Where Do Environmental Benefits from Repurposing Office Buildings into Apartments Come from?

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Analysis

Keywords:

Posted Date: April 22nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1549306/v1

Abstract

Quantitative studies of environmental benefits of repurposing, or adaptively reusing, buildings are very rare. It is generally believed that the structure can be saved in repurposing, but much of the façade and interior materials are often replaced. A life-cycle assessment of the materials needed to repurpose a mid-size 5-storey office building (of which there are about 155,000 in the United States alone, some in excess of market needs) into apartments reveals that 51% of energy, 57% of greenhouse gas emissions, and 75% of generated waste can be avoided when compared to constructing a new apartment building. The key materials driving the embodied energy and emissions are concrete, steel, and façade and interior materials. Replacements of materials and service assemblies in the maintenance phase more than double the embodied energy of initial construction and increase embodied greenhouse gas emissions by 60–77%, while adding just 6–7% to the mass of the buildings.

1 Introduction

Buildings are responsible for huge amounts of resource use, waste generation, and emissions. By the latest estimates, construction and operation accounted for 36% of global energy use and nearly 40% of energy-related greenhouse gas (GHG) emissions (IEA and UN, 2018), 30% of raw materials consumption, and 40% of solid waste generation (Malabi Eberhardt et al., 2021). Of those total GHG emissions, building operations are responsible for 28% and building materials and construction activities (typically referred to as sources of embodied carbon and emissions) are responsible for 11% annually (IEA and UN, 2018). Three major materials (concrete, steel, and aluminum), most of which are used in the built environment (Architecture 2030), account for 23% of total global GHG emissions.

Unlike operational GHG emissions, which can be reduced with building energy efficiency investments and increased use of renewable energy, embodied GHG emissions (associated with materials) are locked in place as soon as a building is completed, also significantly determining future material and construction needs in the maintenance phase. As buildings become more energy efficient in operation through low-energy and net-zero buildings, the embodied energy will represent a larger portion of the total energy impact (Chastas et al., 2016). Röck et al. (2020) showed a reduction trend in life-cycle GHG emissions due to improved operational energy performance of more than 650 buildings (residential and commercial) around Europe, but their analysis also revealed an increase in both relative and absolute contributions of embodied GHG emissions. While the average percentage of embodied GHG emissions from buildings following current energy performance regulations was approximately 20–25% of life-cycle GHG emissions, this figure escalated to 45–50% for highly energy-efficient buildings and surpassed 90% in extreme cases, highlighting the “carbon spike” from building production (Röck et al., 2020).

Three general ways to reduce the impacts from materials are to select ones with low embodied energy and emissions, reuse or recycle materials at the end of their useful lives, and extend the life of installed building materials, including repurposing (adaptively reusing, or rebuilding) buildings, to slow down the flow of materials. Adaptive reuse is a key concept in achieving a circular economy (European Standards, 2012; European Commission, 2020; Rahla et al., 2021) (see SI Fig. 1 in the Supporting Information).

The need to build more homes is urgent in most urban areas and repurposing has been proposed as a strategy to address housing shortages (National Association of Realtors, 2021). Repurposing and rebuilding commercial, government, and other buildings can provide a relatively speedy way to address the need for more residential housing. But is it also environmentally preferable compared to the demolition-new construction cycle?

Systematic analyses of environmental, economic, and social advantages of repurposing are rare (Wijesiri et al., 2021). The current implementations of adaptive reuse are based on descriptive approaches with little to no quantitative analysis and depend on the intuition and experience of practitioners (Sanchez and Haas, 2018).

We have found only four quantitative analyses of adaptive reuse. First, the Australian Greenhouse Office's report claiming that reuse of buildings has saved 95% of embodied energy that would otherwise be wasted as a result of building demolition (Kerr, 2004). Second, Assefa and Ambler (2017) estimated savings of 33% and 34%, respectively, in GHG emissions and fossil fuel consumption as a result of rebuilding a high-rise university building in Western Canada rather than demolishing and replacing it. Third, an analysis by Sanchez et al. (2019) found a 35–38% decrease in primary energy demand, global warming potential, and water consumption, and a 70% decrease in construction costs for the adaptive reuse of a courthouse building in Ontario, Canada. Finally, Hasik et al. (2019) applied LCA to compare adaptive reuse of a historical beer bottling/warehouse facility to an equivalent new construction of an office building in Philadelphia, U.S., and determined that reusing the existing facility helped avoid 75% of GHG emissions compared to new construction.

The limited available literature and wide range of results call for additional studies that incorporate the environmental implications of repurposing projects compared to new construction. Our research has adopted office and apartment building designs that are typical of construction in the United States and many parts of the Northern Hemisphere. We have developed a bottom-up, time-resolved material flow analysis of these buildings over their 50-year service lives, including both initial construction and maintenance. Using life-cycle assessment (LCA), we have quantified embodied energy and GHG emissions as well as the mass of materials and building components (substructure, structural frame, exterior façade, roof system, interior wall system, and other building assemblies). We have calculated the amounts of energy, GHG emissions, and waste avoided by repurposing prototypical office buildings into apartment buildings.

To our knowledge, ours is the first quantitative and systematic study to analyze repurposing of representative-design office buildings into apartment buildings in the United States or anywhere in the world.

2 Methods And Data

The number of office buildings in the United States (as of 2018) is 970,000 (EIA, 2021). They occupy 1.55 billion m^2, with about 15% of that floorspace being medium-sized, 5-10-storey office buildings.

In 2019, it was estimated that 139 million housing units exist in the United States, 8% (~ 11 million) of which are multifamily apartment buildings (with 4 or more stories) that are comparable to medium-sized office buildings and occupy about 1.3 billion m^2 (6% of total housing floor space) (US Census, 2022). The vast majority of housing units are single-family, detached houses.

The selected, representative buildings in our study are prototypical 5-storey, 4,600 m^2 reinforced concrete (RC) structured buildings with metal panel façade for the office and stucco-on-concrete masonry unit (CMU) façade for the apartment buildings. There are about 155,000 such office buildings in the United States. As many companies increasingly allow for employees to telework, it is expected that many such mid-size offices will become increasingly empty. Repurposing all of them into apartments would create about 6 million new average-sized apartments, nearly a 50% increase in the multifamily apartment building stock.

The bill of materials (BOM) data for prototypical office and multifamily apartment buildings were sourced from the industry-leading building information database, the RS Means Cost Data tool (Gordian, 2021). The data were collected in 2021. We categorized them for the following building components:

- Substructure (foundation + slab on grade): Concrete, rebar, and structural steel used in construction of footings, slab-on-grade, foundation walls, and piles and grade beams.

- Structural frame: Concrete, rebar, structural steel, structural wood, and fiber for fireproofing of steel structures.
- Exterior facade: Exterior wall materials (several: metal panels, stucco, cement board, glass wall panels, CMU blocks), several different insulation materials, steel studs, window (aluminum, glass) and door (aluminum, steel, and/or glass) on the façade.
- Roof coverings (asphalt shingles, aluminum, plywood sheathing), and insulation.
- Interior partitions: Partition wall systems (gypsum board, CMU), studs (wood or steel), interior doors (aluminum or steel).
- Staircase: Galvanized steel.
- Interior finishes:
    - Wall finishes (wall paint, ceramic tiles).
    - Floor finishes (carpet, vinyl tiles, ceramic tiles)
    - Ceiling finishes (gypsum board, fiberglass for insulation)
    - Service assemblies: Elevators, air conditioning units, water heater, roof drainage pipes, piping for water supply and sewage.

BOMs from these two buildings were used to quantitatively analyze resource use, embodied energy, and embodied GHG emissions of *two scenarios* over a 100-year time frame: (1) demolition of an office building in year 50, followed by new construction and 50-year service life (with maintenance) of a same-size apartment building, and (2) repurposing, rebuilding a 50-year-old office building into an apartment building with a service life of 50 years by keeping the structural components (foundation, beams, columns, and slabs), steel staircases, and exterior wall studs and replacing the rest of the building, i.e., the interiors. Figure 1 is a representation of the approach for the repurposing scenario, showing what is demolished versus replaced, newly built. SI Table 2, Fig. 3, and Fig. 4 show the details about the material composition of the six major building components and corresponding changes and substitutions that occur in scenarios 1 and 2.

In the two scenarios, structural materials (concrete and steel) make up 86% and 76%, exterior walls (mainly CMU block) 10% and 20%, of the total mass of the office and the apartment buildings, respectively. The remaining 4% consist of interior partition walls, ceiling/floor/wall finishes, and service assemblies (SI Fig. 2).

Embodied energy and GHG emissions were obtained by linking material quantities and environmental product declarations (EPDs) (SI Table 1 and Table 2). The latest EPDs, as specific to U.S. manufacturing and construction material use in our prototypical buildings as possible, were sought out.

Embodied impacts of materials are comprised of those used in the initial construction and those in the maintenance phase over 50 years of a building's lifetime (Junnila et al. (2006). Interior furnishings are outside the scope of analysis because these portable components are not embodied in the building.

Unlike earlier building LCA studies, using representative, specific, geographically consistent, and most-recent EPDs in the calculation of embodied energy and GHGs provided validated and transparent results. For details of calculations, see the Excel spreadsheet in the SI.

3 Results

The embodied impacts have been calculated as 14,600 GJ, 1,460 metric tons (mt) CO_2 eq., and 4,840 mt of materials for the initial construction of the office building and 17,100 GJ, 1,580 mt CO_2 eq., and 5,620 mt of materials for the apartment building (Fig. 2). The buildings' structure and substructure constitute the largest source of embodied GHG emissions and energy, 55–58% and 50–58%, respectively, depending on building type (SI Fig. 5). These numbers are in the range of the findings (50–67%) from the only comparable published study (Assefa and Ambler, 2017).

Repurposing in year 50 can be accomplished with material investments amounting to 8,350 GJ of embodied energy, 690 mt of CO_2 eq. of embodied GHG emissions, and 1,420 metric tons. Overall, 8,690 GJ energy (51%), 890 mt CO_2 eq. (or 57%), and 4,200 mt of materials (75%) can be avoided relative to building a new apartment building.

Replacements of materials and service assemblies in the maintenance phase through the 50 years of lifetime (based on maintenance schedules in SI Table 3) add 105% (15,300 GJ) to the embodied energy, 60% (870 mt CO_2 eq.) to the embodied GHG emissions, and 6% (280 mt) to the mass of materials of the office building's initial construction. For the apartment building, replacements add 124% (21,200 GJ) to the embodied energy, 77% (1,220 mt CO_2 eq.) to the embodied GHG emissions, and 7% (400 mt) to the mass of materials (SI Figs. 3–4 and 6–9) of initial construction.

GHG emissions associated with the recycling of metals and some portion of concrete after demolition of the building in year 100 were not included in the analysis because recycled content is factored into the manufacturing of new materials in year 0 of the next new building.

Key materials that drive the embodied emissions and energy are found to be concrete, steel, façade (aluminum and insulation) and interior materials (when maintenance is factored in).

Structural concrete and steel are responsible for 33% and 23% of embodied GHG emissions in Scenario 1 and 23% and 16% of GHG emissions, respectively, in Scenario 2, 23% and 31% of embodied energy and 74% and 7% of initial mass of materials in Scenario 1, and 16% and 22% of embodied energy and 62% and 6% of the initial mass of materials, respectively, in Scenario 2.

SI Figs. 8 and 9 show that embodied energy associated with the replacement of interior materials, especially carpet and paint, can be as high as 50% and 58% of the total embodied energy for Scenario 1 and Scenario 2, respectively. Materials used for the replacements correspond to 38% and 46% of embodied GHG emissions; 5% and 9% of total mass of materials for Scenario 1 and Scenario 2, respectively.

Over the course of 100 years, structural materials are responsible for 27% and 16% of total embodied energy; 35% and 22% of total embodied GHG emissions; and 76% and 62% of total mass of materials for Scenario 1 and Scenario 2, respectively.

Concrete has the potential to sequester CO_2 due to the ongoing carbonation reaction throughout its service life. Possan et al. (2017) estimated that concrete during its lifetime (which varies considerably) can uptake 40–90% of the CO_2 emitted in its manufacturing process. The study provides CO_2 uptake factors from literature and their model. Accordingly, a concrete structure after 20 years uptakes about 11%, while for a 100-year service life, the uptake is estimated to be between 33% and 57%. Concrete uptake for 70 years of lifetime and 30 years after demolition is 24% of the embodied CO_2 for the service life and 57% of the CO_2 for the demolition portion. Using the 24% factor (a low-range option to cover the uptake for both Scenario 1 and 2), we calculated the CO_2 uptake as:

$$CO_2 uptake(conservative) = 24\% \times Embodied CO_2 emissions from concrete$$

$$CO_2 uptake(maximum) = 57\% \times Embodied CO_2 emissions from concrete$$

Using the 50% factor (50% of CO_2 is emitted during the cement calcination process and the remaining 50% is from the fossil fuel consumption in the cement kiln), we calculated the CO_2 uptake as 49% and 28% of total embodied GHG emissions from concrete used in Scenario 1 and 2, respectively. Therefore, the CO_2 uptake corresponds to 9% and 8% of construction-related embodied GHG emissions in Scenario 1 and 2, respectively. If both construction and maintenance stages are covered, these figures would be 6% and 4% of total embodied GHG emissions in Scenario 1 and 2, respectively (SI Figs. 6 and 7).

4 Uncertainties In Modeling And Data

The purpose of this study was to analyze and compare embodied energy and GHG emissions of repurposing vs. demolishing and newly constructing representative office and apartment buildings using a practical and comprehensive approach. All data sources can be accessed by the readers. Uncertainties are inevitable and result mainly from the following:

- The new apartment building (after the demolishing of the office building in Scenario 1) would occupy the same footprint, have the same number of floors, shape and orientation, and use thus same quantity of materials in the substructure (foundation) and structural frame. Scenario results would change if the BOM were obtained from construction documents of actual buildings instead of prototype buildings developed from the RS Means database.
- Conversion of units given in the RS Means BOM to material mass for the purpose of comparison and coupling units of material quantities with functional units defined in EPDs. Such conversions require the use of unit mass factors (such as mass per surface area, mass per volume, mass per piece, mass per length, etc.) as described in EPDs and/or product description labels.
- Calculation of quantities of some materials in building components if they are not explicitly provided in the BOM, such as percentage of rebar in structural concrete components; estimation of concrete mass and volume in beams, columns, foundation, and slabs; configuration of studs in wall assemblies; roof geometry and configuration; or grid system for water/ sewage pipes, etc. Please see the Excel spreadsheet in the SI.
- Due to the long lifetime of buildings, estimating the changes and patterns in the maintenance of building components and materials would be a source of uncertainty. Maintenance frequencies of materials and service life of buildings in this study are average values taken from literature.
- When EPDs for certain components or materials are missing, we used life-cycle inventories (LCIs) from literature and various sources. The quality of LCI data can affect the accuracy and local or regional representativeness of the results. Data availability during different stages of life cycle of buildings may hinder the development of an accurate LCA. This is because buildings are more complicated than a single product with comparatively long life and multiple functions, and would often undergo various changes (Chau et al., 2015).

The above notwithstanding, we consider the quality of the data used in this research to be relatively high. The RS Means data are based on nationally representative surveys, and the emission factors are based on the latest EPDs. The building materials, energy, and GHG emissions data for both analysis scenarios came from the same sources, which allows for consistent comparisons. Overall, the uncertainties are not significant, and we reported the results to three significant digits.

5 Discussion

Figure 3 shows the net GHG emissions if Scenario 2 was selected over Scenario 1. In year 0, GHG emissions are attributed to the construction of new office building in both Scenarios 1 and 2. Since the office building is the same in both scenarios, the net difference between Scenario 2 to Scenario 1 is, therefore, zero. Repurposing an existing office building at year 50 into a new apartment building would save 192 kg CO_2 eq per m^2 if we keep the existing structural frame and the foundation instead of demolishing it completely and constructing a new apartment building. Carbon uptake in Scenario 1 is shown to be 61 kg CO_2 eq per m^2, which is higher than the carbon uptake (35 kg CO_2 eq per m^2) in Scenario 2, attributed to the additional amount of concrete (830 kg per m^2) used in the construction of a new apartment building in year 50.

Overall, repurposing an old office building into a new apartment building would save about 1,890 MJ/m^2, or 8,700 GJ, or 14% of embodied energy, and (as Fig. 3 shows) 166 kg CO_2 eq. per m^2), or 765 mt of CO_2 eq. for the prototype buildings, that is, about 17% of total embodied GHG emissions over 100 years of service life.

Depending on the type and condition of the materials that come out of the maintenance and demolition phases as well as the existence of recycling industries, they are either landfilled or recycled. By making the decision to choose the repurposing scenario, 584 kg of waste per m^2 would be eliminated from disposal in landfills while 331 kg per m^2 of material would be diverted from the recycling stream. Therefore, the repurposing scenario would eliminate 915 kg per m^2 or a total of 4,210 metric tons of materials that would otherwise be landfilled or recycled (Fig. 3). Concrete and steel rebar constitute the majority percentages of the saved materials.

Results from this study indicate that the value of repurposing depends on the prioritization of environmental goals. Repurposing reduces material-related embodied energy and emissions, but the benefits are limited partly because so much of the embodied energy and emissions during the service lifetime are involved with maintenance after initial construction, highlighting the importance of post-construction material selection. The impacts from repurposing become much more significant when considering material flows and waste avoidance.

The prototypical case buildings that form the basis of this analysis are representative of medium-size reinforced concrete structures in the United States and elsewhere in the Northern Hemisphere. For a more representative assessment, future work should consider the inclusion of low-rise and high-rise reinforced concrete and steel buildings, as well as low-rise wood-framed structures with variations of façade and interior wall systems.

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Declarations

Acknowledgments

The authors gratefully acknowledge the joint support from the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Buildings Technology Office (BTO), the Advanced Manufacturing Office (AMO), and the Strategic Analysis Team (SA). This manuscript has been co-authored by an author at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy. The U.S. Government retains, and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

Figures

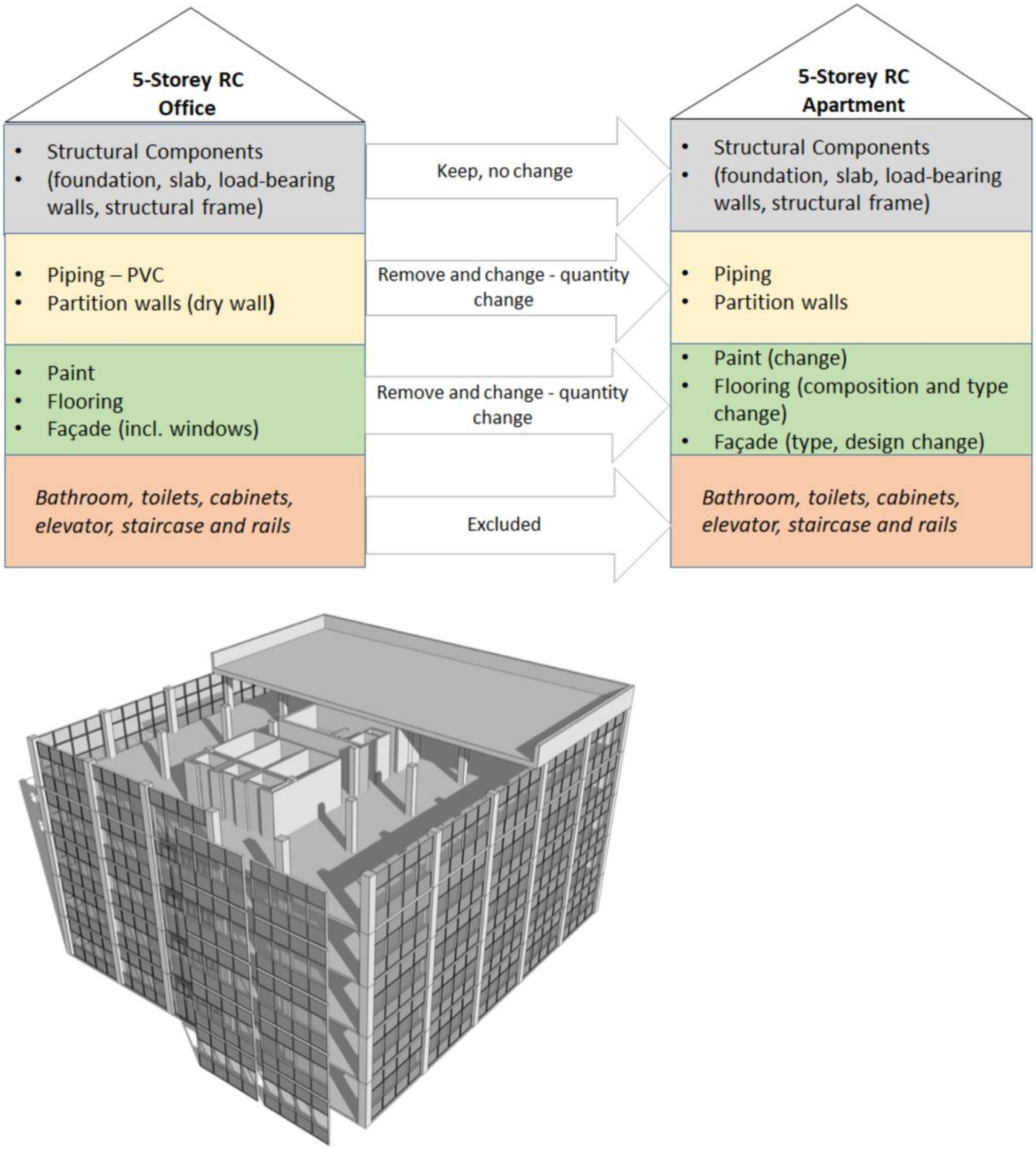

Figure 1

Schematic representation of a typical mid-rise reinforced concrete building and what gets replaced in a repurposing scenario. Bathroom and kitchen products are excluded because they are the same in a repurposed and in a newly constructed building.

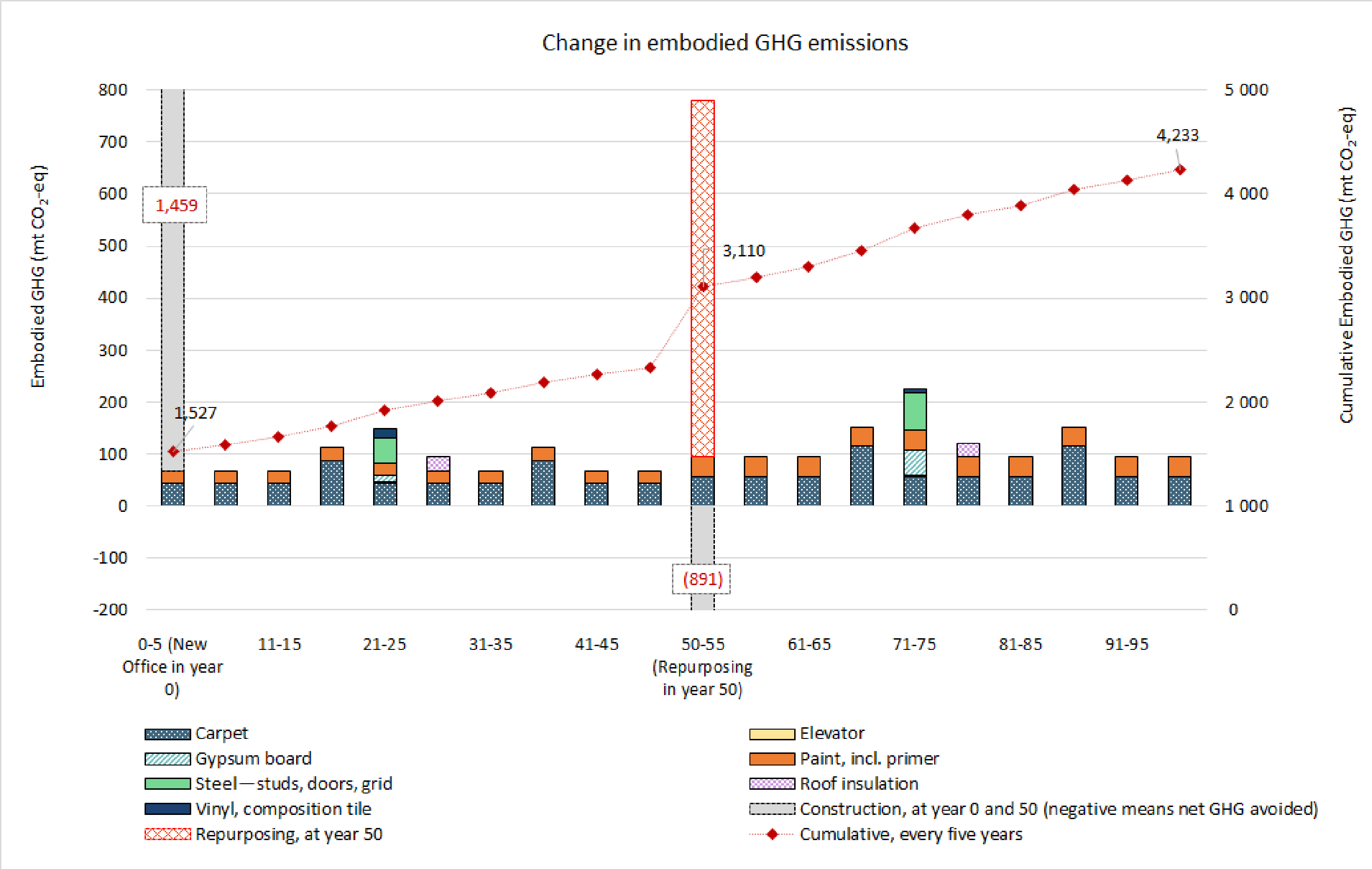

Figure 2

Embodied GHG emissions (mt CO_2 eq.) resulting from initial construction of the office building, repurposing into an apartment building in year 50, and replacement of materials in the maintenance phase of both buildings over 100 years of lifetime, shown in 5-year intervals.

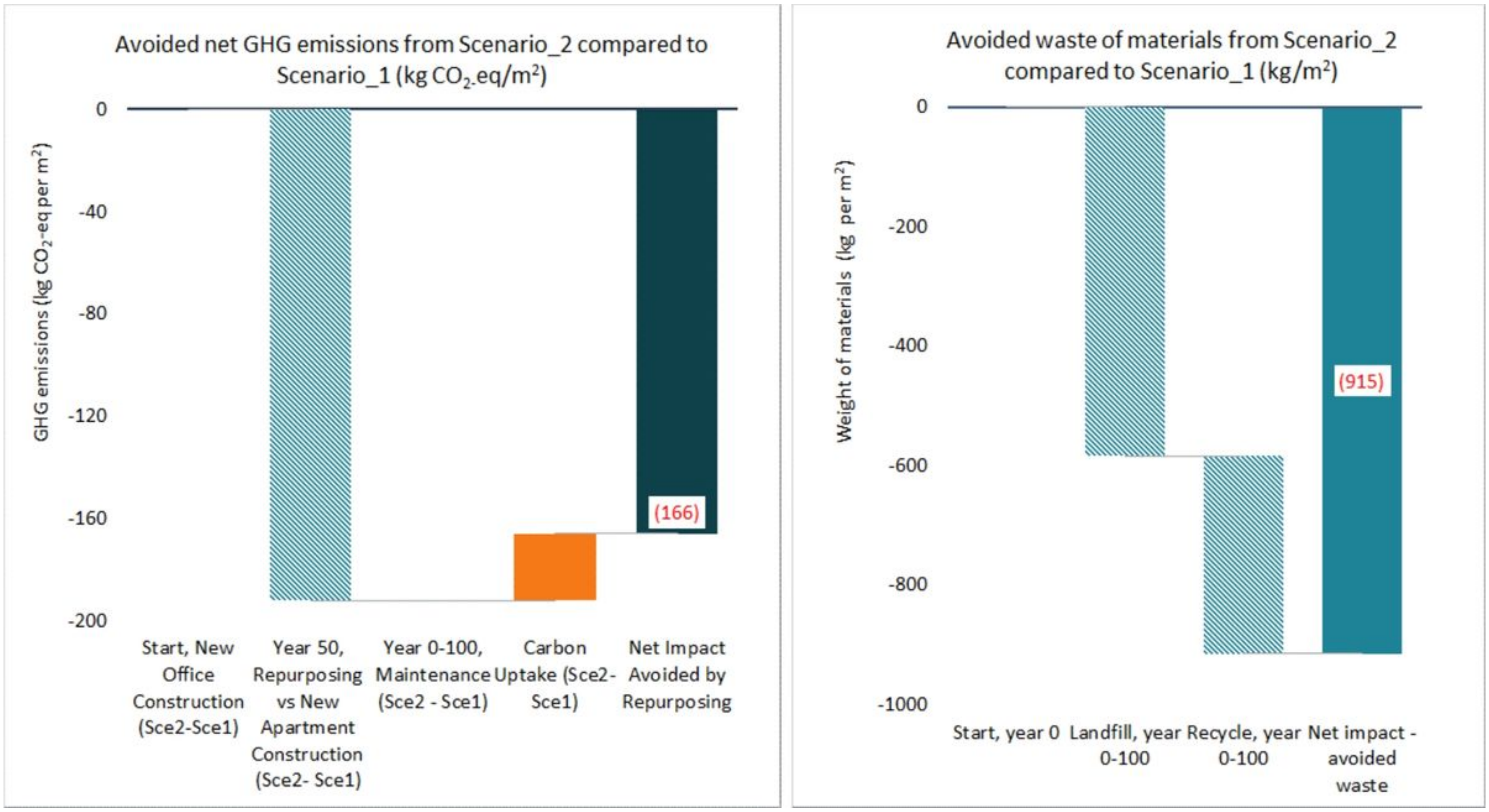

Figure 3

Summary of net GHG emissions avoided and quantity of materials (either landfilled and/or recycled) by selecting Scenario 2 (repurposing) over Scenario 1 (construction of new apartment building) in year 50. (See SI Table 2 for more details.)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- PrototypicalBuildingsCalculationsApril12.xlsx
- RepurposingCalculationsApril12.xlsx
- RepurposingBuildingsSINATSUSTAIN22040883.docx