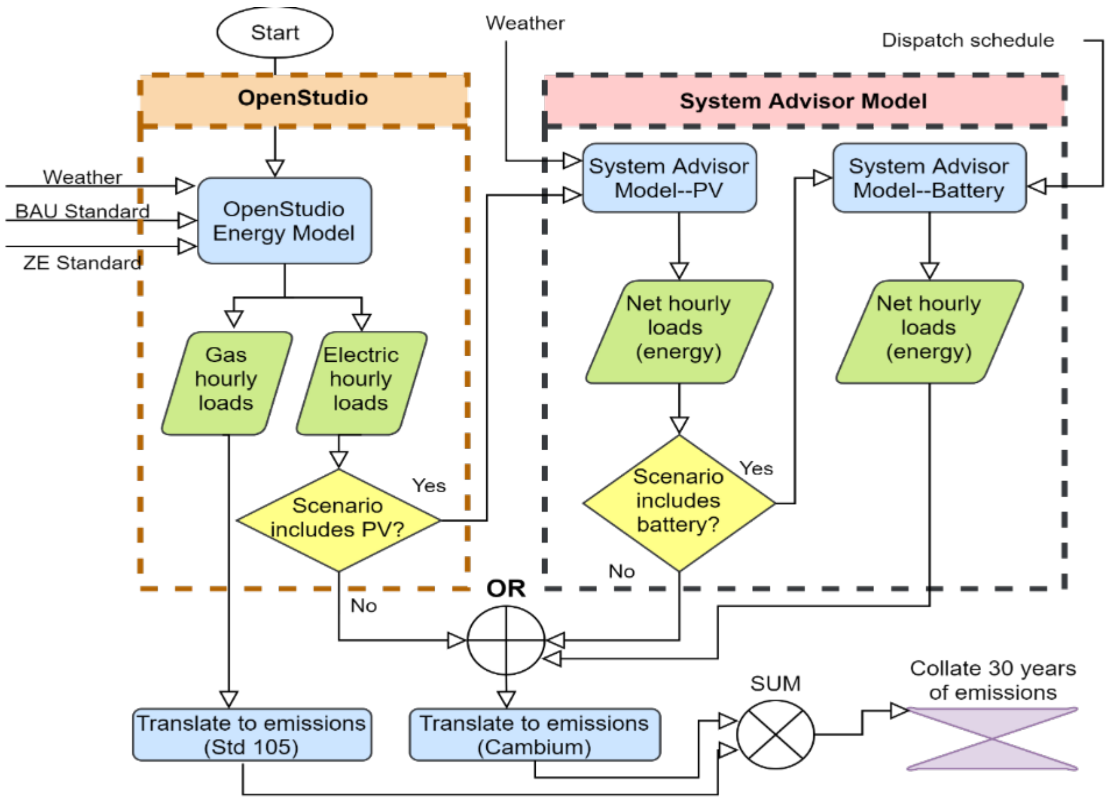

Figure 3. Analysis workflow used for operational energy emissions calculation. *Source*: Klammer et al. 2021.

The emissions factors used from Cambium were "long-run marginal carbon" emissions rates to compare carbon opportunity costs for the theoretical, future (marginal) 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. Figure 4 shows the trend for long-run marginal carbon rates between 2020 and 2040. Natural-gas-related emissions in the prototype reference case, on the other hand, were assumed to be static. Finally, up-front and operational emissions were summed for each year and compared over the 30-year time period.

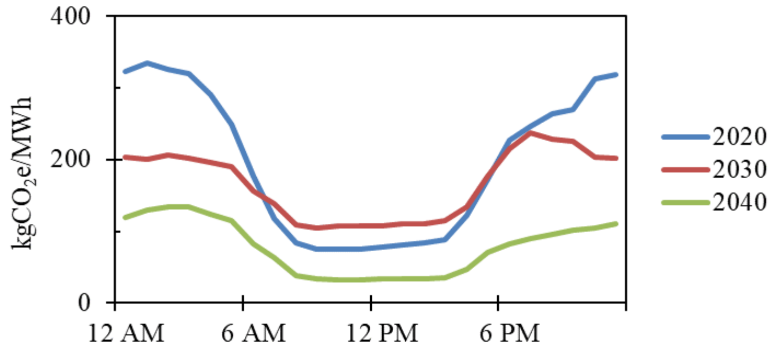

Figure 4. Long-run marginal carbon emission rates. *Source*: Cambium, NREL.

Findings

Methodology Part 1 Findings

Using Methodology Part 1 for cost reduction, we found that a high-performance modular builder may reduce the incremental costs of NZE strategies from +8% to +1% by meeting the outlined road map's conditions and scaling beyond 10,000 annual NZE dwelling-unit production by 2030. Figure 5 illustrates the reduction in incremental NZE cost with increasing annual production volume across the 3 stages of construction and associated learning rates as outlined in Methodology Part 1.

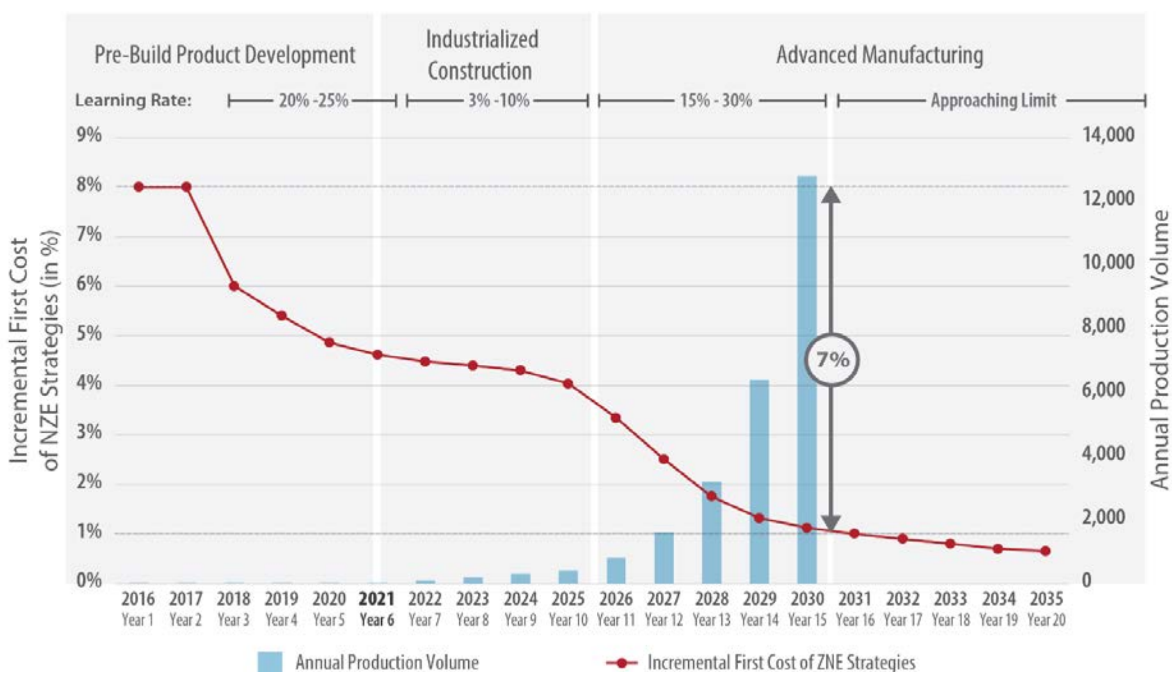

Figure 5. Projected cost curve for NZE strategies across the development roadmap. *Source*: Klammer et al. 2021. Case study analysis and intervention begins in 2021, 5 years after initial product development.

Crucially, the gains in efficiency in the Advanced Manufacturing phase must be enabled by economies of scale. At this point in time, the 1% incremental cost can actually be seen as a 7% cost savings over code-minimum construction, as some codes will require net zero design at this date, including California. A productized builder/developer would be ahead of the curve at the point that NZE performance is required, and would additionally be able to reap the benefits of low energy costs for the building's useful life.

Methodology Part 2 Findings

30-year energy-related carbon emissions for each of the 5 scenarios is presented in Figure 6. Comparing the differences between the scenarios helps inform the decarbonization roadmap.

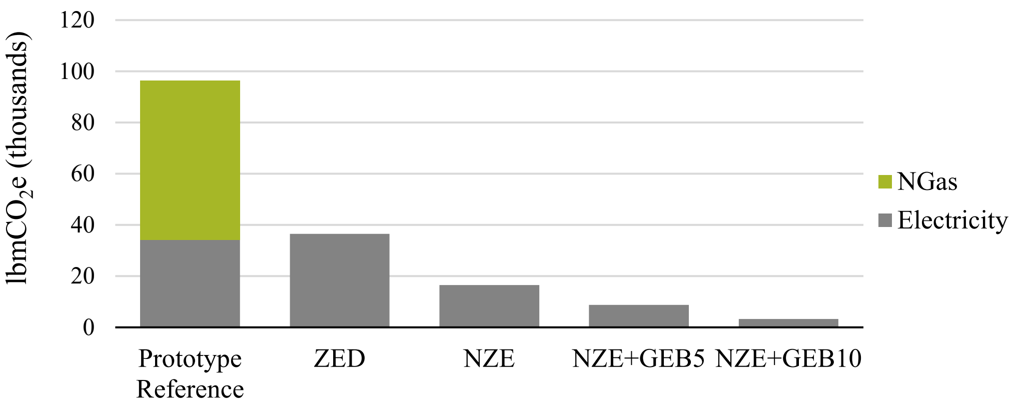

Figure 6. Lifecycle emissions from energy consumption by performance scenario. *Source*: Klammer et al. 2021.

The greatest absolute difference in carbon is between the prototype reference case and the ZED case. Electrifying 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 case. Of course, this really reveals the power of the embedded assumption that grid electricity will decarbonize with time, placing importance on utility decarbonization roadmaps.

Notably, "ZNE" design does not actually equate to net-zero carbon emissions because of the time of energy consumption versus production. Even a 10-kW battery does not achieve net-zero energy-related emissions, which emphasizes the role and cost-effectiveness of energy efficiency and electrification as primary strategies toward decarbonization.

Decarbonization Roadmap

A decarbonization roadmap was ultimately proposed, combining the business-scaling and carbon-accounting methodologies. Figure 7 lays out the 30-year lifecycle carbon emissions of an individual dwelling unit built in the specified year, from 2016 to 2030. Operational emissions are represented in shades of orange, while embodied emissions are in green and purple.

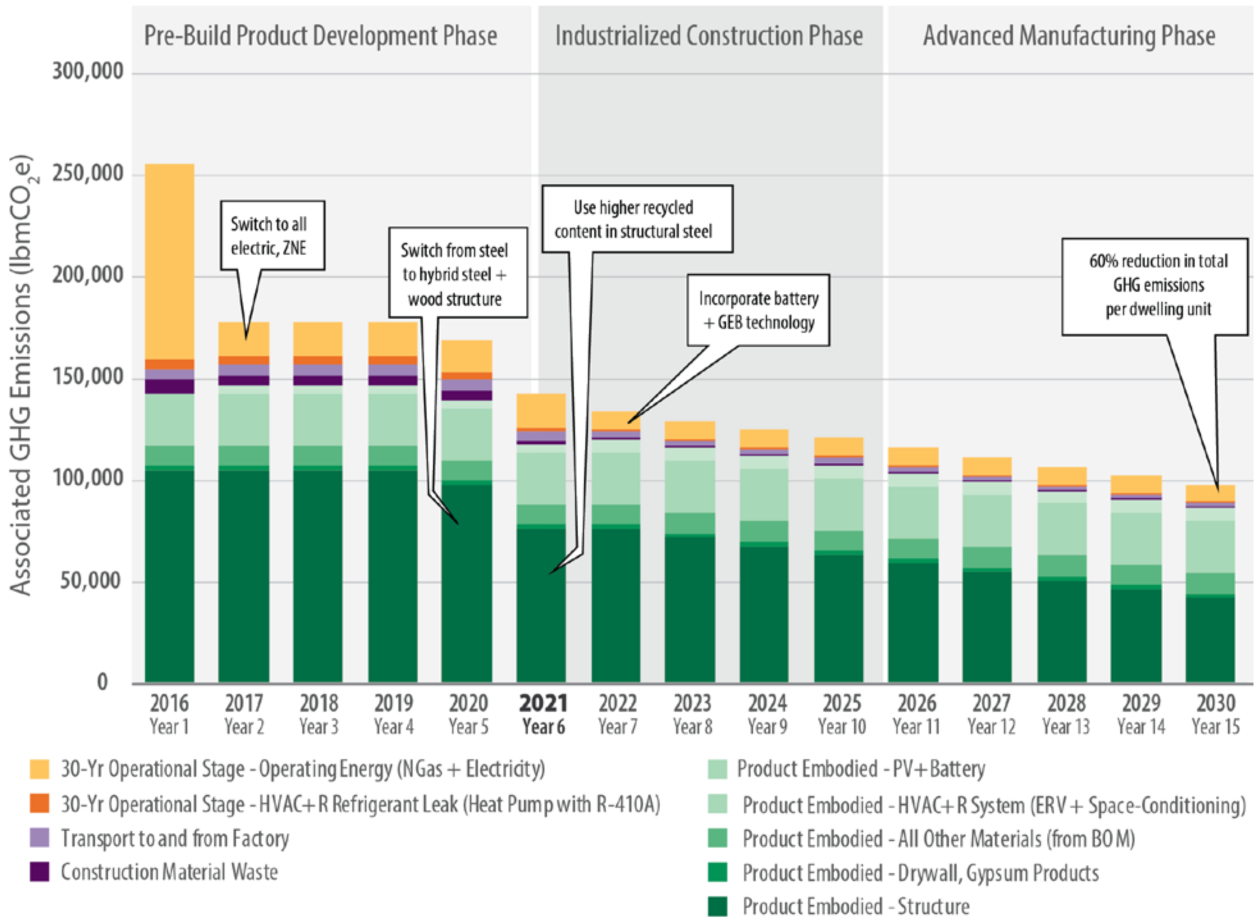

Figure 7. Decarbonization roadmap for 30-year lifecycle + GHG reduction over three phases from 2016-2030.
Source: Klammer et al. 2021.
Case study analysis and intervention begins in 2021, 5 years after initial product development.

Lifecycle carbon savings compound as production scales up, in accordance with the Methodology Part 1 findings. Due to early electrification and on-site renewable energy, operational carbon represents a very small proportion of lifecycle emissions over time, which shifts the focus in the Industrialized Construction phase to embodied emissions, and specifically to the structural products (dark green). Mass production strengthens the company's bargaining power, which promotes access to a supply of increasingly decarbonized steel from higher recycled content, local sources, and cleaner electric-grid mix for manufacturing using electric arc furnaces. Additionally, refrigerant-related embodied carbon decreases over time as reduced refrigerant-piping length is used in design, QA/QC strategies are honed, and low-GWP refrigerants emerge on the market, as foreshadowed by Senate Bill 1383, requiring California to reduce HFC emissions by 40% compared to 2013 levels by 2030, and the ensuing California Air Resources Board proposed GWP limits for refrigerants (ACHR News 2021).

In 2022, a battery is implemented, anticipating both increasingly cost-effective technology and non-financial incentives, including climate resilience and grid interactivity for grid resource balancing—2 key focuses of the California Energy Commission's EPIC Challenge: Reimagining Affordable Mixed-Use Development in a Carbon-Constrained Future. Production and material process efficiencies become the focus of the final production stage, where federal, state, and utility roadmaps to electric-grid decarbonization culminate in a nearly decarbonized grid. Combining learning-curve and scaling efficiencies, material decarbonization, waste reduction, and carbon-reduction technology, the final product can achieve over a 60% reduction in lifecycle emissions compared to the prototype reference case.

Conclusion

This study finds that, by prioritizing low-carbon materials and systems, productized, high-performance developers and builders like Blokable can achieve 60% lifecycle emissions reductions by 2030, without a cost premium, with respect to their particular regulatory environment of building codes. However, unless decarbonization is planned from all levels—from internationally, nationally, and state-level, to utility and industry level—its implementation will be slow and clunky. Without a clear roadmap for energy-performance thresholds or GHG limits for products and materials, developers and building owners should find it reasonably difficult to plan for reducing their future environmental impacts. In contrast, with the aid of staged planning for emissions reduction of building materials, components, and operations, integrated developer-owners can create more accurate roadmaps of their own to stage a path for decarbonization. This points to the important role of policy and legislation in clearly defining decarbonization goals, timelines, and incremental steps. Likewise, suppliers, industry organizations, and energy suppliers can take initiative in planning for decarbonization. With meaningful projections for the decarbonization of increasing aspects of the building lifecycle, companies like Blokable can put increasing stock in their own multi-faceted roadmaps.

The roadmap detailed in this report, whose methodology can be applied to other vertically integrated or productized builders, is aided and supported by legislative agendas, without which it would be difficult to have any confidence in the product decarbonization pathway. For instance, Buy Clean Acts that provide sufficient market and buying power can be incorporated into decarbonization planning. Performance targets, when codified, can help support planning efforts: 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's Local Law 97 sets operational-carbon-emissions requirements, 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.

With all of these efforts combined, this study's findings of a final 1% cost premium for net-zero equates to a 7% cost advantage as code evolves to require net-zero performance. Compared to builders new to net-zero, whose incremental high-performance costs may be more like 8%, productized net-zero builders experience a 7% experience-based cost advantage.

One major area in which legislation can provide impactful direction in the near term is electrification. Emissions from electric energy usage are more easily offset by on-site and off-site renewables than are fuel emissions. 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. A building that is planned to have truly zero operational emissions must ultimately be all electric.

Decarbonization of the electric grid affects both operational-energy emissions and embodied-energy emissions due to manufacturing, and potentially due to transportation, assuming a transition to electric vehicles. Future work on decarbonization roadmaps should explore different grid scenarios in order to weigh technology priorities under the range of possible future circumstances. The timing of grid decarbonization would impact emphasis on development of electric systems such as heat-pumps, and points to the importance of a clearly delineated pathway to achieve utility-level goals. Whether in California, New York City, or elsewhere, it pays to be ahead of the regulatory curve; but first, one must have guidance for this planning.

Acknowledgements

This work was authored by the National Renewable Energy Laboratory, operated by the Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed in this paper do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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