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What are the energy and greenhouse gas benefits of repurposing non-residential buildings into apartments?

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ABSTRACT

This study examines the potential strategies for reducing embodied energy and greenhouse gas emissions through adaptive reuse of non-residential buildings for residential purposes, as compared to new construction of apartment buildings. Such an approach can address housing crises in urban areas with an abundance of underutilized non-residential buildings, promoting sustainable housing growth. A comprehensive assessment of repurposing in California reveals approximately 510 million m^2 of floor space across 230,000 non-residential buildings in the current building stock. The potential reduction in embodied energy and CO_2eq emissions ranges from 0.14 to 1.4 billion GJ and 5.0–70 million metric tons for the state, respectively, contingent upon the percentage of repurposed floor space (10–100%) and adaptive reuse scenario (retaining structural components and façade or solely the structure). A repurposed building avoids about 56% of embodied energy, 34-48% of CO_2 eq emissions, and 72% of materials by mass compared to building a new apartment building. However, various technical, financial, and regulatory challenges may hinder emissions reductions, necessitating proactive policy measures. Cities can potentially expedite the process by streamlining approvals for mixed-use adaptive reuse projects involving both commercial and residential spaces.

1. Introduction

Buildings are responsible for large amounts of resource use, waste generation, and emissions. By the latest estimates (2020), buildings accounted for 36% of global energy demand, 37% of energy-related CO_2 emissions (of which 28% were due to building operations and the rest due to construction materials manufacturing (UNEP, 2021)), 30% of raw materials consumption, and 40% of solid waste generation (Malabi Eberhardt et al., 2021). Three major materials (concrete, steel, and aluminum), most of which are used in the built environment (Architecture 2030, 2022), account for 23% of total global greenhouse gas (GHG) emissions. Thus, material, energy, and emissions savings from building-related actions should be a priority for attention.

As defined in EN 15978, building life-cycle stages (Figure SI 1 in the Supplementary Information) consist of i) Extraction and processing of raw materials, and manufacturing of building materials (A1-A3), ii) Transportation of building materials from production facilities to constriction site and construction into a building (A4-A5), iii) Use of energy and materials for operation and maintenance of a building (B1–B7), and iv) Decommissioning the building (C1–C4) once it has reached its end of life (EOL). A further optional stage beyond EOL (D) is defined to account for the reuse, recovery, and recycling of building materials.

Unlike operational GHG emissions, which can be reduced with building energy efficiency investments and increased use of renewable energy, embodied GHG emissions (i.e., those associated with building materials) are locked in place as soon as a building is completed, and significantly determine future material and construction needs over the life of a building. As buildings become more energy efficient in operation through low-energy and net-zero efforts, 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 residential and commercial buildings in 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 EU 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," i.e.,

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the jump in GHG emissions from the use of building materials at the time of construction (Röck et al., 2020).

Several circularity strategies exist to reduce the consumption of natural resources and materials and minimize the production of waste. They can be ordered for priority according to their levels of circularity in Figure SI 2, as suggested by Potting et al. (2017). Some possible strategies to reduce the impacts from materials are to select materials with low embodied energ and emissions (Kim et al., 2022; Mohammadiziazi and Bilec, 2022; Tavares et al., 2023), enact optimized design (see, e.g., Miller et al., 2016a,b; Miller et al., 2015; Kavvada et al., 2022; Lidicker et al., 2013), reuse or recycle materials at the end of their initial cycle (Gursel et al., 2023), and extend the life of installed building materials, including repurposing (adaptively reusing, or rebuilding) buildings, to slow the flow of materials. Adaptive reuse or repurposing (depicted as R7 in Figure SI 2) is a key concept in achieving a circular economy worldwide (EN 15978; European Commission, 2020; Rahla et al., 2021).

1.1. Literature review

Systematic analyses of the 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 often depend on the intuition and the experience of practitioners (Sanchez and Haas, 2018).

We found a small number of quantitative analyses of adaptive reuse at the whole-building level. Many of the prior studies focused on the environmental impact assessment of refurbishment versus demolition-and-reconstruction of building components, with specific attention to their thermal properties, such as building envelope, insulation materials, windows, lighting, and HVAC systems. Most of them studied environmental impacts from the refurbishment or retrofit of buildings and compared the results with the initially constructed building, not with a new equivalent building that did not have to be constructed (Pittau et al., 2020; Ardente et al., 2011; Sierra-Pérez et al., 2018; Assiego De Larriva et al., 2014; Ghose et al., 2017; Cetiner and Ceylan, 2013).

The first known study that applied a whole-building approach in adaptive reuse was the Australian Greenhouse Office's report, claiming that reuse of buildings had saved 95% of embodied energy that would otherwise be wasted as a result of building demolition (Kerr, 2004). Then came the Ferreira et al. (2015) study that compared the environmental impacts of refurbishment of a historical building (Palace of the Counts of Murça from the seventeenth century in Lisbon, Portugal) with a hypothetical new construction meeting the same requirements in terms of structural aspects, using a cradle-to-gate life-cycle assessment (LCA) approach. Their results showed that the refurbishment solution was environmentally more sustainable than a new equivalent construction. Estimated savings were 13% in global warming potential (GWP), 10% in primary energy, and 542% in generated waste. Later, 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.

More recently, a cradle-to-grave LCA by Marique and Rossi (2018) compared the GHG emissions and energy consumptions of office buildings in Belgium under renovation and reconstruction scenarios, and stated that renovating a building has lower life-cycle emissions than constructing a new building due to the high embodied emissions from construction and material manufacturing. Overall, the impacts of the retrofit project only represented 55% of the rebuild project in terms of energy and 57% in terms of CO_2 emissions. An analysis by Sanchez et al. (2019) found a 35%–38% decrease in primary energy demand, GWP, and water consumption, and 70% savings in construction costs for the adaptive reuse (referring to renovation) of a courthouse building compared to a new courthouse construction in Ontario, Canada. Hasik et al. (2019) applied LCA to compare adaptive reuse of a historical beer bottling/warehouse facility into an equivalent-size office building in Philadelphia, U.S., and determined that reusing the existing facility helped to avoid 75% of GHG emissions compared to new construction. Finally, Feng et al. (2020) evaluated the life-cycle GHG emissions of six different renovation and reconstruction (building a new building) scenarios using a building information modeling (BIM)-LCA combined approach for single-family housing in Vancouver, Canada. Their results showed that embodied GHG emissions generated from the new construction scenarios were 5–6 times higher than the renovation scenarios.

The limited available literature calls for additional studies that quantify the environmental implications of repurposing projects compared to new construction of buildings. To fill this gap, we have developed a methodology to quantify embodied energy and GHG emissions from repurposing of several different non-residential building types into housing units, with a case study based in California.

1.2. Focus and purpose of the study

Since the outbreak of the COVID-19 pandemic, the shift to remote work and online shopping has increased the stock of empty office and other commercial properties, including warehouse and storage buildings, shopping malls, and industrial buildings. It is assumed that by converting underutilized commercial floorspace, we can create hundreds of thousands of housing units with minimal environmental impacts at regional or national level. In fact, the current U.S. office market report shows that the national vacancy rate exceeded 18% at the end of 2022 (Cushman and Wakefield, 2023) while many U.S. cities were struggling to meet their housing requirements according to state regulations. According to Hamann (2023), the top ten major cities facing housing shortages are New York City, Dallas-Fort Worth, Houston, Los Angeles, Washington D.C., Miami, Atlanta, Seattle, San Francisco, and Phoenix. To address this issue, a potential solution is to repurpose (adaptively reuse) available and underutilized non-residential buildings and transform them into residential units. Consequently, several federal, state, and local policies aiming to solve "the dual problems of empty offices and needed housing with one initiative have sprung up, including $400 million in incentives for adaptive residential reuse efforts in California's 2022–24 budget, a hotel-to-housing conversion bill in New York (Bill #A06262B), Philadelphia's conversion policy, and local initiatives in San Francisco and Portland to name a few." (Up for Growth, 2022)

The adaptive reuse approach can address several significant issues that many cities are currently facing. Not only does it help alleviate critical housing shortages by meeting the needs of the community, but adaptive reuse also saves money by eliminating the expenses associated with demolishing and constructing new buildings. The need to build more homes is urgent in urban areas, especially those that have been experiencing population growth, and repurposing has been proposed as a strategy to address housing shortages in California and other locations (National Association of Realtors, 2021).

California, the largest U.S. state with a population of 39 million and the fifth largest economy in the world, is currently facing two major crises: climate change and a severe shortage of residential housing. By recent estimates, more than 2.5 million housing units are needed to be built by 2030 to meet demand. It is essential that any solution to the housing shortage also considers the reduction of energy use and GHG emissions. Buildings are responsible for a quarter of the state's GHG emissions, but this figure does not include embodied emissions from materials and construction activities (Greer and Horvath, 2023). Repurposing and rebuilding non-residential buildings could provide a relatively speedy way to address the need for more housing in California. Moreover, with higher occupancy rates, the repurposed buildings can accommodate more people without the need for additional new construction. But is repurposing environmentally preferable compared to constructing brand new residential buildings?

To answer this question, three prototypical non-residential buildings

– industrial (factory), office, and warehouse – are considered as candidates for repurposing into residential use in California. These three building types were selected since they make up more than 50% of total non-residential building space in California, and their conversion into apartment buildings is considered feasible in terms of structural, architectural, economic, and environmental aspects. Following the selection of candidate buildings, we generated bill of materials (BOM) for the non-residential prototypical buildings and an equivalent new apartment building to analyze avoided material quantities and associated embodied energy and GHG emissions from the 'repurposing of the existing building' versus the 'new construction of an apartment building scenario.

Coupling California's publicly available non-residential building stock data with selected prototypical building analysis results, we have estimated scaled-up material quantities and associated embodied energy and GHG emissions that would potentially be avoided by adapting repurposing strategies to address housing needs statewide.

To our knowledge, this is the first quantitative, systematic, and peer-reviewed study to analyze the embodied energy and GHG emissions associated with repurposing of representative non-residential buildings into residential buildings anywhere in the world.

2. Research methodology

Our methodology estimates the upfront embodied carbon of building materials that correspond to the cradle-to-site, A1-A5, stage (refer to Figure SI 1). 'Upfront carbon' refers to the emissions produced in stages A1–A5 before the building is occupied. This upfront carbon usually comprises the majority of a material's embodied carbon impact and is deemed especially important due to the importance of reducing carbon emissions as quickly as possible (Waldman et al., 2020). Recurring embodied carbon (carbon emitted during the use stage (B1-B5) and is associated with repair, replacement, refurbishment, and maintenance of the building) and EOL-phase embodied carbon (carbon emitted during demolition, deconstruction, transportation of demolished building assemblies, processing, and disposal of material waste (C1-C4)) are excluded from the analysis. The building's operational phase (B6-B7) is outside the scope of the analysis since the focus is on embodied carbon associated with building materials.

The estimation of embodied energy and GHG emissions associated with the materials needed to repurpose eligible non-residential buildings in general and specifically in California is comprised of three major steps:

1 The first step involves the description and analysis of three prototypical non-residential buildings – industrial (factory), office, and warehouse – that would be candidates for repurposing into apartment buildings having comparable architectural (size, shape, height) and structural configurations. These three building types constitute more than 50% of total non-residential building floor area in California, and their conversion into apartment buildings is considered feasible in terms of structural, architectural, economic, and environmental aspects. For comparison purposes, a newly built, typical apartment building is also analyzed to estimate benefits of adaptive reuse via avoided material quantities and associated embodied energy and GHG emissions. Two scenarios - repurposing the existing building versus construction of a new apartment building – are considered in the analysis.
2 The second step describes the process of estimating embodied energy and GHG emissions, which requires coupling material quantities with their related energy use and carbon dioxide equivalent (CO_2 eq.) intensities, obtained from environmental product declarations (EPDs).
3 In the last step, the number and floor space of non-residential buildings (office + warehouse + manufacturing) that would be eligible for repurposing statewide are estimated using California's publicly available non-residential building stock data.

2.1. Description of prototypical buildings and their properties

Three prototypical non-residential buildings and a comparable apartment building are selected as representative buildings that would be candidates in repurposing projects in California:

- Warehouse, One Floor, with Precast Concrete Floor and Reinforced Concrete Structure – 30,000 ft^2 (2787 m^2).
- Industrial (Factory), One Floor, with Tilt-up Concrete Panels and Rigid Steel Structure – 30,000 ft^2 (2787 m^2).
- Office, 3 Floors, with Precast Concrete Floors and Reinforced Concrete Structure – 40,000 ft^2 (3716 m^2).
- Apartment, 3-Floor with Fiber Cement Floors and Wood Frame – 40,000 ft^2 (3716 m^2).

The BOM and the quantities of building materials used in construction of all building types were sourced from the U.S. industry-standard, pay-per-use building information database, the RSMeans Data (Gordian, 2021), which provides both material and construction cost information, as well as BOMs for prototypical buildings of many sizes, designs, and uses, from residential to commercial. The data are representative of how buildings are built across the United States as they are actual building designs with allowance for differences in insulation between climatic zones and differences in the structural system (steel, reinforced concrete, structural wood) (Gursel et al., 2023). Façade type, interior wall systems, and finishes can be modified by the tool's user. The data are representative for 2021 in the latest edition of the database.

The BOMs are categorized into 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 façade: Exterior wall materials (several: metal panels, stucco, cement board, glass wall panels, CMU blocks), several different insulation materials, steel studs, windows (aluminum, glass) and doors (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), and 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.

For a consistent comparison, all four building types are assumed to have the same thermal performance (and are assumed to be in the Mediterranean climate of California) with the same wall insulation value.

The operation (energy used for operation of the building) and maintenance (recurrent embodied energy) are outside the scope of this analysis because the focus is on estimating the upfront embodied energy and GHG emissions (corresponding to A1-A5 stages in Figure SI 1) from repurposing of an existing building versus construction of a new apartment building.

Interior furnishings are outside the scope since these portable components are not embodied in the building.

BOMs for these four building types were used to quantitatively analyze material use, embodied energy, and embodied GHG emissions of two scenarios (repurposing the existing non-residential building versus constructing a new apartment building):

Scenario 1 analyzed new construction of a typical apartment building.

Scenario 2 analyzed repurposing (rebuilding) of the existing commercial building (factory-office-warehouse types) into an apartment building in two sub-scenarios:

- Scenario 2.a considered keeping the structural components (foundation, beams, columns, and slabs), steel staircases, and the façade while replacing the rest of the building, i.e., the partition walls and the interior finishes. However, existing windows and exterior doors are assumed to be replaced with additional door/window openings for residential settings.
- Scenario 2.b considered keeping the structural components and steel staircases, and replacing the rest of the building, including the façade. We assumed that the energy efficiencies of both the new apartment and the repurposed buildings are the same in Scenario 2.a as a result of keeping the façade system. The ramification of façade removal in Scenario 2.b is the requirement for additional insulation for residential settings.

Fig. 1 is a representation of the approach for the two scenarios, showing what is considered in the construction of a new apartment building in Scenario 1 versus what is replaced / repurposed in the existing non-residential building in Scenario 2.

Supporting Information (SI) Tables 1 through 4 provide embodied energy and GHG emissions estimates for four representative buildings studied in this paper. Façade designs and partition walls of the repurposed-into-apartments building and the newly constructed apartment building are noticeably different from the non-residential building's original façade and interiors design, according to the default RS Means data (SI Table 1–4).

2.2. Estimation of embodied energy and GHG emission calculations

Embodied energy and GHG emissions were estimated by coupling material quantities with their related energy use and carbon dioxide equivalent (CO_2 eq.) intensities obtained from environmental product declarations (EPDs) (SI Table 5). The latest EPDs, as specific to Californian or U.S. manufacturing and construction material use in the prototypical buildings as possible, were sought out. EPDs reflect the emissions, or emissions savings, associated with recycled content of the materials analyzed (e.g., steel reflects any recycled content embedded in the material itself as provided in the EPD). GHG emissions associated with the recycling of metals and some portion of concrete after the demolition of the building were not included in the analysis because emissions, or potentially avoided emissions, associated with end-of-life management (including landfilling and recycling) are factored into the manufacturing of new materials which will be used in the next new building. Fig. 2 illustrates the approach used in the estimation of

Scenarios:	**Scenario 1.** Construct **a New Apartment Building**	**Scenario 2a.** Repurpose Existing Non-Residential into Apartment – **Keep Structure and Façade**	**Scenario 2b.** Repurpose Existing Non-Residential into Apartment – **Keep Structure only**
Structure:	Construct a new apartment building structure.	Keep the existing non-residential building structure.	Keep the existing non-residential building structure.
Façade:	Construct a new apartment façade: • Three-coat stucco on self-furring metal lath and CMU for exterior wall system • Additional door and window openings Different roof design	Keep the existing building façade and roof system. (Note additional door and window openings to comply with residential purposes)	Remove the older façade and construct a new one: • Replace with stucco on CMU for exterior wall system • Keep existing exterior wall studs • Additional door and window openings Keep the roof design
Interiors and Service Assemblies:	Construct a new apartment interior wall system: • Increased partition wall length • Additional door openings • Staircase, same design • Interior finishes – change in composition, quantity, and material type • Piping – additional length, but same material • New service assemblies	Remove and replace existing with new interior wall system and finishes: • Composition, quantity, and material type will change • Keep staircase • Remove existing piping and replace with new piping – additional length, but the same material • Remove service assemblies and replace with new ones.	Remove and replace existing with new interior wall system and finishes: • Composition, quantity, and material type will change • Keep staircase • Remove existing piping and replace with new piping – additional length, but the same material • Remove service assemblies and replace with new ones.
Exclusions:	Bathrooms, cabinets, and other interior furnishings are excluded from the analysis.		

Fig. 1. Schematic representation of Scenario 1 (construct a new apartment building) and Scenario 2 (repurpose the existing building into an apartment building, with options to (2a) keep both the existing structure and the façade systems and (2b) keep only the structure and replace everything else). Bathrooms, kitchens, and other interior furnishings are excluded because they are the same in both the repurposed and the newly constructed buildings. Notes: CMU stands for *concrete masonry unit*. Service assemblies include elevators, air conditioning units, water heaters, roof drainage pipes, and piping for the water supply and sewage.

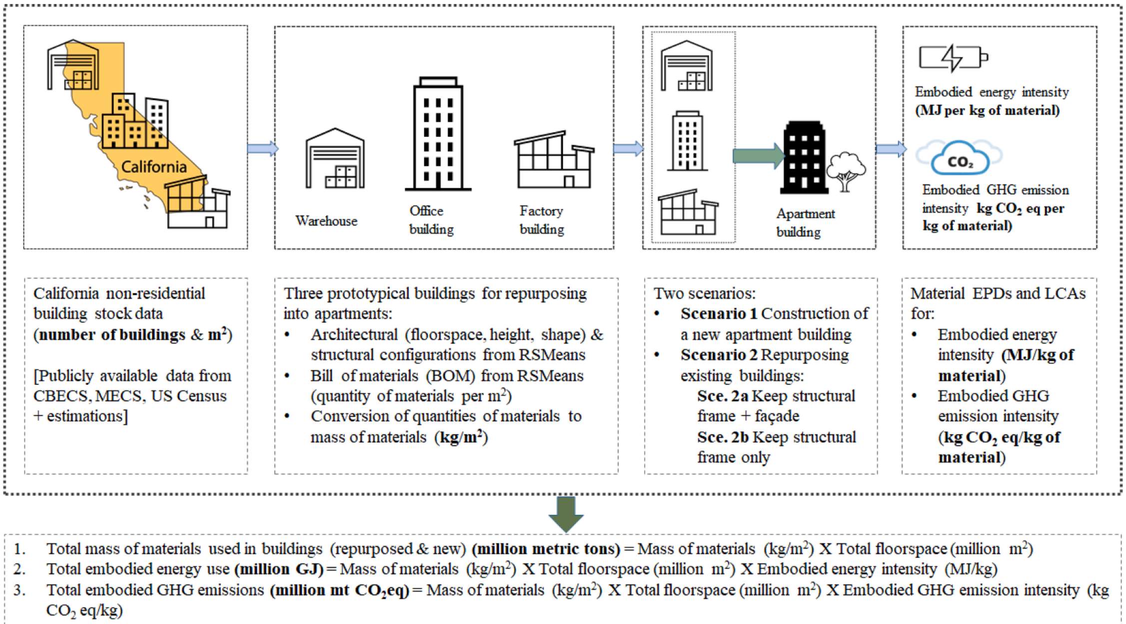

Fig. 2. Description of the approach used in calculating embodied energy and associated GHG emissions from commercial buildings selected for repurposing into apartment buildings in California.

embodied energy use and associated GHG emissions (corresponding to A1-A5 stages in Figure SI 1) for candidate commercial and industrial buildings repurposed into representative apartment buildings in California.

2.3. Estimation of non-residential building stock eligible for repurposing in California

Total floor space and total number of non-residential buildings (office + warehouse + manufacturing) that would be eligible for repurposing in California is estimated on the basis of approach described in SI-Section 1:

Total floor space and total number of non-residential buildings (office + warehouse + manufacturing) that would be eligible for repurposing is, therefore:

$$\begin{aligned}&\textit{Total number of candidate nonresidential buildings}\\&=\textit{Number of office buildings}+\textit{Number of warehouses}\\&+\textit{Number of manufacturing buildings}=\ 90,000+108,000+35,000\\&=233,000\ \textit{buildings}\end{aligned}$$

$$\begin{aligned}&\textit{Total floor space of candidate nonresidential buildings}\ \left(m^2\right)\\&=\textit{Floor space by office buildings}+\textit{Floor space by warehouses}\\&+\textit{Floor space by manufacturing buildings}\\&=0.14\ \textit{billion}+0.20\ \textit{billion}+0.17\ \textit{billion}=0.51\ \textit{billion}\ m^2\end{aligned}$$

Based on the 2021 U.S. Census housing data, median floorspace for a multifamily housing unit in the Western census division is given as 1032 ft^2 (96 m^2) (U.S. Census, 2022). For 10% and 100% conversion (for all office, warehouse, and industrial buildings) rates, that would translate into 500,000 and 5,000,000 units, respectively.

As another datapoint, the Urban Footprint Base Canvas (DiStefano and Calthorpe, 2022), using parcel-based existing land use data, identified 376,000 commercial properties (commercial and industrial together) across California. This estimate included main-street properties in small towns, strip commercial corridors, large, big-box sites on the edges of town, high-rises and skyscrapers in downtown San Francisco and Los Angeles, and more. Of the overall 376,000 commercial parcels statewide, it was found that 42% (159,000 parcels) met the State's adaptive reuse eligibility criteria (according to AB 2011, the Affordable Housing and High Road Jobs Act of 2022). These properties would be projected to introduce 0.44 billion m^2 of land for residential development, that is, roughly 0.1% of California's total land area (DiStefano and Calthorpe, 2022).

3. Results and discussions

3.1. Results for candidate prototypical buildings

Earlier studies analyzed embodied energy and GHG emissions from repurposing of single building case studies in Canada and Europe (Sanchez et al., 2019; Assefa and Ambler, 2017; Ferreira et al., 2015; Marique and Rossi, 2018; Feng et al., 2020). As described above, our embodied energy and GHG analysis was built on representative and geographically consistent building materials data and the most-recent EPDs, yielding relevant and transparent results.

Structural and architectural designs of the repurposed buildings and the newly constructed apartment building are noticeably different based on the RSMeans BOM data:

- The prototypical reinforced concrete warehouse building has a precast concrete façade with smaller windows that take up only 12% of the apartment window surface area. Another notable difference between the apartment and the warehouse building is the interior walls, since apartments require more partitions to serve their purpose as residential spaces as opposed to a warehouse's open space configuration. Partition walls take up 1650 m^2 versus 220 m^2 of surface area in the apartment building and the warehouse, respectively.
- The prototypical steel industrial building has a tilt-up concrete panel façade with window openings that correspond to 60% of window surface area of an apartment building. Partition walls cover 558 m^2, which is around 1/3 of apartment building interior walls.
- The prototypical reinforced concrete office building has a precast concrete façade with windows corresponding to 90% of the apartment window surface area. Partition walls cover 1040 m^2 of office space, which is around 2/3 of the apartment building interior walls.

Structural materials (concrete, steel, and wood together) add up to 72%, 80%, 85%, and 77% of the total mass of the warehouse, factory, office, and the apartment buildings, respectively (Fig. 3). The remaining mass percentage consists of façade, interior partition walls, ceiling/floor/wall finishes, and service assemblies.

Embodied energy and GHG emissions were estimated by coupling material quantities with their related energy use and carbon dioxide equivalent (CO_2 eq) intensities obtained from environmental product declarations (EPDs) (SI Table 5). Depending on the non-residential building type, about 60%–78% of energy is embodied in structural components of reinforced concrete or steel frame (Figure SI 3). For apartment buildings with wood structure, this percentage is comparably low at 54%.

The non-residential buildings' structure and substructure constitute the largest source of embodied GHG emissions, ranging from 63% to 70%, depending on the building type, attributable to large quantities of concrete and steel used. For the apartment building, structural components result in only 34% of the total GHG emissions due to lower CO_2 eq associated with the wood frame (Fig. 4).

Embodied energy and GHG emission results from the analysis are in the range of the findings (50%–67%) from the only comparable published study (Assefa and Ambler, 2017).

Repurposing can be accomplished with material investments amounting to 550 and 570 mt - corresponding to building floorspace (3,716 m^2) times mass per area (Fig. 3), 7790 and 8220 GJ of embodied energy - corresponding to building floorspace times energy per area (SI Figure 3), and 540 and 690 mt CO_2 eq of embodied GHG emissions - corresponding to building floorspace times GHG emissions per area (Fig. 4) for scenarios 2.a and 2.b, respectively. Overall, 10,300 and 9900 GJ of energy (~56%), 500 and 360 mt CO_2 eq (48% - 34%), and 1490 and 1470 mt of materials (~72%) can be avoided relative to building a new apartment building compared to Scenario 2.a and Scenario 2.b, respectively (Fig. 5, SI Figures 4–5).

Most notably, not replacing the façade (exterior wall system) in a repurposing project only modestly improved the material mass and embodied energy numbers, while the impact on CO_2 eq savings is much more pronounced. Repurposing an existing non-residential building into an apartment building would save 360 mt CO_2 eq (96 kg CO_2 eq. per m^2) if the existing structural frame and the foundation are kept instead of constructing a new apartment building. The savings would go up to 500 mt CO_2 eq. (135 kg CO_2 eq. per m^2) if the existing structural frame, foundation, and façade system (Scenario 2.a) were kept (Fig. 5). The difference (~140 mt CO_2 eq) between Scenario 2a and 2b is attributed to the removal and construction of a new façade.

3.2. Results for total embodied energy and GHG emissions avoided via adaptive reuse of candidate buildings into apartments in California

If the buildings identified as candidates for adaptive reuse were repurposed into housing, they would provide 51–510 million m^2 of floor space (calculated in Section 2.3) towards addressing housing needs in California. We have estimated that there are about 233,000 non-residential buildings (office + warehouse + manufacturing) in California. Based on the percentage of total floor space conversion (10% increments) at the state level and two repurposing scenarios, avoided material use, embodied energy and GHG emissions are shown in Table 1.

When 233,000 non-residential (office, warehouse, and industrial) buildings are adapted for reuse as residential buildings in California, housing for about 5 million households is generated. Depending on the percentage of floor space converted, around 20 million (for 10% floor space) to 204 (for 100% floor space) million mt of materials can be avoided (Figure SI 6). Similarly, avoided energy and GHG emissions are estimated to be around 0.14 billion – 1.4 billion GJ and 5.0 million – 70 million mt CO_2eq, respectively (SI Figures 7–8). For context, in 2020 California's GHG emissions were 369 million mt, 23% (85 million mt) and 10% (37 million mt) of which were from the industrial and the buildings (commercial and residential) sectors, respectively (CARB, 2023). In all three figures, savings are shown to be higher if the existing structural frame, foundation, and façade system were kept (Scenario 2.a, represented with gray-, dark blue- and teal-colored bars in each figure, compared to Scenario 2.b, represented with yellow, light blue-, and orange-colored bars) than if only the structural frame and foundation

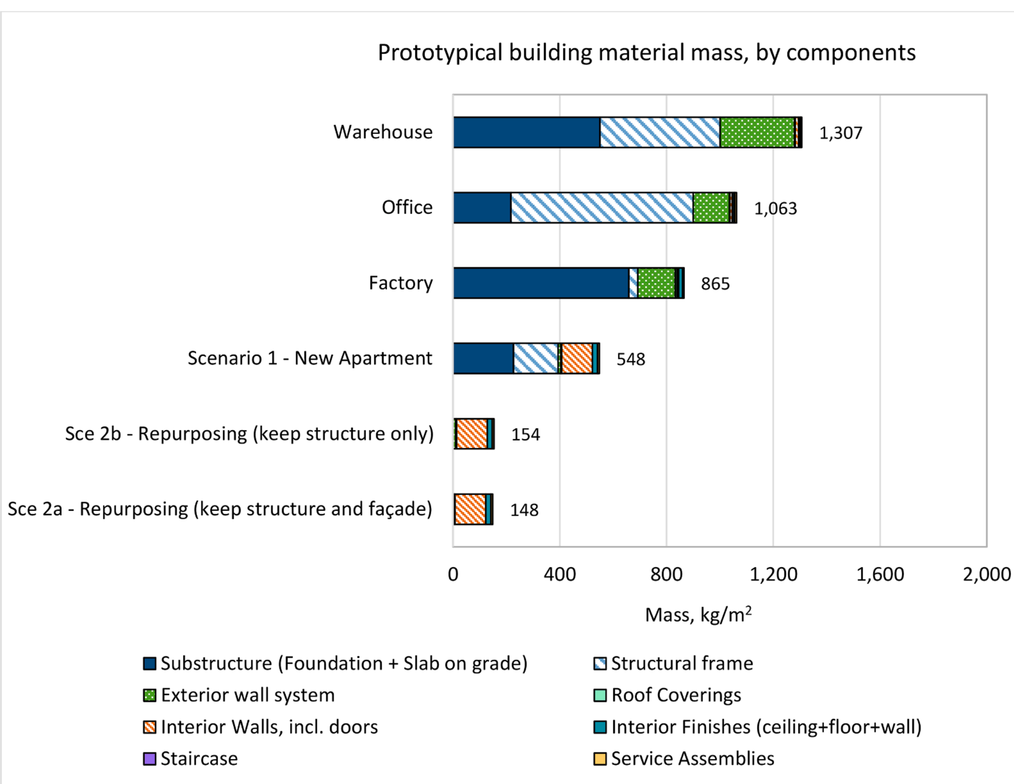

Fig. 3. Contribution of building components to mass per floor space of three prototypical commercial buildings, a new apartment and repurposed apartment buildings in California.
Notes: Scenario 1: Construction of a new apartment building; Scenario 2: Repurposing an existing commercial building into an apartment building by keeping: (Scenario 2.a) Structural components and façade (replace windows only due to residential building requirements), and (Scenario 2.b) Structural components only and replace everything else.

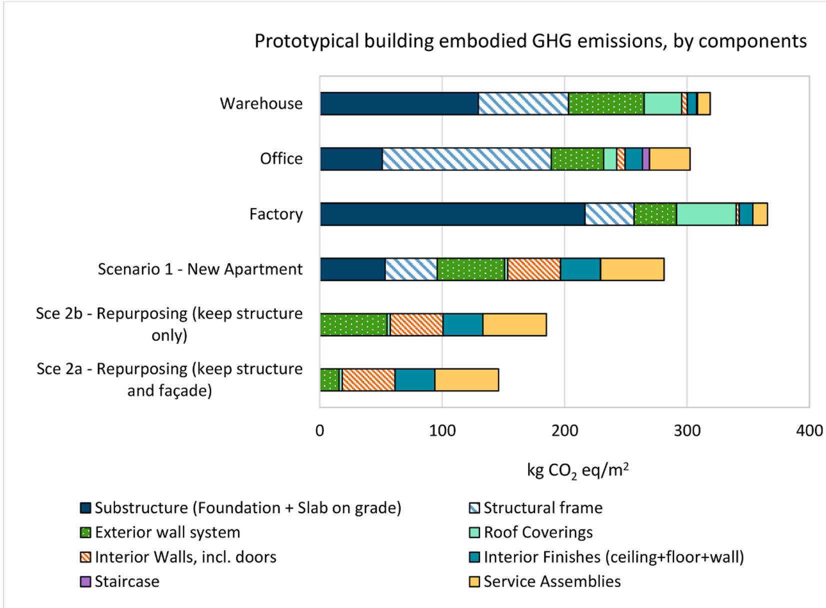

Fig. 4. Comparison of embodied GHG emissions per floor space by building components of three prototypical commercial buildings, a new apartment and repurposed apartment buildings in California.

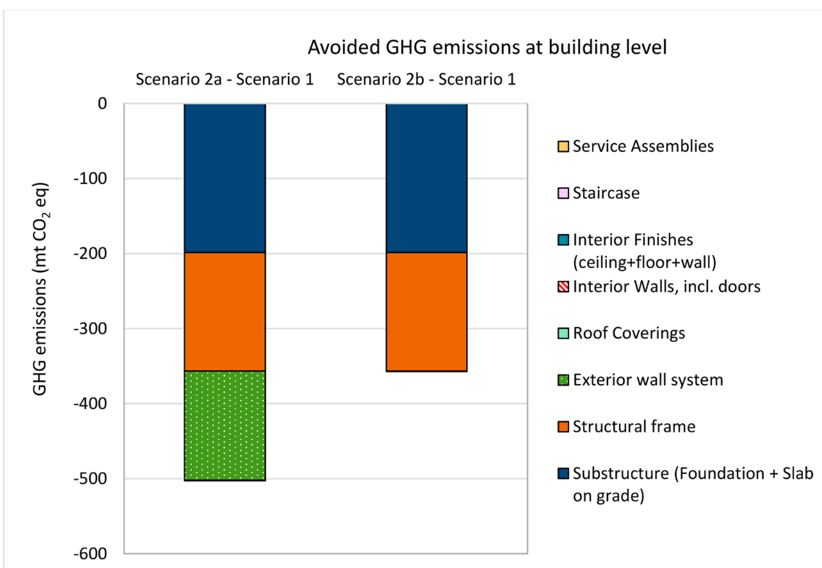

Fig. 5. GHG emissions avoided by selecting Scenario 2 (repurposing) over Scenario 1 (construction of new apartment building) in Californian case study.

Table 1
Mass of building materials, embodied energy, and GHG emissions avoided through converting California's selected non-residential (office + warehouse + manufacturing) buildings to apartment buildings at the state level.

Floor space Conversion%	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
# of buildings converted	**23,300**	**46,600**	**69,900**	**93,200**	**117,000**	**140,000**	**163,000**	**186,000**	**210,000**	**233,000**
Floor space converted (million m^2)	**51**	**102**	**153**	**204**	**255**	**306**	**357**	**408**	**459**	**510**
Materials avoided (million mt), Scenario 2.a.	(20.4)	(40.8)	(61.2)	(81.5)	(102)	(122)	(143)	(163)	(184)	(204)
Materials avoided (mt), Scenario 2.b.	(20.1)	(40.2)	(60.3)	(80.4)	(101)	(121)	(141)	(161)	(181)	(201)
Embodied energy avoided (million GJ), Scenario 2.a.	(141)	(283)	(424)	(566)	(707)	(849)	(990)	(1130)	(1270)	(1410)
Embodied energy avoided (million GJ), Scenario 2.b.	(136)	(271)	(407)	(542)	(678)	(813)	(949)	(1080)	(1220)	(1360)
Embodied GHG emissions avoided (million mt CO_2eq), Scenario 2.a.	(6.90)	(13.8)	(20.7)	(27.6)	(34.5)	(41.4)	(48.3)	(55.2)	(62.1)	(69.0)
Embodied GHG emissions avoided (million mt CO_2eq), Scenario 2.b.	(4.90)	(9.80)	(14.7)	(19.6)	(24.5)	(29.4)	(34.3)	(39.2)	(44.1)	(49.0)

were saved, and the rest of the building was replaced.

3.3. Uncertainties in modeling and data

The purpose of this study was to analyze and compare embodied energy and GHG emissions of repurposing existing representative non-residential buildings versus constructing new apartment buildings using a comprehensive and transparent approach. All data sources can be accessed by the readers. Uncertainties are inevitable and result mainly from the following:

- Quantity units obtained from BOM in RSMeans were converted to mass units for the purposes of comparison and coupling with functional units defined in EPDs. Such conversions require the use of unit mass factors (e.g., mass per surface area, mass per volume, mass per piece, mass per length) as described in EPDs and/or product description labels.
- When quantities of materials and their configuration were not explicitly given in the BOM, we estimated the quantities based on the descriptions and component dimensions provided in the RSMeans database. These materials include concrete and reinforcing steel bars (rebars) used in structural components (beams, columns, foundation, and slabs); studs in wall assemblies; roof geometry and configuration; and the grid system for water/sewage pipes, etc. See Tables SI 1–4).
- When EPDs for certain components or materials were 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 a building's life cycle may hinder the development of an accurate LCA. This is because buildings are more complicated than a single product with a comparatively long life and multiple functions, and would often undergo various changes (Chau et al., 2015).
- While uncertainty information is available in some LCI datasets, it is not available in published EPDs. In a recent study by Waldman et al. (2020), concerns were raised regarding the transparency of EPDs. These concerns stem from data quality issues, such as the overuse of generic data sets, limited availability of data, and poor reliability of results due to uncertainty. Additionally, the lack of common data sources and the use of point estimates without confidence intervals or margins of error further exacerbate the issue. As a result, it is important to exercise caution when comparing EPDs and evaluating their data quality and specificity.
- The estimation of floorspace, number, and type of non-residential buildings in California required a series of assumptions and various sources of data.

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 do not appear to be significant. We reported the results to two significant digits at state level and in the figures and to three digits in Table 1.

4. Discussion of benefits and challenges of repurposing

Adaptive reuse (or building repurposing) projects have their own benefits and challenges just like many other projects.

4.1. Benefits of repurposing buildings

Major benefits include:

- Through adaptive reuse (repurposing), underutilized non-residential buildings can provide much-needed housing without additional land, urban sprawl, and need for energy and water lines. (Additional transportation services may be needed.)
- With higher occupancy rates, the repurposed buildings can accommodate more persons without the need for additional new construction.
- The construction process may be quicker than for typical new construction, but it depends on the availability and experience of construction crews.
- Savings of construction costs are likely by reusing the existing structure, façade, and some building components (such as elevators) and finishes.
- Repurposing can create environmental benefits. As there is no need to demolish the structure and other building components in which large material volumes are embodied, reductions in material use, their embodied impacts (mainly of carbon- and energy- intensive materials such as concrete and steel, and throughout the supply chains), and landfilling of materials can be achieved.

4.2. Challenges of repurposing buildings

Repurposing non-residential buildings into housing has its challenges, too:

- The non-residential (office, warehouse, industrial) buildings are designed and built differently, and it is challenging to maximize the space in the repurposed buildings. These buildings have different cores than newly designed buildings, such as columns in the middle of the living room.
- Office buildings with glass facades are a challenge to convert into apartments because of potential lack of desired privacy and thermal insulation.
- Repurposed floorplan layouts may be unconventional for fitting typical furniture setups.
- A repurposed building could have a shorter lifespan than a brand-new building because of the reuse of structural elements. (However, since the prototype buildings used in this analysis are typically demolished not because of structural problems, but because of functional obsolescence, this may not matter much.) It is important to note that this study estimates the upfront embodied carbon of building materials that correspond to the cradle-to-site, A1-A5, stage. The estimation of emissions from the EOL as well as the operational stage of repurposed and new buildings is considered beyond the current work.
- Typical construction challenges are also prevalent when converting buildings, especially older ones. This includes discovered water damage, structural issues relating to floors and bearing walls, dilapidated roofing, and weathered brick or granite. Depending on the age and condition of the existing buildings, these challenges would require either simple or complicated and expensive solutions.
- The construction process may be slower than for typical new construction (for the reasons mentioned above, for lack of experienced contractors, and for unforeseen circumstances discovered during the rebuilding process).

Overall, the existing condition as well as the location of the respective building should be evaluated carefully in assessing the economic, social, and environmental aspects of repurposing.

4.3. Policy implications

Converting available non-residential buildings into apartment units by repurposing them can be a useful solution for creating quality housing in areas where vacant sites for new developments are limited. It is essential that any solution to the housing shortage also considers the reduction of GHG emissions. The success of a sustainable adaptive reuse strategy depends on various factors that can either help or hinder the process as each property has its unique set of circumstances. The existing building's structure determines the feasibility and cost of conversion, so not every commercial property is suitable for redevelopment. Buildings with specific architectural characteristics, such as shallow floor plates, generous exterior exposure, or unique building features are especially conducive to adaptive reuse (Garcia and Kwon, 2021).

Assessment of the environmental advantages of the repurposing strategy requires adequate knowledge and integration of the different fields involved, such as energy use and associated GHG emissions from building construction and renovation, transportation of building materials, and the electricity grid mix, in addition to community engagement, urban development, as well as economic, structural, and architectural factors. While repurposing buildings for housing may present certain challenges, implementing clear policies that address building code requirements and streamline the permitting process can help increase its effectiveness in meeting housing goals.

5. Conclusions

The results show that the environmental viability of repurposing a building compared to the traditional cycle of constructing a new building is clear. This pathway is also promising to address the housing shortage in urban areas. There is a substantial stock of non-residential buildings that is possibly underutilized, especially after the COVID-19 pandemic, as a result of lifestyle adjustments and widespread shift to remote work and shopping.

This assessment of the environmental implications of converting an estimated 233,000 non-residential buildings (510 million m^2 of floor space, generating housing for about 5 million households) into residential space demonstrates significant avoided building materials use, embodied energy, embodied GHG emissions, and landfilling construction and demolition waste. Depending on the eligibility of the selected non-residential buildings, in terms of percentage of repurposed floor space (from 10%, 500,000 units, up to 100%, 5 million units) and selection of adaptive reuse scenario (Scenario 2.a. and Scenario 2.b.), 0.14 – 1.4 billion GJ of embodied energy and 5.0–70 million mt CO_2eq of GHG emissions would be avoided by converting the selected buildings into housing units.

It is important to note that the prototypical case buildings and their BOMs that form the basis of this analysis are representative of medium-sized office, warehouse, and industrial buildings in California. EPDs used in quantification of embodied energy use and GHG emissions from building materials and components are also representative of materials-manufacturing practices throughout California. However, in addition to energy and environmental assessment, life-cycle cost and societal aspects of this strategy should also be studied.

CRediT authorship contribution statement

Aysegul Petek Gursel: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Visualization, Writing – original draft. **Arman Shehabi:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision. **Arpad Horvath:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare no competing interests.

Data availability

Data is already shared in the Supplementary Information document.

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Supplementary materials

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