Chapter 3

Teardown Index:

Emissions of Single-Family Homes in Vancouver

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ABSTRACT

Replacing older homes with new ones constructed to higher efficiency standards is one way to raise the operating efficiency of building stocks. However, new buildings require large amounts of embodied energy to construct, and it can take years before more efficient operations offset carbon emissions associated with new construction. This chapter looks at the carbon dioxide emission payback period of newly constructed, efficient single-family homes in Vancouver, British Columbia, where the authors find that it takes over 150 years for the operation to equal the embodied carbon associated with the of a typical high-efficiency new home. The findings suggest that current policies aimed at reducing emissions by replacing older homes with new high-efficiency buildings should be reconsidered.

DOI: 10.4018/978-1-7998-2426-8.ch003

INTRODUCTION

Buildings are significant drivers of climate change, generating one-third of global greenhouse gas emissions. Despite their widely acknowledged contribution to climate change, the design of green buildings does not always rest on evidence-based practices, and the policies governing green design frequently lack sound scientific judgment that delivers measurable environmental outcomes. For example, increased efficiency is often used as a justification for new green buildings. Replacing older, inefficient buildings with architecture designed to meet more stringent performance standards can indeed raise the overall operating efficiency of building stocks. However, it can take years before the embodied greenhouse gas emissions incurred by the new construction are offset by their more efficient operation. This chapter investigates the carbon dioxide emission payback period of newly constructed, efficient single-family homes in Vancouver, Canada, using it as a case study. The methods of the study can be applied to different contexts. The chapter finds that the carbon dioxide emission payback period for new homes meeting current efficiency standards in Vancouver averages 168 years, despite forty percent increases in operational efficiency over existing single-family homes. The length of this carbon payback period suggests that replacing older single-family homes with high-efficiency homes in Vancouver adds to—rather than reduces—overall emissions.

Rising carbon emissions in the face of aggressive performance standards can be explained by the fact that environmental performance is only one of many competing factors influencing decision-makers. Rising property values often compel property owners to tear down and replace older buildings as they seek to capitalize on growing market demand. In this scenario, more efficient building operation is, at best, a positive externality. A statistical model called the Teardown Index is presented, which correlates rising land value to increases in carbon emissions. This model indicates that replacing older poorly performing homes with new high-efficiency homes in Vancouver will result in 1.3–2.8 million tonnes of additional carbon dioxide equivalent emissions between 2017 and 2050. For each percent increase to the compound annual growth rate of property values, an additional 150 thousand tonnes of CO_2 equivalents will be released between 2017-2050. The findings suggest that current policies in Vancouver aimed at reducing emissions by replacing functional buildings with new high-efficiency buildings, while well-intentioned, should be reconsidered.

The research presented suggests that land economics have a significant impact on overall emissions from the built fabric due to their influence on construction cycles. The methods used in the study can be applied to other contexts to determine the carbon dioxide emission payback period when replacing existing structures. However, the carbon payback period of buildings is highly context-specific, and the results will vary greatly from region to region. Many factors influence initial embodied carbon emissions, operating carbon emissions, and the longevity of structures. These factors include the type of construction materials and methods (e.g., wood-frame or masonry), envelope design, morphology (single-family vs. multi-unit residential), climate (severe or mild), and the available energy sources (e.g., coal-fired versus hydroelectricity), each of which can affect the carbon payback period. The chapter concludes by looking at the relative effect of these factors on the conclusions reached for Vancouver and their influence on the applicability of the findings to different contexts.

BACKGROUND AND CONTEXT

Carbon dioxide (CO_2) emissions are significant drivers of climate change, which constitutes an intensifying threat to human and natural systems (IPCC 2014c). Buildings generate one-third of global greenhouse gas (GHG) emissions (Ürge-Vorsatz et al. 2007; Pérez-Lombard et al. 2008; IEA and OECD 2016; De Wolf et al. 2017) and consume approximately 30% of secondary energy. GHG emissions from buildings have more than doubled since 1970, and are projected to double or triple by 2050 (IPCC 2014a). Reducing CO_2 emissions of buildings will be a key component to meeting the Intergovernmental Panel on Climate Change (IPCC) recommendations, which call for the reduction of CO_2 emissions by a factor of 4 to prevent irreversible changes to climate (IPCC 2014b).

Operating and Embodied Impacts

Buildings cause environmental impacts at every stage of their life cycle, from construction to operation and maintenance, to decommissioning at end-of-life (Cabeza et al. 2014). Operating impacts refer to environmental impacts produced by basic building operations, such as heating and cooling, lighting, appliances and equipment, and plug loads. Embodied impacts refer to the environmental impacts associated with constructing the buildings themselves. Embodied impacts include upstream effects associated with producing construction materials, such as extracting raw materials, processing, and manufacturing, as well as the impacts of the construction itself, which include transporting materials to a site and assembling them. Finally, embodied impacts include maintenance or replacement of components during the useful life of the building, as well as decommissioning, disassembly, and recycling or disposal at the end of life (Reddy and Jagadish 2003).

Quantifying operating and embodied impacts requires a consistent methodology to ensure accurate assessments and comparisons. Methods for measuring the embodied impacts of buildings have been reviewed by many authors (Treloar et al. 2003; Menzies et al. 2007; Dixit et al. 2010; Chang et al. 2010; Abanda et al. 2013) and can be broadly categorized into (1) input-output, (2) process and (3) hybrid-based analysis. Life Cycle Assessment (LCA), which is a leading internationally accepted method that can be used to compare the environmental impacts of similar products or services (ISO 2006), is becoming among the most commonplace metric used for buildings. LCA has been employed to compare the cumulative operating and embodied impacts of buildings on the environment during all lifecycle stages, from products and assemblies to construction, use, end-of-life and beyond (Buyle et al. 2013; Pomponi and Moncaster 2016).

Although LCA is governed by ISO standards, comparisons across studies can be complicated due to a lack of agreement about system boundaries. These unresolved debates include whether to measure primary versus secondary energy or account for indirect as well as direct effects of resource use (Huijbregts et al. 2004; Lloyd and Ries 2007; Bribián et al. 2009; Dixit et al. 2012; Ibn-Mohammed et al. 2013). Also, Pomponi and Moncaster (2016) demonstrate that the duration investigated in LCAs varies. 90% of existing LCAs cover less than 60% of a building's life cycle stages, and often little data is available on the use and end-of-life stages. The same study also demonstrates that the lack of consistency in system boundaries (Matthews et al. 2008) and varied assumptions yield strong variations in results that prevent effective benchmarking across studies. Haapio and Viitaniemi's (2008) analysis of 17 environmental assessment tools concludes that comparing different LCAs is "difficult, if not impossible" due to variations in building types or lifecycle stages between studies, and a general lack of methodological transparency. Despite these challenges, LCA studies of buildings can provide a useful approximation of the impacts of buildings on the environment, particularly as regards the relationship of operating to embodied impacts. A survey of 73 LCA's of conventional (as opposed to high-performance) residential and commercial building indicates that operating impacts typically account for between 75-90% of environmental effects over a period of 50 years (Ramesh et al. 2010; Cabeza et al. 2014).

The Interrelation of Operating, Embodied, and Total Impacts

Current policies aimed at reducing the environmental impacts of buildings in North America and Europe have focused exclusively on operating impacts (Dixit 2017), in keeping with their dominant contribution to overall impacts. However, focusing exclusively on operating impacts remains, at best, an incomplete strategy, which fails to acknowledge the interrelationships between operating and embodied impacts. For example, a common method of reducing operating energy is to increase insulation, which adds to the embodied impacts of the building (Sartori and Hestnes 2007).

Research has shown that embodied impacts can reach up to 60% of total impacts in high-efficiency houses (Thormark 2006; Sartori and Hestnes 2007; De Wolf 2014). As building operations become more efficient, reducing the total impacts of buildings will require a thorough understanding of the relationship of operating to embodied impacts.

Emission Payback Period

The relationship between operating and embodied impacts can be understood in terms of its payback period, a term borrowed from finance that refers to the length of time required to recover the cost of an initial investment. We use the term "emission payback period" to refer to the length of time required for the reductions to operating CO_2e emissions to equal the initial "investment" of embodied CO_2e (carbon dioxide equivalent) emissions released during upgrades required to improve efficiency. The emission payback period is a function of the amount of embodied CO_2e emissions released, the time it takes for the consequent reductions to operating CO_2e emissions to equal the embodied impacts, and the service life of the new building or renovation. For example, Verbeeck and Hens (2010b) show that in the Belgian context, the embodied impacts of upgrading building envelopes with additional insulation are paid back in less than three years by reduced energy consumption. Once the initial investment of embodied CO_2e emissions are recovered, reductions to overall CO_2e emissions result. The CO_2e emission payback period can also illustrate the ineffectiveness of certain measures. For instance, Huang et al. demonstrate that shading devices on a particular Hong Kong building facade have a minimal effect on energy consumption and never achieve payback, adding to CO_2e emissions over the life of the building, rather than reducing them (Huang et al. 2012). A growing body of literature attests to the importance of assessing the emission payback period of environmental impact mitigation strategies (IPCC 2014a), which makes it possible to assess the viability and effectiveness of potential environmental impact mitigation strategies.

Case: Vancouver, BC

We use the emission payback period to assess the environmental effects of the recent development of single-family homes (SFHs) in Vancouver, Canada. Between 2005-2017, residential property prices in Vancouver increased by 261%, with a 28% price increase in the last three years alone (Real Estate Board of Vancouver 2017). This dramatic rise in property values has produced Canada's most expensive real estate (Holzhey and Skoczek 2016). One result of rapidly escalating property values is that increasing numbers of older SFH are torn down and replaced as owners seek to maximize property values in areas where nearly all available lots are already built out. Between 1985 to 2017, 26,800 SFH, or 40% of all SFHs in residentially (RS) zoned areas, were demolished and replaced with new SFH (BC Assessment 2015b, von Bergmann and Dahmen 2016). BC Assessment standards dictate that when 65% or more of a home is replaced, it is considered new construction; less than 65% is considered a renovation. During the period of 2005-2011, 97% of all permitted construction activity in BC was above the 65% standard; only 3% of construction activity consisted of renovations or 206 of 6521 permits issued (BC Assessment 2015b). The data shows that complete teardown and replacement of existing SFH is currently the dominant approach in the Vancouver context.

Replacing older building stock with newer buildings constructed to higher efficiency standards in Vancouver is often defended by local authorities on the grounds that it reduces operating emissions, despite numerous studies that have shown renovation to be an effective strategy for reducing operating emissions (Ma et al., 2012; and Rysanek and Choudhary 2013). It is generally (though not always) true that new buildings built to higher energy standards reduce operating emissions. In the case of RS-zoned areas of Vancouver, new SFH must meet aggressive efficiency performance standards that restrict the CO_2e emissions of new homes to 12 kg $CO_2e/m^2/yr$, from the 2007 baseline of 23 kg $CO_2e/m^2/yr$ (Vancouver 2016). This represents a nearly 50% gain in efficiency, which is substantial. At least one study has shown that similar gains could also be realized through renovation instead of total replacement (Mohammadpourkarbasi and Sharples 2017). However, approximately 97% of all SFHs in Vancouver consist of wood-frame construction, with older homes insulted minimally or constructed without insulation altogether. The relatively poor quality of typical wood-frame construction here results in renovations that preserve little more than the shell of the building, and frequently include pouring a new concrete foundation. While establishing the impacts of these deep renovations is beyond the scope of the current research, they likely approach that of new construction. When embodied emissions are considered, the environmental justification for both total replacement or deep renovation is questionable. What is the overall effect of teardown and replacement on total emissions for SFH in Vancouver? Answering this question requires calculating the emission payback period for the structures in question, at the scale of the individual building lot, and the city as a whole.

Research Contribution

This paper presents a method for assessing total CO_2e emissions resulting from SFHs in Vancouver, at the scale of a single building lot and the entire city. The method includes operating and embodied impacts, and the payback period required to offset embodied impacts through reductions to operating impacts is calculated. At the scale of the lot, the research compares the typical average environmental impact of a new SFH against the existing SFH it replaces, by calculating the emission payback period and comparing it to the impacts of the original structure. At the scale of the city, the research establishes a relationship between rising real estate values and changes to the replacement rate of SFHs in Vancouver. Finally, by applying the environmental impacts established in 1) to the correlation of real estate values with replacement rates in 2) enables us to 3) assess the impact of changing land values on the total CO_2e emissions of the city's SFH stock.

The research focuses exclusively on RS (Residential Single) areas of Vancouver, which at the time of writing are zoned for detached single-family and duplex homes with a secondary basement suite. New construction has only slightly higher rates of secondary suites than the existing stock, so new SFH construction adds few additional dwelling units to the overall supply in the city. Laneway homes can also be added to existing lots without impacting the main house, but we ignore them in this discussion, as their construction does not typically require demolition of an existing home. With few exceptions, available building lots in RS-zoned areas of Vancouver are completely built out. As a consequence, almost all new SFH construction in these areas follows the teardown of an existing SFH. As such, the RS-zoned areas of the city offer a unique opportunity to compare the environmental consequences of replacing existing buildings with more efficient buildings of the same type.

The research is motivated by a desire to create a method capable of establishing the total impacts of building replacement that accounts for embodied as well as operating impacts. The methods presented enable a more accurate assessment of impacts and outcomes associated with replacing older buildings with newer, more efficient structures, as well as the time required to realize any projected savings. Sound policymaking must rest on accurate information. The research will be of value to municipalities seeking evidence-based environmental policies to meet building emissions targets currently in place and, ultimately, to strengthen climate change mitigation efforts.

Materials and Methods

Assessing the environmental impacts corresponding to different rates of replacement of existing single-family homes requires three elements: 1) a method for establishing operating and embodied CO_2e emissions of new and existing SFH building stock; 2) a method for establishing the period of time, referred to as the "emission payback period" required to recover the CO_2e emissions released to build the new, more efficient building and 3) a model capable of predicting how many SFH will be replaced, to enable projected outcomes into the future at the scale of the city.

Although operating and embodied impacts include impacts on human health, ecosystem quality, natural resource use, and climate change and others, for the sake of simplicity, the study employs global warming potential (GWP), which indicates the contribution to climate change expressed in CO_2 equivalents (CO_2e) (Pomponi and Moncaster 2016). As defined by RS zoning, SFHs refer to detached homes, which includes duplex homes and auxiliary dwelling units where they occur on the same property, but excludes low- and high-rise multi-unit residential buildings.

Overview of Operating Emissions

Operating CO_2e emissions from SFHs in Vancouver come from two primary sources: electricity and natural gas. The latter is used primarily for space and water heating in homes where electricity is not used for those purposes. Estimating operating CO_2e emissions requires establishing usage rates for electricity and natural gas, and then converting energy usage in each category to associated CO_2e emissions based on geographically specific conversion factors determined by the methods used to produce the energy from primary sources. Approximately 66% of SFH energy demand in Vancouver is met by electricity, of which 98% is produced from low-carbon renewable sources such as hydroelectricity (BC Hydro 2017). The uncommonly high percentage of renewable energy in Vancouver means that emissions per unit of energy consumed in the city are lower than regions that rely on non-renewable, high-carbon sources of energy. Determining energy consumption for existing buildings or new construction requires different methods, as indicated below.

Operating Emissions of Existing Buildings

Establishing the operating CO_2e emissions associated with existing SFHs of different vintages in Vancouver is difficult due to a lack of specificity about the age and location of buildings in available data sets documenting actual energy use. However, a reasonably accurate account of operating CO_2e emissions of SFH by vintage can be achieved through comparison and extrapolation of available consumption data sets. Energy consumption by end-use (e.g., space heating, lighting, etc.) and typical energy source (gas, electricity) for SFHs in Lower Mainland, (the region surrounding and including Vancouver), was obtained from BC Hydro and Power Authority (BC Hydro), which supplies electricity to Vancouver (Appendix: Table 4, Young 2017). BC Assessment data was used to calculate the areas of SFHs in the Lower Mainland, (BC Assessment 2015b), so that energy consumption data by end-use and energy source could be converted to consumption per area (Appendix: Table 5). This yielded a general picture of consumption rates across all vintages.

Space heating and ventilation energy requirements per square meter account for 48% of SFH energy demand in Vancouver. To generate vintage-specific operating CO_2e emissions, emissions from these sources were adjusted using gross thermal output by vintage cohort and by building type data. The raw data was drawn from the Natural Resources Canada Comprehensive Energy Use Database (CEUD) (Natural Resources Canada 2014) for SFHs across BC (Appendix Table 6). The CEUD database indicates that gross thermal output across Canada varies widely by building vintage, with older buildings generally consuming more thermal energy. The remaining end-use categories (hot water, space cooling, appliances, lighting, electronics, and other) were held constant across vintages, as it was assumed that consumption in these categories does not vary significantly by the age of the building. Finally, the average consumption of natural gas and electricity per square meter was calculated by vintage for SFH in the Lower Mainland. (Appendix: Table 7). This secondary energy data was converted to primary energy, scaling up consumption by factors of 2.05 for electricity and 1.02 for natural gas (Energy Star 2013) to account for the energy required to extract, process, and deliver the fuel to the building (Deru and Torcellini 2007). Carbon emissions associated with electricity and gas use were calculated using regionally-specific environmental impact conversion factors provided by the British Columbia Ministry of Environment (British Columbia 2016). As a final step, the data was checked for accuracy by comparing it with the Vancouver Community Energy and Emissions Inventory (British Columbia, 2012), which measures aggregate CO_2e emissions at the municipal scale, but does not differentiate by building type or age. The aggregate operating CO_2e emissions calculated were found to be within 10% of the Vancouver Community Energy and Emissions Inventory, which was deemed acceptable.

The operating energy data sets considered demonstrate that operating energy consumption, and the corresponding CO_2e emissions, generally vary with building age in the Canadian context. This finding is supported by previous studies (by Swan and Ugursal 2009; Kavgic et al. 2010; Tooke et al. 2014a; Tooke et al. 2014b), which have demonstrated the viability of using building age as a predictor of energy consumption and GHG emission rates for bottom-up and archetypical analyses of multiple buildings. The operating emission rates of Vancouver SFHs by vintage (using NRCan's CEUD vintage cohorts) are summarized in Table 1.

Operating Emissions of New Buildings

Operating CO_2e emissions for newly built SFHs are assumed to follow guidelines established by the Zero Emissions Building Plan (ZEBP, Vancouver 2016), a municipal policy first proposed in Vancouver in 2016. While the policy is still under review, it establishes an aspirational municipal emission target that will exceed

Table 1. Vancouver SFH primary operating CO_2e rates and area metrics by vintage

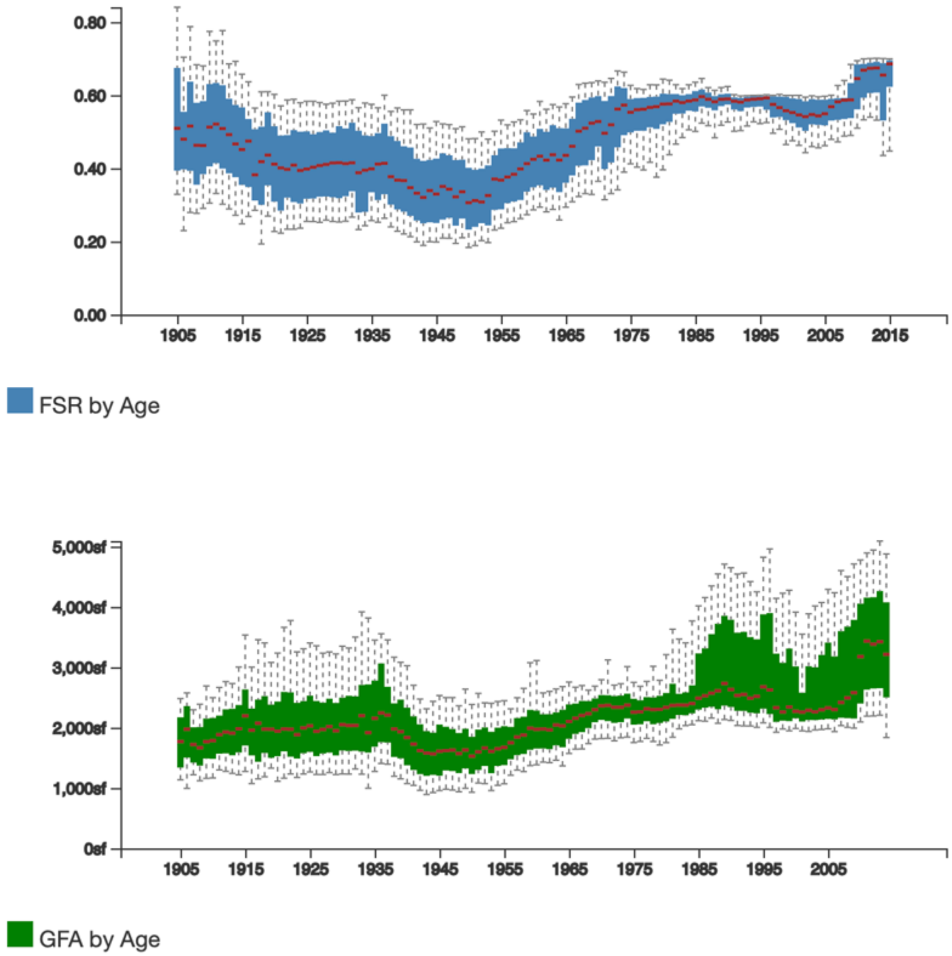
Vintage	Operating Carbon Emissions ($kgCO_2e/m^2/$year)	Number of SFH	SFH Internal Floor Area (m^2)	Average Lot Area (m^2)	Average Unused Buildable Area (m^2)
Prior to 1946	**15.42**	20,147	266	499	108
1946–1960	**14.17**	10,606	220	499	154
1961–1977	**12.43**	9,014	259	467	91
1978–1983	**11.00**	3,180	304	432	20
1984–1995	**9.78**	11,909	411	502	-34
1996–2000	**8.74**	3,227	357	487	8
2001–2005	**8.56**	3,447	316	475	40
2006–2010	**7.99**	2,938	368	493	1
2011–2017	**7.74**	3,468	392	520	-2

Source: Dahmen, von Bergmann and Das (2017), derived from data from the following sources: BC Assessment (2015b), Natural Resources Canada (2014), Energy Star (2013) British Columbia (2012), Eddie Young (BC Hydro).

provincial requirements in British Columbia. The ZEBP mandates that SFH built from 2020 to 2025 emit at most 7 kg CO_2e/m^2/year, or approximately 50% less than SFH constructed prior to 1946. Allowable operating carbon emissions of SFH will be reduced to 0 kg CO_2e/m^2/year after 2025. The research assumes that SFHs built from 2017 to 2020 will emit at the same rate as SFHs built from 2011 to 2017.

Although the ZEBP reduces operating CO_2e emissions for newly built SFHs on a per square meter basis, the average single-family home is growing in size. The average single-family homes built since 2000 has an internal space of 359m^2, a gain of 16% when compared to the average internal size of SFH's constructed prior to 2000. Homes constructed between 2011-216 contained 32% more internal space than homes constructed prior to 1946. Figure 1 below shows the rise in floor space ratio (FSR), which is the ratio of the total floor area of the home to the lot size of single-family homes constructed in Vancouver from 1905 - 2015. Almost all new single-family homes are now built to the maximum FSR, which is the main metric the city uses to regulate the maximum size of a building. The rise in FSR beginning in 2009 corresponds to the laneway house legislation, which enabled property owners to build secondary structures on RS lots. Single-family homes are getting larger as a result of increased FSR. Gross floor area (GFA) is an absolute measure of building size. The increase in overall size mitigates somewhat the reductions to overall operating impacts of new construction brought about by the ZEBP and also increases the embodied impacts of new construction.

Figure 1. Floor space ratio and gross floor area in Vancouver 1905-2016
Source: Authors, derived from data provided by BC Assessment (2015b).



Embodied Emissions

Embodied CO_2e emissions can be divided into two categories: initial and recurring (Ibn-Mohammed et al. 2013). Initial embodied CO_2e emissions do not repeat and are predominantly concentrated in lifecycle stages preceding the use stage. Recurring embodied CO_2e emissions reflect the emissions resulting from maintaining, repairing, and replacing building components that have shorter lifespans than the overall building itself, such as the roof of exterior cladding.

Embodied Emissions of Existing SFHs in Vancouver

The materials required to replace existing SFHs with new buildings produce embodied CO_2e emissions that would not otherwise be incurred. Embodied CO_2e emissions are thus calculated for new construction, whereas the embodied CO_2e emissions of existing SFHs are considered to be a "sunk costs" and are not calculated, as they do not affect the CO_2e emission payback period. There is one exception, however. Recurring embodied CO_2e emissions have been applied to existing SFH. Verbeeck and Hens (2010a) establish that embodied CO_2e emissions increase with building age due to recurring embodied CO_2e emissions. An LCA by Treloar et al. (2000) investigates a two-story semi-detached residence building in Australia constructed with brick veneer with a timber upper floor, finding that recurring embodied energy added 32% to the initial embodied energy outlay after 30 years, while the LCA by Zhang et al. (2014) of a wood-framed SFH in Vancouver revealed that 33% of the total embodied CO_2e emissions over the 60-year lifespan of the building were attributed to recurring embodied carbon, representing an annualized rate of 1 kg CO_2e/m^2/year. Thus, a rate of 1 kg CO_2e/m^2/year of recurring embodied CO_2e emissions has attributed to existing SFHs in Vancouver.

Embodied Emissions of New SFHs in Vancouver

Embodied emissions of buildings vary widely by building type (e.g., residential vs. commercial) and construction method (e.g., wood-frame versus masonry). An analysis of sales data since 2000 by the authors demonstrates that 96% of new SFH built since 2000 in Vancouver consist of two-and-one-half story light wood platform framing on concrete foundations. Accordingly, 48 LCAs of North American residential buildings under 465 m^2 between 1 and 6 stories were reviewed from an embodied CO_2e benchmark study by Simonen et al. (2017), in addition to 3 LCAs of Canadian wood-frame residential structures (Norman et al. 2006; Zhang et al. 2014; Salazar and Meil 2009) and 2 Passivhaus LCAs (Brunklaus et al. 2010; Dahlstrom et al. 2012). LCAs which did not directly account for Stage A (cradle through construction), as well as those with outlying embodied CO_2e emissions above 1000 kg CO_2e/m^2 or below 100 kg CO_2e/m^2, were removed from the data set provided by Simonen et al. The average embodied CO_2e emissions during Stage A for the 34 remaining LCAs is 232 kg CO_2e/m^2 (see Appendix: Table 8). An LCA by Dahlstrom et al. (2012) comparing an SFH built to conventional versus PassiveHouse standards finds that the building to PassiveHouse standards results in an increase in embodied CO_2e emissions from 216 kg CO_2e/m^2 to 251 kg CO_2e/m^2, or 16%. Because the ZEBP energy and CO_2e emission guidelines accord with or surpass PassiveHouse standards, the 232 kg CO_2e/m^2 average for North American residential construction was increased by

16% to account for the additional embodied CO_2e impacts of building to a higher standard. This yields a benchmark initial embodied CO_2e emission rate for new SFH in Vancouver at 269 kg CO_2e/m^2. This figure lies within the range of 201 kg CO_2e/m^2, the median value of the 53 LCAs North American residential buildings under six stories and less than 465m^2 filtered from the review by Simonen et al. (2016), and 400 kg CO_2e/m^2, determined by Salazar and Meil's (2009) LCA of a high-efficiency wood-framed SFH in Canada. The size of new SFH was assumed to be the maximum allowable FSR, in keeping with the trends indicated in Figure 1 above. To the initial embodied CO_2e of new SFHs was added 1 kg CO_2e/m^2/year in recurring embodied CO_2e emissions. This rate is also applied to existing SFHs.

It could be argued that the embodied CO_2e emissions of demolition should be counted toward the overall embodied CO_2e emissions of new SFHs because these emissions are released as part of the site preparation required for new construction. However, embodied CO_2e emissions of the demolition of existing SFH have been omitted from the study due to a lack of reliable data. This omission was deemed acceptable, as numerous studies find that demolition accounts for less than 2% of overall embodied impacts of buildings (Junnila and Horvath 2003; Norman et al. 2006; Ramesh et al. 2010; Cabeza et al. 2014; Zhang et al. 2014; Vilches et al. 2017).

Total Emissions, Building Longevity and Payback periods

Once operating and embodied CO_2e emissions are determined, it is possible to calculate the total CO_2e emissions. Total CO_2e emissions are the sum of operating emissions and embodied emissions, expressed as CO_2e. The total CO_2e emissions of a newly constructed SFH are evaluated against the operating emissions of the older SFH it replaces, using a payback period calculation. The payback period represents the number of years required for the total CO_2e emissions of the new construction to equal the annual operating CO_2e emissions of the existing SFH, had it not been replaced. The payback period calculation is expressed in Equation 1 below:

Equation 1: SFH payback period formula

$$Y = ECi / [\ (ECr' + OC') - (ECr + OC)\ ]$$

Legend: (Y) Payback period; (EC) embodied CO_2e emissions; (OC) operating CO_2e emissions; (i) initial; (r) recurring; (') existing SFH.

Replacing an existing building with a new building with lower operating CO_2e emissions results in a positive CO_2e payback period, measured in years. If the replacement of an existing building has the same overall operating carbon emissions, the denominator is zero and the payback time is infinite. Embodied emissions can never be paid back because no additional efficiencies were introduced. The payback period is negative if the new building has higher operating emissions than the building it replaces.

The payback period is the relative yardstick by which emission savings or debt of new SFHs can be measured, compared to a control state that consists of the operating emissions and recurring embodied emissions of the original building. If a replacement SFH is younger than its payback period, the total emissions of that lot exceed the emissions that would have been incurred had the SFH been left in place (CO_2e debt). If the new SFH is older than its payback period, the total emissions of the lot are lower than the emissions of the original SFH (CO_2e savings). Since operating CO_2e rates vary by SFH vintage cohort, and replacement SFHs maximize their allowable buildable square footage per lot, payback periods will vary by vintage, as well as by any potential increase in the size of new construction.

Teardown Index

Assessing the environmental benefits of replacing different vintages of SFH with more efficient buildings requires estimating the life expectancy of the new construction. If the payback period exceeds life expectancy, the structure efficiency gains are unlikely to be realized. Rosenthal et al. (1994) developed a land and building value assessment model that concludes that the relative building value, which refers to the quotient of the assessed building value over the total value of the property, can be used to predict reliably whether a building will be demolished when it is sold. The lower the relative building value, the more likely a building is to be demolished, as new owners seek to balance the value of the building with the overall value of the property.

Building on the work of Rosenthal et al., we developed a statistical model called the Teardown Index to assess the duration of life of individual SFH's in Vancouver. This general linear logistic model uses the relative building value at the time of sale to predict the probability that an SFH will be replaced when it is transacted (bought or sold). Historic land transfer data and land value assessments from BC Assessment were used to identify the determinants of SFH teardown/rebuilds within RS zoning. Confirming the earlier research by Rosenthal et al., all but 1.3% of historic teardowns of SFH could be associated with the property being transacted (BC Assessment 2015a, 2015b; BC Assessment et al. 2016). This represents a binary outcome (i.e., the building will be torn down, or will survive). We have expanded on this model by also considering in floor area, total building value, lot size, building age, and year of last major improvement as other potential predictors. To fit and evaluate the model, we used single-family homes in single-family zoned areas transacted between 2006 and 2015. To account for homes being torn down some time before or after the transaction, we used a moving buffer of up to four years around the transaction time, which narrowed the time window considered. We found little variation in model parameters or accuracy across time windows.

We experimented with several improvements to the model because of high dependence among some of the predictors. However, the accuracy of the model was not significantly improved by adding variables like lot area or the total building value, nor by using more sophisticated models. We added an L1 and L2 regularization penalty to diminish the effect of co-linearity. We also build a random forest model, in which a large number of individual decision trees operate as an ensemble, which yielded an improvement in predictive power by 3% when compared to the naive single variable logistic regression. We decided that the added complexity and lack of transparency did not justify the inclusion of the random forest method in the final model, based on the relatively small increase in accuracy it produced. Prediction accuracy of the logistic model was constant across test and training data. The final analysis was fit on 23,101 homes transacted between 2006 and 2012 in order to allow for enough time for a transacted property to get torn down and rebuilt. The model is 82% accurate.

The fitted logistic model yields the following equation, which uses the relative building value to predicts the teardown probability in the event of a property transaction. The modeled probability of a transacted SFH with relative building value x to be torn down is given by Equation 2:

Equation 2. Teardown index formula

$$P(x) = \frac{1}{1 + e^{-(0.53 - 20.23 * x)}}$$

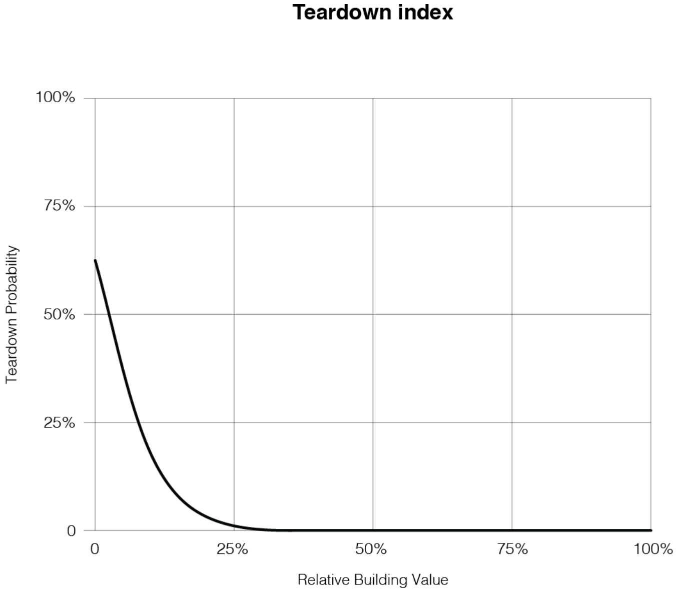
This work relied on BC Assessment's valuations of land and buildings, which we found to be an unbiased estimator of building values, although at times with high variance on individual buildings. The teardown probability tops out at 63% for essentially worthless buildings, which cannot fully be explained by inconsistencies in property assessments, and indicates that speculation on future land value gains is an important factor in some of these transactions.

Projecting Total Emissions of Vancouver's SFH stock to 2050

Correlating the predictions with emission payback periods for different vintages of SFHs makes it possible to estimate the total CO_2e emissions of different scenarios at the scale of the city. Six scenarios are modeled to study their effect on total CO_2e

Teardown Index

Figure 2. Teardown Index graph



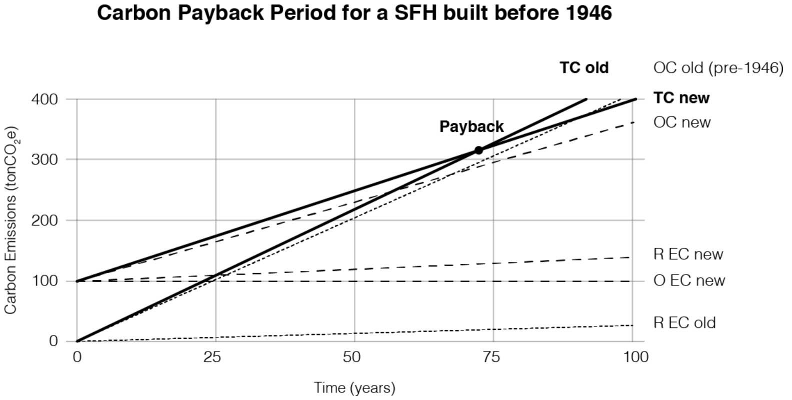
emissions of SFH in Vancouver from 2017 to 2050. The first scenario is a control, which is defined by no change in property prices and an artificial mechanism whereby no SFHs are replaced, resulting in emissions produced entirely building operation, with no new embodied emissions. The remaining scenarios project the evolution of the SFH stock to 2050 using average price compound annual growth rates (CAGR) from -2% to 8.24%, which reflect different CAGR in Vancouver over the past 8 years. The effect these different scenarios produce on total CO_2e emissions is presented below.

RESULTS

Emission Payback Periods by SFH Vintage

The average CO_2e payback periods by SFH vintage cohort calculations are summarized in Figure 3 and Table 2 below. Because operating emission rates of existing SFHs increase with age, new SFH homes that replace older SFH demonstrate shorter payback periods. For example, a new SFH replacing an SFH built prior to 1946 has a payback period of 73 years, if constructed between 2020 and 2025, and 25 years if built after 2025, when emissions standards are tightened for new construction. In contrast, replacing an average SFH built after 2011 has a CO_2e payback period

Figure 3. CO_2e Payback Period for a new SFH replacing pre-1946 SFH



of 344 years, which is reduced to 34.6 years if built after 2025. For all SFHs in Vancouver, the weighted average CO_2e payback period is 168 years, which drops to 29 years for SFH built between 2020 and 2025 and those built after 2025, when operating emissions effectively drop to zero.

Scenarios of Real Estate Appreciation

Table 3 summarizes the CO_2e emissions from Vancouver SFHs for different real estate price compound annual growth rates (CAGR). The growth rates of 2.23%, 5.08%, and 8.24% correspond to the CAGR of SFHs prices in Vancouver over the

Table 2. Replacement SFH CO_2e payback periods by vintage

Vintage	Payback period of SFH built from 2020 to 2025 (years)	Payback period of SFH built after 2025 (years)
Before 1946	73.1	25.2
1946–1960	291.3	34.0
1961–1977	138.6	30.1
1978–1983	82.6	26.2
1984–1995	71.8	25.0
1996–2000	176.3	31.6
2001–2005	548.4	35.9
2006–2010	277.5	33.8
2011–2017	343.9	34.6

last one, five, and three years, respectively. The 2% reduction to the CAGR scenario is added to provide insight into the likely effect of a loss of value on replacement rates. The six scenarios test the sensitivity of CO_2e emissions toward different land value change scenarios, holding building values constant. This changes the relative building value over time, which in turn impacts the probability of a building getting torn down when transacted. We then run simulations to randomly transact properties at historical rates, apply our model to predict teardowns, and compute the resulting CO_2e emissions. Given the probabilistic nature of this estimate, we repeat this process for each scenario and average over the predicted CO_2e missions until they converge. The results are listed in Table 3.

In the control scenario, in which no SFHs are replaced and the current stock of SFHs is conserved, the total CO_2e emissions released by operating and maintaining these homes between 2017 and 2050 amount to 8.9M mt CO_2e.

Running the Teardown Index for an SFH price CAGR of 2.23% over the same time period projects that an estimated 32,366 SFHs will be demolished and replaced. Exploiting maximum FSR buildable area during rebuilding in keeping with the trends documented in Figure 1 above will add 3.2M m^2 of interior space to those structures. From 2017-2050, the total emissions from this scenario will amount to 10.9M mt CO_2e, which represents an increase of 1.9M mt CO_2e emissions when compared to the control scenario mentioned above.

At a CAGR of 5.08%, the Teardown Index projects that 39,929 SFHs will be replaced, and 3.3M m^2 of interior space will be added to the housing stock, causing total emissions from 2017-2050 to reach 11.3M mt CO_2e. This represents a 26.5% increase from the control scenario.

In the extreme growth scenario, based on the 8.24% CAGR rise recorded in SFH prices from 2015-2017, 47,276 SFH would be replaced between 2017-2050, resulting in a net increase of 3,390,215 m^2 of interior space, and 11.7M mt CO_2e of total emissions, a 31.8% increase over the control scenario.

Notably, the model shows that for a CAGR of -2%, 21,921 SFH will be replaced, producing 10.2M mt CO_2e emissions. A 2% reduction in property value does not affect the low relative building values significantly enough to cause a major change in replacement rates.

The Real Estate Price Elasticity of SFH CO_2e Emissions

Price elasticity refers to the responsiveness of one variable to changes in another. Generated by the median value of 100 teardown index simulations, the real estate price elasticity of SFH CO_2e emissions is presented in Figure 4. This curve represents the change in total, operating, and embodied CO_2e emissions from the total stock of SFHs over the 2017-2050 period given a change in the CAGR of SFH land values

Table 3. Total CO_2e emissions by scenario

Scenario	**Real estate CAGR (%)**	**SFH replaced**	**Net increase of SFH stock internal area (m^2)**	**Total carbon emissions (metric tonnes of CO_2e)**
1	Moratorium	0	0	8,913,000
2	-2%	21,921	2,627,278	10,214,801
3	0%	26,183	2,836,140	10,441,025
4	2.23%	32,366	3,178,000	10,856,000
5	5.08%	39,929	3,262,000	11,275,000
6	8.24%	47,276	3,390,000	11,744,000

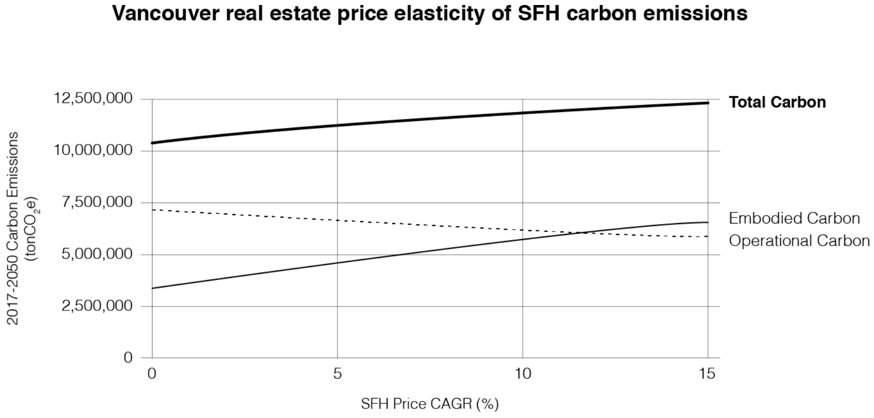
Source: Authors, 2019

over that period. For each percentage point increase in CAGR land value price gains, an additional estimated 130M tonnes of CO_2e are added between 2017 to 2050.

DISCUSSION

The results show that the environmental benefits of tearing down and replacing even very poorly performing buildings are dubious at best in Vancouver. The average CO_2e payback period of 168 years for a typical home built to current standards renders it unlikely that emission savings will be realized before the structure is replaced. Even the shortest CO_2e emission payback time of 71 years for new SFH constructed to current emission standards may easily exceed the life of the home

Figure 4. Real estate price elasticity of SFH CO_2e emissions



in the current economic climate, in which buildings are torn down and replaced at a frenetic pace. Increasingly stringent net-zero energy standards after 2025 bring down the payback period significantly, although the CO_2e emission payback period ranges between 25 and 36 years even under the zero operating consumption scenario. It is as yet uncertain whether these aspirational guidelines will be achieved on the proposed schedule. It is certain that the current practice of tearing down functional homes and replacing them with new homes built to present performance standards is a losing proposition environmentally, at the scale of both the individual building lot and the city.

The long payback times documented give rise to large CO_2e emission debts for all of the real estate growth scenarios considered at the scale of the city. For all of the scenarios considered, replacing existing SFH with more efficient buildings causes a significant net increase in CO_2e emissions for the period between 2017-2050. It is especially notable that the increases to overall emissions occur despite 50% reductions to operating emissions on a per square meter basis, which can be considered very significant, although reductions are mitigated by the overall increase in GFA as homeowners seek to maximize FSR. This finding can be considered conservative in terms of the environmental effects of replacement. Carbon emissions associated with the demolition of existing SFHs were not considered, which would add additional CO_2e emissions to new construction. More significantly, among the many impacts of building construction, only CO_2e emissions were considered. The overall impacts of new construction would increase considerably were impacts on human health, ecosystems, water quality, and overall resource use to be taken into account.

It should be noted that the findings reported are highly specific to Vancouver. The predominance of wood-frame SFH construction in Vancouver is typical of most North American cities, but Vancouver benefits from a climate considerably milder than the rest of Canada. The mild climate reduces operating energy requirements, which in turn reduces operating emissions, lengthening the payback period for building replacement. A more severe climate would increase operating energy consumption, which would also reduce the CO_2e payback periods for renovation or replacement. Vancouver also benefits from an unusually high percentage of renewable energy, reducing the emissions per unit of energy that is consumed. Hydroelectricity and natural gas, the predominant sources of operating energy in Vancouver, have low emission factors per unit of energy consumed. CO_2e payback periods would diminish considerably for localities where operating energy demand is met by non-renewable energy sources with higher emission factors, such as coal-fired electricity or oil heat. Put another way, an SFH constructed in Vancouver, with its mild climate and renewable sources of energy, will have a significantly longer CO_2e payback period than an identical SFH constructed in a city such as Calgary, with its severe climate and energy grid based on non-renewable sources of energy.

The payback times for SFH are also influenced by the type of materials and assemblies used in new construction, which have a significant impact on initial impacts, ongoing maintenance, and associated energy costs. The predominant structural method used to construct new SFH in Vancouver is wood-frame with a concrete foundation, which has a relatively low initial embodied impacts. Other construction types, such as masonry, would likely lengthen payback times, further due to higher initial embodied impacts. Unlike the low carbon sources of energy used to operate buildings in Vancouver, many of the construction materials used to build homes in the city are the product of global supply chains that do not benefit from renewable energy or sustainable practices. The carbon-intensive sources of energy used to manufacture many construction materials increase the initial carbon investment of new construction, lengthening the payback time.

The site-by-site analysis shows that in a mild climate with ample sources of low-carbon energy, the current practice of demolishing functional SFH and replacing them with more efficient SFHs of the same type does not make environmental sense. However, measures can be taken to reduce the payback periods of new construction, which currently exceed the life expectancy of the new buildings. The most straightforward method for reducing payback periods is simply to adopt more stringent energy performance standards. If Vancouver adopts PassivHaus standards in 2025, payback periods will be reduced to between 25-35 years, depending on the vintage of existing SFH. Realizing the environmental benefits of this approach would require adopting a "one and done" replacement policy that would incentivize the construction of high-efficiency buildings while ensuring that the new structures themselves are not torn down and replaced prematurely due to low RBV.

Preventing reconstruction of efficient SFH could perhaps be done by downzoning, such that reconstruction after initial replacement would have an associated GFA/FAR penalty that would create a powerful disincentive to rebuild once efficiency was achieved. Another alternative could be to adopt policies that would require owners or developers to provide carbon accounting at the building permit stage. In this scenario, new construction that could be shown to diminish overall emissions within a reasonable payback period could proceed without additional fees; where this was not the case, owners would pay the penalty in the form of a carbon tax. This would require reliable methods of establishing impacts of buildings as well as setting a price on carbon in a manner similar to that of cap and trade systems. The inconsistency of current carbon accounting, as well as the difficulty of adopting carbon pricing in Canada to date, suggests that this method, although perhaps the most efficient and just, would be challenging to implement.

Although the policy measures outlined above give some sense of how carbon emissions could be dealt with on a site-by-site basis in Vancouver, these alternatives do little to address the underlying reason that so many SFH are torn down. The decision to replace SFHs is typically made by individual owners on economic grounds, as the relative building value used to calculate the probability of replacement suggests. In Vancouver, the average relative building value of existing SFH currently hovers around 12%. At this rate, the Teardown Index model predicts that one in four homes will be torn down when the property changes hands. All but the most expensive new homes constructed in Vancouver are below 30% relative building value, well under the 70% typical of a healthy housing market. The problem is getting worse. Property values are rising faster than the cost of construction, driving the relative building value of both new and existing SFH ever lower. This produces a teardown cycle, as new owners demolish existing homes and rebuild commensurate with the overall value of their property. When property values rise so high that even high-end SFH are unable to maintain sufficient value to avoid becoming tomorrow's teardown, it points to the need to rethink land use more broadly through zoning revisions.

The teardown cycle is unlikely to be broken until RS zoning is loosened to allow alternatives to SFH. Revising zoning so that SFH can be selectively replaced with row-housing up to four or five stories built to PassivHaus standards would offer improved energy efficiency, decreasing emissions and shortening carbon payback to acceptable time frames. The higher initial cost of these high-density residential structures will increase their relative building value, decreasing the likelihood that they will be torn down before their carbon debt is repaid. Although affordability will still present a challenge, the cost of construction will be shared among more residents than an SFH. Finally, the row-house typology will increase the overall supply of housing to inhabitants in close proximity to the downtown core, reducing transportation and related impacts associated with neighborhoods comprised of SFH.

Assumptions and Limitations

The research focuses on CO_2e emissions as the most closely linked to global warming. Relying on a review of prior LCAs to determine embodied CO_2e emissions means that the research inherits their shortcomings in the form of scenario, boundary, and other model uncertainties (Lloyd and Ries 2007). Moreover, many other types of environmental impacts are associated with the construction, maintenance, operation, and replacement of SFHs, such as ozone depletion, respiratory inorganics, human toxicity, ionizing radiation, ecotoxicity, ozone formation, acidification, terrestrial eutrophication, land use, waste, and resource consumption. When these are considered, it is likely that the impacts could increase unevenly between operating and embodied impacts. In addition, the scope of the study is limited to CO_2e emissions directly associated with SFHs. Indirect emissions associated with infrastructural requirements of SFHs, such as roads and parking are not considered, nor are the indirect emissions due to transportation, or from consumption-related emissions (Kellett et al. 2013).

Emissions are considered on a per-area basis, which does not account for the number of people served by spaces, and as such may be a less accurate method of accounting for emissions than a per capita basis. It is likely that replacing SFHs with denser forms of inhabitation, such as mid-rise, ground-oriented development, would lead to a profound reduction of CO_2e emissions per capita.

Projecting SFH total CO_2e emissions to 2050 requires making assumptions about current policy while disregarding the possibility of potentially significant policy changes. The Zero Emissions Building Plan is used to predict future energy consumption, despite uncertainty about its prospects for approval and anticipated enforcement and compliance. The projections also assume that the current distribution of energy sources will be maintained in the future. Natural gas produces over sixteen times more CO_2e per unit of energy than hydroelectricity. If homeowners move toward replacing natural gas with electric heat pumps for space and water heating that account for more than half of the energy demands of SFH, the projections will overstate operating CO_2e emission rates. This would lengthen CO_2e emission payback periods further than currently predicted.

Finally, the research presented accounts only for the environmental impacts of SFH construction and operation at the scale of individual buildings. Where the environmental effects are indicated at the scale of the city, they are calculated by aggregating the effects of individual buildings. This method does not account for the additional environmental impacts of carbon-intensive patterns of living commonly associated with suburban configurations. Reserving large areas of land in proximity to the central business district for SFH land use also carries an opportunity cost: it requires a large portion of the metropolitan population to live farther away from jobs, forcing them into longer commutes. Accounting for these additional impacts would have an effect of the carbon payback time of SFH.

FUTURE DIRECTIONS

Operating energy efficiency gains are likely to be realized across the stock of SFH in Vancouver in the future, as the city progresses toward net-zero operational goals. Operating emissions will diminish as a result, making embodied impacts a larger proportion of total building impacts. The growing importance of embodied impacts will make it essential to account for and regulate embodied CO_2e emissions in future policy. Moving forward, establishing clear accounting practices (Basbagill et al. 2013; De Wolf et al. 2017), strengthening access to LCA data for building components and processes, such as a localized Environmental Product Declarations database, and mandating institutional oversight are likely prerequisites to that end. Such measures could facilitate the introduction of embodied CO_2e emission accounting in the design phase of construction (Häkkinen et al. 2015) at the scale of the SFH, rather than on an ad hoc post-occupancy basis, as is currently the case. Fortunately, the City of Vancouver is requiring developers to track embodied carbon in new commercial construction, the first step toward a stated goal of reducing embodied carbon in new buildings in the city by forty percent by 2030 (Pander, 2019).

The results also point to the relevance of the renovation of poorly performing existing structures, as opposed to outright replacement. Mohammadpourkarbasi and Sharples (2017) note that bringing two Victorian houses in the UK to near Passive-House standards results in a 75% reduction in operating emissions, with a CO_2e payback period of 6 years. Ma et al. (2012) and Rysanek and Choudhary (2013) note that renovation can be an effective method of increasing the sustainability of buildings, but that complex factors influence adoption. In the case of Vancouver, where older single-family homes typically consist of light wood framing on foundations of marginal quality, the impacts of extensive renovations are likely to be comparable to the impacts of outright replacement. Future research should apply similar methods to quantify the carbon payback of renovation to assess its viability as an alternative to replacing buildings entirely. It may be that simply upgrading building systems would offer the shortest payback times in the Vancouver context. For example, replacing gas-fired space heating equipment with electric heat pumps powered by renewable hydroelectricity would address the consumption of natural gas, which is the largest source of CO_2e emissions for many SFH. Quantifying the impacts of different renovation strategies and their associated payback times is beyond the scope of the present study but would provide important information to policymakers.

The research strongly suggests a need to rethink land-use strategies in Vancouver through changes to zoning in the future to permit buildings that are more commensurate with property values than SFH. A natural extension of this research would be to quantify the most carbon-efficient way to grow the metropolitan region, accounting for embodied and operating carbon, as well as associated emissions due to transportation and land-use changes.

Finally, the research presented could be extended by accounting for regional effects. The abundance of low-carbon electricity sources makes it possible to adhere to stringent carbon emission requirements in Vancouver without reducing operating energy consumption significantly. However, the grid infrastructure that provides low-carbon electricity to Vancouver is also connected to other regions throughout the Pacific Northwest. Reducing electricity consumed in Vancouver would potentially provide more low-carbon electricity that could be used to offset more carbon-intensive electricity in Washington, Oregon, and California. A systems-based investigation of energy savings in Vancouver could identify potentially significant regional reductions to overall emissions.

CONCLUSION

Buildings emit up to a third of CO_2e emissions globally. Most emission mitigation strategies to date have focused on reducing operating impacts due to their large share of overall impacts. However, as the proportion of embodied impacts increases due to operational efficiencies, accounting for embodied impacts is imperative. Embodied impacts can be understood in the context of the CO_2e emission payback period, which refers to the period of time required for operational savings to recover the amount of embodied CO_2e emitted by constructing a new building. This study uses CO_2e payback periods to assess total CO_2e emissions for the stock of single-family houses in Vancouver Canada in the context of the city's plan to reduce the CO_2e emissions of building by 80% by 2050. The amount of time for the total emissions of replacement SFHs to equal those of replaced SFHs ranges from 73 to 548 years for SFHs built to 2020 efficiency standards, and 25 to 36 years for SFHs built to 2025 efficiency standards. A statistical tool called the Teardown Index was used to project future demolition and replacement of single-family homes in Vancouver. Four scenarios of real estate capital appreciation growth rates were investigated, ranging between -2% to 8.24% CAGR. Generally, higher rates of real estate growth translate to higher rates of demolition and replacement of SFH. Each percentage point increase in annual land value price gains corresponds to an additional 130 million tonnes of CO_2e released between 2017 to 2050 as a result of operating and embodied impacts. Despite significant operating efficiency increases, replacing existing buildings with new efficient buildings will emit between 2-3.2 million tonnes of additional CO_2e emissions. These findings suggest that replacing functional older SFH with SFH constructed in accordance with current efficiency standards in Vancouver is not an effective strategy to achieve municipal CO_2e emission mitigation goals when all impacts are considered. Rather, increased efficiency standards should be adopted to decrease carbon payback times, and changes to land use should be considered to increase building longevity.

ACKNOWLEDGMENT

The chapter was adapted from an article originally published as “Teardown Index: Impact of property values on carbon dioxide emissions of single-family housing in Vancouver“ in the journal Energy & Buildings 170 (2018) 95–106.

An interactive data visualization of the Teardown Index is available online here: https://mountainmath.ca/teardowns

The authors are grateful to the Peter Wall Institute for Advanced Studies for supporting the research.

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APPENDIX

Operating Impacts

Table 4. Average energy requirements by end-use and fuel source per SDH per year for 2014 in lower Mainland, BC. (Source: Young 2017)

Fuel	Gas (kWh)	Gas (GJ)	Gas %	Electric (kWh)	Electric (GJ)	Electric %	Total (kWh)	Total (GJ)	Total %
Space Heating	8,132.6	29.3	81.44%	1,853	6.7	18.56%	9,985.6	35.95	44.66%
Hot Water	2,380.0	8.6	77.78%	680	2.4	22.22%	3,060.0	11.02	13.68%
Space Cooling	0.0	0.0	0.00%	78	0.3	100.00%	78.0	0.28	0.35%
Appliances	0.0	0.0	0.00%	3,244	11.7	100.00%	3,244.0	11.68	14.51%
Lighting	0.0	0.0	0.00%	1,871	6.7	100.00%	1,871.0	6.74	8.37%
Electronics	0.0	0.0	0.00%	1,784	6.4	100.00%	1,784.0	6.42	7.98%
Other	0.0	0.0	0.00%	1,460	5.3	100.00%	1,460.0	5.26	6.53%
Ventilation	0.0	0.0	0.00%	879	3.2	100.00%	879.0	3.16	3.93%
Total	**10,512.6**	**37.8**	-	**11,849**	**42.7**	-	**22,361.6**	**80.50**	**100.00%**
% of total energy	**47.01%**	**47.01%**	**47.01%**	**52.99%**	**52.99%**	**52.99%**	**100.00%**	**100.00%**	**100.00%**

Embodied Impacts

Table 5. Average energy requirements by end-use and fuel source per SDH m^2 per year for 2014 in Lower Mainland, BC. (Source: Young 2017)

Fuel	Gas (kWh/ m^2)	Gas (GJ/m^2)	Gas % of Use	Electric (kWh/m^2)	Electric (GJ/ m^2)	Electric % of Use	Total (kWh/ m^2)	Total (GJ/m^2)	Use % of Total
Space Heating	36.825	0.133	81.44%	8.390	0.030	18.56%	45.215	0.163	44.66%
Hot Water	10.777	0.039	77.78%	3.079	0.011	22.22%	13.856	0.050	13.68%
Space Cooling	0.000	0.000	0.00%	0.353	0.001	100.00%	0.353	0.001	0.35%
Appliances	0.000	0.000	0.00%	14.689	0.053	100.00%	14.689	0.053	14.51%
Lighting	0.000	0.000	0.00%	8.472	0.030	100.00%	8.472	0.030	8.37%
Electronics	0.000	0.000	0.00%	8.078	0.029	100.00%	8.078	0.029	7.98%
Other	0.000	0.000	0.00%	6.611	0.024	100.00%	6.611	0.024	6.53%
Ventilation	0.000	0.000	0.00%	3.980	0.014	100.00%	3.980	0.014	3.93%
Total	**47.60**	**0.17**	**-**	**53.65**	**0.19**	**-**	**101.25**	**0.36**	**100.00%**
% of total	**47.01%**	**47.01%**	**47.01%**	**52.99%**	**52.99%**	**52.99%**	**100.00%**	**100.00%**	**100.00%**

Table 6. Vintage adjusted space heating and ventilation energy requirement (Source: Derived from Natural Resources Canada Comprehensive Energy Use Database, 2014)

Vintage	Total Single Detached Floor Space (in BC, million m^2)	Gross Output Thermal Requirements for Single Detached in BC (GJ/household)	Gross Output Thermal Requirements for Single Detached in BC (GJ/m^2)	Gross Output Therm. Req. weighted average by m^2 per vintage (GJ/m^2)	Gross Thermal Output Delta from weighted average	Vintage adjusted space heating and ventilation energy requirement (GJ/m^2)
Before 1946	8.17	80.20	0.57	-	67.54%	**0.297**
1946–1960	9.97	76.38	0.51	-	50.79%	**0.267**
1961–1977	34.16	70.59	0.43	-	27.67%	**0.226**
1978–1983	23.59	66.89	0.37	-	8.52%	**0.192**
1984–1995	44.77	59.09	0.31	-	-7.75%	**0.163**
1996–2000	16.73	49.33	0.27	-	-21.59%	**0.139**
2001–2005	15.56	51.20	0.26	-	-23.94%	**0.135**
2006–2010	20.48	49.31	0.23	-	-31.55%	**0.121**
2011–2014	13.65	50.12	0.22	-	-34.97%	**0.115**
Average	-	-	-	-	-	-
Total	**187.08**	-	-	**0.339**	-	-
source	*NRCan CEUD 2014: Table 19*	*NRCan CEUD 2014: Table 32*	*NRCan CEUD 2014: Table 33*	*derived*	*derived*	*derived*

Table 7. Primary operating CO_2e emissions per m^2 of lower mainland SFH adjusted by vintage (Source: Derived from data from BC Assessment (2015b), Natural Resources Canada (2014), Energy Star (2013), British Columbia (2012), British Columbia (2016), Young (2017)1.)

Vintage	**Space Heating+Ventilation: Total (GJ/m2)**	**Space Heating+Ventilation: Gas (GJ/m2)**	**Space Heating+Ventilation: Electricity (GJ/m2)**	**Water Heating: Total (GJ/m2)**	**Water Heating: Gas (GJ/m2)**	**Water Heating: Electricity (GJ/m2)**	**Appliances: Total - All Elec (GJ/M2)**	**Lighting: Total - All Elec. (GJ/M2)**	**Space Cooling: Total - All Elec (GJ/M2)**	**Electricity total (GJ/ m2)**	**Gas total (GJ/m2)**	**Electricity Converted to primary in GJ**	**Gas converted to primary in GJ**	**Prim. elec in kgCO2e**	**Prim. Gas in kgCO2e**	**Total Prim. Operating Energy (kgCO2e/m2/ year)**
Before 1946	0.297	0.242	0.055	0.050	0.039	0.011	0.106	0.030	0.001	0.204	0.280	0.418	0.286	**1.238**	**14.183**	**15.42**
1946–1960	0.267	0.217	0.050	0.050	0.039	0.011	0.106	0.030	0.001	0.198	0.256	0.406	0.261	**1.204**	**12.961**	**14.17**
1961–1977	0.226	0.184	0.042	0.050	0.039	0.011	0.106	0.030	0.001	0.191	0.223	0.391	0.227	**1.158**	**11.275**	**12.43**
1978–1983	0.192	0.157	0.036	0.050	0.039	0.011	0.106	0.030	0.001	0.184	0.195	0.378	0.199	**1.120**	**9.878**	**11.00**
1984–1995	0.163	0.133	0.030	0.050	0.039	0.011	0.106	0.030	0.001	0.179	0.172	0.367	0.175	**1.087**	**8.691**	**9.78**
1996–2000	0.139	0.113	0.026	0.050	0.039	0.011	0.106	0.030	0.001	0.174	0.152	0.357	0.155	1.060	7.681	**8.74**
2001–2005	0.135	0.110	0.025	0.050	0.039	0.011	0.106	0.030	0.001	0.174	0.148	0.356	0.151	1.055	7.510	**8.56**
2006–2010	0.121	0.099	0.022	0.050	0.039	0.011	0.106	0.030	0.001	0.171	0.138	0.351	0.140	1.040	6.955	**7.99**
2011–2014	0.115	0.094	0.021	0.050	0.039	0.011	0.106	0.030	0.001	0.170	0.133	0.348	0.135	1.033	6.705	**7.74**
Average	0.177	0.144	0.033	0.050	0.039	0.011	0.106	0.030	0.001	0.181	0.183	0.372	0.187	1.103	9.256	10.36
Total	-	-	-	-	-	-	--	-	-	-	-	-	-	-	-	-

Table 8. Source: Data extracted from Simonen et al.

BLDG_PUB	BLDG_TYP + BLDG_US	BLDG_LOC	BLDG_NEW	$BLDG_ AREA_M2	$BLDG_ AREA_FT2	BLDG_$	BLDG_ST	LCA_YEAR	LCA_RE	LCA_SOUR	LCA_STAG	LCA_BLDG	LCA_MAT_Q	EC_WB_EX	EC_LCAA_ PERM2
A05	Residentia Single-fam	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2004			A	SFEI	Y	46826000	**244.31**
A05	Residentia Single-fam	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2004			A	SFEI	Y	37047000	**193.29**
A05	Residentia Single-fam	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2004			A	SFEI	Y	28004000	**139.93**
A05	Residentia Single-fam	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2004			A	SFEI	Y	21367000	**106.77**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	40	**266.67**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	28.4	**258.18**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	25.8	**258**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	38.4	**256**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	43.1	**253.53**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	27.6	**250.91**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	39.7	**248.13**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	39.3	**245.63**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	45.6	**240**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	30.7	**236.15**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	23.3	**233**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	25.6	**232.73**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	34.4	**229.33**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	24.8	**225.45**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	29.2	**224.62**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	35.6	**222.5**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	34.9	**218.13**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	27.6	**212.31**

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Table 8 continued

BLDG_PUB	BLDG_TYP + BLDG_US	BLDG_LOC	BLDG_NEW	$BLDG_ AREA_M2	$BLDG_ AREA_FT2	BLDG_$	BLDG_ST	LCA_YEAR	LCA_RE	LCA_SOUR	LCA_STAG	LCA_BLDG	LCA_MAT_Q	EC_WB_EX	EC_LCAA_ PERM2
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	42	**210**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	22.5	**204.55**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	42.9	**204.29**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	26.3	**202.31**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	30.2	**201.33**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	29.8	**198.67**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	27.4	**195.71**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	31.2	**195**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	27.3	**182**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	26.7	**178**
A05	Residentia Other	North Ame	New	94 to 465	1 001 to 5 000	0	1 to 6	2011	60		ABC	SEI	N	24.8	**177.14**
A05	Residentia Single-fam	North Ame	New	94 to 465	1 001 to 5 000	0		2014	60		ABCD	SFEI	Y	184.79	**746.64**