RESEARCH

# USING LIFE CYCLE ASSESSMENT METHODS TO GUIDE ARCHITECTURAL DECISION-MAKING FOR SUSTAINABLE PREFABRICATED MODULAR BUILDINGS

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## ABSTRACT

*Within this work, life cycle assessment modeling is used to determine top design priorities and quantitatively inform sustainable design decision-making for a prefabricated modular building. A case-study life-cycle assessment was performed for a 5,000 ft² prefabricated commercial building constructed in San Francisco, California, and scenario analysis was run examining the life cycle environmental impacts of various energy and material design substitutions, and a structural design change. Results show that even for a highly energy-efficient modular building, the top design priority is still minimizing operational energy impacts, since this strongly dominates the building life cycle's environmental impacts. However, as an energy-efficient building approaches net zero energy, manufacturing-phase impacts are dominant, and a new set of design priorities emerges. Transportation and end-of-life disposal impacts were of low to negligible importance in both cases.*



## KEYWORDS

life cycle assessment, design priorities, modular building, green building priorities, energy efficiency, materials, renewable energy


## INTRODUCTION

The environmental impacts attributable to building construction, use, and end of life are unevenly accrued throughout the life cycle of a building. Keolean, *et al.* demonstrated this phenomenon for residential structures,[1] Scheuer *et al.* for commercial structures,[2] and, indirectly, Burgess and Brennan for industrial processing infrastructure systems.[3] Thus, commercial architects, with the goal of improving the sustainability profile of commercial buildings, must understand how environmental impacts accrue over the building life cycle to effectively reduce impacts through efficient, economical design actions.


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The multistage conceptualization, programming, preliminary design, final design, and construction of conventional buildings is a complex process, involving thousands of actions and decisions, and taking years of planning and execution. In light of this complexity, comprehensive evaluation of sustainability impacts of buildings during the design processes is rarely undertaken.[4] Numerous software tools exist to help architects and building designers leverage quantitative sustainability assessment methods; these include Athena, Eco-Bat, Eco_Quantum, LEGEP, and LTE OGIP, SimaPro, and GaBi, among a host of others. While these are powerful environmental impact analysis tools, their data-intensive nature often makes them uneconomical for the traditional building design process. Architects have noted that such tools are too complex, inaccessible, or do not provide value beyond the firm's current sustainability evaluation toolset.[5] Conducting comprehensive sustainability assessment requires collection of life cycle inventory data for numerous materials and processes and manually entering quantities and transportation distances into software tools. This process is time-intensive and is not done by contractors or architects.[5] Thus, the quantitative benefits of various sustainable design strategies remain insufficiently measured.

This lack of quantifiable benefits from specific design actions has made it difficult for highly efficient, more sustainable architectural designs to diffuse throughout the building inventory. Rogers notes that characteristic traits of "relative advantage" and "observability" are essential to stimulate rapid innovation diffusion processes.[6] Without quantification of the benefits of individual sustainable design actions, their observable relative advantage over conventional design approaches can remain uncertain. This shortcoming represents a barrier to widespread design for sustainability that goes beyond energy-efficient equipment substitution and moves toward implementation of "integral innovations" that cross multiple building systems, contractor trades, and life cycle stage boundaries within a project. Such integral innovations have been defined by Sheffer,[7] Henderson and Clark,[8] Ferlie, *et al.*,[9] and Taylor and Levitt.[10] The rapid diffusion of such sweeping innovations is necessary for attaining aggressive environmental reduction targets, such as the 2030 challenge adopted by the American Institute of Architects.[11]

Prefabricated buildings, however, are a unique opportunity to understand design priorities in green building. For such buildings, architectural decision-making can afford to spend more time and effort achieving sustainable, energy- and material-efficient designs, because design costs will be amortized over a large number of installations. Such optimization is also important because even small environmental performance improvements can become large by having many units installed. In addition, specific design lessons can be iteratively practiced through targeted design changes, with later generations of the building design being improved by data gathered from earlier installations. As a result, architects and engineers designing these structures can go beyond general guidelines and standards to incorporate the findings of sophisticated sustainability analysis tools.

The goal of this study is to apply comprehensive, quantitative sustainability assessment tools to a prefabricated building application in which they have significant leverage. Its results should also be instructive for non-prefabricated buildings of similar construction type. While other individual building projects may have slightly different specific analysis results than the findings here, this study demonstrates the value of quantitative analysis for prioritizing decisions throughout the design process.

## BACKGROUND

As noted previously, the environmental impact of buildings accrues unevenly throughout their life cycle. Specifically within commercial buildings, the use and operation phase of the material and building life cycle is so dominant that the impacts of construction, demolition/disposal, and transportation are nearly irrelevant for most traditionally constructed buildings. Scheuer *et al.*[2] found that nearly 95% of life cycle energy consumption and emissions stem from the use phase in a commercial building. Junnila *et al.* found that for conventional office buildings in Europe and the United States, the use phase makes up over 90% of life cycle energy consumption, 80% of life cycle carbon dioxide emissions, and 65% of life cycle $SO_2$ and $NO_x$ emissions.[12,13] Similar results have been reported by Ochoa *et al.*,[14] Gustavsson *et al.*,[15] and Khasreen *et al*.[16] In a comprehensive review of 16 other studies, Sartori and Hestnes found a strong correlation between total life cycle energy consumption and operating (use phase) energy consumption.[17]

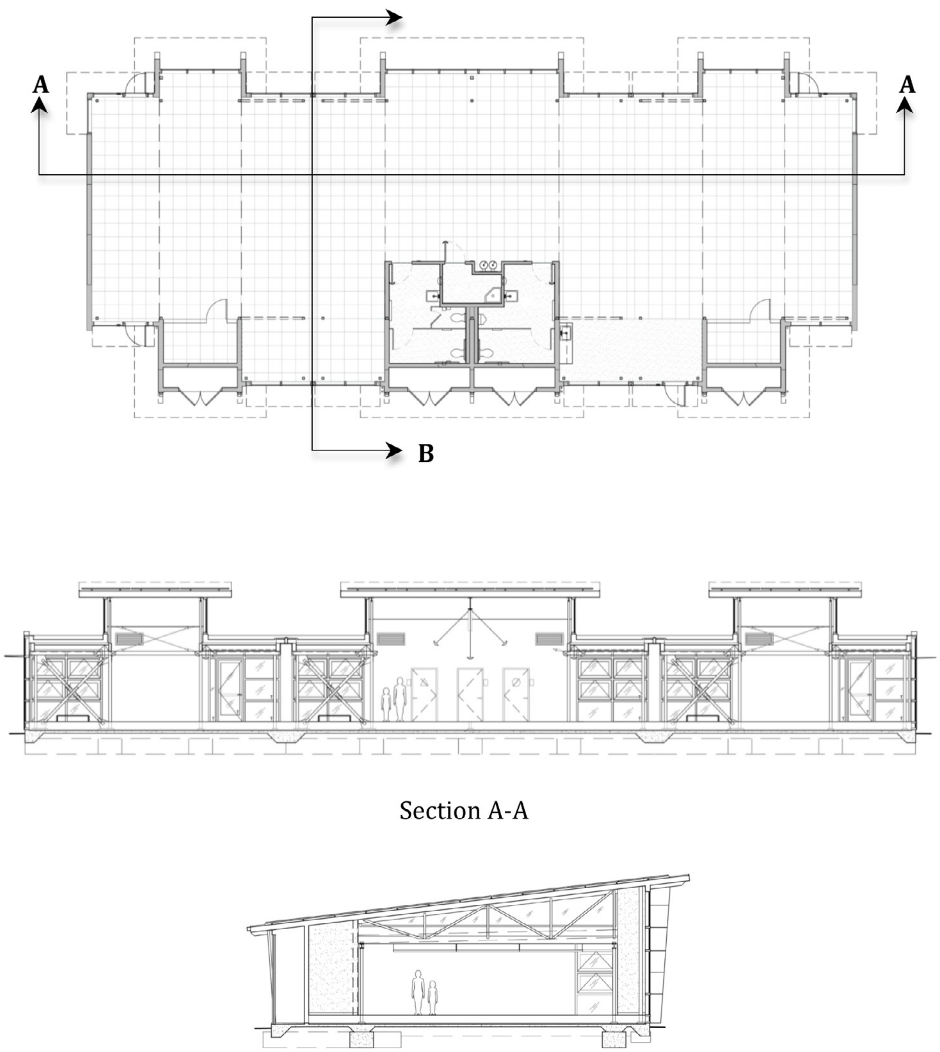
As evidenced by such studies, designing for energy-efficiency is of critical importance for increased sustainability of buildings. However, as the energy-efficiency of buildings improves over their lifetime due to retrofitting with future higher efficiency technologies, and as energy resources become less environmentally damaging (e.g. wind and solar resources come online through the implementation of State Renewable Portfolio Standards), building materials will become a significant part of the overall energy and emissions footprint of the building. Thus, it is increasingly important for architects and designers to weigh both the use phase energy consumption impacts and the impacts from material choices, in order to make the best design decisions, as discussed by Simonen.[18]

While it is worthwhile to calculate the sustainable design priorities of any green building, it is especially important for prefabricated buildings, as these are intended for mass quantity construction. The environmental impacts of one particular design can be extremely large once hundreds of units are fabricated and installed. Recognizing this, Kim *et al.* conducted a preliminary comparative life cycle assessment of a modular and conventional residential building.[19] A negative aspect of such modular homes was that the total amount of the materials placed in them is roughly 8% higher than a conventional home. This is due to the fact that the modular home is framed with larger studs and requires additional structural components to accommodate transportation loads that onsite construction does not impose. However, due to the use of modern manufacturing controls and efficiencies, Kim *et al.* found that the conventional home produces 2.5 times more construction waste than the modular home. Such savings in construction waste generation more than compensate for the increased material used in the constructed prefabricated structure.

Similar to other studies previously referenced for commercial buildings, Kim *et al.* found that the use phase comprises more than 93% of the life cycle energy consumption and over 95% of the total greenhouse gas emissions for both prefabricated and onsite built homes. However, total life cycle energy consumption and greenhouse gas emissions for the modular home were 5% less than for the conventional site home. The use phase energy consumption and greenhouse gas emission differences were attributed to the higher air tightness (0.194 ACH) of the modular home when compared to the conventional home (0.35 ACH). This increased air tightness results in 7% less natural gas consumption over the building 50-year service life. Such findings validate the benefits of prefabrication including higher quality control for increased efficiency, faster construction cycle times, and more efficient (less wasteful) construction processes, all of which lead to improved sustainability of prefabricated structures.

The building design analyzed in this study is aimed at educational and small-scale commercial markets. It was designed by Project Frog, a San Francisco-based venture specializing in prefabricated, modular building systems with high energy efficiency and indoor environmental quality. The case-study project is a community center commissioned by the San Francisco Redevelopment Agency for urban renewal of the Hunters Point Shipyard. This building design is applicable to many markets and geographic locations throughout the continental US and Pacific islands, with some variations for climate. The design evaluation framework presented within this study could be generalized to other buildings, including but not limited to prefabricated buildings, as the design incorporates common prefabricated construction practices, and materials common to both prefabricated and site-built buildings. These include a structural steel frame with light-gauge steel wall panels and aluminum curtain walls. The completed floor plan and cross sections of the prefabricated structure used in the case study are shown in Figure 1. The completed structure is shown in Figure 2.

**FIGURE 1.** Floor plan and sections of case-study prefabricated modular building.




Section A-A

Section B-B

**FIGURE 2.** Completed case-study prefabricated modular building.

## METHODOLOGY

To help guide the decision-making process for design of more sustainable prefabricated buildings, a process-based attributional life cycle model was developed. Life cycle assessment (LCA) is an analytical framework for measuring the environmental, social, and economic impacts of a product, process or system by quantifying the inputs and outputs of a product or process. The analysis can include inputs and outputs from throughout the product's life cycle, from acquisition of the raw materials, through production, use, and final disposal or recycling, including transportation needed between these phases.[20] The use of life cycle models for enhancing products and processes has evolved over the last two decades. While the first assessments were product-based and narrow in scope,[21] numerous life cycle assessments have now been done on larger, more complex systems, including buildings, validating this method for use as an analysis tool for comprehensive environmental impact measurement and guidance in decision-making within this study.

As mentioned previously, the building design analyzed in this study is a new community center (general commercial use) commissioned by the San Francisco Redevelopment Agency for urban renewal of the Hunters Point Shipyard. The building is designed with 5,000ft$^2$ of commercial space rated for seismic category E (ground accelerations of 1.17g), with an open floor plan and flexible program. It is designed for LEED® silver or gold certification. The functional unit for the analysis was chosen to be 50 years of service for a 5,000ft$^2$ general-purpose commercial building; this allows the case-study building to be compared to other scenarios with different lifetime energy impacts, such as an average building or a net-zero-energy building. This estimated lifetime is conservative, given the average service life for assembled structures in the United States is 80 years[22]. All assumptions are aimed to make the analysis applicable to prefabricated buildings of this type nationwide, except modeling lifetime energy demand. This requires detailed calculations whose results vary greatly between climate zones, so site-specific values are used.

### *Materials*

Construction materials were chosen by Project Frog as best-in-class components that fit within their kit-based concept of the prefabricated building, such that interclass materials can be substituted to meet cost targets without changing the overall design. Best-in-class performance was measured using environmental product declarations (EPD) and other specifications documents for each component or material as reported by each manufacturer. The life-cycle inventory of building materials also includes the manufacturing methods used to process them into the forms used for construction; for instance, the light-gauge steel includes the cold-rolling of that steel into studs, and the structural steel includes the hot-rolling of that steel into tubing and plates.

Structurally, the design consists of a steel frame on a concrete mat foundation with a raised floor plenum for under-floor air distribution. Solid walls are composed of thermally-broken light-gauge steel framed insulated panels, and window walls are composed of thermally-improved extruded aluminum curtain walls. The roof design is a structural metal deck with top-mounted block insulation and Duro-Last® poly-vinyl-chloride roof membrane with a high Solar Reflectance Index (110 as measured by ASTM E 1980). The building envelope insulation is expanded polystyrene for walls with an R-19 insulation value and polyisocyanurate for roofs with an R-30 insulation value. Thermal bridging is avoided in the walls by using prefabricated wall panels with double studs of smaller "hat channel" profiles (comprised of a single channel with two outward flanges), only joined at the top and bottom of walls. The windows selected throughout the design have U-values of 0.26–0.28, solar heat gain coefficients of 0.27, and visible light transmittance of 64%. The exterior finishes are FSC-certified composite wood rain screens. The chosen interior finishes are traditional gypsum wallboard with low-VOC paints and high recycled content, low VOC carpets. However, the analysis did not account for the recycled content of the carpets; it simply assumed half the carpet mass was virgin nylon 6 carpeting and half was virgin PVC backing.

Material quantities for construction of the modular building were taken from 3D CAD models. Since the 3D CAD model data is used for automated manufacturing of structural steel and light-gauge steel parts by computer-controlled laser cutting and robotic welding, these values are highly accurate. The volume and mass of concrete in the mat foundation is calculated by creating a 3D CAD model of the foundation from architectural drawings. Initially, it is modeled as ordinary Portland cement concrete. Masses and volumes for other components such as aluminum and glass in the curtain walls, rebar, insulation, roof membrane, and wood rainscreen, were obtained either from vendor submittals or by calculating values based on general vendor data and dimensions from the 3D CAD model or other architectural drawings.

Plumbing design includes two bathrooms and a kitchenette with linoleum flooring and low-flow fixtures, using standard copper, steel, and PVC pipes. Plumbing pipe is estimated by length of pipe runs for copper piping and PVC piping; joint hardware was not included. Plumbing fixtures (toilets, urinals, sinks) are based on the weight of four ceramic toilets, a conservative overestimation. Other fixtures such as grab bars and mirrors are not included, as they are known to not be significant impacts. For simplicity of the case study, water use was not measured in the impacts, though energy use for hot water was part of the building's energy model. The life cycle design approach being evaluated here could be expanded to include water use metrics.

The building's HVAC equipment is entirely electric since no natural gas service is provided at the building site. The structure is designed to use heat pumps and exhaust fans with operable windows and displacement ventilation. The HVAC system is modeled as a decentralized ventilation system with steel ductwork capable of delivering 120 cubic meters of conditioned air per hour. Within the case study, all electrical and mechanical systems comply with or exceed ANSI/ASHRAE/IESNA Standard 90.1.

The building's lighting system is based on T8 fluorescent bulbs in highly efficient Peerless direct/indirect fixtures with daylighting controls to dim the lights. Since the building envelope is designed to maximize daylighting, building models estimate that it will need little electric lighting for most daytime hours. The lighting system equipment is modeled as an assembly of component materials, including the required material and manufacturing inputs for bulbs, ballasts, and associated electronic fixtures. Wiring is estimated by length of wiring runs from 3D CAD models. Junction boxes and circuit breaker panels are not included.

### *Transportation, Construction, Maintenance, and End of Life*

Transportation impacts of most building materials, except the foundation, were modeled with transportation of 1000 miles by truck. This is a simplifying assumption based on a weighted average travel distance from Lebanon, Kansas (the geographic center of the United States) to major US population centers. This assumption is meant to be applicable for most locations in the continental US, not only the case-study location, as are all assumptions other than energy modeling. While a few building elements are known to have traveled 2000 miles, many materials were transported less than 500 miles to qualify for LEED rating points. Due to the highly perishable nature of fresh ready-mixed concrete used in the foundation, a transport distance of 25 miles is assumed for it.

These assumptions capture the impacts of transportation from premanufacturing plants to the building site; the impacts of transportation from raw material extraction and processing plants to prefabrication plants are included in the impacts of the materials themselves, quantified within each life cycle inventory. Only one-way trips were considered since third party logistics providers were assumed to facilitate backhauling. In the event that backhauling is not possible the results remain robust given that doubling the transportation impacts would still not comprise a significant percentage of total ecological impacts. Transportation of workers to and from the site was outside the scope of this study. Cursory estimates for 10 jobsite workers commuting 25 miles daily for 4 months show only a 0.6% increase of lifetime impacts for the building as built, and less for a building with average energy use.

Transportation ultimately comprised a small part of total impact, approximately 2%, thereby minimizing the importance of transportation assumptions on the total building impact profile. These transportation impacts, as a percentage of total building impacts, are also in line with that found by Scheuer *et al.*[3] in their analysis of traditionally constructed commercial buildings and those found by Kim *et al.*[12] for modular home prefabrication performed in Topeka, Indiana.

On-site construction impacts are primarily energy used by heavy machinery and power tools. No data was available on construction impacts for the case study building, but they were estimated to be 5% of material and manufacturing impacts. This is based on estimates or data from Scheuer *et al.,*[2] Kim *et al.,*[19] Junnila *et al.,*[12] and Blengini and Di Carlo.[23]

Apart from maintaining and replacing roof-mounted photovoltaic panels, impacts from maintenance, cleaning, and repairs during the operation of the building were not considered. These activities have been shown by others (e.g. Scheuer *et al.*[2]) to have little impact compared to energy consumption or material production.

For material disposal at end of life, the EPA disposal scenario for durable goods in the US is used (EcoInvent process "Durable goods waste scenario/US S")[24, 25]. It assumes recycling of commonly-recycled materials such as steel, and landfill or incineration of less commonly recycled materials, such as many plastics. This assumption was validated by modeling a scenario of 100% landfilling of building materials, and in both cases disposal was a negligibly small portion of the building's life-cycle impacts, so further refinement of the EPA scenario was not investigated. Ultimately, end of life demolition and disposal comprised 3% of total life cycle impacts in this case study.

### *Lifetime Energy Use*

Use-phase energy consumption is a critical part of this analysis, since it makes up such a large part of the life cycle impact. Due to the long use-phase of buildings, accurate modeling of energy use during service life is essential for an accurate analysis. One should not simply assume average values across the US. Currently, a large number of tools exist for assessing energy performance in buildings. The U.S. Department of Energy has published a comprehensive list of the available tools.[26] Recently, Maile [27] proposed EnergyPlus as a preferred energy-modeling tool for use during building design due to its finer level of detail, ability to model various complex HVAC components, and ability to model a variety of geometries. However, EnergyPlus is not yet accepted as a California standard for measuring compliance with California Code of Regulations Title 24 Building Energy Efficiency Standards for Residential and Nonresidential Buildings.[28] Accepted standard energy modeling tools in California include eQuest and EnergyPro.[29] Therefore, energy use was modeled using both EnergyPlus and eQuest software.

Building energy models constructed in eQuest show that a 5,000ft$^2$ commercial building compliant with California Code of Regulations, Title 24 Building Energy Efficiency Standards for Residential and Nonresidential Buildings[30] would consume 70,200 kWh annually, while operation of the newly designed and constructed 5,000ft$^2$ case study Project Frog building consumes an estimated 47,500 kWh annually.

Modeled energy consumption was compared to average energy intensity of a commercial building in Northern California using the US Department of Energy's Commercial Building Energy Consumption Survey (CBECS) data for the Pacific census division, climate zone 4.[31] Modeling for the location and program of the actual building, rather than assuming a national average, was the best means to ensure accuracy of results. The average commercial building in CBECS Pacific census division, climate zone 4, when normalized to a square footage of 5,000ft$^2$, uses 62 MWh/yr of electricity, 1.6 MMBTU/yr natural gas, 95 MMBTU/yr of fuel oil, and 9.6 MMBTU/yr of district heat. Obviously this is an average, as most buildings would not use all these different modes simultaneously.

While an analysis modeling energy use for the Project Frog building across many different locations and with many different programs would be valuable, it is outside the scope of this paper. However, to make results as applicable to nationwide building installations as possible while still relying on accurately-modeled data, the environmental impacts per kilowatt of electricity used were for US average electricity mix. For those seeking to further localize the results of this study, Northern California electricity power supplies for the Western Systems Coordinating Council (WSCC) utilize 37% less coal, 47% more natural gas, and 290% more hydroelectric power than the US average grid, creating 26% less $CO_2$ emissions per average kWh.[32] For those seeking more average results, the assumption of a Northern California climate reduces the importance of building operations versus building materials in full life-cycle impacts, given the very mild climate of the San Francisco area. In harsher climates, operation energy for heating and cooling would play a more dominant factor throughout the building use phase.

Numerous studies have shown that buildings do not perform as they were simulated during design.[33,34,35,36] Therefore, sensitivity analysis was performed to account for unknown and potentially large variations in use patterns, construction qualities, and appliance efficiencies ranging from highly optimistic to highly pessimistic scenarios. A complete discussion of this sensitivity analysis can be found in Faludi and Lepech.[37]

The case study building has 30% of its power provided by rooftop solar building integrated PV panels. In addition to modeling this, the environmental impacts of electricity use were also modeled for two other scenarios: one has average Northern California energy use as mentioned above, with no on-site energy generation; the second is net zero energy, having the same energy demand as the case study building, but with 100% of its energy supplied by rooftop photovoltaics.

### *Analysis*

The life cycle assessment is performed in SimaPro analysis software. The impact assessment methodology used for determining total impacts is EcoIndicator 99 with 'egalitarian' weighting. The selection of Eco-indicator 99 as an impact assessment scheme was done for demonstration purposes in this study given its large number of impact categories and its inclusive weighting scheme. Individual designers and life cycle analysts are advised to select the most applicable life cycle impact assessment scheme for their location and study goal and scope. The methodology used to determine greenhouse gas emission impacts (global warming potentials) was IPCC 100-year Global Warming Potentials. Wherever materials or processes were not available to describe components of the building, similar surrogates were selected from existing processes in existing datasets.

## RESULTS

### *Design Lessons From Overall Life Cycle Impacts*

Figure 3 and Figure 4 show the LCA results for (1) a building with average Northern California energy use, (2) the case study building, and (3) a net zero energy (100% solar PV-powered) building. The results are reported by life-cycle stage. Additional detail on the findings can be found in Faludi and Lepech,[36] though without the estimated construction impacts. Note that here the ecological impacts of manufacturing the solar panels are allocated to the lifetime energy use phase; as such, the "as built" and "net zero energy" columns show the same materials and manufacturing impacts. Figure 3 uses metrics of EcoIndicator99 (egalitarian weighted) points, while Figure 4 uses greenhouse gas emissions (IPCC 100-year global warming potential in kilograms of carbon dioxide equivalents). As noted above, the case study ("As Built") building had 30% of its power supplied by rooftop photovoltaics, with the rest supplied by grid electricity (modeled as US average electricity fuel mix, as noted above); the "Average Energy Use" building used the CBECS regional average mix of gas, fuel oil, district heat, and electricity (again US average electricity mix).

It can be seen immediately that for an average building, and even for a highly energy-efficient building, energy use during the building's life is the biggest impact; but once the building's energy needs are fully met by clean power generation, materials and manufacturing become the dominant factor. Over the 50-year life cycle, 83% of the average building's environmental impact (in EcoIndicator points) stems from the production of electricity consumed during the use phase of the building; 14% is materials and manufacturing, while shipping, construction, and building disposal are rounded to 1% each. For the case-study building, 65% of the impacts are from electricity use and generation; of this, 62% is from grid electricity use, while 3% is from manufacturing and replacement of the PV panels that provide 30% of building energy. Energy thus accounts for over double the 28% of impacts for materials and manufacturing. However, for the net zero energy building, materials dominate at 62%, over double the energy use (all PV manufacturing and replacement) at 24%.

The building as built shows its energy use to be a significantly lower percentage of lifetime impacts than values noted by Scheuer *et al.*,[3] Keoleian *et al.*,[1] and Junnila *et al.*,[18,19] for traditional buildings and, as expected, in line with values reported by Blanchard and Reppe[38] for energy efficient construction. When comparing to other studies, it is important to remember that these results are based on a building lifetime of 50 years. For comparison to a 75-year

**FIGURE 3.** Total life cycle impacts by life cycle phase for a prefabricated commercial building with average California energy use, the building as built (30% of power supplied by photovoltaics), and net zero energy (100% of power supplied by photovoltaics), in units of EcoIndicator99 points.

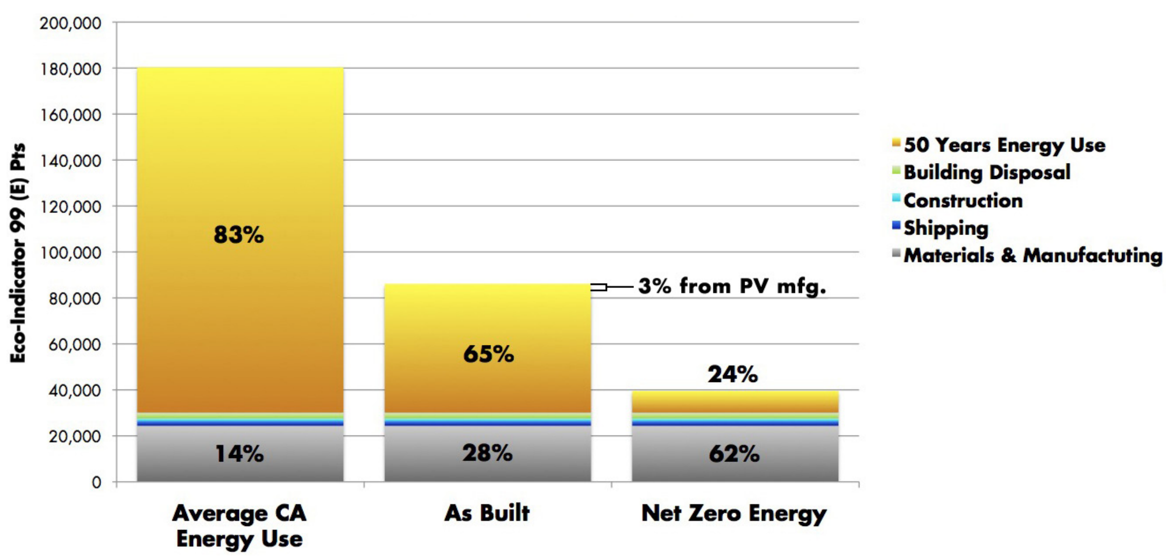
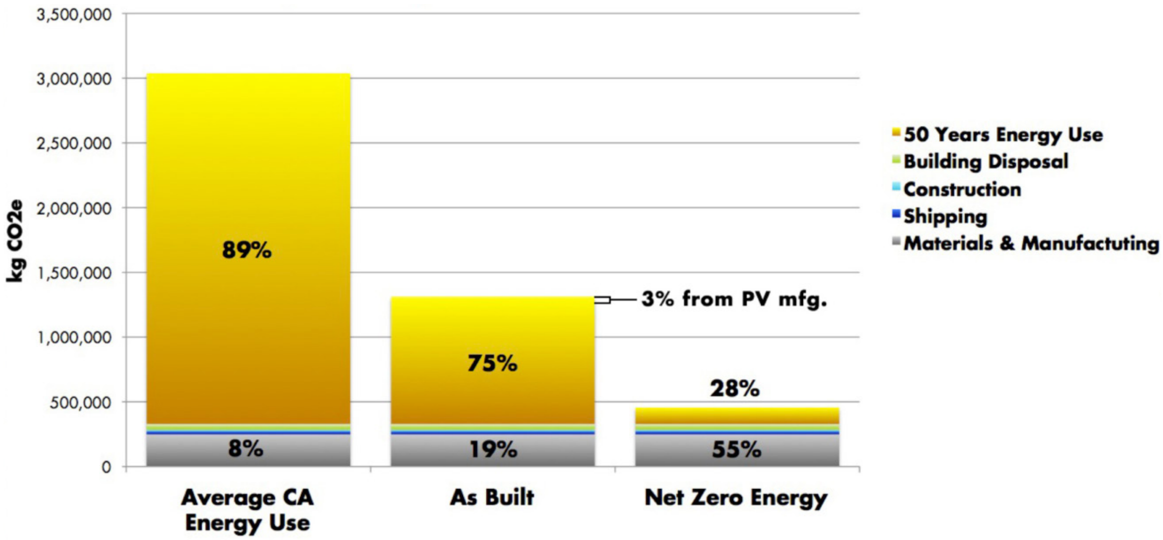


**FIGURE 4.** Life cycle greenhouse gas emissions by life cycle phase for a prefabricated commercial building with average California energy use, the building as built (30% of power supplied by photovoltaics), and net zero energy (100% of power supplied by photovoltaics), in units of kg $CO_2$-equivalent.




assumed building lifetime (in line with Scheuer *et al.*), the impacts of energy consumption during the use-phase would be 50% higher. For example, the average building would have energy use be 88% of lifetime EcoIndicator impacts and materials & construction as 10%; the building as built would have energy use as 74% and materials as 21%; and the net zero energy building's energy generation would be 32% and materials as 55%. It is also important to recall that San Francisco's mild climate requires less energy use than most regions in the country.

For the purposes of guiding designers, the lower use-phase impact and carbon footprint of the building as built, compared to traditional construction, is due to a combination of the building's high energy-efficiency and the benefits of the rooftop PV panels providing 30% of building energy. As detailed in Faludi and Lepech,[31] energy models show that with efficiency alone, the prefabricated building will use approximately 60% less energy than an equivalent average building in this climate zone and geographic region (between 42%–81% taking into account uncertainty in occupant use profiles, construction quality, and installed appliance efficiencies), even before the advantage of the PV panels is included.

Design decisions associated with supply chain transportation, building construction, and end of life make up consistently small percentages of the building's total EcoIndicator 99 life cycle impacts and greenhouse impacts, in all scenarios. The average building's shipping, construction, and building materials disposal are rounded to 1% each. The case study building shows shipping as a mere 2%, construction 1%, and building disposal 3%. For the net zero energy building these values start to become significant, with shipping at 5%, construction 3%, and disposal 6%, but even here these values summed together are still far less than energy or material impacts. For greenhouse emissions, the average building has 1% each from shipping and disposal, and construction is .4%. For the building as built, 2% of greenhouse emissions are shipping, 1% construction, and 3% disposal. For the net zero energy building, 5% is shipping, 3% construction, and 10% disposal. Clearly, then, these factors are not high priorities for sustainable design until energy and materials have been dealt with. It is likely well worth it to import an exotic building material from far away if it will significantly improve the building's energy performance. However, low percentages for disposal should not be assumed to mean that recyclability is a low design priority—in this analysis, the benefits of recycling would be allocated to lower manufacturing impacts for the next building, rather than appearing as negative impact scores for this building.

As with energy and materials results, the proportions of greenhouse emission impacts due to different life-cycle stages are similar to the proportions of EcoIndicator impacts. Thus it seems that, as seen by Scheuer *et al.,*[3] multi-impact life cycle metrics (including ozone depletion potential, acidification potential, nutrification potential, and solid waste generation) correlate closely with life cycle greenhouse gas emissions and primary energy consumption. However, we will see later that this is not always true.

Two lessons for designers can be taken from this analysis: First, the design and management of energy systems is always a high priority. Lifetime energy use energy dominates traditional and even energy-efficient building life cycles, by far. In such cases, other environmental concerns are nearly always trumped by energy performance. Once a building meets all energy needs by clean power generation (whether it be on-site PV panels, PV grid power, or other equally clean renewables not analyzed in this study), then building materials and manufacturing becomes the dominant life cycle impact phase. However, even here the manufacturing, maintenance and replacement of PV panels over the building life cycle still constitute a significant life cycle impact (24% of total life cycle impacts) for a single product in the building's bill of materials. The second lesson is that manufacturing is always a higher priority than shipping, construction, and end-of-life concerns. Thus preferences for local materials should be subordinate to sustainability in energy and manufacturing, though as mentioned above, recyclability is still an important factor as it improves the manufacturing impacts of the next building.

### *Design Lessons From Manufacturing Impacts*

Given the aggressive Architecture 2030 goals for net zero energy built environments and increasing Renewable Portfolio Standards (RPS) throughout the US, manufacturing impacts will become more important for buildings in the future. This trend was investigated by Faludi and Lepech when studying the impact of on-site solar energy production on the life cycle performance prefabricated, modular buildings.[31] Therefore, the present work provides designers with guidelines for assessing impacts associated with the manufacturing and on-site construction stages in closer detail. Design impacts can be broken down by assembly within the building, as shown in Figure 5 and Figure 6.

Aggregated environmental impacts and global warming potential impacts are fairly evenly distributed across most building assemblies, aside from HVAC and lighting equipment production impacts, which are comparatively small. Thus, these results do not suggest obvious design priorities among the building systems and subsystems. To better determine the nature and source of impacts coming from design decisions, each building assembly is further broken down by material type or product in Figure 7 and Figure 8. In these figures, products made of a similar, single materials are grouped together into single material categories. For a single product that consists of multiple materials, it is kept as a separate product and impacts are shown for the entire product. Within Figure 7 and Figure 8, "Sheet steel" includes light-gauge steel framing, corrugated roof decking, flashing, and other sheet steel. "Raised flooring"

**FIGURE 5.** Total life cycle impacts for the manufacturing stage by assembly in units of EcoIndicator99 points.

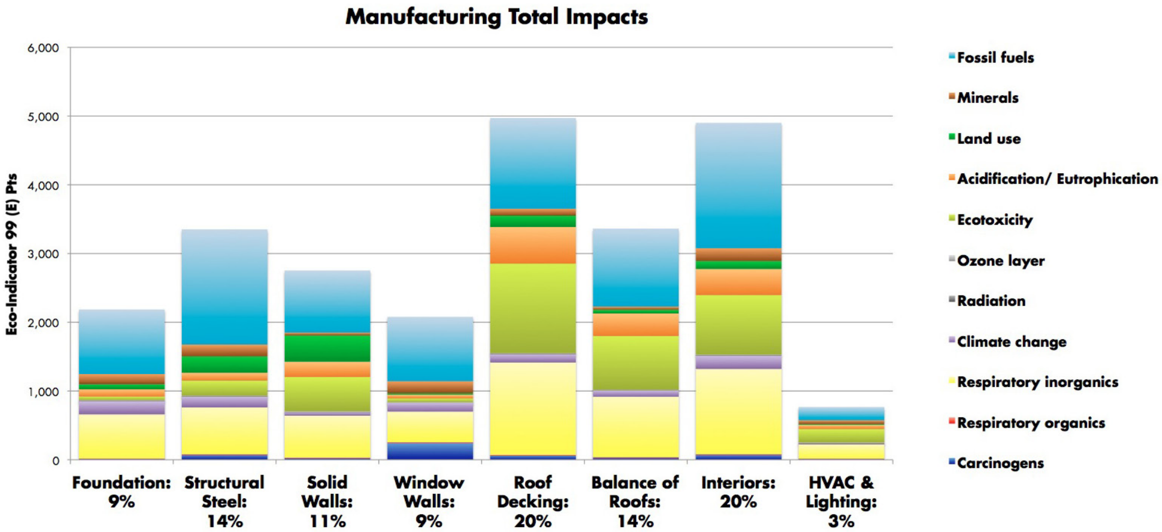
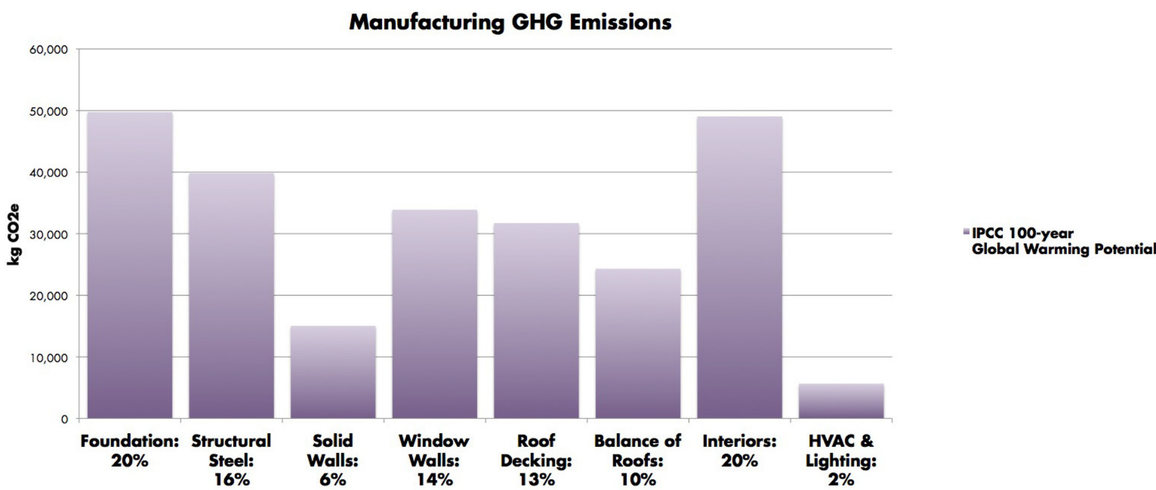


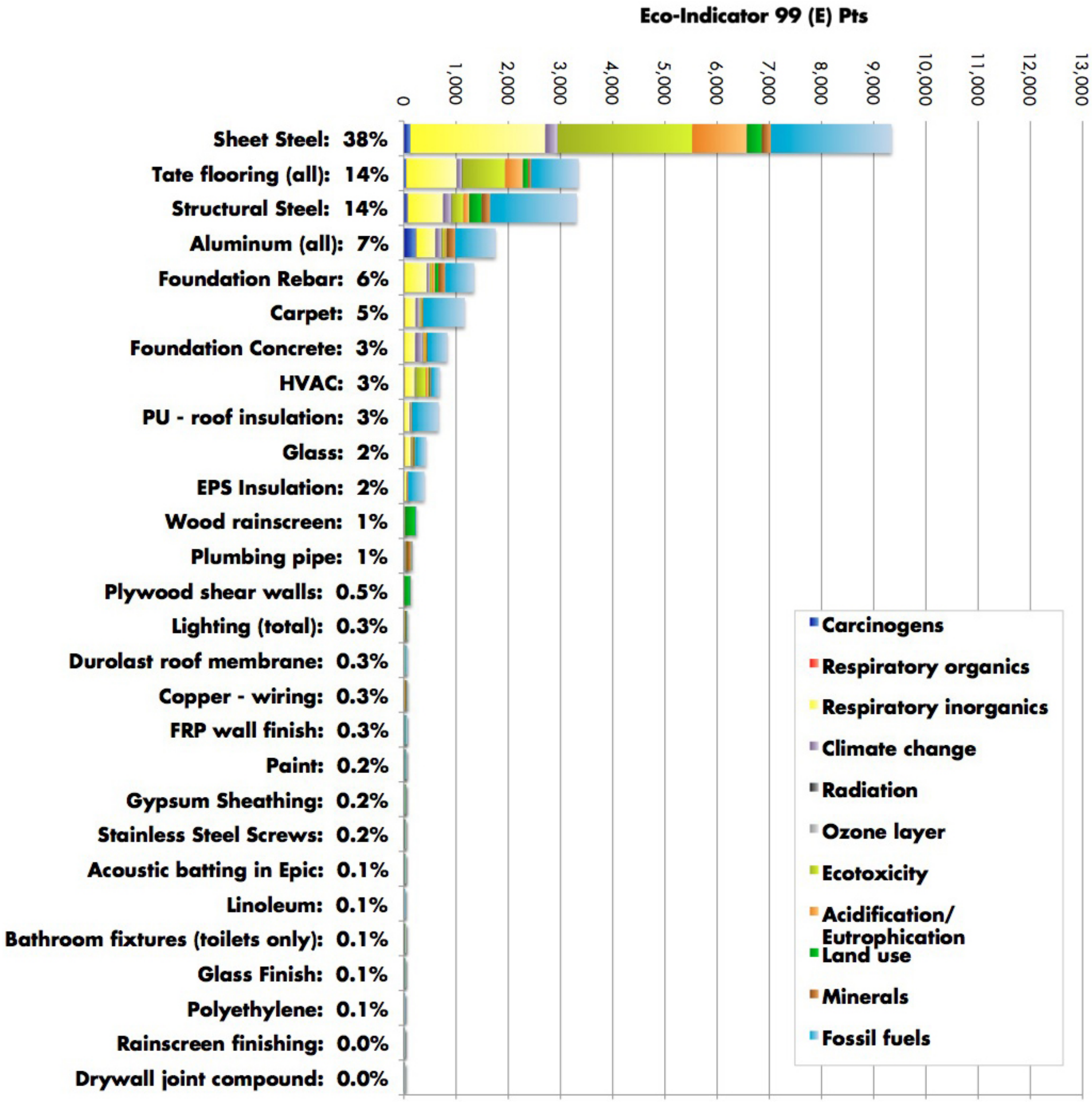

**FIGURE 6.** Greenhouse gas impacts for the manufacturing stage by assembly.




includes both the steel and concrete used in the raised access flooring system. "Aluminum" includes materials in the structural system in the curtain wall, roof fascia, low-emissivity foil used as a radiant barrier around the building walls, and foil tape used to seal the barrier. "Carpet" includes both carpet and backing.

Total life cycle impacts are dominated by three materials or products: sheet steel, raised flooring, and structural steel. Also significant are aluminum, foundation concrete and rebar, and carpeting. Surprisingly, the largest material impact is not structural steel or concrete material (which comprise the largest material categories by mass), but sheet steel. This is due to the fact that structural steel has a very high recycled content, while sheet steel usually contains 25% or less recycled content. Additionally, sheet steel is galvanized to resist corrosion. The galvanization process, while necessary for the durability and corrosion-resistance of the material,

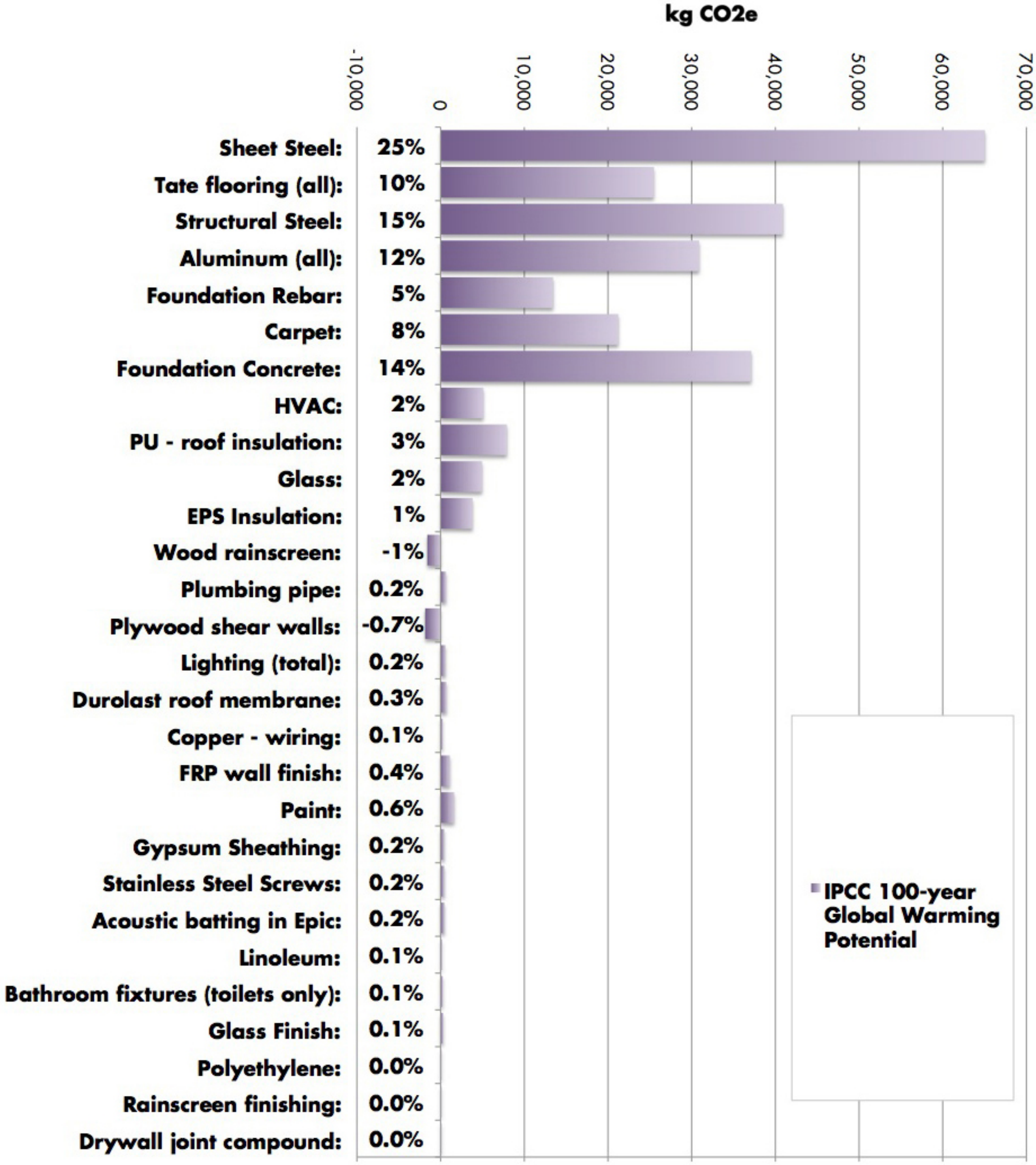
**FIGURE 7.** Total life cycle impacts for the manufacturing stage by product / material type in units of EcoIndicator99 points.




results in high respiratory inorganic and ecotoxicity impacts. The majority of the impacts of the raised flooring system are also from its use of galvanized sheet steel.

Replacing sheet steel with aluminum was investigated as a viable design alternative, but analysis quickly showed that this would increase, not decrease, environmental impacts. Aluminum is a small percent of total impacts due to low total mass within the building. Aluminum sheet and extrusions available in architectural products generally have little or no recycled content; therefore, their impacts are much higher than steel. Including material production, sheet rolling, galvanization and painting for steel or anodizing for aluminum, LCA showed that aluminum had nearly double the number of EcoIndicator points per unit weight

**FIGURE 8.** Greenhouse gas impacts for the manufacturing stage by product / material type.




as steel (0.86 pts/kg vs. 0.44 pts/kg), and over five and a half times more greenhouse emissions (14.8 kg $CO_2$-eq/kg vs. 2.6 kg $CO_2$-eq/kg). While less mass of aluminum could be used to replace steel, it is only 1.4 times as strong and only one third as stiff per unit weight—not enough of a reduction to overcome the higher impacts for virgin aluminum.

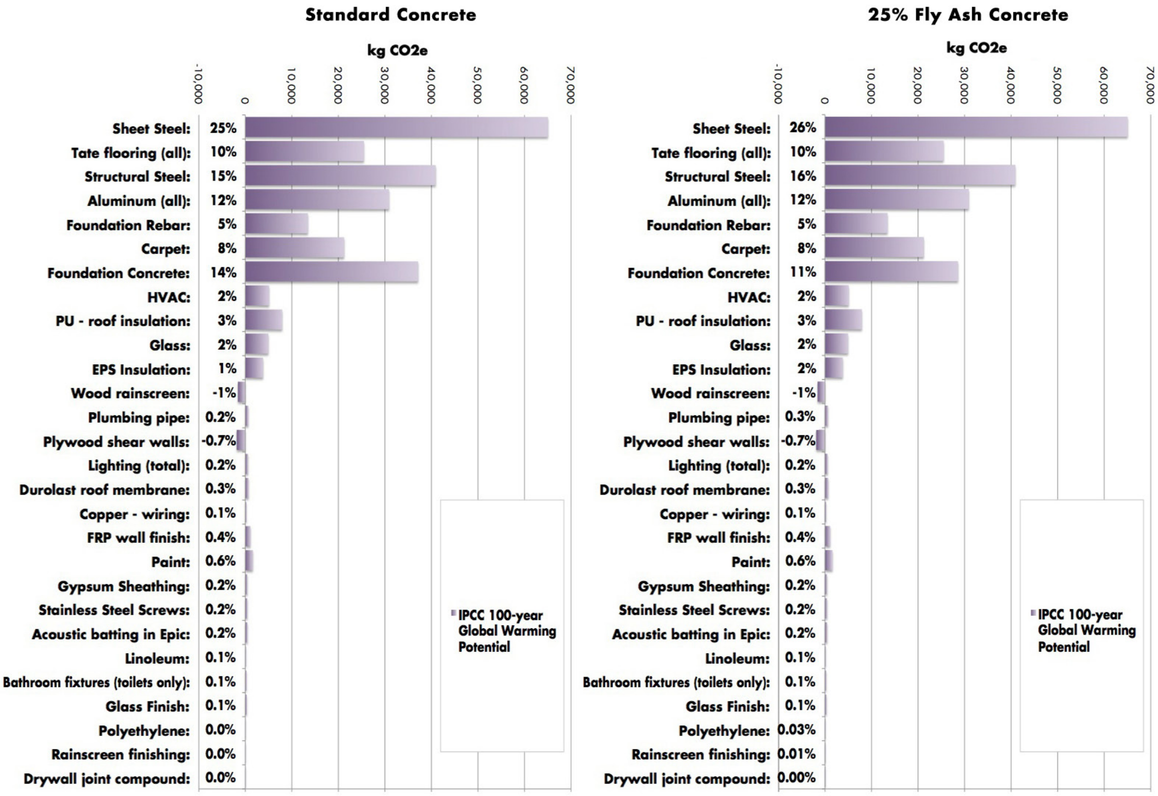
Manufacturing and assembly of the raised floor ventilation system comprises a significant negative impact within the manufacturing stage. Therefore, this could be indentified as a potential candidate for focused sustainability redesign. However, the decision of whether to alter this element requires consideration of the entire building life-cycle. The raised floor serves as a plenum for under-floor air distribution, enhancing the energy-efficiency of the building. Figure 3 and Figure 4 show that design decisions involving energy use have a much larger effect on life cycle environmental impact than manufacturing-stage decisions. Thus, any design recommendations intended to reduce manufacturing impact of the raised floor system should not compromise its role in building energy efficiency.

The impacts of the concrete foundation, particularly global warming potential impacts, are high. The initial model is based on ordinary Portland cement concrete without the use of supplementary cementitious materials (SCMs) such as fly ash or ground granulated blast furnace slag. These materials are well known to reduce the global warming potential of concrete materials by replacing carbon-intensive cement with cementitious industrial waste products.[39] The actual building studied used a high percentage (70%) of blast furnace slag in its concrete foundation, so its impacts are a great deal smaller than shown in these models. However, San Francisco's mild climate allows higher percentages of fly ash or slag than regions which must contend with harsh freeze-thaw cycles. ACI 318-08, Building Code Requirements for Structural Concrete,[40] places a limit of 25% replacement of cement with fly ash for harsh environmental exposure conditions. Conservatively assuming this replacement limit for this case study, in order for the results to be applicable nationwide, the substitution of cement with fly ash still significantly reduces the greenhouse gas impact of the concrete materials in the assembled prefabricated structure. This comparison is shown in Figure 9. As seen, just through this simple material change (which has no impact on the structural performance or construction timeline), a 3.4% reduction in material-related greenhouse gas emissions is achieved. This change also reduces the relative impact of concrete materials within the prefabricated structure from 14% to 11%, taking it down in priority from the third-largest cause of greenhouse gases to the fourth-largest.

Carpeting, surprisingly, comprises much larger impacts than glass for windows or the much larger volumes of plastics used for insulation in the building. The simple carpet model assumed virgin nylon and PVC, as mentioned in the "Methodology" section. This is in contrast to the actual high-recycled-content carpet used in the building. The surprisingly high result was not so large that improving the model's accuracy was deemed useful for this study, but it is recommended for future studies and design recommendations.

As seen when comparing Figure 5 and Figure 6 or Figure 7 and Figure 8, greenhouse gas emissions are not always well-correlated with broader environmental impacts. Perhaps most noteworthy is the concrete for the foundation, which in Figure 8 exhibits the 3rd-highest greenhouse impact but in Figure 7 only exhibits the 7th-highest total life cycle impact. Concrete has disproportionately low total impacts as compared to global warming impacts because of the large amounts of $CO_2$ emitted at the cement plant during calcination of limestone (calcium carbonate) for the production of cement. This $CO_2$ from calcination is in addition to process $CO_2$ emissions from burning fuel to heat the cement kilns. Another notable example is sheet steel. Due to the chemicals used for galvanization, sheet steel has disproportionately higher overall environmental impacts as compared to climate change impacts. Wood also has disproportionately higher overall environmental impacts than $CO_2$ impacts because wood products sequester carbon dioxide during growth, thereby reducing climate change impacts. The relatively poor correlation of climate change impacts with broader environmental impacts indicates that for materials production, energy consumption or greenhouse gas emission

**FIGURE 9.** Greenhouse gas impacts for the manufacturing stage by product/material type for case study building using (left) conventional concrete (duplicating Figure 8) and (right) concrete incorporating 25% fly ash replacement of cement in concrete.




should not be used by designers as a surrogate for total environmental impacts. Rather, a more complete life cycle assessment should be used. A similar trend was also noted by Sartori and Hestnes.[18]

Having identified the sources of largest impact, designers can begin to make targeted decisions for reduction. Strategies for material impact reduction, for instance, could include material use reduction, increased recycled content, material substitutions, or process substitutions (i.e. replacing galvanization with other less intensive processes that do not reduce the expected lifetime of the building, since that would likely cause a net worsening of impacts despite reduced sheet metal processing impacts). Particular design recommendations are application-specific and outside the scope of this paper, but this LCA-based framework can be used to determine the marginal environmental cost of different decisions, thus allowing designers to rationally weigh their costs and benefits.

A number of potential design recommendations have been discussed here, including the use of supplementary cementitious materials to replace cement in concrete, and the use of recycled carpet. In each case, the design recommendation involves a material substitution. More sustainable designs can also include changes to an entire building system, such as reducing insulation, or eliminating the raised floor ventilation system, but these would have to be weighed against their impacts to energy performance during the use phase.

## CONCLUSION

As seen from the findings, the top priority for the more sustainable design of a prefabricated commercial building is reducing energy impacts during the building use phase, through energy efficiency and clean energy generation. This falls in line with the findings of life cycle assessments conducted for conventionally constructed commercial buildings. Even when designed for energy efficiency, built using advanced prefabrication manufacturing techniques, and generating 30% of its own energy from on-site solar PV, energy consumption still makes up over 60% of life cycle impacts. However, once a building approaches net zero energy, the largest remaining impacts become construction material choices. As efforts such as Architecture 2030 make net zero energy buildings more widespread, green materials and manufacturing will become more of a priority for sustainable design.

In a prefabricated building of the type studied here, the three largest material and manufacturing impacts that can be addressed without significantly affecting the use-phase energy consumption of the building are use of galvanized sheet steel, structural steel, and concrete foundation design.

This study demonstrates that design decisions can be rationally prioritized and directed with the aid of life cycle assessment tools. For instance, LCA modeling showed that although eliminating the under-floor heating and cooling system would reduce material impact intensity, it may not be beneficial from a life cycle perspective, since it affects energy consumption during the use-phase, which dominates life cycle environmental impacts. It also showed that replacing sheet steel with aluminum would not be environmentally beneficial with existing virgin aluminum building products. Modeling also showed that the use of fly ash in the foundation concrete (as used in the actual building) is very beneficial, despite being a simple and inexpensive material substitution. Finally, the analysis showed that some materials had surprisingly high impacts (such as sheet steel and carpet), which helps designers be aware of where their intuitions of high-impact materials may be wrong. The design of green buildings is a complex interplay of many factors, and LCA is a powerful tool to help prioritize and evaluate design options.

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