A Life Cycle Decarbonization of Modular Building Solutions

Preprint

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A Life Cycle Decarbonization of Modular Building Solutions

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Abstract

Off-site construction methods offer the opportunity to compress costs of net zero energy housing using the advantages of mass production. Blokable, LLC, a vertically integrated modular builder, wanted to know how the learning curves of mass production would help them decarbonize their existing modular housing prototype at a relative cost advantage. The method developed for this question looked at the life cycle assessment of an individual apartment and used learning curve efficiencies to approximate the relative advantage of construction-at-scale. Greenhouse gas emissions were quantified by a learning-affected, whole life carbon emissions model and demonstrated a path to a 60% reduction of whole life CO_2-equivalent in the 2030 production year. The resultant roadmap considers a best-first approach to decarbonizing a modular building product line, and the method can be replicated for other modular builders.

Introduction

Affordable, zero carbon emissions is an important climate-performance target for the future of multifamily housing (*Architecture 2030* 2016), and multifamily construction methods hold 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 alone (Khater et al. 2021). Affordable housing with low whole life carbon is not being designed, constructed, and delivered across the United States as quickly as needed (Carroll 2021, Team Zero 2021), and greenhouse gas (GHG) emissions from the construction industry continue to contribute substantially to climate change.

Industrialized construction is one approach to efficiently achieve affordable housing that implements net zero energy (NZE) strategies (Barbosa et al. 2017, Juillerat and Donovan 2019, Podder et al. 2020). Industrialized construction is a modern approach to construction wherein construction modules are manufactured at an off-site factory and then transported to their ultimate project site (Quale et al. 2012). Research partner and modular builder, Blokable, LLC, is the company behind one such modular product, which they term the "blok" (Figure 1). These dwelling units aim to be 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.

Figure 1 A modular "blok" apartment unit is craned onto site. Credit: NREL image #62503.

Blokable, LLC, wanted to know how the learning curves of mass production would help them decarbonize their modular housing prototype at a relative cost advantage. Many previous studies have used life cycle assessment (LCA) or life cycle cost analysis (LCCA) as a framework for comparing the efficacy of energy conservation measures (Neuberg et al. 2003, Cubí and Bergerson 2014, Schwartz et al. 2018, Jusselme et al. 2019). However, there has been limited investigation on the trade-offs between site-built and industrialized methods of construction from the perspective of reducing GHG emissions during the production and operational stages of the building life cycle (Kamali and Hewage 2015, Johnstone et al. 2020, Simonen et al. 2020). Additionally, as new construction becomes more energy-efficient, the GHG emissions from the construction methods (building materials and construction activities) play a proportionately larger role in environmental impact and must be considered when evaluating methods of construction. The working assumption supported by literature (Carr 1946, Krawiec et al. 1980, Sundaram 2015, Wong 2015, Srour et al. 2016) is that the learning curves of mass production would have add-on effects that reduce the cost of decarbonizing the product line.

This conference paper presents methods and results of a joint research effort (Klammer et al. 2021) between industry and academia to answer this strategic question with actionable pathways. That effort demonstrated a pathway to affordability and emissions reduction via specific strategies within the framework of industrialized construction and mass production. The case study was analyzed over the years 2016–2030, where the production builder began instituting the analysis and intervention five years after initial product development. The modeling and analysis methods presented herein are novel—we present a "chained" simulation approach with life cycle assessment, building energy modeling, distributed energy modeling, and grid forecasts—and can be applied to other productized modular builders.

Simulation Methods

For the product line decarbonization exercise, two simulation scopes were simultaneously considered: i) the whole life carbon of the individual product as well as ii) the larger effects-in-aggregate of learning curves and as the product moved from prototype into mass production. In this paper, greenhouse gas emissions, as measured by LCA, is the key performance indicator for both scopes although marginal first-cost (stated in %) was also considered in the original analysis (Klammer et al. 2021). 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.

Individual Whole Life Carbon Analysis

The simulation scope of the individual product unit was conducted with the life cycle assessment framework so that the material-related carbon and operational carbon could be compared relatively. Additionally, the recent publication of time-resolved electric grid emissions forecasts (Gagnon et al. 2020) presented an opportunity to evaluate the operational carbon savings of load-shifting and other grid-interactive efficient building (GEB) approaches. Different energy performance and "bill of material" product scenarios were simulated to assess the relative efficacy of decarbonization pathways.

Table 1 Life cycle assessment goal statement.

LCA Goal Category	Description
Intended Application (what)	A 30-year life cycle assessment including both material-related and operational stages of a modular apartment unit prototype and its future design iterations.
Reason for Study (why)	To quantitatively compare decarbonization strategies for a modular product line.
Intended Audience (for whom)	Blokable, LLC, an integrated modular builder and other interested stakeholders.
Comparative assertions? (how)	No, the results are not meant to compare against other third-party products

Life Cycle Assessment

To form the basis for the analysis, a reference bill of materials and energy performance level was developed from the modular prototype documentation provided by Blokable, LLC. ISO standards 14040 and 14044 (ISO, 2006a, 2006b) required that the goal of an LCA study be unambiguously stated and include: the intended application (what); the reason for carrying out the study (why); the intended audience (for whom); and whether the results are intended for comparative assertions intended to be disclosed to the public (how). The goal statement is given in Table 1.

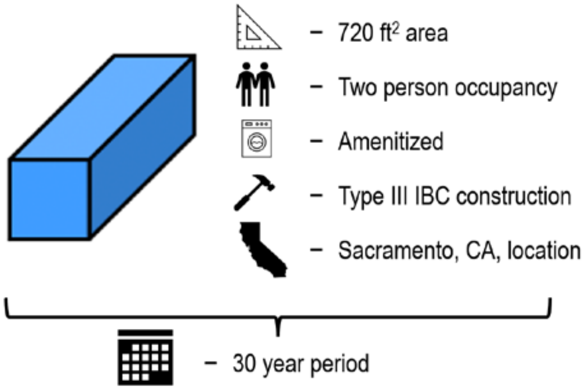

Figure 2 The functional unit of study is a 2-bedroom apartment and is defined for the life cycle assessment with the operational assumptions above.

The scope (functional unit and system boundary) of the LCA must also be stated and is graphically summarized in Figure 2. The functional unit of the study is a 720-square-foot, 2-bedroom modular apartment designed to the requirements of a Sacramento, CA, location and operated as a two-person residence for a period of 30 years. The full LCA methodology and system boundary can be found in Klammer et al. (2021).

Life Cycle Inventory Data

After the bill of materials was developed with a high degree of certainty, the accuracy of the material-related carbon became subject to the accuracy of the life cycle inventory data. The majority of the inventory data used from the LCA portion of the analysis came from the Athena Impact Estimator for Buildings software (Athena Sustainable Materials Institute 2019). The authors found the Athena database to be highly reliable but did apply a few key substitutions and additions where needed. The fully transparent sources and uses for inventory data are given in Klammer et al (2021).

Key Inventory Substitutions

The inventory data for structural steel was substituted to reflect better temporal and geographical representation of U.S.-made structral section (EPA 2020, Steel Tube Institute 2021, Nucor Tubular Products 2021) and cold-formed steel studs (SCAFCO 2019). The background inventory data for vehicle miles traveled was substituted to better reflect the findings of Quale et al. (2012) for the construction logistics of modular, off-site construction. Beneficial learning effects in logistics were considered for actual distance units of miles.

Key Inventory Additions

The material-related carbon of heating, ventilation, air-conditioning equipment was added and came from the method of Rodriguez (2019). Refrigerant leakage during building operation was added and modeled with assumptions from Hamot et al. (2020) and CIBSE TM-65 (2021). Photovoltaic modules and the associated "balance-of-system" equipment for certain product scenarios were added with the best temporal and geographical approximate inventory data available (Krebs et al. 2020). The material-related carbon of lithium-ion-type home batteries was added for some product scenarios; this inventory data was the least certain of any and required a more nuanced approach that was detailed in Klammer et al. (2021). Operational carbon in the "use" stage of the building life cycle was accounted for in the manner described below.

Building Energy Model

As stated previously, time-resolved grid consumption scenarios were needed to quantify the carbon benefits of storage and load-shifting GEB strategies. To arrive at a suitable output required several dimensions of "post-processing" simulation, starting with a building energy model realized through OpenStudio (Guglielmetti et al. 2011). The two building performance scenarios were articulated based on the previous design guide of Langer et al. (2020) and the documentation provided by Blokable, LLC. The model parameters for the two scenarios are summarized in Table 3 at the end of text. The hourly energy use output data from the two performance scenarios were kept for further post-processing.

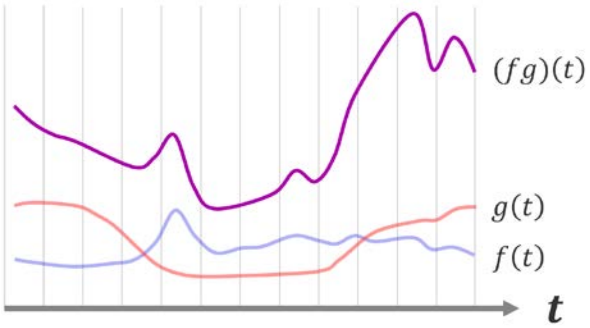

Figure 3 Illustrative example of the daily curves for the building net load $f(t)$, the grid emission factor $g(t)$, and their resultant net emissions product $(fg)(t)$.

Coupled PV-Battery Model

For the product scenarios that included either standalone generation or generation and storage, the "Coupled PV-Battery Model" from the System Advisor Model software was used (DiOrio et al. 2015). In product scenarios that included coupled battery storage, the simulated battery dispatch was controlled in a way that minimized the operational carbon on the simulated grid. The optimization algorithm of Cutler et al. (2017) was leveraged with a custom objective function containing the simulated grid data of Gagnon et al. (2020). The output from this additional simulation was the net grid load. One final post-processing step remained to cast this data in a usable form for the LCA.

Energy to Emissions

The net grid loads of the previous simulation step were then translated from units of energy into units of carbon emissions in the final step. For product scenarios with natural gas use, the units of energy were translated with a static emissions factor of 147 lbmCO_2e/MMBtu (ASHRAE 2014). The time-resolved electricity use was translated with the help of the "long-run marginal emission rate" variable in the dataset of Gagnon et al. (2020) illustrated by the example in Figure 3. The net effect of this sequential simulation is summarized by a flow chart in Figure 4. The whole life carbon calculation method will be summarized below.

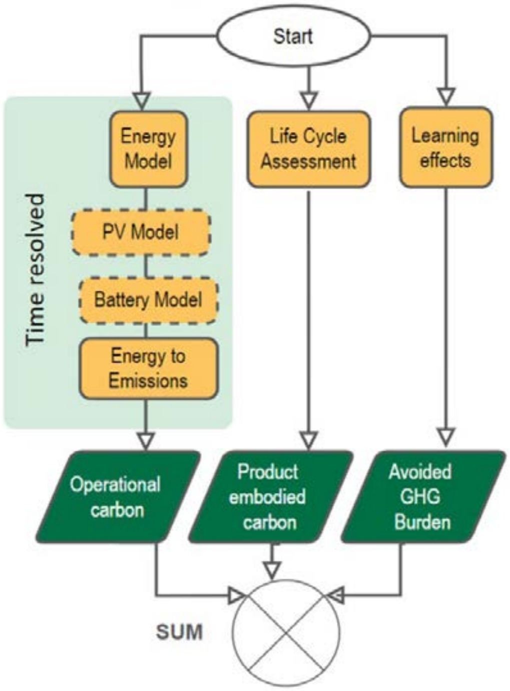

Figure 4 Flow chart for learning-affected whole life building emissions model.

Resultant Calculation

The mathematical formulation of the whole life carbon calculation can be seen in (1). The global warming potential for a modular unit in production year p, GWP_p

$$GWP_p = \sum_{i=1} \beta_{i,p} \cdot (x_{i,p} \cdot W_{i,p}) + \sum_{y=1}^{30} \sum_{h=1}^{8760} e_h \cdot C_{(p+y),h} \qquad (1)$$

is the total of the material-embodied carbon summation (indexed with i) and the operational carbon double summation. The embodied carbon for material i in year p, $\beta_{i,p}$ is affected by its "billed" material quantity $x_{i,p}$ and a waste/inefficiency factor $W_{i,p}$. The operational carbon is the product of the annual hourly energy use e_h and an energy emissions factor $C_{(p+y),h}$ indexed by its annual hour h and the forecast year $(p+y)$. The full nomenclature is given at the end of the text. The aggregate learning effects from the scaling of production are discussed next.

Aggregate Learning Effects

Learning effects models were empirically developed by Wright in 1936 for unit production cost reduction of airplanes. We bring together two widely used learning- and experience-curve models, the Cumulative Average Model (applied to the Product Development stage) and the S-Curve Model (applied to the Industrialized Construction Phase and Advanced Manufacturing Phase), into a sequential cost-reduction methodology for NZE strategies. 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. We have also applied learning effects to the Pre-Build Product Development Phase (due to integrated design and elimination of "forgetting" from project to project) to reduce construction material waste from drywall (high waste factor).

Results

Prioritization of Strategies

A key result of applying the product line decarbonization method for the Blokable "blok" product was the prioritzation of strategies on a first-best basis. Our whole life carbon accounting methods showed that operational energy efficiency measures continue to prove the greatest carbon reduction when compared to the appropriate baseline building. Our finding was that a switch to the all-electric system efficiencies described in the design guide of Langner et al. (2020), accompanied by a 3.4 kWdc photovoltaic system should be completed as soon as possible in the product life cycle (product year 2 in Figure 5). This approach is effective in two parts: i) potentially climate-changing energy use on the contemporary grid is avoided and ii) the rate of emissions per unit energy supplied on the studied California electric grid is certain to decrease in the future of the building's operation.

The next scheduled product line change was the lessening of the total weight of structural steel by substituting secondary structural elements with engineered wood joists.

Table 2 Product global warming potential for the highest scrap-input steel purchasable steel in the U.S. market.

Year	Steel Global Warming Potential Assumed (lbmCO$_2$e/lbm steel)
2016 – 2021 average	3.05
2022 – 2026 average	2.56
2027 – 2030 average	1.84

This efficacious change does not sacrifice structural performance and can be completed at the individual firm level without dependencies on external market forces or new technologies.

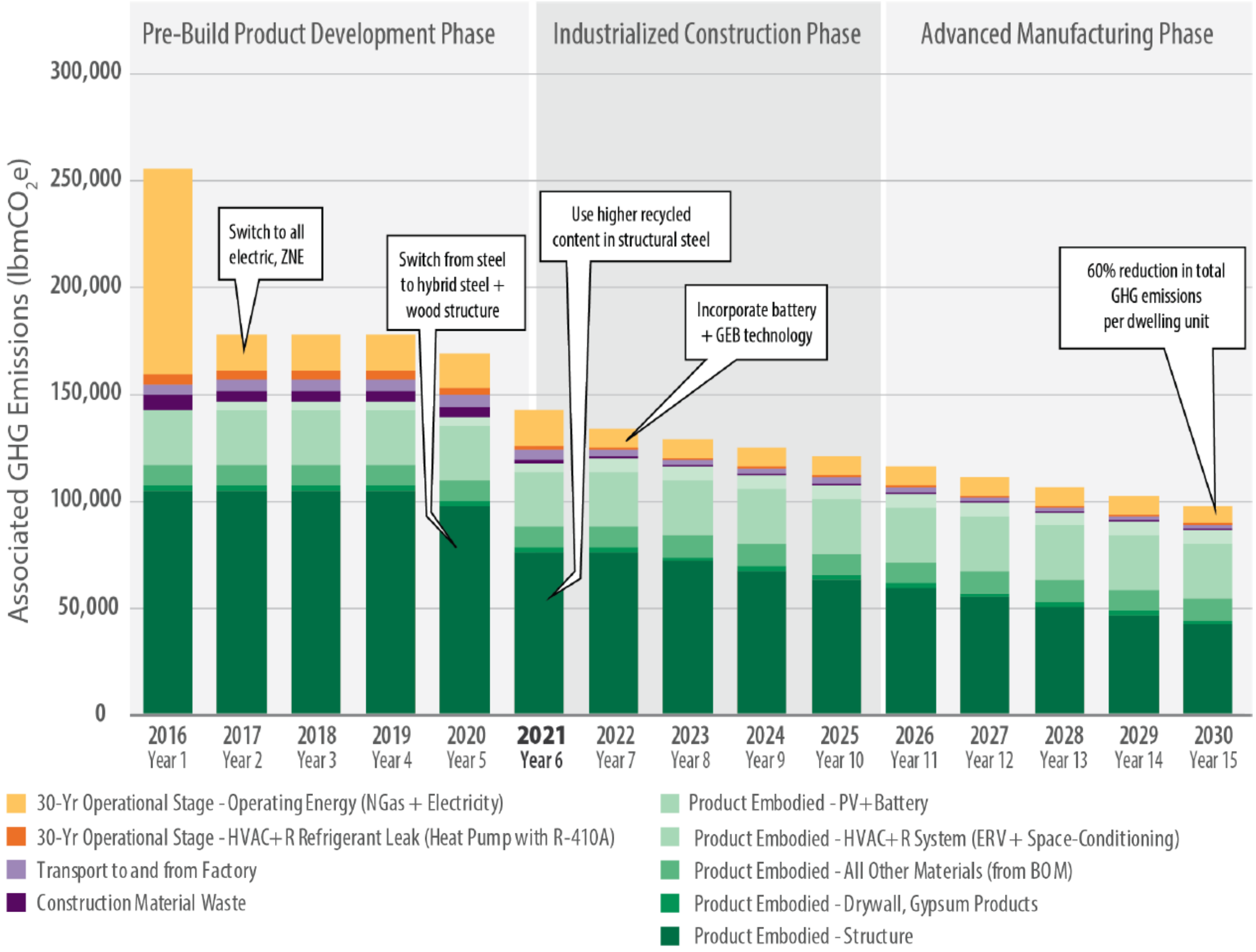

Figure 5 Whole life carbon of each iteration of the product life cycle annotated by the recommendations of the decarbonization roadmap.

By product year 6, scrap-based steel production is more mature and the purchasing volume of the modular builder is sufficient to effectively procure low-GHG steel product equivalents. From a materials perspective, structural steel is the largest contributor of embodied carbon and presents perhaps the greatest opportunity for decarbonization. However, this product decarbonization exercise had less leverage to reduce the structure-embodied carbon as it is highly subject to i) the existing modular platform system and ii) the contemporary U.S. steelmaking practices. The authors presented a research-backed scenario for the lowest global warming potential steel building products in the U.S. market in Table 2. Full methodology can be found in Klammer et al. (2021).

In product year 7 in Figure 5, batteries coupled to the photovoltaic system are recommended. The modeled batteries were controlled to store low-carbon electricity and discharge or backfeed during periods of high-carbon electricity (as determined by the dataset of Gagnon et al. (2020)). The continued reductions in whole life product carbon in the years following product year 7 come from the net effects of the learning curve simulation, namely efficiences of scale and experience. By the fifteenth year of production (calendar year 2030 in Figure 5), the product whole life carbon is 60% less than that of the prototype reference (calendar year 2016).

Temporal Aspects of Whole Life Carbon

Using the methodology described herein, the temporal aspects of the product's carbon emissions were visualized in Figure 6 with time as the x-axis dimension. For the sake of illustration, all material-related carbon, also known as embodied carbon, occurs in the initial year 1. The absolute difference in embodied carbon between the prototype reference product and the product scenario "NZE + GEB5" is shown in the solid bars as well as the relative embodied carbon makeup of the "NZE + GEB5" scenario. Moving forward in time in the postive x-direction, building life carbon emissions increase as the apartment unit consumes an energy mix of part fossil fuels. By the end of the analysis period of 30 years, the whole life carbon of the prototype reference is greater than twice that of the "NZE + GEB5" scenario. One great detriment of the prototype reference is its domestic water heating system powered by natural gas. Unlike the hourly and seasonally changing emission factors of the electricity fuel type, the emissions factor of natural gas fuel is more or less static into the midterm horizon.

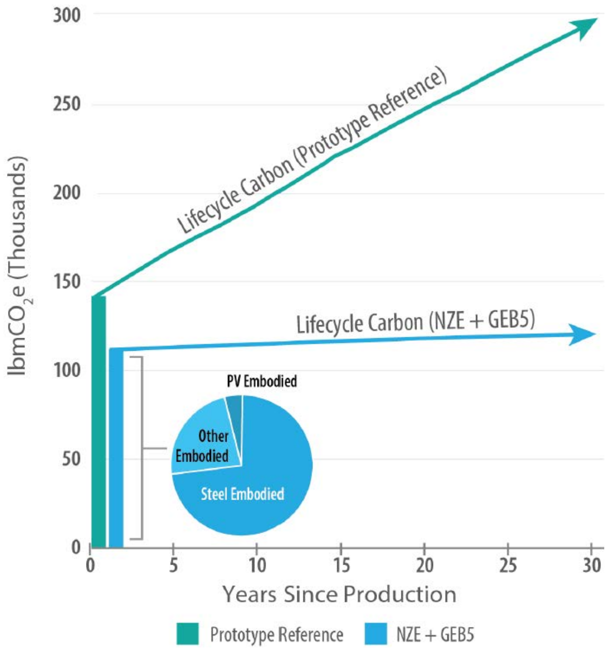

Figure 6 Lifecycle greenhouse gas emissions versus time for a prototype reference design and a battery-enhanced net-zero energy design.

Discussion

Of the all the decarbonization strategies described in the Results section, energy efficiency measures are the most efficacious way to reduce whole life carbon of a building when compared to the appropriate baseline (Figure 6). This was an important finding because the appropriate baseline building was complaint to a nationally leading energy performance code in California in 2016. One may not expect that operational energy performance is still the greatest opportunity for greenhouse gas reduction.

After this upgrade has been made, the material-related, embodied carbon of the product makes up most of the whole life carbon (non-yellow colors in calendar years after 2016 in Figure 5). The embodied carbon of the structural steel is the greatest contributor remaining in the scope considered. As discussed in the Results section, the decarbonization the product's steel-related carbon is largely outside the influence of the company and is heavily subject to industry-wide trends. Fortunately, there are promising developments on this front supported by recently enacted procurement regulation like the Buy Clean California rule (CA Dept. of Gen. Services 2021).

We simulated a theoretical battery control strategy based on minimizing carbon emissions during operation, however, this control strategy is not yet feasible in real applications. We included this strategy nonetheless because it demonstrates the powerful lever point of the timing of grid generation/consumption.

The decarbonization exercise herein was applied to the product line of Blokable, LLC, and the overall methodology to determine first-best strategies can be applied to other modular builders' product lines. However, the exact means of the analysis would need to change based on the modular product in question and the contemporary context. We recommend that other analyses incorporate an LCA goal and scope statement (see the Simulation Methods section) to avoid any confusion.

Conclusion

This paper presented a novel, future-looking method of whole life carbon analysis and reduction for a modular product line that benefits from the learning curves of mass production. Learning effects of mass production were introduced as another dimension of building simulation and analysis. Many previous studies considered the embodied carbon trade-offs of operational decarbonization strategies, but this study is the first to make modular product development recommendations based on whole life carbon reduction. The product line recommendations included a tailored set of strategies regarding embodied carbon of the structure, grid-interactive efficient buildings, and material and cost efficiencies from production. We also found that Blokable and other high-performance, productized modular builders possess the unique leverage to build to net-zero performance with little to no marginal cost due to the scalabilty of an integrated design-build-operate process.

Acknowledgment

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Nomenclature

Symbol	Definition
$\beta_{i,p}$	Embodied carbon coefficient for a building material i in production model year p. Includes
$C_{(p+y),h}$	Carbon factor of kWh energy consumed in annual hour h of calendar year $(p + y)$
e_h	kWh energy consumed by the building in annual hour h - held constant across p and y
GWP_p	Global warming potential impact for declared study unit constructed in production model year p
h	*Subscript* – annual hour $h \in [1..8760]$
i	*Subscript* – building component
p	*Subscript* – production model year $p \in [2016..2030]$
$W_{i,p}$	Material waste factor for a material i in production year p
$x_{i,p}$	Mass quantity for a building material i in production model year p
y	*Subscript* – year of building life. $y \in [1..30]$

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Table 3 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
No. of occupants (no. of bedrooms)	2.5 (2)	2.5 (2)
Occupant Equivalent Full-Load Hours	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 (0.13 ACH)	14 CFM (0.07 ACH)
Infiltration Schedule	Linear function of wind speed	Linear function of wind speed
Plug Loads		
Equipment Power Density	66.3 W/ft^2	66.3 W/ft^2
Equipment Equivalent Full Load Hours	0.0042	0.0042
Lighting		
Lighting Power Density	0.14 W/ft^2	0.14 W/ft^2
Lighting Equivalent Full Load Hours	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 Hours	0.037	0.037
Gallons per Day 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
SEER/HSPF	13.0 / 8.2	19.0 / 14.0
ERV Flow Rate at Max. 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-ft2, 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, as a whole, of the above table were deemed to be energy performance equivalent to the location's governing energy code (California Energy Commission 2019) even though some parameters may not meet the minimum prescriptive requirements.