RESEARCH

ECOLOGICAL PAYBACK TIME OF AN ENERGY-EFFICIENT MODULAR BUILDING

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ABSTRACT

Ecological payback time was calculated for demolishing an existing commercial building with average energy performance and replacing it with an energy-efficient, prefabricated building. A life-cycle assessment was performed for a 5,000 ft² commercial building designed by Project Frog and prefabricated in San Francisco, California, and compared to the impacts of annual energy consumption and continued status quo *operation of a comparable average commercial building. Scenarios were run both with and without rooftop solar panels intended to make the prefabricated building net zero energy. The analysis considers the materials and manufacturing, transportation, annual energy use of the new building, and disposal of the existing building, compared to continued annual energy use of the existing building. The carbon payback of a new building with no solar against operation of an existing commercial building was found to be roughly eleven years, and a building with enough rooftop solar to be net zero energy was roughly 6.5 years. The full EcoIndicator99 environmental impact payback for a new efficient building with no solar was found to be twenty years, and a solar net-zero building was roughly eleven years against operation of an existing commercial building.*

KEYWORDS

life cycle assessment, modular building, ecological payback, payback time, energy efficient building, renewable energy

INTRODUCTION

Owners and operators of legacy commercial buildings are faced with an increasingly difficult challenge when looking to balance the life cycle economic, ecological, and environmental health impacts of their existing building stock. When existing buildings are functioning as designed but are inefficient in terms of energy and resource consumption compared to new buildings, and provide building occupants with poor indoor environmental quality, it may make environmental sense to demolish the building and replace it with a new building that would be less energy-consumptive and provide a healthier space for the occupants. However, there are significant environmental impacts associated with landfilling and processing the

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large amount of construction demolition waste in addition to the production, manufacturing, transportation, and field construction of the materials needed for new buildings. Owners and operators must be able to assess the tradeoffs between these scenarios to determine how the environmental burdens associated with ongoing operation of a legacy commercial building compare with the construction and operation of a new commercial building.

It may be constructive for owners to perceive this tradeoff as the "environmental or ecological payback" of such demolition and new construction. Ecological payback time in the strictest sense could extend until the complete ecological restoration of a building site, but in previous literature[1,2,3,4] it commonly refers to the length of time until less environmental impact is accrued by the alternative as compared to a control case. Using payback period methods commonly applied in corporate finance decision-making,[5] calculating the ecological payback time can help answer these questions, thereby allowing owners and facility managers to make more informed, rational environmentally-focused decisions.

When looking to improve the environmental profile of an existing commercial building, the design choices available to an owner or manager are nearly limitless. At the extremes these include continuing operation and maintenance of the *status quo* building to demolition and complete replacement of the structure. There also exist a continuum of renovations and retrofits that can be designed ranging from simple changes to lighting fixtures (replacement of general lighting with more efficient task lighting) to extensive redesign of HVAC systems. Without doubt, the renovation of existing structures can provide significant environmental improvements with less impact than construction of an entirely new building, but they may also provide less benefit due to systemic limitations resulting from structural form, inefficient building materials, and poor siting of the old building. Due to the wide range of renovation options, the analysis of payback timelines for renovations are outside the scope of this paper. However, by modeling the two extreme cases associated with the environmental management of commercial buildings (continuation of the *status quo* and complete replacement) the range of decision variables is bounded. Logically, the design of a completely new structure, taking advantage of every possible benefit of new technology, siting, and holistic design practices will be more environmentally efficient than any renovation or retrofit options which are inherently constrained by at least one existing building parameter. Likewise, the environmental impact of an entirely new structure is greater than any renovation or retrofit since it includes consumption and emissions associated with new structural systems, foundations, or other building components and systems that would remain in place during renovation. Bound by these extremes, this paper examines the payback of new construction to replace an existing building to better inform building owners and managers of the metrics and mechanics of building ecological payback.

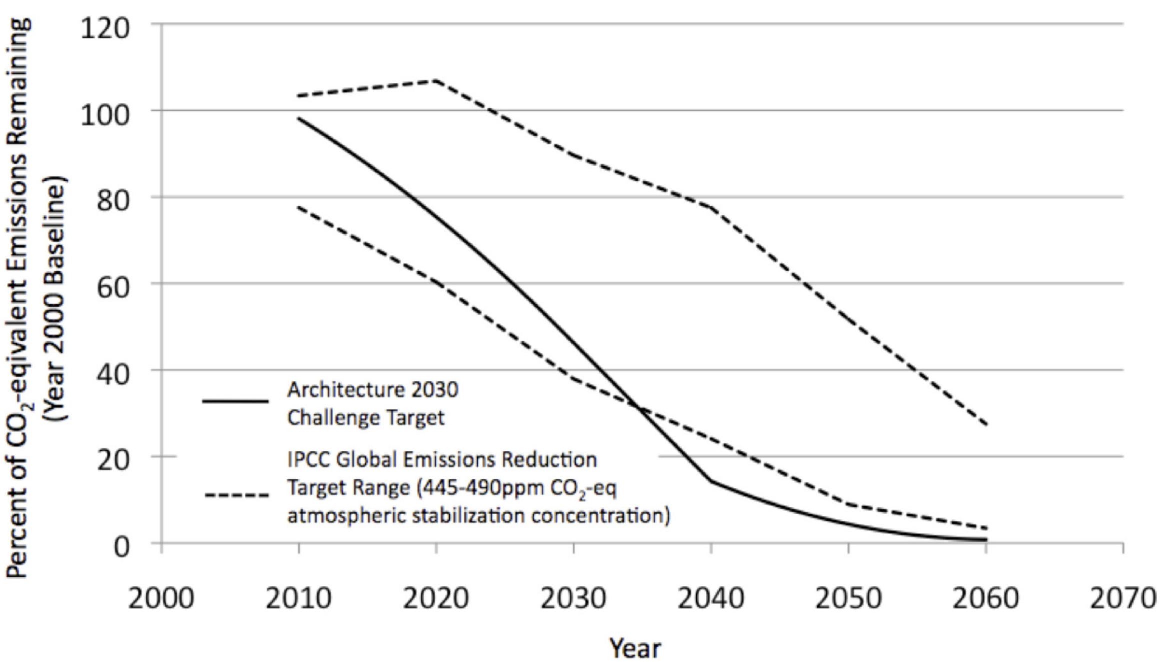
This problem is significant because replacement of existing buildings represents a large market segment of commercial construction, comprising a larger segment of new building construction than cases in which no building was present before (i.e. greenfield sites). According to the US Department of Energy, the commercial building sector expands 0.8% to 1.5%[6] per year by square footage with total annual building stock turnover averaging 3.2%[7] by square footage. Thus, the amount of construction activity devoted to building replacement averages 1.1 to 3.0 times the amount of construction activity associated with greenfield sites in which entirely new buildings are built. More importantly, this problem is significant due to the time-dependent nature of many environmental challenges. Considering annual turnover rates of commercial building square footage, it will take approximately 30 years to replace the existing inefficient building stock with energy-efficient, high performance buildings.

To achieve levels of greenhouse gas reductions necessary for minimum expected average global temperature increases of between 2.0°C and 2.4°C (stabilized atmospheric carbon dioxide equivalent concentration between 445ppm and 490ppm),[8] the Architecture 2030 Challenge has proposed reductions in fossil fuel derived building energy consumption of 70%, 80%, 90%, and 100% in years 2015, 2020, 2025, and 2030, respectively. Accounting for US commercial building stock turnover rates, meeting such a timeline provides nearly a 100% reduction in fossil fuel derived carbon emissions from buildings by 2060. The relation of these proposed building-centric reductions to global emission reductions proposed by IPCC, accounting for the historical rate of turnover within the commercial building sector, is shown in Figure 1.

To realistically achieve these progressive goals, the environmental costs and benefits associated with drastic asset management decisions such as demolition and replacement of significant portions of the building stock must be carefully examined. The timing of these activities, and the length of time to payback of "invested" energy resources and carbon emissions must be taken into account. Finally, recognizing that for commercial buildings these decisions must be economically driven if possible, commercial building owners and facility managers must be shown the environmental and economic benefits of replacing their buildings and incorporating energy efficiency and clean energy generation.

A number of simplifying assumptions are made at the outset of this comparative study to provide manageable boundaries for analysis. Adverse occupant health impacts from poor indoor environmental quality were not considered in the ecological payback calculation since these are not only building specific but also occupant specific. Maintenance, cleaning, and repairs during the operation of the buildings were also not considered, conservatively assuming

FIGURE 1. Proposed Architecture 2030 Challenge Fossil Fuel Derived Building CO_2-eq Emissions and IPCC Global CO_2-eq Emission Reductions (445ppm – 490ppm Atmospheric Stabilization Concentration).



that these impacts would be the same for the two buildings. The primary use-phase difference between the old building and the new prefabricated building was assumed to be energy use. Studying the total life cycle of commercial buildings, Scheuer *et al.* found that all life cycle impact categories measured (global warming potential, ozone depletion potential, acidification potential, nutrification potential, and solid waste generation) correlate closely with primary energy demand.[9] Kommonen and Svan[10] and Hara-Lindström[11] reported similar correlation among impact categories for commercial buildings. Thus, in this study energy is used as a surrogate during the use-phase to guide the decision analysis between continuing *status quo* building operation and new building construction and operation.

Options for renewable energy generation were considered to meet operational energy use demands. The building analyzed has rooftop-mounted solar photovoltaic ("PV") panels that will generate roughly 30% of its energy needs. Following this base case, analyses were also done for scenarios with 0% of power demand being supplied by PV panels and 100% of power demand being supplied by PV panels to make the building fully net zero energy, since both of these scenarios are planned in other buildings by the manufacturer. Ultimately, the goal of this study was to determine the ecological payback period of replacing an inefficient commercial building with a high performance, energy-efficient structure.

BACKGROUND

Numerous studies have demonstrated the importance of the use and operation phase in long lasting, highly durable systems, such as buildings. Scheuer *et al.*[9] 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 either Europe or 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] Conclusively, energy-efficiency is enormously important for buildings. If a property owner or facilities manager is planning to construct a new building, it should be constructed using as many energy-efficient technologies as possible. Likewise, numerous studies have quantified the ecological payback of specific building materials or products such as insulation or solar panels.[18, 19, 20, 21] However, no studies have yet examined the ecological payback of completely replacing existing construction with high performance, more sustainable buildings. Such studies are becoming important as industry looks to maintain or accelerate the rate of building stock turnover, thereby diffusing new building technologies more rapidly through the stock and achieving greenhouse gas emission targets and other sustainability goals.

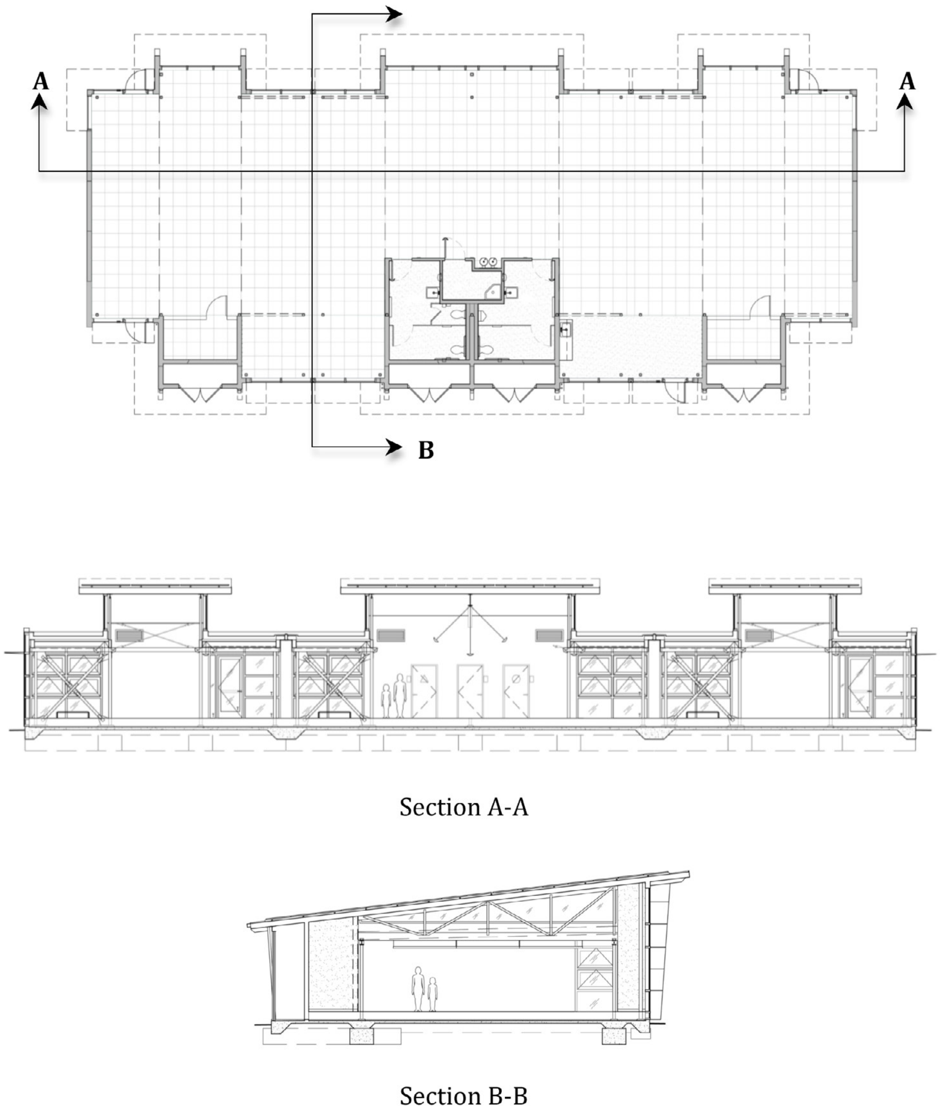
While calculating the ecological payback of any green building initiative is a worthwhile undertaking, it is especially important for prefabricated buildings as these are intended for mass-quantity construction. The environmental impacts of one particular design can be extremely large once hundreds of units are installed. Kim conducted a preliminary comparative life cycle assessment of a modular and conventional residential building.[22] That research found that the total amount of the materials used to construct the conventional home are 9%

less than for the modular home. This is primarily because the modular home was framed with larger 2″ x 6″ studs and required additional structural components to accommodate transportation. However, the conventional home produced 2.5 times more construction wastes than the modular home due to manufacturing process efficiencies. Similar to other studies already mentioned, Kim 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 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 resulted in 7% less natural gas consumption over its 50-year service life. Finally, while the modular home required additional transportation energy compared to the conventional home for delivering the fabricated modular unit to the building site, the very short fabrication cycle of the modular home (5 days) allowed the modular system to significantly reduce employee transportation energy compared to that of the conventional home. While Kim studied the benefits of prefabrication for residential structures and the present work focuses on prefabrication for commercial structures, Kim's findings validate the benefits of prefabrication. Disadvantages of prefabrication associated with increased material use and transportation energy are made up for by increased energy efficiency from better quality control, faster construction cycle times, and more efficient (less wasteful) construction processes, all of which lead to improved sustainability of prefabricated structures.

Focusing on the commercial building sector, the prefabricated building system analyzed in this study is aimed at educational and small-scale commercial markets and is designed by Project Frog, a product company supplying prefabricated green building systems. The floor plan and characteristic cross-sections of the building analyzed are shown in Figure 2. The building was chosen because it is representative of the energy efficiency and indoor environmental quality of the company's common baseline product, the Frog 2.2 Series, which is applicable to many markets and geographic locations throughout the continental US and Pacific islands, with some modifications for climate zone. The analysis presented within this study could also be generalized to buildings of different sizes in other climates by modeling the energy use of a Frog and average building in a specific location, and then normalizing other life-cycle impacts by square footage.

The metric chosen for decision-making between continuation of the *status quo* building operation and replacement with a modular, prefabricated building system is payback time, specifically ecological payback time. While payback time is a commonly accepted metric in business operations, a number of well recognized problems are associated with its use in the academic field of finance.[5] First, the timing of payments within the payback period must be taken into account. This is accomplished in finance through a discount rate, as will be done in this study. However, unlike finance discount rates that are set by the market, the discount rates for future energy consumption and environmental impact are highly uncertain.[23,24,25] Therefore, a sliding range of discount rates, as proposed by Weitzman[25], for future environmental costs was adopted. Second, payments made after the payback period are not taken into account. Within life cycle analysis this is accounted for through the use of a "functional unit" that provides a quantitative unit for normalization and comparison. Through the well-defined

FIGURE 2. Floor plan and sections of case study prefabricated modular structure.



functional unit of a building system with a defined service life, this common problem with payback analysis is resolved. Finally, the cut-off date or minimum desirable payback length is arbitrarily set. Within finance, the comparison of financial returns to the return of risk-free assets serves as a benchmark for evaluation. In finance, these benchmarks are arbitrarily chosen, but this problem does not apply to ecological payback analysis since there is no comparative "risk-free" asset for comparison to energy or environmental impact reduction efforts. Any effort that eventually pays back energy or environmental impact "investments" over time is desirable, thus not requiring a standard for undesirability other than its ability to pay back. Those that fully pay back sooner, and continue to pay back further into the future, are simply more desirable. In this way, payback methods can be used to evaluate the energy and environmental sustainability of comparative systems without the commonly recognized shortfalls of payback method analysis in traditional finance.

METHODOLOGY

A process-based attributional life cycle model was developed to support the payback analysis. 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 throughout its life cycle, from acquisition of the raw materials, through production, use, and final disposal or recycling, included transportation needed between these phases.[26] The use of life cycle models for enhancing products and processes has evolved over the last two decades. The first applications of LCA were comparative assessments of consumer products.[27] While the first assessments were product based and narrow in scope, numerous life cycle assessment 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 in this study.

The building analyzed in this study is a new community center (commercial use) commissioned by the San Francisco Redevelopment Agency for urban renewal of the Hunters Point Shipyard for a service life of 50 years. The analysis was performed before construction began. The building contains 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 will be certified LEED® silver or gold, and has 30% of its power provided by rooftop-mounted solar PV panels.

Materials for construction were chosen as best-in-class components that fit within the kit-based concept of the prefabricated building concept for Project Frog such that interclass materials can be substituted to meet cost targets without changing the overall design. In this study, best-in-class performance is measured using environmental product declarations (EPD) for each component or material as reported by each manufacturer.

The structure is comprised of a structural steel frame on a concrete slab with a raised floor plenum for under-floor air distribution. It uses thermally-broken light-gauge steel framed insulated wall panels for its solid walls and thermally-improved extruded aluminum curtain walls for its window walls. The roof is a structural metal deck with block insulation on top. It was modeled using a combination of insulated standing-seam steel roof panels and Duro-Last® polyvinyl-chloride roof membrane. Both roof finishes have high Solar Reflectance Indices (over 88% reflectance as measured by ASTM C1549). The building insulation is comprised of 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 roofs by installing the insulation entirely above the structural steel decking, and it is avoided in the walls by having 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 used throughout 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. Interiors are traditional gypsum wallboard with low-VOC paints and high recycled content, low VOC carpets. There are two bathrooms and a kitchenette, which use linoleum flooring and low-flow fixtures. Water use was not measured in the impacts. The building HVAC system is entirely electric since no natural gas service is provided at the building location. Therefore the structure uses heat pumps and exhaust fans with operable windows and displacement ventilation. The lighting system uses T8 fluorescent bulbs in highly efficient Peerless direct/indirect fixtures with daylighting controls to dim the lights. Since the building envelope was designed to maximize daylighting, it is estimated that the building will need little to no electric lighting for the great majority of daytime hours. The plumbing system uses standard copper, steel, and PVC pipes.

Operations & maintenance impacts such as cleaning and repairs were assumed to be the same between the continued operation of the existing building and the new Frog building, so these were not considered. This is taken as a conservative assumption, since older buildings are typically in greater need of maintenance than new buildings.

Due to the long use-phase of buildings, accurate modeling of energy use during service life is essential for an accurate payback analysis. Currently, a large number of tools exist for assessing energy performance in buildings. U.S. DOE has published a comprehensive list of the available tools.[28] Crawley et al. detail the functionality and differences of 20 major energy assessment tools. [29] Recently, Maile[30] 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.[31] Accepted standard energy modeling tools in California include eQuest and EnergyPro.[32] Therefore, energy use throughout the use-phase of the prefabricated building was modeled using both EnergyPlus and eQuest software. While these may be preferred or accepted tools, all such models continue present limitations in their ability to capture variation in quality of construction, building occupant use patterns and behaviors, building system operation and maintenance, and appliance operational efficiencies that will last over decades. Several 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. These scenarios were performed in either EnergyPlus or eQuest in the case of a California Title 24 minimum-compliant structure with similar size, shape, orientation, and geographic location of the Project Frog prefabricated structure being considered.

The control case for energy use was an existing average commercial building of the same size in the San Francisco region. This data was not modeled, but came from empirical energy use surveys by the US Energy Information Administration, in its Commercial Buildings Energy Consumption Survey (CBECS) database[37]. To find an average commercial building's energy intensity in the region, the CBECS data was filtered for Pacific census division, climate zone 4. See the Findings section for all energy values, both empirical and modeled.

Although the Frog and existing commercial buildings analyzed are located in San Francisco, and the Frog's energy use was modeled to be for San Francisco, and the control case energy use was taken from commercial building survey data in the region (using CBECS data for Pacific census division, climate zone 4), the environmental impacts of electricity use were modeled to be a US average electricity generation mix, not the San Francisco electricity mix. This was done to make the results applicable nationwide, as such buildings are planned for installation throughout the country. The 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.[38] The building's energy consumption was 100% electricity due to the lack of natural gas service at the building location. No attempt was made to estimate the average energy used in other climate zones, but such analysis could be pursued in further research. The assumption of a San Francisco climate is conservative in comparison to a nation-wide application, as northern California's moderate climate reduces use-phase energy consumption due to the relatively few heating or cooling degree-days compared to most of the US. This pushes the limit of the continued building operation versus complete replacement comparison since the use phase impacts (in which replacement scenarios show the greatest benefits) are smaller in northern California than in most climates throughout the US.

The life cycle assessment was performed in SimaPro analysis software. The impact assessment methodology used for determining total impacts was EcoIndicator 99 with “egalitarian” weighting. The methodology used to determine greenhouse gas emission impacts (global warming potentials) were the Intergovernmental Panel on Climate Change 100-year Global Warming Potentials. Wherever materials or processes were not available to describe components of the building, suitable surrogates were selected from existing processes in existing datasets.

To determine transportation impacts, most building materials, except the foundation, were modeled with transportation of 1000 miles by truck. This is an overestimation. While a few elements are known to have traveled 2000 miles, many materials were transported less than 500 miles to achieve LEED rating points. Transportation ultimately comprised a small part of the overall impact, approximately 2% (see Figure 3), such that even with 100% error in transportation modeling, the total impact would not alter final results significantly. These transportation impacts, as a percentage of total building impacts, are also in line with that found by Scheuer *et al.* in more thorough analysis for traditionally constructed commercial buildings and those found by Kim[22] for modular home fabrication performed in Topeka, Indiana.

Fabrication was modeled as energy consumption needed to assemble and erect the structure, since all input materials are modeled separately and few materials are consumed during fabrication. The fabrication energy was found be to negligible, similar to that found by Kim,[22] which comprised less than 0.1% of total life cycle energy consumption. Disposal of the entire building was modeled to follow the US “durable goods waste” scenario. End of life demolition and disposal comprised 3% of total Frog life cycle energy consumption and emissions. For payback analysis, scenarios were also run modeling disposal as 100% landfill.

Material quantities for construction of the modular building were taken from 3D CAD models. Since the 3D CAD model data is used for manufacturing the structural steel and light-gauge steel parts by means of computer-controlled laser cutting and robotic welding, these masses are known to be accurate. The volume and mass of concrete in the foundation was estimated by creating a 3D CAD model of the foundation from architectural drawings. Masses and areas 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 or other architectural drawings. Material quantities for the status quo control case were zero for construction impacts, since the control case is continuing to operate an existing building. Material quantities for the control case’s demolition impacts were assumed to be the same as the Frog building due to their comparable size and commercial use class. Since building disposal is only 3% of a Frog’s life-cycle impacts (see Figure 3), even a gross error of 100% in the volume of demolition waste would not significantly affect the overall analysis.

The lighting system was modeled as component materials, including the required input for all bulbs, ballasts, and associated electronic fixtures. The HVAC system was modeled as a decentralized ventilation system with steel ductwork capable of delivering 120 cubic meters of conditioned air per hour. Wiring was estimated by length of wiring runs from 3D CAD models. Junction boxes and circuit breaker panels were not included. Plumbing was estimated by length of pipe runs with only copper piping being included. Various plumbing fixtures (toilets, urinals, sinks) were estimated to simply be the weight of four ceramic toilets; other fixtures such as grab bars and mirrors were not included. As discussed later, since the material production energy and emissions make up such a small portion of the overall life cycle impacts, these small exclusions of plumbing fixtures, electrical junction boxes, and electrical breaker boxes do not introduce appreciable amounts of modeling error or distort the study conclusions. These electrical and mechanical systems comply with or exceed ANSI/ASHRAE/IESNA Standard 90.1.

Electricity production from the rooftop PV panels is assumed to be constant over the payback period. The panels are warrantied by the manufacturer to produce within 20% of the rated production for the first 25 years of use. Since the ecological payback is reached before the expiration of the warranty, the assumption of constant output over the length of the payback period remains valid for this analysis.

It should be noted that during the course of the project, it was found that the Idemat database values for the impacts of extruding aluminum are overstated by a factor of 1000, since the data was accidentally entered in units of kg rather than metric tons.[39] (This error appears in all software using the Idemat database, including both SimaPro and SustainableMinds.) The administrators of the database have been notified of this error. For the purposes of this study, a workaround was used, where the mass of aluminum in the extrusion process was 1/1000th the actual mass of aluminum used.

As noted previously, a sliding discount rate was adopted for appropriate discounting of future environmental impacts. While the environmental impacts reported are not monetarily valued, the application of a discount rate remains applicable regardless of valuation prior to or after discounting. Following the recommended sliding scale proposed by Weitzman[25] in which events in the immediate future (within 1 to 5 years) are discounted (marginally) at 4%, events in the near future (within 6 to 25 years) are discounted at 3%, events in the medium future (within 26 to 75 years) are discounted at 2%, events in the distant future (within 76 to 300 years) are discounted at 1%, events in the far-distant future (over 300 years into the future) are not discounted. Given the "immediate" or "near future" nature of building systems, the application of discounting changes the outcome very little compared to the same analysis with no discounting.

FINDINGS

LCA Results

The ecological payback of replacing an existing average building with an efficient prefabricated building relies on the results of life cycle assessments of the existing building's energy use and the new building's construction and energy use. LCA results for the Frog building are shown by life-cycle stage in Figure 3 and Figure 4, in terms of both EcoIndicator99 egalitarian-weighted points and greenhouse gas emissions (kg CO_2-eq), respectively. In each use-phase scenario, 30% of the building's power is supplied by rooftop photovoltaics.

Over the total 50-year life cycle, Figure 3 shows that 63% of the as-constructed (30% solar powered) prefabricated building's impact stems from the production of grid electricity consumed during the use-phase of the building. This is significantly lower than values noted by Scheuer *et al.* and Junnila *et al.,*[12, 13] who found that 95% of life cycle energy consumption and emissions and 90% of life cycle energy consumption and 80% of life cycle carbon dioxide emissions stem from the use phase. The lower use-phase total impacts and carbon footprint

FIGURE 3. Total life cycle impacts by life cycle phase for a prefabricated commercial building with 30% of power supplied by photovoltaics in units of EcoIndicator99 points.

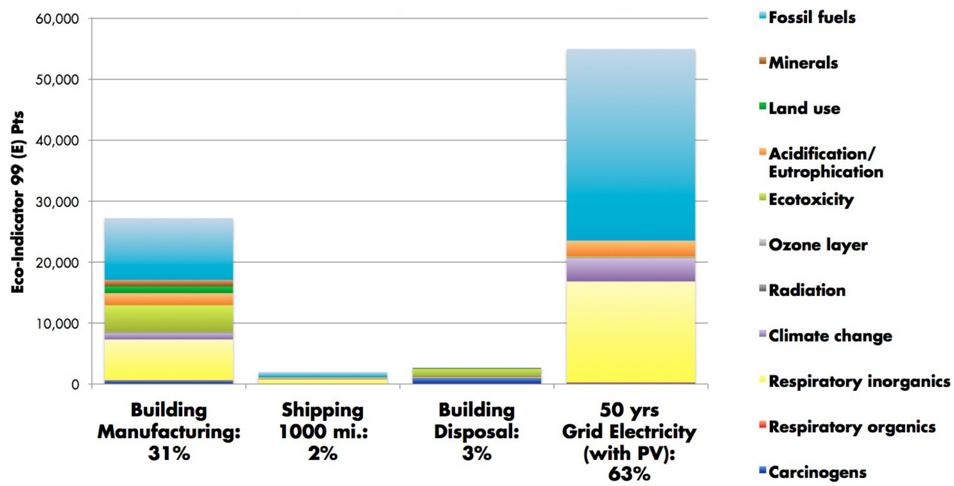
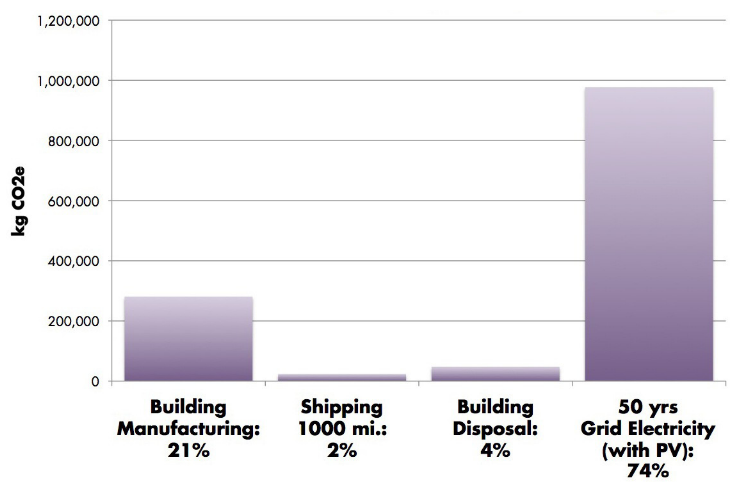


FIGURE 4. Total life cycle greenhouse gas emission by life cycle phase for a prefabricated commercial building with 30% of power supplied by photovoltaics.



are due to a combination of the relatively mild San Francisco climate (fewer degree heating and cooling days), lower use phase energy consumption for the prefabricated building, and the benefits of the rooftop PV panels providing 30% of building energy. An existing average commercial building (the control case) with square footage equal to the Frog building will use 93,413 kWh/yr, according to CBECS survey data for Pacific census division, climate zone 4.[40] Building energy models constructed in eQuest predict that even a new commercial building compliant with California Title 24 consumes slightly more than 70MWh annually, from space heating (3,500 kWh/yr), space cooling (13,600 kWh/yr), indoor fan operation (8,000 kWh/yr), domestic hot water heating (17,900 kWh/yr), lighting (15,200 kWh/yr), and plug receptacles (12,100 kWh/yr). By contrast, the newly constructed Frog building was predicted to consume roughly 47,500 kWh annually.

As cited previously, constructed buildings often do not exhibit actual energy consumption in line with building energy models. Thus, sensitivity analysis was conducted to investigate the robustness of Frog building energy models. Variations in the modeling of space heating, space cooling, and water heating requirements were investigated, corresponding to aggregated variation in building occupant behavior, roofing solar reflectance, window heat gain coefficients and visible light transmittance, envelope air tightness, and appliance efficiencies. Accounting for this variation, EnergyPlus modeling showed that Frog building energy use may range from a low estimate of 17,100 kWh/yr (low occupancy with few appliances / electronics and no hot water) up to 54,100 kWh/yr (high occupancy with numerous plug loads and appliances, with significant hot water use). To compare with the Title 24 model, the eQuest model of the Frog predicted 47,500 kWh/yr (roughly 1,500 kWh/yr space heating, 3,600 kWh/yr space cooling, 6,300 kWh/yr fans, 17,000 kWh/yr hot water heating, 7,000 kWh/yr lighting, 12,100 kWh/yr plug loads). Accounting for this variation in predicted energy use, the Frog building represents an energy use reduction of 23% to 76% with respect to a newly-constructed equivalent Title 24-compliant building, and an even larger 42%–81% reduction compared to an average existing building. For payback calculations, the 47,500 kWh/yr prediction was used as the expected energy use of the Frog building, and was compared to a scenario of a new building with Title 24 energy demand.

The raw material acquisition, supply chain transportation, and building fabrication phases make up 31% of the building's life cycle impacts. As noted previously, transportation of materials to the fabrication site make up approximately 2% of total life cycle impacts. Demolition and disposal of wastes at end of life make up 3% of total life cycle impacts, including landfill and recycling impacts.

Greenhouse gas emissions are often correlated directly with broader environmental impacts. However, in this analysis there is a significant difference in life cycle environmental impacts and life cycle carbon dioxide emissions contributed by each life cycle phase. Due to the environmentally intensive and potentially toxic manufacturing processes that are used to produce building materials (aluminum smelting, steel forging, galvanization, etc.) the aggregated environmental impact, expressed as Ecoindicator99 points, of the material production and fabrication phase are disproportionate to energy consumption and greenhouse gas emissions in each phase. This indicates that energy consumption or greenhouse gas emissions should not be used as a surrogate for comparing interphase aggregated environmental impacts. A similar trend was also noted by Sartori and Hestnes[17] in a review of other building life cycle analysis studies.

Figure 5 and Figure 6 show the effect of energy source on total impact from annual energy consumption, measured using Ecoindicator99 impact points, and on global warming potential measured as kilograms of carbon dioxide equivalents. Three scenarios were investigated for new, prefabricated buildings: annual energy use for the building using 30% of energy derived from PV (as built), 100% of energy provided by rooftop PV panels (grid-connected net zero energy), and 0% of energy provided by rooftop PV panels (all power coming from the grid); they are compared with the control case of the continued *status quo* operation of an average commercial building located in San Francisco (from CBECS data). While PV manufacturing impacts were included in the overall lifetime analysis (Figure 7 and Figure 8), these impacts are not included in the annual energy use comparison shown here in Figure 5 and Figure 6 because they were allocated to the construction phase of the building's life-cycle.

FIGURE 5. Total impacts of annual energy use in a prefabricated commercial building with 30% (as-built), 0%, and 100% of power supplied by rooftop photovoltaics as compared to an average existing commercial building (control).

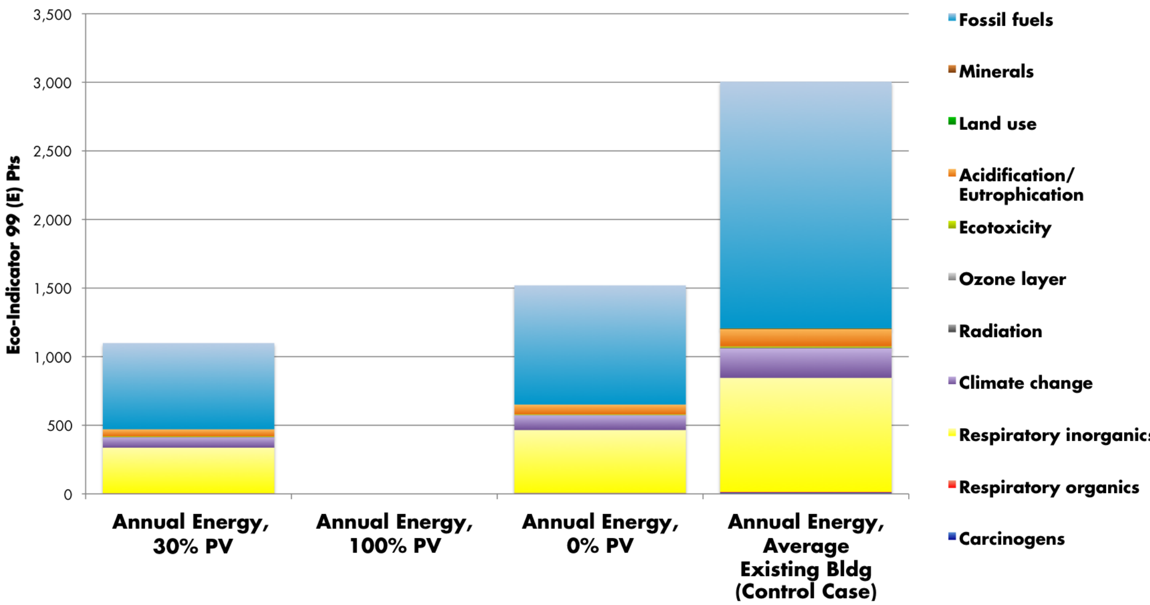
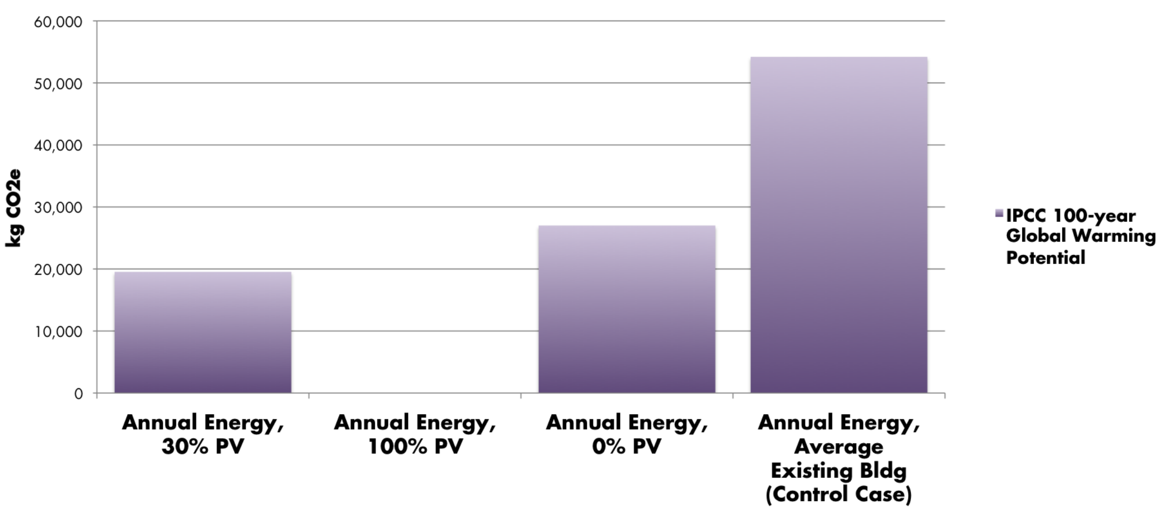


FIGURE 6. Greenhouse gas emissions from annual energy use in a prefabricated commercial building with 30% (as-built), 0%, and 100% of power supplied by rooftop photovoltaics as compared to an average existing commercial building (control).



Ecological Payback Results

Using the payback method detailed previously with the necessary alterations to account for the commonly cited shortfalls of payback analysis, the time needed to recoup the initial "environmental investment" in the construction of the highly efficient prefabricated building system was determined. Based on the life cycle assessment results, twelve scenarios were run: three variations of the new building and two variations of the disposal of the old building, and two variations of building energy consumption profiles. Scenarios for the new building were (1) the Project Frog building only relying on energy efficiency gains (no on-site renewable energy generation), (2) fully net zero energy capabilities via rooftop solar panels (100% renewable energy and grid connected), and (3) the building meeting roughly 30% of its energy needs supplied by rooftop photovoltaics (as built).

Scenarios for old building disposal were 100% landfilling of construction and demolition waste, and application of EPA average recycling rates material-by-material for durable goods in the United States, as listed in the SimaPro software. In retrospect the selection of a disposal scenario has very little impact on the analysis because the disposal stage of the building life cycle was much smaller than the other life cycle phases. The difference between the 100% landfill scenarios and the average recycling scenarios were between 0.3% and 1.2%, far smaller than the margins of error of data collection and performance assumptions.

Scenarios for building energy consumption reflect (1) likely energy use of the Frog building as modeled using EnergyPlus and (2) Title 24 energy use expected for the Frog building. Running each permutation of the three power generation scenarios, two landfill scenarios, and two energy consumption scenarios, twelve analysis were conducted for the Frog building. Due to the small difference between the two disposal scenarios, only the six 100% landfill scenarios are presented here. The scenario descriptions are summarized in Table 1.

For scenario 0PV-100LF-EP (0% PV with expected energy performance), the building analyzed would have a full EcoIndicator99 ecological payback of 20 years, and a carbon payback of eleven years. For scenario 100PV-100LF-EP (net zero energy PV with expected energy performance), the full EcoIndicator99 ecological payback would be eleven years, and the carbon payback would be 6.5 years. For scenario 30PV-100LF-EP (the building actually constructed by Project Frog), the full EcoIndicator99 ecological payback would be 16.5 years, and the carbon payback would be nine years. Depending on the power generation scenario and the impact category chosen, the Title 24 energy use scenarios (0PV-100LF-T24, 30PV-100LF-T24, and 100PV-100LF-T24) push the EcoIndicator99 ecological payback or carbon payback further into the future between one and ten years.

TABLE 1. Life Cycle Scenario Descriptions.

Prefabricated Building PV Percentage	Existing Building Disposal Scenario	Prefabricated Building Energy Model	Scenario ID
0% PV	100% Landfill	EnergyPlus	0PV-100LF-EP*
		Title 24	0PV-100LF-T24*
	EPA Landfill Model	EnergyPlus	0PV-EPALF-EP
		Title 24	0PV-EPALF-T24
30% PV	100% Landfill	EnergyPlus	30PV-100LF-EP*
		Title 24	30PV-100LF-T24*
	EPA Landfill Model	EnergyPlus	30PV-EPALF-EP
		Title 24	30PV-EPALF-T24
100% PV	100% Landfill	EnergyPlus	100PV-100LF-EP*
		Title 24	100PV-100LF-T24*
	EPA Landfill Model	EnergyPlus	100PV-EPALF-EP
		Title 24	100PV-EPALF-T24

(*Denotes scenario presented in results section)

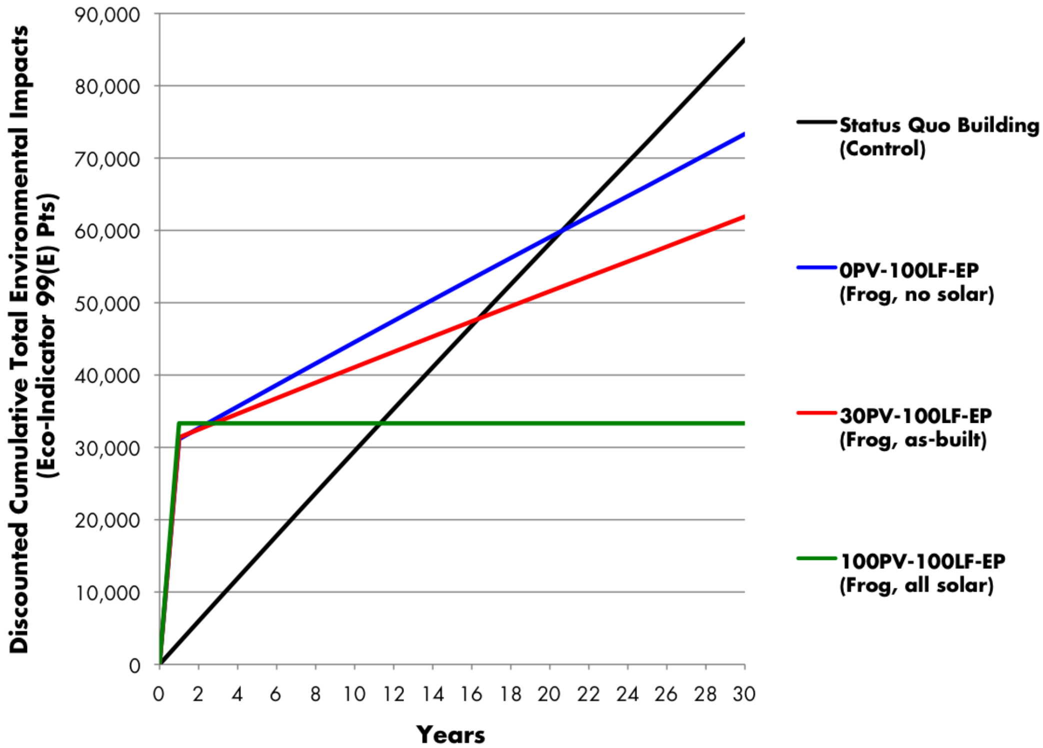
Figure 7 and Figure 8 show these trends over time for cumulative environmental impact points and greenhouse gas emissions, respectively, illustrating the longer-term benefit of building replacement beyond the payback period. As mentioned, the status quo building impacts are considered the control case; the figures show the cumulative impacts of an existing average building's continued inefficient operation, accumulating year by year linearly. As the cumulative impact from each scenario intersects the control case, "ecological payback" is achieved. The long-term benefits of a prefabricated building incorporating PV are clear for all three new building scenarios. The Frog building net zero energy scenario with expected energy consumption (100PV-100LF-EP) exhibits half the environmental impact of continued operation of an existing equivalent building within 22 years, and shows half the carbon impact within 13 years, demonstrating the long-term benefits of a prefabricated building incorporating PV. As mentioned, impacts of maintenance and cleaning are not included in the calculations because they are conservatively assumed to be equal between the new prefabricated building and an existing building.

All scenarios assume that energy use will remain constant throughout the analysis period. However, according to the DOE, commercial electricity consumption will increase over the next 25 years; the largest increases will be from miscellaneous loads (increasing 90% over 2009 consumption by 2035) and heating, cooling, and ventilation (increasing 30% over 2009 consumption by 2035).[41] The large increase in miscellaneous loads will be due to electricity use for "other" office equipment such as servers and mainframe computers, which increases by 2.5 percent per year as demand for high-speed networks and internet connectivity grows.[41] Equal increases in such loads could be expected in both prefabricated new commercial buildings and operating existing commercial building, and will negate one another in this analysis. However, the 30% increase over 2009 heating, cooling, and ventilation consumption in the next 25 years only strengthens the argument for replacement of inefficient commercial buildings with highly energy efficient prefabricated commercial structures.

In addition to ecological payback, economic payback of a new building is also of interest to many building owners. While not the main focus of this study, a simple payback period analysis was carried out accounting for negative cash flows that include the cost of existing building demolition, new building construction, and PV installation. Positive future cash flows were modeled as the savings of future energy reductions. The cost of demolition of an existing 5,000 ft^2 building is approximately $21,750.[42] Construction of a new, 5,000 ft^2 modular building is $450,000.[42] Purchase and installation costs for small scale and large-scale solar PV systems (to provide either 30% or 100% of building electricity) are $40,500 and $146,400, respectively.[43] The cost of electricity in San Francisco is $0.226/kWh.[44] Annual inflation on electricity costs is 1.6%.[45] The applied discount rate of capital is 4.0%.[46] As a result, payback times for new buildings with 0%, 30%, and 100% of electricity needs being met by PV are 114, 101, and 86 years, respectively. While it can be a good investment to build a new energy-saving building instead of a new average building, it is not financially advantageous to tear down an existing building to build a new energy-saving building, unless there are highly beneficial economic circumstances such as tax or other policy incentives.

These long economic payback periods are in contrast to the much shorter ecological payback periods of 11, 16, and 20 years shown in Figure 7. This is due to the mismatch between the economic cost of electricity and environmental impact of electricity production. Over its lifecycle, the prefabricated structure's use-phase energy costs comprise less than half of total lifecycle costs. However, use-phase energy impacts comprise 63% of total lifecycle impacts.

FIGURE 7. Ecological payback timeline for the prefabricated commercial building incorporating 0%, 30% and 100% photovoltaic power sources as compared to status quo existing (control) commercial building operation assuming (top) eQuest modeling energy consumption and (bottom) Title 24-compliant energy consumption.



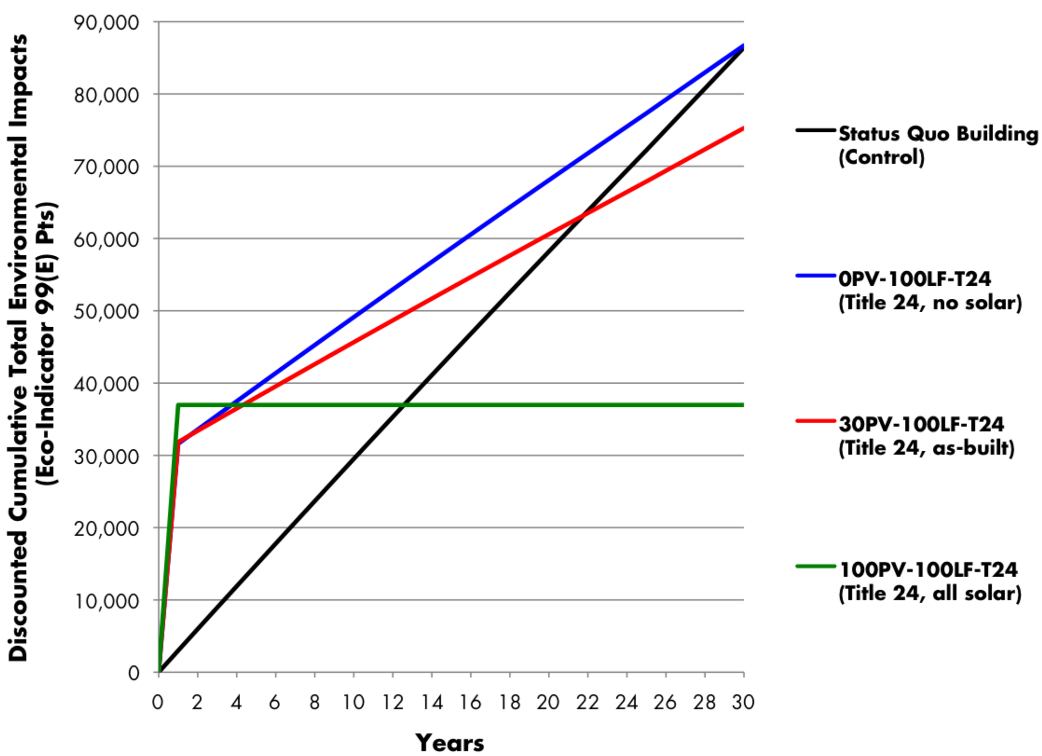
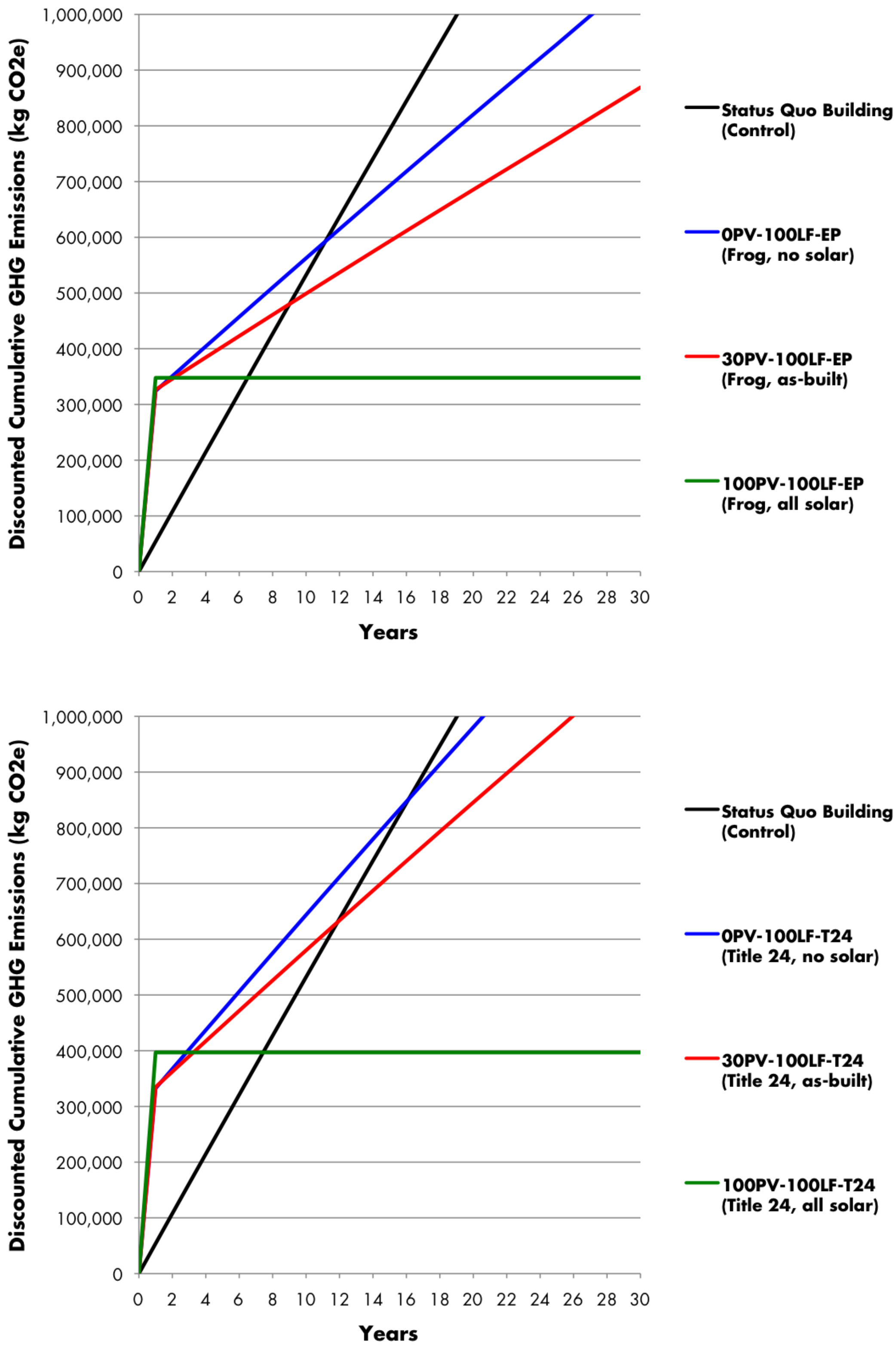


FIGURE 8. Greenhouse gas emission payback timeline for the prefabricated commercial building incorporating 0%, 30% and 100% photovoltaic power sources as compared to status quo existing (control) commercial building operation assuming (a) eQuest modeling energy consumption and (b) Title 24-compliant energy consumption.



Such inaccurate pricing of electricity production externalities challenge building owners to replace inefficient buildings and suggest a broad need for better emission pricing markets to meet the goals of the Architecture 2030 Challenge.

CONCLUSIONS

Overall, the necessary time to ecological payback for new, high performance, energy-efficient commercial buildings is on the order of years, not decades, when compared to continued operation of existing commercial buildings. While ecological payback timelines for new building investments should not be judged using the same standards as financial return rates, it is promising that a new energy-efficient building which can last many decades is justified by a greenhouse gas payback in as little as 6.5 years, and total ecological impact payback in as little as 11 years. Given the rapid decreases in global emissions recommended by national and international environmental agencies over the next decades, such rapid ecological payback times are even more desirable.

Ultimately, given new technologies and improvements in the prefabrication and manufacturing of commercial building systems, it can make good ecological (if not economic) sense to demolish existing, poorly performing commercial buildings and replace them with high performance, energy-efficient structures that exhibit good durability and flexibility of use. While the energy embodied in the existing commercial structure is considerable, the ecological losses associated with the materials consumption for new construction are soon overshadowed by the gains in operational efficiency that make up nearly two-thirds of total ecological impacts and nearly three-quarters of total greenhouse gas emissions, in even the most highly efficient and well constructed commercial buildings. Aggressive recycling and reuse of construction and demolition waste further accelerates these gains.

Given the extreme nature of the scenarios considered (continued *status quo* operation of an existing, inefficient average commercial building versus complete replacement by a high performance, energy-efficient prefabricated commercial building), the entire cadre of renovation options making up the spectrum between these extremes are also recommended. Given the inaccuracies in building energy modeling, future monitoring of building performance and energy use is also recommended to more accurately track ecological payback accounts and determine the ecological payback point when it is reached. While such renovations and monitoring may offer a range of ecological payback times different from those shown here, they will likely also make up a significant part of the future building energy solution portfolio.

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