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Whole building life cycle environmental impacts and costs: A sensitivity study of design and service decisions

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ABSTRACT

Improvements in building performance have focused on improving the energy efficiency of buildings, while, more recently, impacts associated with material production have also gained interest across the industry. However, emerging issues surrounding sustainability and resilience of buildings warrant a more holistic understanding of building design. This study presents a framework for the quantitative assessment of a range of sustainability and resilience performance aspects during early building design. The framework brings together a multitude of developed methods such as environmental life cycle assessment, life cycle costing, energy modeling, and seismic loss assessment to estimate the energy, water, and material-related environmental and economic costs. The framework is then used to conduct a sensitivity study investigating the potential shifts in the importance of various design and service aspects related to buildings. The main novelty is the broader consideration of building-scale and regional-scale energy and water services along with other typically considered building design features, and the consideration of regional seismic hazards for lifetime repairs. The results reinforce the long-known significance of use phase energy consumption for environmental impacts but show how the energy source type overshadows typical energy-efficiency design aspects, which are also less cost-effective considering the current state of the electricity market. The results also show the potentially significant contribution of different wastewater treatment scenarios on the environmental impacts of buildings and the changes in the share of embodied material impacts across locations. The presented framework could be used more broadly for a holistic building assessment useful for early design decision making.

1. Introduction

Buildings account for around 36% of energy use and 39% of greenhouse gas emissions globally [1]. With residential and commercial building space expected to continue to rise [1], there has been a substantial push towards more sustainable and resilient buildings. There have been many approaches to address building performance in this area including changes in mandatory building codes, development of rating systems, creation of qualitative assessment and guidance documents, and development of quantitative assessment tools [2]. Despite the growing knowledge in this field and options in quantitative assessment tools, there often seems to be a narrow focus on assessing individual performance aspects of buildings independently instead of understanding them holistically [3]. Additionally, many sustainability and resilience strategies are most effective when considered from the early onset of design, but in current practice, they are often not considered and evaluated until the later phases [4]. To address these issues, this study focuses on quantitative analysis of sustainability and resilience of buildings from a broader life cycle perspective while utilizing approaches feasible for early design phases.

Life cycle assessment (LCA) is one of the most frequently used tools for quantifying environmental aspects of sustainability, as it provides ways of assessing resource and emissions flows throughout the life cycle of products and processes. Similarly, life cycle costing (LCC) is also utilizing the life cycle approach, but from an economic perspective. Resilience, while inherently related to sustainability [2], focuses on the ability of products and systems to react and adapt to disruptions or deviations from normal operations [5,6]. One of the most common

Abbreviations: ODP, Ozone Depletion Potential; GWP, Global Warming Potential; SFP, Smog Formation Potential; AP, Acidification Potential; EP, Eutrophication Potential; FFD, Fossil Fuel Depletion Potential; LCA, Life Cycle Assessment; LCC, Life Cycle Costing; LCI, Life Cycle Inventory; MEP, Mechanical electrical and plumbing systems

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ways of studying and addressing the resilience of buildings has been through assessment of potential effects of natural hazard events on their structural integrity, for which there have been various developed assessment methods [7,8]. This study focuses on connecting tools from the fields of LCA, LCC, and hazard loss assessment, but from a resilience perspective focuses strictly on building's performance in seismic events. It should be noted that other events such as hurricane damage or climate change adaptation are not considered in this study but would be an interesting addition in the future.

Most early whole building LCAs were done as retrospective case studies of residential, office, and educational buildings [9–11]. While case studies are valuable for improving our understanding of a building's environmental performance, they have limited potential in providing widespread guidance to other buildings due to buildings' functional and temporal specificity. We know that buildings have many attributes (e.g., based on aesthetic, psychological, space, energy, and other requirements) that make them unique and difficult to compare. Nevertheless, Scheuer, Keoleian and Reppe [9] conducted one of the most complete early building LCA studies, accounting for the most LCA stages and functional aspects such as on-site material use, operational energy use and source types, and water demands and treatment. Most subsequent whole building LCAs have focused mainly on material use and operational energy use. Fig. 1 shows the various life cycle stages identified in international standards [12,13] and the subjective frequency of investigation in building LCA literature, based on a non-exhaustive series of papers published over the past 20 years and discussed throughout the rest of this section.

Related to LCA, the energy demand, as well as energy-related impacts are usually calculated based on reported numbers for case study buildings or have been obtained using simulation results [11,14,15]. Bawden and Williams [16] used national energy consumption database to obtain energy demand and then applied factors to obtain the total energy-related impacts, while Berggren et al. [17] used a similar approach but using energy demand data from a different database of green buildings certified in Europe. Al-Ghamdi et al. [18] also investigated differences of material and energy-use related environmental impacts across multiple locations around the world based on model simulations.

As shown in Fig. 1, operational water use is also listed in the ISO 21931 [13] and EN 15870 [12] standards for environmental impact assessment of buildings; however, it is almost entirely missing in building LCA literature due to perceived low importance. There have been numerous water and wastewater life cycle studies outside of the building LCA literature [19–22], with some of these studies being conducted by researchers informing certification schemes [23,24]; however, the knowledge is not always successfully relayed to building designers. Major LCA databases such as ecoinvent [25] or GaBi [26] do contain data needed to include water-related impacts. Although this generic data may not exactly represent processes and infrastructure in specific locations, it can still provide a useful context for other areas of the building assessment. The disconnect between water and building-related life cycle studies has resulted in some progressive buildings pursuing treatment technologies detrimental to some aspects of their environmental performance [27]. Studies focused on comparing varying treatment types have found great differences in impacts and have pointed out the potential significance of water treatment when related to buildings.

With increasing concern over the resilience of infrastructure, there have been efforts to bring resilience aspects into the LCA field. This has included efforts to bridge the development in the hazard loss assessment and performance-based design field with LCA specifically related to earthquake [8] and hurricane engineering [7]. Including these aspects may help in addressing the current limitation of building LCA, which focuses largely on material quantity reduction and consideration of component service life based mainly on assumptions. Including potential repair demands based on hazard damage can capture the benefits of enhanced structural systems and the need for premature replacement of damaged components. Repair is also listed in the ISO and EN standards; however, limitations related to data availability and approaches to such assessment have left this stage largely unaddressed. Simonen et al. [28] were the first authors developing a database related specifically to this stage.

Including some of these other life cycle stages may become more important as new building technologies improve energy efficiency, enable more on-site resource harvesting, and mainstream the use of innovative structural systems [17,29,30]. The potential changes in impacts and costs due to changing technologies can be studied using scenario analyses, parametric studies, and sensitivity studies, all of which have been increasing in the building LCA literature in the past decade. Parametrization and sensitivity studies in LCA generally fall within two categories: 1) studies aimed at understanding how study setup, assumptions, and LCA methods affect study outcomes, and 2) studies aimed at understanding the variability in life cycle results for alternative building designs. Studies falling within the first category have investigated the sensitivity of environmental impacts to service life of building components [31–33], building lifetimes and study periods [34], life cycle inventory data and tools [35,36], changes in boundary definitions [36], variability in component quantities [33], and level of detail in modeling components [37]. Studies in the second category have typically aimed to improve the understanding and selection of the best physical designs of whole buildings (e.g., size, shape, orientation, etc.), systems, and materials (e.g., wall types, window types, HVAC types, etc.). Studies in the second category are also more aligned with the nature of this study; however, they have typically narrowed down their focus on embodied impacts from the production of envelope systems and the effects on operational energy use.

One of the earlier studies in the second group was a multi-objective optimization study by Wang, Zmeureanu and Rivard [38], which considered life cycle costs and environmental impacts related to inputs consisting of varying envelope parameters and building shapes.

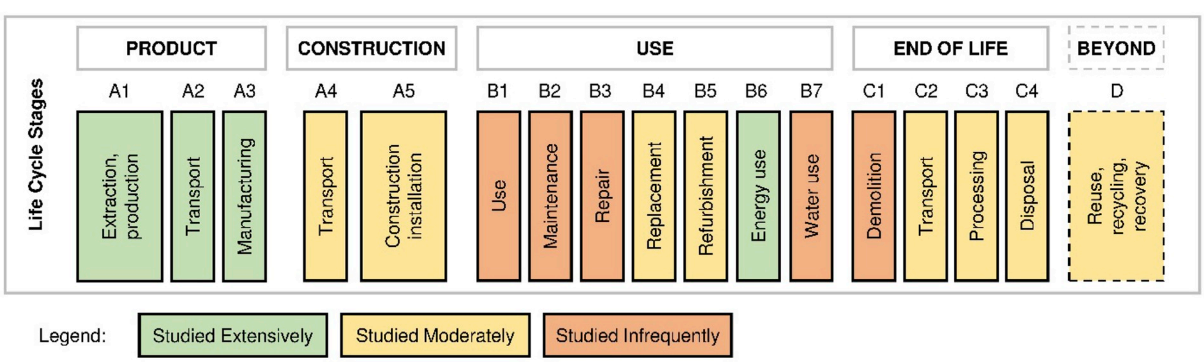

Fig. 1. Building life cycle stages (adapted from ISO 21931 [13] and EN 15978 [12]).

Similarly, Basbagill et al. [39] used EnergyPlus, RS Means cost data, Whitestone maintenance database, Excel, and Matlab to obtain impacts for almost 6000 unique design combinations. The parametric aspects of the study considered varying material types and thicknesses for structural, envelope, interior, and equipment components, as well as building shape, and number of floors. More recently, multiple studies have focused on using parametric approaches to identify significant model inputs and interaction effects between energy demand, thermal comfort, daylight and the embodied impacts of materials in various envelope systems [40–44]. Although research in this area is growing, a study by Bukoski, Chaiwiwatworakul and Gheewala [45] has been one of the only parametric studies that has looked at varying types of structural systems and operational energy sources.

Parametric and sensitivity studies have the potential to find optimal solutions, as opposed to the traditional one-at-a-time approach [40]. Conversely, most building LCA tools are set up for manual comparisons of individual design alternatives. While valuable for making material selections during later stages of project delivery, this approach limits the ability to consider the effects, interactions, and tradeoffs of more widespread design changes. Certification systems such as LEED currently address building LCA from material use and require percentual reductions from an arbitrary reference design [46]. Living building challenge requires carbon emission reductions, where life cycle assessment can help document such reductions and can span both material and energy impacts, but often overlooks other life cycle aspects [47]. One of the major hurdles for implementation of building LCA in practice has been the difficult task of identifying useful benchmarks. One recent development in this area was a study by Simonen, Rodriguez, McDade and Strain [48] where the authors collected a most extensive collection of cumulative LCA results to date. While this study was a significant step towards creating a more standardized and level playing field, it still considers a relatively small sample size of buildings relative to the wide range of possibilities.

To the best of our knowledge, no study to date has looked comprehensively at a wide variety of impact categories and costs for varying building designs across different locations while accounting for material, energy, and water performance of buildings simultaneously. There are two main objectives this study aims to address: 1) include typically excluded water and repair stages within a whole building life cycle study, and 2) consider multitude of options within various building design and service parameters to understand the range of effects on the building's economic and environmental performance. Additionally, the study uses the same approach for the analysis of conceptual building designs in two different locations to consider some of the geographical effects on the results. The objectives are achieved using life cycle assessment (LCA), life cycle costing (LCC), and seismic loss assessment in a broader building life cycle framework; the broadest set of parameters in this kind of assessment to date known to the authors. The presented approach or an adapted version of thereof could potentially be used for benchmarking or decision making in LCA and green building rating systems based on specific building type and location.

2. Materials and methods

2.1. Framework and tools

The first part of this paper focuses on establishing the framework for a parametric assessment of building performance using LCA, LCC, and seismic loss assessment methods. Fig. 2 shows the overview of the simulation, beginning with 1) the specification of general building characteristics, model design options, and service options, followed by 2) energy simulation (using EnergyPlus in this study) of all physical variations of the building, 3) application of predefined service-related scenarios and calculation of material costs and impacts, and 4) results analysis. The entire simulation shown in Fig. 2 was coded with Python programming language to allow for automation and easy adjustment of parameters of interest. Various data inputs are needed throughout all phases of the simulation and are further discussed throughout the rest of section 2.

2.2. Scope and boundaries

Fig. 3 shows the life cycle stages and building systems included in the sensitivity analysis. At the building scale, the boundary focuses on materials, components, and systems that typically have the largest share of material-related impacts, are affected by the changes in the building's shape or affect the building's energy consumption. More specifically, this includes structural, enclosure, and some interior components (further discussed in section 2.3). Standard mechanical, electrical, and plumbing (MEP) systems within the building are excluded due to no expected changes between building design alternatives and the difficulty of modeling those systems for LCA purposes; however, any MEP components related to on-site water conveyance, storage, and treatment as well as on-site energy generation (i.e., photovoltaic installations) are included for designs utilizing those systems. This makes the system boundaries for both the off-site and on-site energy generation and water treatment comparable. Note that life cycle stages A4 and A5 are not included in this study; however, the impacts in those stages are typically low relative to product-stage impacts [9].

2.3. Study and model setup

2.3.1. Project and climate setup

The onset of discussions about a new building typically has some broader project objectives firmly set. In this case, we considered the following parameters as known and fixed: building use type, gross building area, study period, and location. Keeping these parameters constant for a given project ensures comparability of various design and service options. Fixing some of these parameters is also equivalent to defining the functional unit in LCA studies and ensuring fair comparison across alternatives. This study focuses on the assessment of medium office buildings and could easily be adjusted for use on other use types, depending on the availability of related models and data (e.g., energy model inputs, water consumption profiles, etc.).

The buildings are analyzed in two locations, Philadelphia, Pennsylvania and Oakland, California, to understand how varying climatic conditions, hazard exposures, infrastructure systems, and service cost scenarios affect the results (see Table 1 for an overview of main differences between locations). Climate data for these locations include 1) weather files for the energy models, 2) design day files for sizing HVAC systems, and 3) precipitation data for stormwater runoff calculations. Weather files and design day files were obtained from the EnergyPlus website [50], while precipitation data was obtained from the National Oceanic and Atmospheric Administration (NOAA) [51].

The sensitivity of HVAC system and operational parameters were not the focus of this study and were, therefore, fixed at a single option, although their parametrization could be implemented in future studies or practical applications. Other studies have already investigated these parameters' effect on the operational energy use of commercial [52] and residential buildings [41].

2.3.2. Building design

The building geometry is based on the Department of Energy (DOE) Medium Office Reference Building model [62] with adjusted dimensions. The DOE model for a medium office building is a 3-story, square building and includes four perimeter zones, one core zone, and one plenum zone on each level (shown in Fig. 4). The geometry is adjusted for the sensitivity analysis based on inputs of gross building area, building shape, aspect ratio (north-south to east-west length), floor-to-ceiling height, floor-to-floor height, number of stories, and window-to-wall ratio (WWR). Some of these parameters are fixed according to

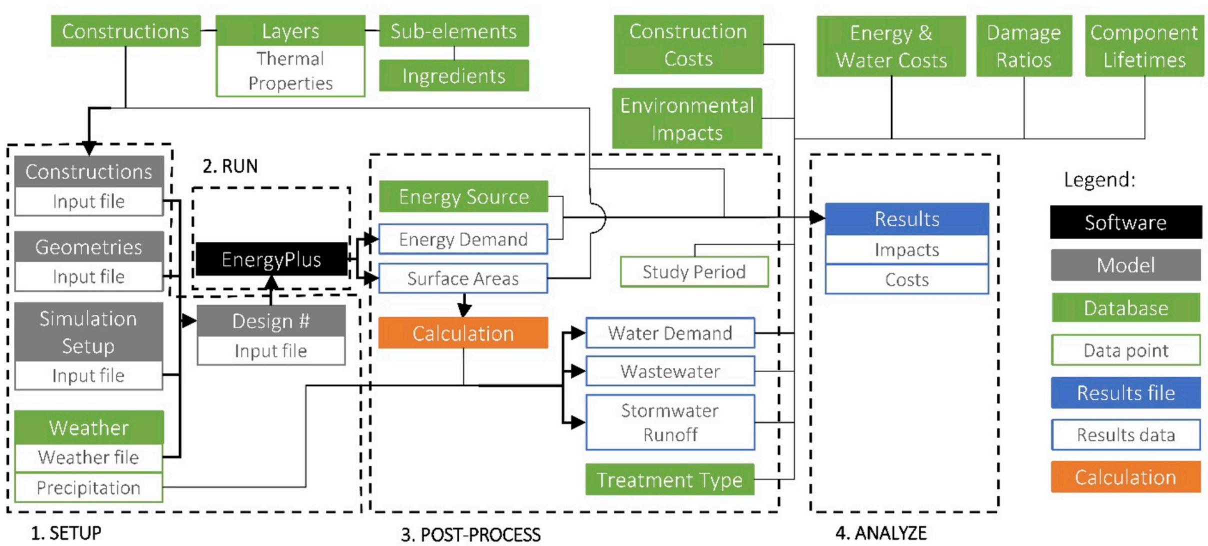

Fig. 2. Overview of the simulation setup.

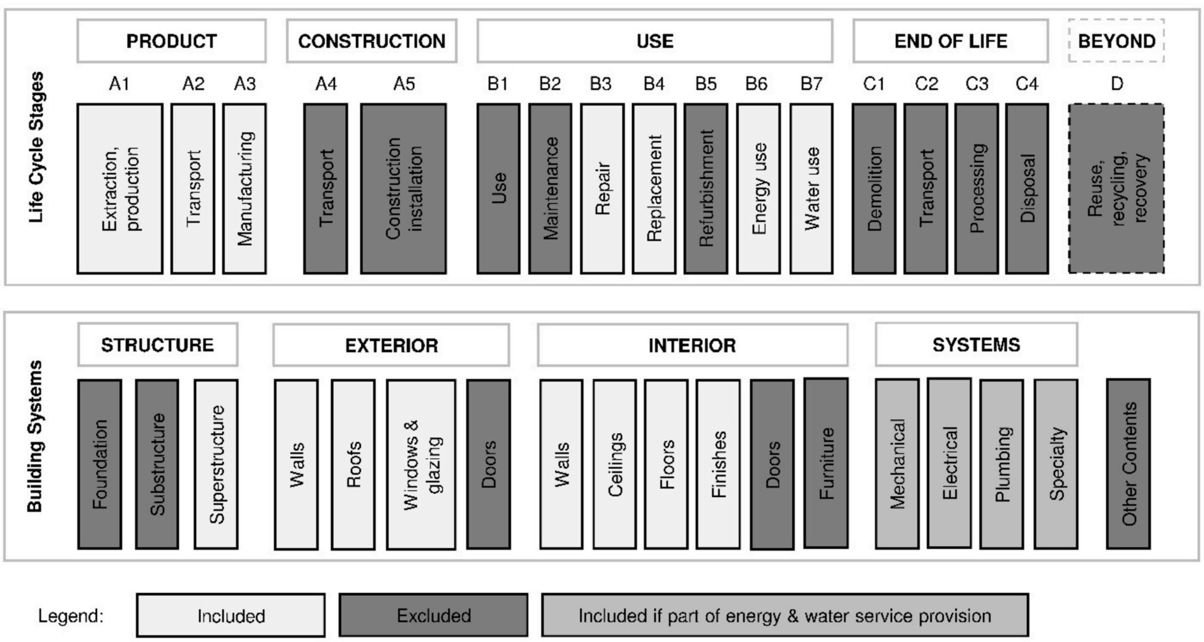

Fig. 3. Scope of included life cycle stages (based on ISO 21930 [49]) and building systems.

Table 1
Summary of main differences between locations.

	Philadelphia, PA, USA	Oakland, CA, USA
State	Pennsylvania	California
Economic Region [53]	Mideast	Far West
International Energy Conservation Code Climate Zone [54]	4A	3C
Köppen-Geiger Climate Classification [55]	Cfa	Csb
Precipitation, Local Annual Average [51]	1,055 mm (41.5 in)	528 mm (20.8 in)
Peak Ground Acceleration at 2% Probability of Exceedance in 50 Years [56]	0.1	0.8
National Energy Reliability Corporation Region	RFC	WECC
Grid Electricity Cost, State Average [57]	$101/MWh	$167/MWh
Natural Gas Cost for 1000 ft^3, State Average [58]	$8.15	$8.42
PV System Installation Cost, Regional Average (2015–2017) [59]	$4.27/W	$4.18/W
PV System Output for 1 kW DC, Local Annual Average [60]	1,394 kWh AC	1,597 kWh AC
Potable Water Cost for 1 m^3, Local Average (2016) [61]	$3.89	$5.94
Sewage Cost for 1 m^3, Local Average (2016) [61]	$3.75	$1.46

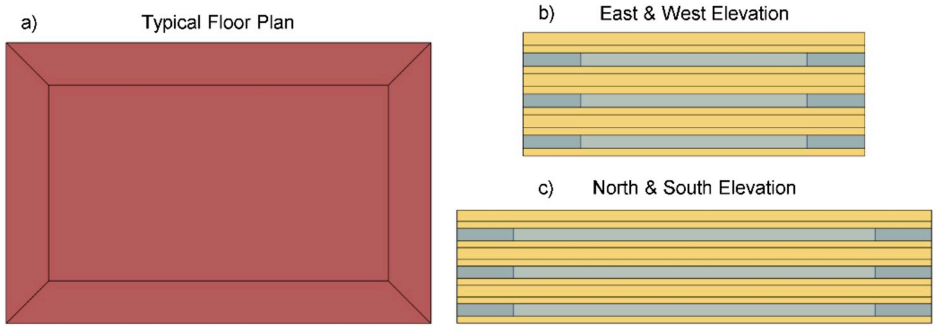

Fig. 4. Typical building model floor plan (a) with perimeter zones, east and west elevations (b), and north and south elevations (c) with plenum zones.

Table 2, while the number of stories and WWR are adjusted according to Table 3 (physical model variations are shown in Fig. 5). Additionally, Table 4 shows an overview of the parameters that change based on the geographic location of each building.

All surfaces defined in the energy model also require all of the construction layer properties, including roughness, thickness, conductivity, density, specific heat, thermal absorptance, solar absorptance, and visible absorptance for opaque surfaces and u-factor, solar heat gain coefficient, and visible transmittance for windows. These properties were obtained from the National Renewable Energy Laboratory's (NREL) OpenStudio and Building Component Library datasets [63] and are shown in the Appendix Table A1, A3, A4 and A5. Some of the properties, such as thickness and density, are also used to convert between area, volume, and mass quantities for material impact and cost calculations. This approach of automatic unit conversion is crucial for components or materials which use different approaches for estimating impacts and costs. For example, clay bricks may have an environmental impact factor for 1 kg of clay brick material, while its cost factor is based on 1 m^2 of wall area using a brick of a specific size.

Structural quantities were obtained from the Skidmore, Owings, and Merrill Environmental Analysis Tool™ (SOM EA Tool™) [64]. This tool was developed by SOM structural engineering team based on data from hundreds of SOM projects and observation of general trends in various structural systems. The structural quantities for the superstructure are determined based on the following four parameters: main structural material, number of stories, wind loading, and seismic loading. The tool's superstructure quantities include floor materials which were also included in the energy model and were therefore subtracted to avoid double-counting. Although the SOM EA Tool allows for analysis of multiple types of superstructure systems, this study only considered conventional steel and concrete moment frames. The decision to limit the analysis only to these two systems was based on the limited choice sets in the Hazus software for loss analysis and the assumptions that moment frames are the most representative of the general building stock in the presented scenario.

Table 3
Parameters and options for sensitivity analysis.

Parameter	Options
Stories	3, 6
Exterior wall types	Exterior Wall A, Exterior Wall B
Window types	Single glazed, Double glazed
Window-to-wall ratios	0.1, 0.33, 0.6
Roof types	R15 XPS, R40 XPS, R15 PIR, R40 PIR
Structural materials	Steel, Concrete
Energy sources	NERC Grid-Mix, On-Site Solar
Potable sources	Centralized Conventional, Centralized Direct Filtration
Sewage treatment	Centralized, On-Site Septic Aerobic, On-Site Septic Anaerobic
Runoff treatment	Centralized, None
Total combinations:	4,608

Cost data for all building materials come from RS Means Building Component Cost book [65], and environmental impact data is obtained from the ecoinvent database [25]. Most of the components considered in this study are components which can be shipped long distances from their manufacturing facility, justifying the use of national or even global average data for environmental impact assessment. However; one unique material in this regard is concrete, which is typically a material sourced locally, and its associated impacts may be highly dependent on the regional material extraction and supply networks [66]. This study does not take this geographic uniqueness of concrete (and other materials) into account and could be addressed in future studies of this kind.

The physical model and component information is then used to run EnergyPlus simulation for each building design scenario and obtain the energy consumption (i.e. total energy demand for heating, cooling,

Table 2
Fixed project and design parameters.

Parameter	Details
Study period	60 years
Gross area	~5,000 m^2
Building type	Medium office building
Shape	Rectangular
Aspect Ratio	1.5
Floor to ceiling height	2.74 m
Floor to floor height	3.96 m
Perimeter zone depth	5 m
Slab on grade type	304 mm reinforced concrete with 6 mm carpet
Interior floors	152 mm reinforced concrete with 6 mm carpet
Structural frame type	Moment frame
HVAC system	ASHRAE 90.1–2013 Medium Office defaults (exported from OpenStudio):two-speed DX cooling with a 3.39 coefficient of performance; packaged variable-air-volume (PVAV) gas heating with 80% efficiency; and PVAV fans with 60% efficiency
Schedules and Loads	ASHRAE 90.1–2013 Medium Office defaults (exported from OpenStudio)
Occupancy	ASHRAE 90.1 Medium Office default: 18.6 m^2/person (200 ft^2/person)

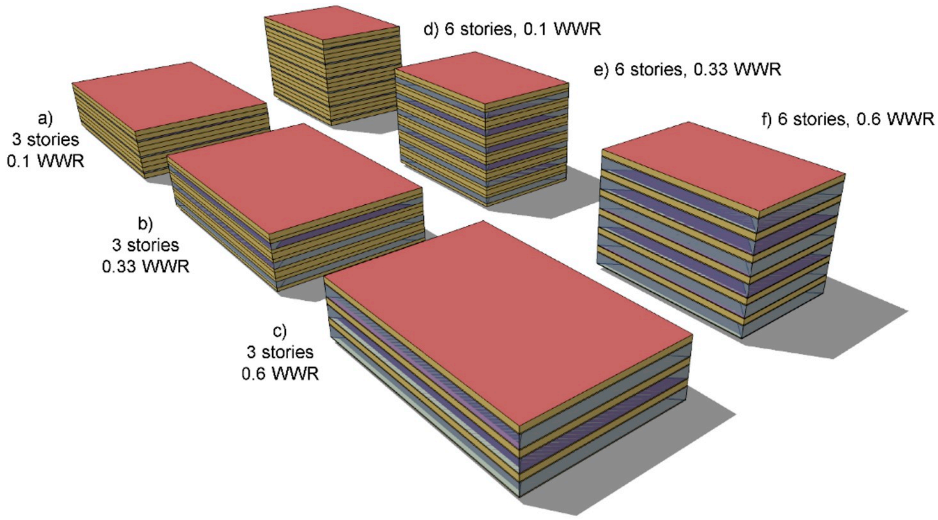

Fig. 5. Building shape (3 or 6 stories) and window-to-wall ratio (0.1, 0.33, 0.6) variations, including the Department of Energy Medium Office Reference Building setup (b).

Table 4
Location sensitive parameters.

Parameter	Details
Energy use	Depends on climatic conditions (heating and cooling loads)
Energy sources	Grid electricity mix and costs, solar potentials, PV system installation costs, and natural gas costs depend on location
Water and wastewater treatment	Overall costs and electricity sources used for treatment depend on location
Structural quantities	Dependent on wind and seismic loading specific to location
Water runoff	Depends on rainfall and snowfall
Damage repair	Depends on the probabilities of seismic damage

lighting, equipment, and plug loads) for the particular design, further linked with service options discussed in section 2.3.3 for cost and environmental impact calculations. Water consumption is based on the buildings gross area and building type using US average data from the 2012 Commercial Buildings Energy Consumption Survey [67]. The on-site water treatment scenarios discussed in section 2.3.3 also require the input of building occupancy, which uses the same approach as the energy model's DOE reference building national average data for occupancy based on a building type. For example, office buildings are expected to provide about 18.6 m^2 of space to each occupant, which can be used to calculate the total occupancy of the building [62].

2.3.3. Service options

The electricity demand of a particular building design is combined with the type of electricity supply option, which includes either a location-specific grid-mix source or an on-site photovoltaic (PV) system installation (as shown in Table 3). It should be noted that the on-site solar PV scenarios showcase an idealized case where there is no space limitation constraint put on the size of the system (e.g., roof area), and there is no consideration of the temporal variations (e.g., load matching) and the potential need for energy storage. There could be some differences in our results if we implemented a more dynamic approach similar to Collinge et al. [68]; however, we do not anticipate the difference to be substantial in this case due to the similarity between occupancy and load patterns in office buildings and the availability of solar energy. Future studies could implement more dynamic approaches, especially when studying other building use types.

The cost of grid electricity by state was obtained from the U.S. Energy Information Administration (EIA) [57] and applied to the specific energy consumption of each building design scenario on a kWh basis. Similarly, PV system installation costs were obtained from the NREL Open PV project, which collects non-utility-based PV system data from actual projects around the United States [59]. Solar energy potential for sizing of the on-site PV system was also obtained via an API service from NREL's PV Watts project [60] (see Appendix Table A6). Environmental impact data for the grid-mix electricity is based on ecoinvent data for each of the US-based regions defined by the National Energy Reliability Corporation (NERC). The PV system environmental impact data is also based on ecoinvent data and scaled to the size needed to supply each building design with enough energy, similarly as in the cost calculations. The environmental impacts of grid electricty and PV are shown in the Appendix Table A7.

Environmental impact data for centralized water and wastewater treatment was based on ecoinvent inventory with adjusted electricity supply mix for the NERC region where the building is located. This approach captures the average centralized treatment operations but does not capture the location-specific differences in treatment plant management, which could substantially change the outcomes [69] and could be addressed in future studies. Environmental impacts for on-site treatment systems considered physical infrastructure, operational energy use, and direct emissions and were based on data from a study by Hasik et al. [70] and scaled to the size of the buildings considered in this study. The data includes both initial and recurring impacts associated with on-site treatment systems. The costs associated with an on-site water treatment system were obtained from the EPA's Onsite Wastewater Treatment Systems Manual [71] and also included both capital and recurring costs. Water and wastewater costs are based on a U.S. Department of Energy report [61], which collected the potable water and wastewater treatment costs for consumers in about 20 major cities around the US. The provided information includes the utility name, city, state, and cost data in 2016 US dollars per 1,000 gallons (3.78 m^3) of water. While there may be slightly different rates for commercial customers, these rates are expected to be roughly representative of rates for office buildings. A summary of key data for

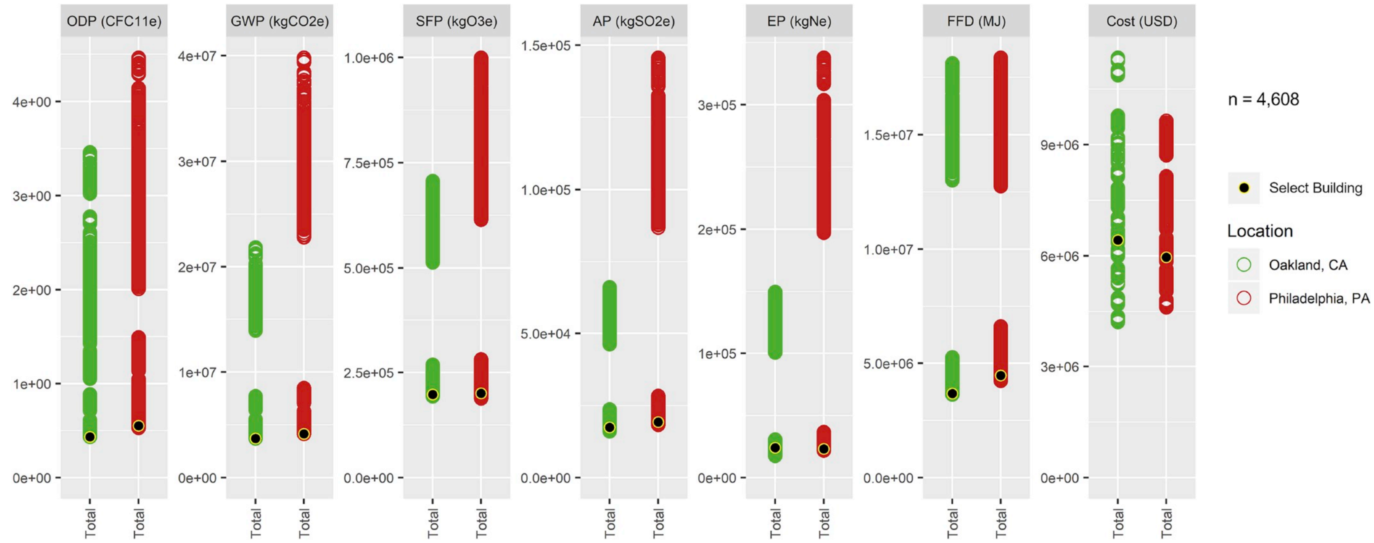

Fig. 6. Overall life cycle environmental impacts and costs of all 4,608 buildings in each location over a 60-year study period. Each circle represents a building with unique design and service parameters from Table 3. A select building is highlighted in black as an example of a single unique design and service combination scenario.

water and wastewater treatment is shown in the Appendix Table A2.

2.3.4. Repair and replacement

Regular replacement of components in the building is approached using typical component service life method, where the component impacts and costs are multiplied by the number of units needed in the building over the study period. This is an idealized and simplified scenario used in most building LCA tools and assumes equal replacement in the future regardless of technological changes or maintenance regimes. In the sensitivity analysis specifically, most of the structural systems are expected to last the entire study period, while glazing systems, gypsum board walls and ceilings, and roof membranes are defined as having a 40-year service life and carpet having a 15-year service life (all assumed component service lives are provided in the Appendix Table A4 and A5).

Costs and impacts in the repair stage are based on hazard loss assessment coupled with LCA and LCC. Specifically, this study used an approach that uses the Hazus tool [72] developed by the Federal Emergency Management Agency (FEMA) for regional studies on earthquake, hurricane, and flooding hazards. This tool is more appropriate for regional studies of the general building stock instead of single building designs, but it does feature the Advanced Engineering Building Module that can be used for analyzing individual buildings [73]. It was deemed suitable for this study based on the early design (low specificity) focus, investigation of a typical building, and the design size and simplicity. The specific data used in this study was based on default Hazus models for office buildings built with steel and concrete moment frames and designed to a high code, which were most representative of the conditions studied in this study.

While the Hazus tool provides results in economic costs of damage to the study building, it does not provide environmental impact estimates. Environmental impacts were calculated by applying the economic loss ratios to groups of components (i.e., structural, non-structural drift-sensitive, non-structural acceleration-sensitive, contents) to the initial manufacturing and construction impacts of the building [8]. The loss ratios represent the annualized losses from a probabilistic seismic loss assessment aggregated over the study period of the analysis. It should be noted that probabilistic seismic loss results are ideally represented with probability distribution functions; however, Hazus and this study rely on a deterministic representation by using only the median values. Additionally, Hazus enables the loss assessment associated with other natural hazards such as hurricanes and flooding, which could be implemented in future studies.

2.4. Decision metrics

Decision metrics (also referred to some as decision variables or design objectives) considered in this study consist of economic costs and various environmental impact categories. All economic cost data in this study uses US dollar as the currency; however, different tools within this study may rely on different reference years and are adjusted accordingly using the RS Means historical cost index [65]. All results shown in this study represent the 2016 US dollar currency, based on the main data source used for this purpose. Environmental impact results are based on the TRACI 2.1 characterization method [74]. Although TRACI 2.1 method covers ten different impact categories by default, we narrowed down the scope to only the six impact categories that are typically reported for LEED certification and in environmental product declarations (EPDs). This includes the following impact categories: ozone depletion potential (ODP) in kg CFC-11 eq, global warming potential (GWP) in kg CO_2 eq, smog formation potential (SFP) in kg O3 eq, acidification potential (AP) in kg SO2 eq, eutrophication potential (EP) in kg N eq, and fossil fuel depletion (FFD) in MJ surplus [46].

While many of the methods used within this assessment are simplified approximations of the general building stock, they are expected to be sufficient in this study for understanding the relative influence of various aspects of typical buildings. More robust tools and methods could be used within individual parts of the overall framework for improving the utility on specific projects.

3. Results and discussion

3.1. Overall results across locations

The simulations for all the combinations of the parameters from Table 3 yield 4,608 unique buildings in each of the studied locations. Fig. 6 shows the total life cycle results for a 60-year study period for each of 4,608 buildings across all metrics. Each building is represented by a single circle. As an illustrative example, the black circles represent a single building design and service combination scenario out of the 4,608 possibilities (the building's parameters are shown in Table 5). Many of the buildings' totals in a given metric are so close to each other that they form a visually continuous line, but in fact they are many clustered circles. This clustering indicates that there are many buildings

Table 5
Parameters and global warming potential (GWP) results over a 60-year study period for select buildings from Fig. 6.

	Oakland	Philadelphia
Stories	6	6
Window-to-wall ratio	0.1	0.1
Exterior wall type	Exterior Wall B	Exterior Wall B
Window type	Double Glazed	Double Glazed
Roof type	PIR R15	PIR R40
Structural material	Steel	Concrete
Energy source	On-Site Solar	On-Site Solar
Potable source	Centralized Direct Filtration	Centralized Direct Filtration
Sewage treatment	Centralized Treatment	Centralized Treatment
Runoff treatment	None	None
GWP (kgCO2e)	3,185,787	3,247,521

whose design or service decision differences yield very small differences to the overall results in that metric. Conversely, large gaps between these clusters indicate a major influencing factor diverting the results clusters apart. For example, all environmental metrics for buildings in Philadelphia show two major clusters which are associated with the buildings' use of either the centralized electric grid (upper cluster) or solar (lower cluster) electricity in their use stage. On the other hand, the ozone depletion category for Oakland buildings appears almost fully continuous, indicating that there are more equal contributions to the life cycle impacts across all the different design and service aspects. Most of the environmental impacts only show one major divergence, indicating that the influence of other factors (e.g., shape, WWR, etc.) is more evenly distributed. The cost metric shows minor divergence, especially in the Oakland buildings, indicating multiple factors with larger differences in influence on the overall results. Section 3.3 provides more detail on the influence of individual parameters across all metrics.

The presented analysis approach can be used to gain an understanding of a design's reductions from worst-case scenarios in each of the metrics. In other words, the generated results can be used as benchmark values specific to the building under study. This way of visualizing the results also allows for seeing tradeoffs across different metrics. For example, the select buildings in Fig. 6 were selected as the buildings with the lowest GWP, and also happen to have close to the lowest ODP, SFP, AP, and FFD; however, they are not amongst the buildings with the lowest cost. Table 5 shows the select buildings' parameters, i.e., the parameter combinations that result in the lowest GWP in each respective location. While most of the parameters between the lowest GWP designs in Oakland and Philadelphia are the same, there are changes in the roof type and structural material parameters. The selections indicate that the Philadelphia building benefits from the increased insulating properties of the thicker roof insulation even though it increases its embodied GWP. Conversely, in the milder Oakland climate, the embodied GWP of the roof becomes more important, and having a low WWR and well-insulated walls is sufficient for reducing operational energy use. The differences in structural systems are related to differences in seismic loads that each frame has to be designed for which affects the quantities of structural concrete or steel. The results indicate that the GWP of the concrete frame increases more rapidly with a more robust structural system than a steel frame design. However, it should be noted that the outcomes could change depending on the sourcing scenarios for the concrete and steel (e.g., concrete with high fly ash content, steel produced in a blast oxygen furnace). It is likely that if the accompanied database and number of possible parameters increased, there would be an even larger number of observed tradeoffs between locations, decisions, and metrics, and could be further explored in future studies.

The tradeoffs between decision metrics were also analyzed using parallel coordinate plots and 2D scatter plots, as shown in Figs. 7 and 8, for Oakland and Philadelphia, respectively. The parallel coordinate plots, a graphical illustration of the complete solution set, show the existence of tradeoffs between adjacent objectives indicated by the solution lines crossing. For example, many of the solution lines between the Cost and GWP metrics cross each other, indicating there is a relatively significant tradeoff between these two metrics. Further inspection of the metric pair was conducted through their 2D scatter plot projection. The 2D scatter plots reveal the non-dominated designs with respect to minimizing all metrics. The non-dominated designs show design combinations that have the lowest value in at least one decision metric. The non-dominated designs consist of the following attributes for both locations: 6 stories, 0.1 WWR, exterior wall B, various thicknesses of PIR roof insulation, and no treatment of stormwater runoff (runoff infiltration). The untreated stormwater runoff setup assumes well-designed building that does not contribute to sewer overflows and does not release harmful substances into the ground. Because of this and the fact that it does not require additional wastewater treatment, the environmental impacts and costs are zero for that setup. In Philadelphia, all non-dominated designs also feature double-glazed windows and concrete moment frames, while in Oakland, all non-dominated designs feature on-site solar electricity. Potable water source and sewage treatment selections vary across locations and metrics, indicating that design decisions would change depending on which

Table 6
Input parameter and result interaction table.

Stories/shape	Exterior wall type	Window type	Window-to-wall ratio	Roof type	Structural material	Energy source	Potable source	Sewage treatment	Runoff treatment	
	ME	ME	ME	ME	M	E			W	Stories/shape
			ME			E				Exterior wall type
			ME			E				Window type
						E				Window-to-wall ratio
						E				Roof type
										Structural material
							W	W	W	Energy source
										Potable source
										Sewage treatment
										Runoff treatment

M = affects results related to material use
E = affects results related to energy use
W = affects results related to water use

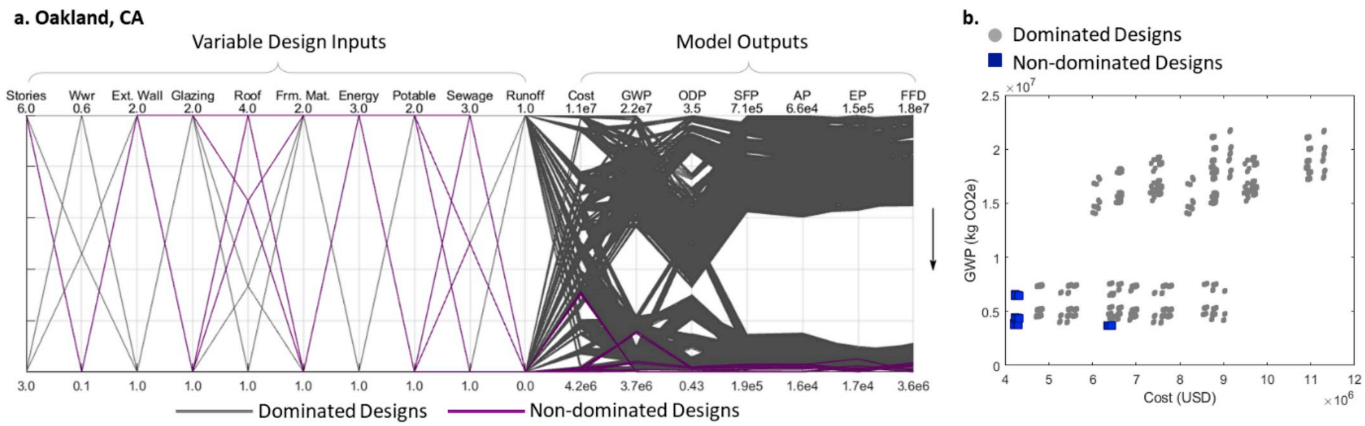

Fig. 7. Parallel coordinate plot for all inputs (Table 3) and outputs (a) and 2D scatter plot for GWP and Cost (b) identifying the best buildings in Oakland, CA.

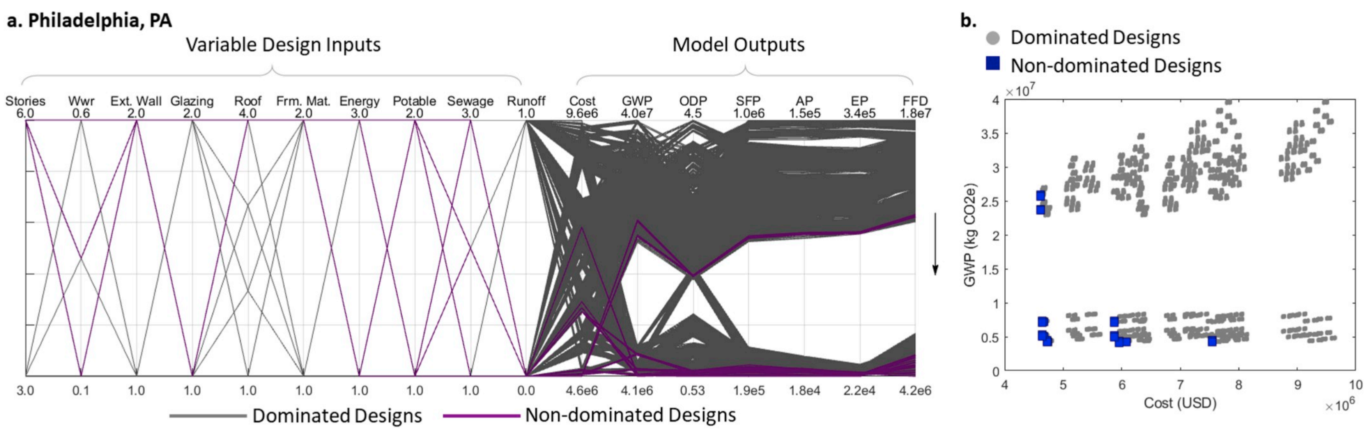

Fig. 8. Parallel coordinate plot for all inputs (Table 3) and outputs (a) and 2D scatter plot (b) identifying the best buildings in Philadelphia, PA.

decision metric is of most interest to the designers or stakeholders. The visualizations were based on approaches by Østergård, Jensen and Maagaard [40] and Unal, Warn and Simpson [75].

3.2. Performance across life cycle stages

Fig. 9 shows the results for the same 4,608 buildings as in Fig. 6 (representing design and service variations from Table 3), except the results are by life cycle stages. In other words, where each circle in Fig. 6 represented the total for each building, in Fig. 9 that total is split into five circles each showing the contribution of a particular life cycle stage (i.e., manufacturing, repair, replacement, energy use, and water use). The results show that, as expected, operational energy use amounts to significantly higher impacts and costs across both locations,

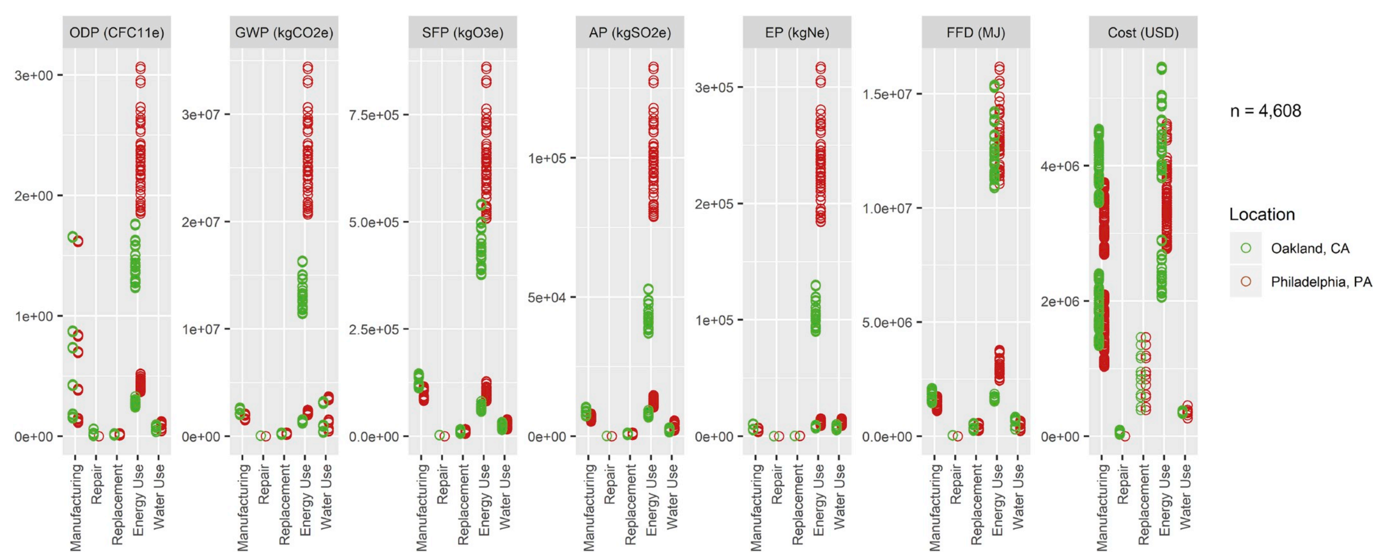

Fig. 9. Life cycle environmental impacts and costs of all 4,608 buildings by life cycle stage. Each circle represents the total for each of the 4,608 buildings (design combinations based on Table 3) related to a specific life cycle stage over a 60-year study period.

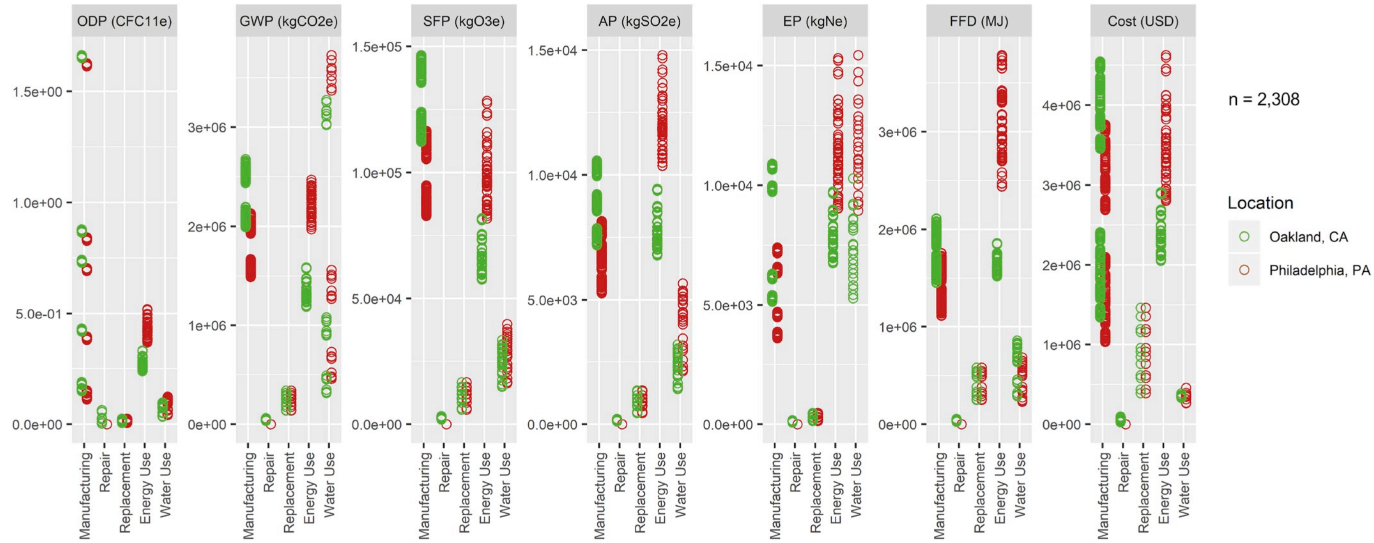

Fig. 10. Life cycle environmental impacts and costs of the 2,304 buildings with on-site photovoltaic systems only (with other parameter combinations based on Table 3).

and that those impacts and costs are higher in Philadelphia than Oakland. This finding is not surprising based on previous studies and mostly reinforces that knowledge; however, the results also show the large range in the impacts and costs in that stage relative to other stages. The likely reason for Philadelphia having higher environmental impacts in this stage is due to the harsher climate and heavily fossil-fuel based electricity grid. The lower end of the energy use stage's environmental impacts is associated with the sourcing of electricity from on-site solar panels.

Fig. 10 shows the results for the 2,304 buildings with on-site photovoltaic systems, in which case, the impact of other stages becomes almost equally if not more important. This is true especially in the ozone depletion, global warming potential, and eutrophication impact categories, where the importance of building material and water-related impacts increases. Another interesting finding when focusing on costs between the scenarios with only on-site solar energy and both solar and grid sources is the fact that solar electricity is in the lower range of costs of energy use in Oakland but are evenly spread in Philadelphia. This means that while the environmental benefits are similar in both locations, there are location-specific economic tradeoffs.

Material manufacturing impacts are low relative to the complete energy source scenarios but show a noticeable spike in the ozone depletion impact category. The relative influence of the material manufacturing stage to the energy use stage in the solar energy source scenarios is similar across global warming potential and smog formation categories in Philadelphia, while it is similar or higher in all categories in Oakland. The manufacturing-related economic costs appear to have a relatively large and even spread between the individual data points, indicating many similarly priced design alternatives amongst the studied set of designs. The costs of materials are also seen to be relatively closer to the energy use stage costs than is the case across the environmental metrics. It should be noted that the results show the total lifetime impacts, and therefore, the manufacturing stage relative to use stage impacts change relative to the length of the study period. In other words, if we considered a 30-year study period instead of the 60 years, the relative influence of the manufacturing stage would increase, while with a longer study period it would decrease (contingent on the replacement periods for various types of components and materials).

The repair stage impacts are found to be very close to zero, except in the ozone depletion potential category in Oakland, CA. The Hazus-based, probabilistic, median loss estimates for the 60-year study period amounted up to 1.37% and 4.03% loss in structural and non-structural components, respectively, for the buildings in Oakland, CA, a location with high seismic activity potential. In Philadelphia, PA, the same component groups amounted to less than 0.01% and 0.04% of probable losses over 60 years, considering there is a very low probability and magnitude of seismic activity in the region. These numbers are slightly lower than what other studies of environmental impacts from seismic damage have found [76,77]. The probability distributions of such assessments may vary widely due to the nature of seismic events, and the actual impacts and costs may be significantly higher in some scenarios. For example, in the case of a building collapse, the repair-related impacts and costs could equal or exceed the total impacts and costs of the manufacturing stage. While our results find the repair stage to be negligible, the findings may point more towards the difficult task of considering sustainability and resilience quantitatively using a single assessment and visualization approach. Future studies may explore other approaches for communicating resilience aspects from a life cycle perspective.

Lastly, while the water use stage environmental impacts are relatively low, they are comparable to material manufacturing stage in categories such as global warming potential and eutrophication potential. This is due to the potential greenhouse gas emissions from anaerobic systems [27,70] and direct emissions to water bodies from centralized treatment systems. The water use costs are very low compared to the other aspects of the buildings.

3.3. Design and service option influence

We aimed to better understand how individual design and service decisions influenced the overall impacts and costs. This was not an easy task given the study setup and various interactions between the factors (e.g., energy sources, stories, wall types, etc.). All of the interactions that are known and built-in to the simulation algorithm and post-processing calculations are shown inTable 6. The table shows which factors interact with each other and which part of the results they influence (e.g., material, energy, or water-related impacts and costs).

We used the random forest algorithm [78] to analyze relationships between the input parameters and results across the decision metrics. Random forest cross-validation with five folds indicated the best

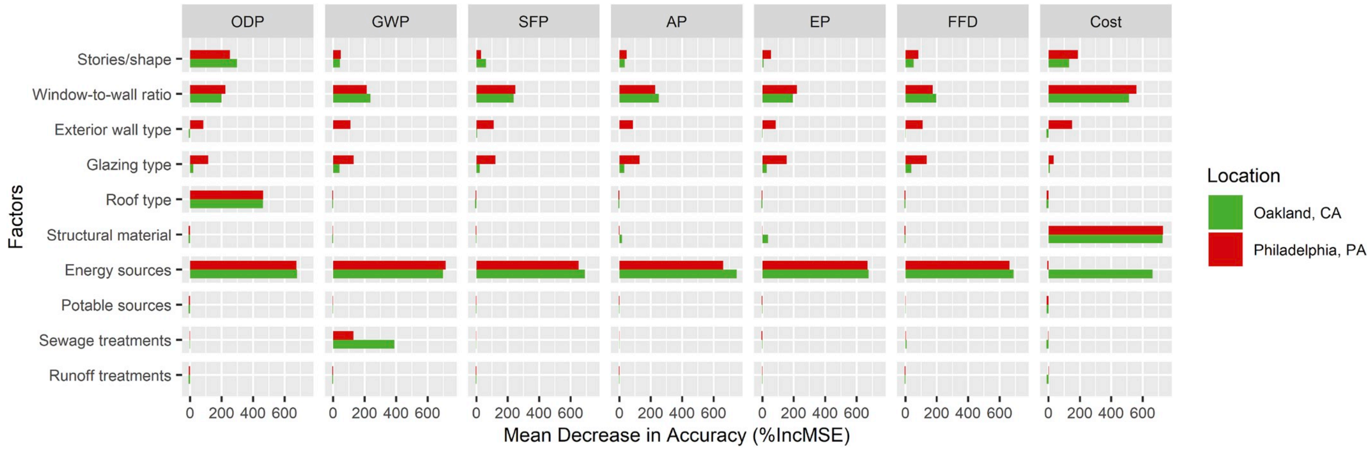

Fig. 11. Importance plot of design and service parameters across performance metrics.

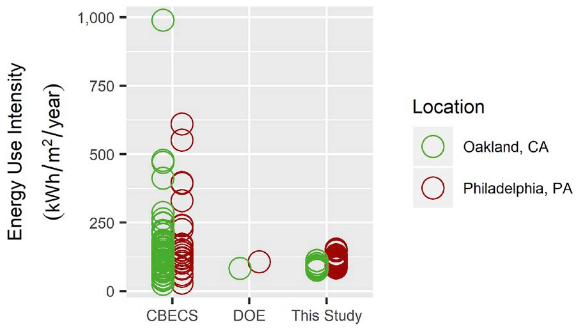

Fig. 12. Comparison of this study's energy use intensity against the Department of Energy (DOE) reference buildings and Commercial Buildings Energy Consumption Survey (CBECS) data.

performance with five variables randomly sampled at each split ('mtry'). The number of trees ('ntree') was kept at the default 500, which was enough for the error rate to level off in all metrics. The algorithm's Mean Decrease in Accuracy (%IncMSE) results (shown in Fig. 11) were used as an indicator of the input parameters' influence on the results in each metric. The random forest algorithm randomly selects a (test) subset of observations and predictor variables and tests its ability to predict results in the rest of the dataset (the validation subset). The %IncMSE shows how much influence dropping a particular variable has on the algorithm's ability to accurately predict the validation subset results. It should be noted that random forest algorithm may not be feasible for predicting building design options outside of the training data set and in this case only serves as a means of regression of the existing data. It should also be noted that when applied to this study, the algorithm's prediction ability is influenced by 1) the individual factors' influence on the total results, but also by 2) the factors' interaction, and 3) the range of levels within each factor (e.g., the variety of studied wall types).

Fig. 11 reveals which of the factors has the largest, independent, relative influence on the total results in each location and metric. The most influential parameter across all metrics was found to be the type of energy source supplied to the building, which is consistent with the findings discussed in the previous section. The second most important factor across all metrics was the WWR, which affects the energy-efficiency, but also material quantities related to the buildings' envelope. Most of the parameters influencing the energy-efficiency of the buildings are more influential in Philadelphia than in Oakland due to the differing climates. Sewage treatment shows high influence in the GWP category, showing similar or higher influence than some of the more typically addressed building design decisions, such as wall and glazing types, WWRs, and roof types. This is due to the potential of on-site anaerobic systems having large direct emissions of greenhouse gases [79,80]; this study shows how influential the selection of a sewage treatment type is in the overall building performance. In ODP, roof type is the second most influential factor. In this case, the only differences across the roof types were the types of insulation used (extruded polystyrene vs. polyisocyanurate), indicating large differences in the materials' impacts in this category, likely due to the types of blowing agents used during their manufacture. The last most apparent finding from Fig. 11 is the influence of window types, WWRs, and structural materials alongside stories and energy sources on the cost metric. This indicates the wide-ranging differences in costs of various options within these factors and the similarity in the potential for cost reductions. Overall, the fact that some of the factors do not show large influence does not mean they do not affect the results; it means they do not have as much weight in affecting them independently. In other words, a decision in a factor that shows larger influence in Fig. 11 indicates there is a design option that is clearly better than others, while low influence indicates there are tradeoffs across multiple factors and they need to be considered simultaneously on a building-by-building basis.

The presented results are from simplified, early conceptual design models and are therefore not expected to be able to provide an exact prediction of the buildings final impacts, and rather serve as a means of relative comparison of design alternatives and reveal the worst-case impact scenario for potential benchmarking of later project stages. The following section addresses some of the similarities and differences from actual projects and more detailed models.

3.4. How do the results compare to other references?

While there is no established way of validating results of LCA and LCC, the best way of checking the results is by comparing inputs to other projects or conducting a sensitivity analysis. This study already presents the results of a sensitivity analysis, and adding parameters would increase the study complexity and execution time. Instead, we compared some of the midpoint and endpoint results to real projects and other references.

3.4.1. Energy use

Since energy use was one of the main contributors to impacts and costs, it was imperative to check the validity of our midpoint energy use estimates. To check that our estimated Energy Use Intensities (EUI) for the modeled buildings were realistic, we compared them to the original DOE Reference Buildings (ASHRAE 90.1–2013 version) in OpenStudio

[62,81] and to data from CBECS 2012 dataset [82] (see Fig. 12). The DOE data presented here is related to the medium office building reference models located in the two studied locations. The CBECS data was filtered by census region (i.e., Pacific for Oakland, CA and Middle Atlantic for Philadelphia, PA), primary building activity (i.e., office), and size (i.e., 2,300–9,300 m^2). For Oakland, CA, CBECS and DOE median EUIs amount to 136 and 83 kWh/m^2/year, respectively. This study's median EUI for that location was 92 kWh/m^2/year, or about 33% lower than CBECS median and about 10% higher than the DOE reference building values. For Philadelphia, PA, CBECS and DOE median EUIs amount to 149 and 107 kWh/m^2/year, respectively, as compared to 122 kWh/m^2/year in this study (i.e., about 18% lower than CBECS median and about 12% higher than DOE). These results show that the EUIs estimated in this study are well within the expected range.

3.4.2. Material use

Material quantity estimates are crucial for calculating manufacturing, repair, and replacement results. To ensure that our model inputs and algorithm yields realistic values, we checked the material-related GWP results against two other data sources: 1) the Embodied Carbon Benchmark (ECB) study published by the Carbon Leadership Forum [48] and 2) values from six reference building projects collected by the authors of this study. Although we cannot disclose detailed information about the six buildings, they are of similar use type and size and in the general vicinity of the studied locations. Data from the ECB study includes only new office buildings between 2,322 and 9,290 m^2 (25,000 and 100,000 ft^2) of floor area. The impacts shown are representative of main structural and envelope components, with some interior finishes being included as well. The results study boundaries may not be fully equivalent in all scenarios but are expected to provide an adequate range for checking the validity of the results in the sensitivity study.

Fig. 13 shows the results of the global warming potential per 1 m^2 of gross building area across the ECB buildings, the 6 reference buildings, and all the unique physical designs considered in this study (192 unique physical design combinations in each location). The global warming potential of the ECB buildings ranged between 70 and 1,314 $kgCO_2e/m^2$ with a median of 441 $kgCO_2e/m^2$ and the reference buildings ranged between 143 and 836 $kgCO_2e/m^2$ with a median of 376 $kgCO_2e/m^2$. In comparison, the embodied global warming potential of materials in this study was found to range between 329 and 605 $kgCO_2e/m^2$, with a median of 461 $kgCO_2e/m^2$.

Overall, the results of our sensitivity study appear within a reasonable range with respect to other studies and projects, reinforcing the validity of our results.

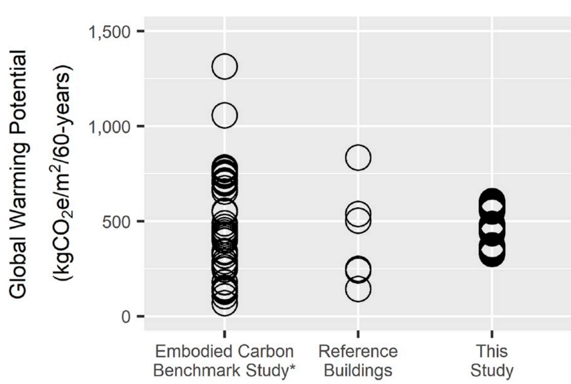

Fig. 13. Comparison of embodied material global warming potential (GWP) to reference projects. Each circle represents an individual building. (*Embodied Carbon Benchmark Study results reflect only product and construction stages without maintenance and replacement).

4. Conclusion

This paper provides a framework for a broader life cycle sustainability and resilience assessment of buildings focused on the evaluation of building design and service decisions during the early stages of design. The broader set of life cycle stages included material extraction and manufacturing, regular material replacement, repair of potential damage from seismic events, and operational energy and water use including upstream infrastructure. The sensitivity study did not include construction/installation, and end-of-life disposal due to additional modeling requirements. Addition of those two stages would bring the study closer to reporting most of the life cycle stages prescribed in the ISO and EN standards for sustainability assessment of buildings. The application of the framework on the sensitivity study used a combination of modeled and average reported data, making it a hybrid approach. Future studies could take a more homogenous approach in either full bottom-up modeling of all aspects or top-down assessment based entirely on reported data.

Overall, the influence of grid-based electricity was found to be the overwhelming contributor to the environmental impacts of all the building design options across both locations. In the cost metric, it is not as influential, and instead, material aspects can be the primary reason for high costs. The energy related impacts can be greatly reduced with the use of on-site solar panel systems, which then shifts the remaining burdens to the water resources and impacts from material production, especially in ozone depletion, global warming, and eutrophication potential categories.

Analysis of the influence of individual design and service parameters reinforced the findings of the visual analysis of the life cycle stages. It again indicated the overwhelming influence of the type of energy source across all metrics. The second most-often influential factor was the number of stories each building had, which is also linked to the energy consumption of the buildings. Other aspects such as roof types, sewage treatment type, window type, WWRs, and structural materials were all influential in individual metrics, such as ODP, GWP, and costs.

Most design optimization efforts focus on minimizing the energy and water demand of buildings; however, the source type for those resources can be more influential from an environmental impact perspective. Future studies could explore a wider range of building systems, building designs, and building types for the sensitivity analysis by expanding the underlying databases. Other efforts could focus on more sophisticated regionalization of the approach and data. The presented sensitivity study also did not consider uncertainty related to upstream data, such as the uncertainty in the representativeness of the environmental impact data and costs, and the uncertainty related to performance modeling, such as predicted energy consumption and lifetime damage repair. Future studies could investigate the significance of including such uncertainty data in similar sensitivity studies and for design decision making.

Acknowledgments

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Appendix

Table A1
Construction types and material layers.

Construction	Material layers	U-value [W/m^{2}K]
Roof R15 XPS	Concrete RF slab 6 in (152 mm)	0.35
	XPS 60 psi (6.89 kPa) 3 in (76 mm) R15 (RSI 2.64)	
	EPDM 60 mil (1.5 mm)	
Roof R40 XPS	Concrete RF slab 6 in (152 mm)	0.14
	XPS 60 psi (6.89 kPa) 4 in (102 mm) R20 (RSI 3.52)	
	XPS 60 psi (6.89 kPa) 4 in (102 mm) R20 (RSI 3.52)	
	EPDM 60 mil (1.5 mm)	
Roof R15 PIR	Concrete RF slab 6 in (152 mm)	0.35
	PIR 2–1/2 in (64 mm) unfaced R14.40 (RSI 2.54)	
	EPDM 60 mil (1.5 mm)	
Roof R40 PIR	Concrete RF slab 6 in (152 mm)	0.14
	PIR 3–1/2 in (89 mm) unfaced R20.16 (RSI 3.55)	
	PIR 3–1/2 in (89 mm) unfaced R20.16 (RSI 3.55)	
	EPDM 60 mil (1.5 mm)	
Slab on Grade	Concrete RF slab 6 in (152 mm)	2.12
	Concrete RF slab 6 in (152 mm)	
	Carpet 1/4 in (6 mm)	
Floor	Concrete RF slab 6 in (152 mm)	n/a
	Carpet 1/4 in (6 mm)	
Ceiling	Gypsum board 1/2 in (13 mm)	n/a
Interior Wall	Gypsum board 1/2 in (13 mm)	n/a
	Gypsum board 1/2 in (13 mm)	
Exterior Wall A	Plaster 1/2 in (13 mm)	2.09
	Brick 8 in (203 mm)	
	Plaster 1/2 in (13 mm)	
Exterior Wall B	Brick 4 in (102 mm)	0.44
	EPS 2 in (51 mm)	
	CMU 4 in (102 mm)	
	Plaster 1/2 in (13 mm)	
Window A	Single 1/4 in (6 mm) clear	5.78
Window B	Double 1/4 in (6 mm) clear	2.67

XPS - extruded polystyrene insulation, EPS - expanded polystyrene insulation, PIR - polyisocyanurate insulation, RF - reinforced concrete, CMU - concrete masonry unit, EPDM - ethylene propylene diene monomer rubber.

Table A2
Water and wastewater treatment data.

Treatment type	Ecoinvent data	Treatment energy [a]	Aerator energy [b]	One-time cost [c]	Recurring cost [d]
Centralized Conventional	Tap water, production, conventional treatment	4.27	0	0	0
Centralized Direct Filtration	Tap water, production, direct filtration	2.86	0	0	0
Centralized Wastewater	Wastewater, treatment of, capacity 1.1E10 l/year	0.22	0	0	0
On-Site, Septic, Aerobic	–	4.65	4.47	8,924	1,344
On-Site, Septic, Anaerobic	–	4.65	0	8,924	1,344

[a] Amount of electricity needed to treat a volume of water [25,80]. [kWh/m^3].
[b] Only applicable to on-site systems [80]. [kWh/day].
[c] Only applicable to on-site systems [71]. [$].
[d] Only applicable to on-site systems [71]. [$/year] See Table 1 for location-based centralized water and wastewater costs.

Table A3
Glazing subcomponent quantities and links to life cycle inventory (LCI) data.

Name	Subcomponent	LCI Name*	Amount per glazing area		Material density		Service life	
Single 1/4 in clear	Glazing	Flat glass, coated, 6 mm	15.6	kg/m^2	2600	kg/m^3	40	years
	Framing	Aluminium alloy, AlMg3	4.83	kg/m^2	2700	kg/m^3	40	years
	Sealing	Synthetic rubber	0.29	kg/m^2	860	kg/m^3	40	years
	Hardware	Steel, chromium steel 18/8	0.20	kg/m^2	7800	kg/m^3	40	years
Double 1/4 in clear	Glazing	Flat glass, coated, 6 mm	15.6	kg/m^2	2600	kg/m^3	40	years
	Glazing	Flat glass, coated, 6 mm	15.6	kg/m^2	2600	kg/m^3	40	years
	Framing	Aluminium alloy, AlMg3	4.83	kg/m^2	2700	kg/m^3	40	years
	Sealing	Synthetic rubber	0.29	kg/m^2	860	kg/m^3	40	years
	Hardware	Steel, chromium steel 18/8	0.20	kg/m^2	7800	kg/m^3	40	years

* Based on ecoinvent database.

Table A4
Glazing unit properties [63] and links to life cycle inventory (LCI) [25] and cost data [65].

Name	U-Value	SHGC	Visible Transmittance	Glass Thickness	LCI Name	Cost Name	Service Life
	[W/m²·K]	–	–	[m]			[Years]
Single 1/4 in clear	5.78	0.819	0.881	0.006	Single 1/4in clear	Single glazed, average	40
Double 1/4 in clear	2.67	0.703	0.781	0.013	Double 1/4in clear	Double glazed, average	40

Table A5
Material properties [63] and links to life cycle inventory (LCI) [25] and cost data [65].

Name	Thickness	Conductivity	Density	Specific Heat	Thermal Absorp.	Solar Absorp.	Visible Absorp.	LCI Name	Cost Name	Service Life
	[m]	[W/m·K]	[kg/m³]	[J/kg·K]	–	–	–			[Years]
Brick 4in	0.102	0.720	1920	840	0.90	0.70	0.70	Clay brick	Brick 4x4x8in	100
Brick 8in	0.203	0.720	1920	840	0.90	0.70	0.70	Clay brick	Brick 4x4x8in	100
Carpet 1/4in	0.006	0.060	288	1380	0.90	0.75	0.75	Carpet, Mohawk, EPD	Carpet tile	15
CMU 4in	0.102	0.190	600	1000	0.90	0.70	0.70	Concrete block	CMU 8 × 16x8in	100
Concrete RF 6 in	0.152	1.900	2300	840	0.90	0.70	0.70	Concrete, 30–32 MPa, reinforced	Concrete Reinforced Slab	100
EPS 2 in	0.051	0.035	25	1400	0.90	0.75	0.75	Polystyrene, expandable	EPS 2in	60
Plaster 1/2 in	0.013	0.500	1300	1000	0.90	0.92	0.92	Clay plaster	Plaster 1/2in	60
Gypsum 1/2 in	0.013	0.160	800	1090	0.90	0.70	0.70	Gypsum plasterboard	Gypsum board, standard	40
XPS 60 psi R15	0.076	0.029	29	1210	0.90	0.70	0.70	Polystyrene, extruded	XPS R15	60
XPS 60 psi R20	0.102	0.029	29	1210	0.90	0.70	0.70	Polystyrene, extruded	XPS R20	60
PIR 2–1/2 in R-14.4	0.064	0.025	24	1590	0.90	0.70	0.70	Polyurethane, rigid foam	PIR 2–1/2in R14.4	60
PIR 3–1/2 in R-20.2	0.089	0.025	24	1590	0.90	0.70	0.70	Polyurethane, rigid foam	PIR 3–1/2in R20.2	60
EPDM 60 mil	0.002	0.200	1371	2000	0.90	0.70	0.70	Synthetic rubber	EPDM roofing 60 mil	40

Note: Name and Cost Name columns include names with IP units based on the naming convention of the sources (RS Means for Cost Names). Physical properties and LCI Name include SI units based on the convention of the data sources (i.e., EnergyPlus for physical properties and ecoinvent database for LCI Name).

Table A6
Photovoltaic system properties [60].

Parameter	Value
Azimuth angle	180°
Panel tilt	40°
Array type	Fixed (open rack)
Module type	Standard
Cell material	Crystalline silicon
Nominal efficiency	15%
Module cover	Glass
Temperature coefficient of power	−0.47%/°C
System losses incl. soiling, shading, wiring, degradation, etc.	14.08%
DC-to-AC conversion efficiency (%)	96%

Table A7
Electricity source type environmental impact data [25].

Source type	Per	Ozone depletion	Global warming	Smog formation	Acidification	Eutrophication	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	MJ surplus
Grid mix - RFC	1 kWh	6.91E-08	7.76E-01	1.95E-02	3.00E-03	7.22E-03	3.51E-01
Grid mix - WECC	1 kWh	5.45E-08	5.04E-01	1.69E-02	1.64E-03	4.06E-03	4.64E-01
PV array	1 kW system	4.65E-04	2.06E+03	1.19E+02	1.33E+01	1.45E+01	2.01E+03

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