Densification of Vancouver's Neighbourhoods: Energy Use, Emissions, and Affordability

by

Aaron Pardy

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Examining Committee:	**Chair:** Shahid Hossaini Master of Resource Management Candidate

Mark Jaccard
Senior Supervisor
Professor

Rose Murphy
Supervisor
Postdoctoral Fellow

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Abstract

The City of Vancouver in British Columbia has committed to use 100% renewable energy and reduce emissions by 80% by 2050. Like many cities in North America, much of the Vancouver's land area currently consists of single-family detached home neighbourhoods—a type of land use that has been associated with higher than average per capita energy use and emissions. In this study, I used an energy-economy-emissions model, CIMS, to evaluate how densifying these low-density neighbourhoods with medium-density housing forms would influence energy use, emissions, and home energy and personal transportation affordability. While densification was found to have a modest influence on reducing building emissions, zero-emission building regulations were found to be much more effective, highlighting the importance of energy-switching policy for residential building decarbonization. However, an affordability co-benefit of densification was found: smaller, more energy efficient dwellings in dense building forms reduce annual energy costs relative to detached homes, especially when coordinated with policies and actions to limit vehicle ownership.

Keywords: urban GHG policy; energy-economy modelling; urban density; affordability; Vancouver, BC

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CO2e	Carbon dioxide equivalent
EMRG	Energy and Materials Research Group
GHG	Greenhouse gas
GHGI	Greenhouse gas emissions intensity
GJ	Gigajoules
kt	Kilotonnes
MS	Transportation mode shift
MURB	Multi-unit residential building
NG	Natural gas
PJ	Petajoules
PKT	Person kilometers travelled
RCS	City of Vancouver's *Renewable City Strategy*
TEDI	Thermal energy demand intensity
VKT	Vehicle kilometers travelled
ZEBP	City of Vancouver's *Zero Emissions Building Plan*

Chapter 1.

Introduction

As the effects of a warming world become increasingly evident, so too does the necessity of effective climate policymaking for decarbonizing our economy (IPCC, 2018). This policymaking has traditionally been considered solely the responsibility of national and provincial/state governments; however, in recent years the number of local governments around the world pursuing ambitious climate action has grown considerably. At the forefront of this trend in Canada is the City of Vancouver (Vancouver) in British Columbia. In 2015, Vancouver set ambitious targets to use 100% renewable energy and reduce greenhouse gas (GHG) emissions by 80% by 2050 as part of its *Renewable City Strategy*. Since adopting these goals, Vancouver has implemented policies aimed at reducing emissions in buildings, transportation, and waste and announced plans and programs for future policy action (City of Vancouver, 2017).

In June 2018, Vancouver brought forward its *Making Room Housing Program*, a strategy for densifying low-density residential neighbourhoods within its borders. Much of Vancouver's land area currently consists of neighbourhoods dominated by single-family detached homes—a type of land use that has been associated with high per capita personal transportation and home energy use and emissions (Brownstone & Golob, 2009; Ewing & Rong, 2008; Norman et al., 2006). *Making Room* aims to change the composition of these neighbourhoods by fostering medium-density housing options within the city, including triplexes, quadplexes, sixplexes, row houses, and low-rise apartments, among others (City of Vancouver, 2018a). As a quick-start, interim first step of *Making Room*, nearly all detached home properties within the city have been rezoned to duplex zoning. If the implementation of this program continues, additional rezoning policies will likely be brought forward to further densify these neighbourhoods with other medium-density building forms.

The potential transformative power of *Making Room* in the context of Vancouver's ambitious climate-energy targets make it an interesting case study for better understanding the emissions reduction role of residential densification. Although Vancouver's rationale for *Making Room* is firmly rooted in housing availability and affordability, if the program's vision is met, the resultant change in urban density could have implications for the city's renewable energy and emissions reduction targets. Many studies have found evidence of negative correlations between urban density—the number of people inhabiting an urbanized area per unit land area—and per capita energy use and emissions in buildings and personal transportation. However, the strengths of these interactions are still subject to much debate (Gudipudi et al., 2016). These relationships appear to be highly context-specific, and the effects of densification—the process of increasing density over time—are not well understood, particularly in low-density suburban neighbourhoods.

In this study, I sought to address the research question: What is the influence of residential densification on energy use and GHG emissions in Vancouver? To answer this question, I used an urban-level energy-economy-emissions model, CIMS, to evaluate three hypothetical densification scenarios in Vancouver in terms of energy use and emissions. In my first scenario, *"Detached",* I assumed Vancouver's residential neighbourhoods would continue to evolve as they have over the past decade—when detached homes are demolished, they are predominately replaced with detached homes. In my second and third scenarios, "*Triplex"* and "*Sixplex"*, these demolished homes are instead replaced with triplexes and sixplexes respectively.

Because the relationship between urban density and personal transportation is not simulated endogenously in this version of CIMS I utilized in my study, an additional transportation "mode shift" sub-scenario was applied to *Triplex* and *Sixplex* scenarios to act as a crude sensitivity analysis for the reasonable bounds of densification's effect on mode shifting. In "mode shift" scenarios, it was assumed that Vancouver will meet its *Transportation 2040* target—two-thirds of trips by walking, cycling, or transit by 2040—due to parking restrictions in new buildings and improved and expanded public transit and cycling networks made possible by increased density.

Finally, scenarios were also compared both with and without the continued implementation of Vancouver's *Zero Emission Building Plan* (ZEBP), a plan that defines targets and policy pathways for mandating new buildings to have zero operational emissions by 2030 (City of Vancouver, 2016). This additional sub-scenario comparison was performed because the future rollout of the ZEBP's higher stringency policies is highly uncertain. Additionally, this comparison provides insights on the effectiveness of these strategies—densification and energy-switching policy—for emissions reduction at their evaluated stringency levels.

Residential densification in Vancouver has the potential to influence another energy-related metric: affordability. Typically defined as the ability to spend less than 45% of household income on housing and transportation costs, affordability is a key priority for local governments. Proponents of *Making Room* argue that increasing the supply of housing in low-density neighbourhoods will contribute to affordability by lowering home and rent prices. Although not as significant as rental or mortgage costs, household energy costs are another key component of affordability that could potentially be influenced by densification (Green et al., 2015). A household's energy costs are comprised of its home energy and personal transportation expenditures, both of which have been linked to urban density (Litman, 2017; CTOD, 2006).

Recognizing that densification is being pursued in Vancouver for an affordability rationale, my study sought to answer an additional question: What is the effect of densification on home energy and personal transportation affordability in Vancouver? To address this question, I used an ex-post analysis of my model results to evaluate the influence of residential densification on home energy and transportation costs for archetypal households in each of my three densification scenarios across both "mode shift" and "ZEBP" sub-scenarios.

In summary, the objectives of this study are to better understand how residential densification in Vancouver:

1) Influences energy use and greenhouse gas emissions in the context of Vancouver's *Renewable City Strategy* targets;

2) Interacts with and compares to other potential urban-level GHG policies including zero-emission building regulations; and

3) Affects household home energy and personal transportation costs.

The remaining sections of this report outline the details of my study. In Chapter 2, I provide background information on the context for local government GHG policy, the role of urban density in emissions reduction, and Vancouver's current and proposed densification policy landscape. In Chapter 3, I describe my research methodology including the CIMS model, my model scenarios and assumptions, and my ex-post affordability analysis. After presenting and discussing my results in Chapter 4, I summarize my results and discuss study limitations and areas for future research in Chapter 5.

Chapter 2.

Background

2.1. The Context for Local Government GHG Policy

Climate change is a threat to the health and wellbeing of our species and planet. Human activity, primarily the burning of fossil fuels, is increasing the concentration of atmospheric GHGs, which in turn is causing a rise in average global temperature. The impacts of this warming—including sea level rise, increased intensity and frequency of extreme weather events, and disruptions to sensitive ecosystems—are evident today and predicted to intensify by the end of the century if emissions are left unabated. Recognizing the severity of this threat, the global community came together in 2015 to adopt the Paris Agreement, committing to hold global warming well below 2°C, with 1.5°C as a target. This agreement was hailed as a watershed in the fight against climate change as it was the first time both developing and developed nations have together agreed to reduce their emissions.

While the Paris Agreement is an important step forward toward international coordination in combating climate change, history has shown that commitment does not equal action. In the past, many promises of climate action from national and provincial/state governments have been broken because they were followed up by ineffective or misguided policies—and there is little evidence that this is changing. Since the Agreement's signing, governments have largely failed to implement the GHG reduction policies necessary for meeting its lofty targets (IEA, 2018; IPCC, 2018). Canada, for example, is projected to miss its 2030 Paris GHG target by 66 megatons given the policies outlined in its Pan-Canadian Framework on Clean Growth and Climate Change (Environment and Climate Change Canada, 2017).

Frustrated by this lack of leadership by senior governments, many cities around the world have set ambitious emissions reduction and renewable energy adoption targets (Bloomberg Philanthropies, 2018). This trend has been fostered by international networks such as C40 and the Global Covenant of Mayors, and now includes a growing list of prominent cities on every continent (except Antarctica)—New York City, Toronto, London, Copenhagen, Berlin, Rio de Janeiro, Johannesburg, and Yokohama, to name a few. Many cities pursuing ambitious climate action have committed to the popular 80 x 50 target (80% emissions reduction by 2050), while others are also pushing for a transition to 100% renewable energy. Although large cities have received the most attention, many smaller municipalities have joined these movements as well: over 50 British, 70 American, and 150 German local governments have committed to switch to renewable electricity in the coming decades (Sierra Club, 2018; Worldwatch Institute, 2017). In Canada, six local governments have recently committed to move to 100% renewable energy by 2050 including Vancouver, Victoria, Nelson, and Saanich in British Columbia, Oxford County and Guelph in Ontario, and Regina, Saskatchewan. Additionally, the country's largest city, Toronto, recently approved an 80 x 50 target.

The details of these targets vary among cities. Some cities' targets are in line with those of their senior governments, while many others have the most ambitious targets in their province, state, or country. A number of cities allow for offsets or emissions neutrality in meeting their emissions targets; others do not allow for such flexibilities. Caveats also exist in many renewable energy targets, such as a narrow focus on electricity, ignoring all transportation, residential, commercial, and industrial fossil fuel use. Nonetheless, this recent push for aggressive climate action by local governments is quite novel, especially in North America.

Urban GHG emissions, as defined in this study, are GHG emissions released within the geographic boundaries of a city. In Vancouver, for example, these emissions come from natural gas consumption in residential, commercial, and industrial buildings and gasoline, diesel, and natural gas consumption in personal and freight transportation. Excluded from this emissions accounting are any carbon emissions from biologically-derived fuels such as ethanol, biodiesel, and biogas. When combusted, the carbon dioxide molecules in these biofuels return to the atmosphere from which they came.

Many cities include electricity GHGs in their emissions targets and reporting even though most electricity generation occurs outside their borders (C40, 2015). My study does not include electricity GHGs or other upstream GHGs in the production of biofuels, fossil fuels, or hydrogen in its definition of urban emissions, as reducing these emissions is typically not within the jurisdictional authority of local governments, including Vancouver. It should be noted that the upstream emissions of energy consumed in Vancouver are small relative to combustion emissions that occur within the city. Vancouver's electricity is supplied by an almost entirely renewable grid, and the upstream emissions of fossil fuels are substantially lower than the emissions released during combustion. Furthermore, recent modelling shows a declining rate of upstream emissions in biofuels (Jaccard et al., 2016).

Cities are an obvious focal point for climate-energy policy. Over 54% of the world's population lives in cities, a number that is expected to grow to 66% by 2050 (World Bank, 2018). Furthermore, cities produce a significant portion of global emissions within their borders and city-dwellers tend to be more receptive to GHG reduction policies relative to their rural counterparts (Rosenzweig et al., 2010). Implementing effective GHG policy at the local level can be difficult, however. In Canada, local governments have limited legislative powers relative to senior levels of government. This is particularly true for GHG policy, where senior governments can levy carbon taxes, set emissions caps, and regulate the technology and fuel choices of households and firms—all things local governments may find difficult or impossible within the legislative framework in which they operate. Recent studies have found that Vancouver and Victoria, two major cities in British Columbia that have committed to 100% renewable energy and 80% emissions reductions by 2050, will likely have a difficult, if not impossible time reaching their targets without significant policy support from senior governments (Braglewicz, 2018; Zuehlke et al., 2017).

This is not to say cities have no role or ability in reducing emissions; instead the appropriate view of cities is both as policy takers and policy makers (Braglewicz, 2018). Local governments can decarbonize their own corporate operations (including city-owned buildings and transit systems), as well as prevent methane release at municipal landfills. Further, they possess considerable control over transportation activity within their borders through mechanisms such as road pricing, parking policies, electric vehicle charging station installations, mixed land-use zoning, and transit and active transportation network improvements. They also possess numerous options—albeit some more effective than others—for influencing building stock emissions. They can update building codes to improve the energy efficiency of new buildings[1], promote the development of efficient and low-emission district energy systems, incentivize home energy efficiency retrofits through targeted subsidy and information campaigns, and increase urban density through zoning bylaws.

2.2. The Role of Urban Density in Emissions Reduction

Urban density is an important metric in urban planning. Popular planning theories such as Smart Growth, New Urbanism, and Transit-oriented Development champion density as an essential component for achieving sustainability, livability, and affordability goals. While advocates of these theories often tout the energy use and emissions reduction benefits of densification, this relationship is more nuanced in the literature. There is indeed a general consensus of a negative relationship between urban density and per capita emissions. However, studies investigating the strength of this interaction have shown conflicting results (Gudipudi et al., 2016).

Density is a result of urban form and the built environment. In North American cities, low-density areas are often characterized by single-family detached homes on large lots. Denser areas consist of more compact housing forms including duplexes, triplexes, row houses, and low-rise apartment buildings. The densest areas are characterized by high-rise apartment buildings. Different levels of density are not only associated with different building types but also different neighbourhood forms and transportation networks. Urban density is thereby linked to two sectors of critical importance for reducing emissions in cities: energy use in personal transportation and energy use in buildings. Research over the past two decades has investigated these links, often testing hypotheses that increased density reduces per capita or per dwelling emissions by (1) decreasing travel demand and promoting transportation mode shifting, and (2) reducing energy consumption in residential buildings.

[1] This authority is dependent upon provincial/state building code legislation. In some provinces—BC and Quebec for example—municipalities hold considerable control over the building code regulations they follow. In other jurisdictions, such as Ontario, local governments do not possess this ability.

2.2.1. Urban Density and Personal Transportation

Many studies have found evidence of a correlation between higher densities and lower per capita personal transportation energy use and emissions (Gudipudi et al., 2016; Chester et al., 2013; Brownstone & Golob, 2009; Norman et al., 2006; Holden & Norland, 2005). It is posited that as urban density increases, per capita travel demand decreases because the distance individuals need to travel between locations is reduced, thereby cutting emissions from fossil fuel-powered modes of transport. Moreover, these shorter trips make walking, cycling, and taking public transit more attractive, further reducing emissions by promoting mode shifting away from personal vehicles. While studies such as the ones cited above have found evidence of this relationship, it appears to be quite modest and highly context-specific (Kim & Brownstone, 2013).

When researchers isolate the effect of density by controlling for other variables, density's impact on per capita travel demand and vehicle use appears to be very limited. Instead, a complex suite of factors determines travel behavior in an urban environment, making it difficult to attribute any meaningful decline in transportation emissions to density alone. For example, mixed-use development—the combining of land uses such as residential and commercial within the same area or building—is a particularly important variable (Hachem, 2016; Potoglou & Kanaroglou, 2008). Walkability, employment density, and transit quality have also been found to be important factors (Mindali et al., 2004; Badoe & Miller, 2005). These results suggest that densification that does not incorporate mixed-use development or transportation network improvements will have little effect on per capita personal transportation demand and mode shifting (Clark, 2013).

2.2.2. Urban Density and Residential Buildings

As mentioned above, a second prominent hypothesis in the literature is that increased density reduces per capita energy use and emissions in residential buildings. Energy end uses in residential buildings include space conditioning, water heating, lighting, cooking, refrigeration, and all other appliance use and plug loads. Many studies support this hypothesis, finding evidence of negative correlations between density and per capita energy use in residential buildings (Ewing & Rong, 2008; Holden & Norland, 2005; Lariviere & Lafrance, 1999). A related negative correlative relationship has also been found between density and per capita building emissions. Because space conditioning is often supplied by fossil fuels such as natural gas and heating oil, reduced energy consumption observed in dense urban areas leads to a reduction in building emissions (Gudipudi et al., 2016; Lee & Lee, 2014; Norman et al., 2006).

Density influences residential building energy use and emissions through two mechanisms, the first of which is floorspace. Dwellings in dense neighbourhoods tend to have lower average floor space than dwellings in less dense neighbourhoods. Holding building shell and space conditioning technologies constant, these smaller dwellings use less energy simply because they have less volume to heat up and cool down and brighten with lighting (Steemers, 2003). The second way urban density influences building emissions is through the promotion of increased thermal performance. Dwellings within multi-unit buildings have less walls exposed to the temperature extremes and fluctuations of the outside environment. By sharing walls with the dwellings around them, these dwellings benefit from increased thermal performance and thus require less energy for space conditioning (Martilli, 2014). These declines in energy use reduce emissions from carbon-based heating fuels.

Just like the relationship between density and per capita transportation emissions, the link between density and per capita building emissions appears to be highly context-specific and can vary in strength depending on the location, scale, and method in which it is measured. Some studies have found a limited effect of density on per capita building energy use and emissions, noting occupancy rates (Perkins et al., 2009), building age (Holden & Norland, 2005), and neighbourhood type (Mindali et al., 2004) as important factors in this relationship. However, several recent studies have found a considerable effect. For example, in a study that used regression analysis to assess emissions in American urban areas, Gudipudi et al. (2016) found that a doubling of population density was associated with a residential sector per capita emissions reduction of 41%. In a similar study, Lee & Lee (2014) found a doubling in population density was associated with an emissions reduction of 35%.

Many studies have evaluated the relationship of density and building emissions; however, less research has investigated the dynamic effects of increasing density over time. This is partly because most studies that have investigated this relationship, including many of the ones cited above, have used static (i.e. time invariant) techniques. Common methods in these studies include employing statistical models to find correlations between variables in large, single-year datasets or using engineering and design equations to estimate energy use and emissions for archetypal buildings and neighbourhoods. Although these studies help us understand relationships between density and energy use and emissions under current conditions, they cannot be directly applied to the future, as this would ignore all future technological and policy changes that could hold considerable influence over these relationships.

While many static analysis studies make inferences about the effectiveness of future densification as an emissions reduction strategy, other researchers have utilized multi-year datasets or employed dynamic simulation models to overcome the limitations of time-invariant analysis (Leibowicz, 2017; Ishii et al., 2010; Behan, 2008). However, the models used by these studies have tended to focus on a narrow set of policies and actions, failing to account for future policy interactions with energy efficiency and energy-switching building policies. Moreover, these models also tend to rely on user-defined technical assumptions on how changes in urban form influence building energy use, thus lacking an empirical basis from behavioural research (Reinhart & Cerezo Davila, 2016).

2.3. The History and Potential Future of Residential Densification Policy in Vancouver

The City of Vancouver in British Columbia (BC) is the densest city in Canada, with over 630,000 inhabitants in an area of 115 square kilometers. While this density of 5,493 people/km^2 is less than one-fifth that of other major cities such as Hong Kong and Paris, it is considerably higher than Canada’s two largest cities, Montreal (4,662 people/km^2) and Toronto (4,334 people/km^2) (Statistics Canada, 2016). In addition to high levels of active transportation and public transit use, examples of green building design, and a series of ambitious sustainability targets including the goal to be the “greenest city in the world by 2020”, this density has led to Vancouver being widely recognized as a global leader in city-led climate action (City of Vancouver, 2012a).

Although Vancouver is well-known for its high-density, transit-friendly urban core, over 50% of the city’s land area is comprised of low-density single-family detached home neighbourhoods[2]. Years of rising real estate and rental prices have resulted in Vancouver being the most unaffordable housing and rental market in Canada, and many observers note that densifying these low-density neighbourhoods could help alleviate the city’s tight housing supply. (Wright & Hogue, 2018). The standard measure of housing affordability is the ratio of average house price to average income, with many experts considering a ratio of 5 to be ‘seriously unaffordable’. Vancouver’s has recently been measured between 11 and 13 (Gordon, 2016).

Responding to housing affordability and availability concerns, over the past 15 years Vancouver has promoted gradual densification in its single-family neighbourhoods through secondary suite and laneway home zoning policies. Secondary suites—self-contained dwelling units within a larger principal dwelling—have been allowed in several single-family neighbourhoods since the late 1980s. In 2004, Vancouver changed its zoning bylaws to allow secondary suites in single-family detached dwellings in all neighbourhoods, raising the allowable dwelling density per lot from one to two (City of Vancouver, 2009). Five years later, in 2009, Vancouver began permitting laneway houses on single-family lots in certain neighbourhoods, extending this policy to all neighbourhoods in 2012. It is now estimated that there are over 30,000 secondary suites within Vancouver’s approximately 70,000 detached dwellings, and the number of laneway houses is nearing 3,000 (City of Vancouver, 2018b).

While these policies have increased the density of Vancouver’s single-family residential neighbourhoods, more aggressive policy is currently under consideration. In June 2018, Vancouver approved the *Making Room Housing Program*, a strategy for promoting the “missing middle” of housing options between single-family houses and

[2] Please note that the terms single-family detached, single-family, and detached are used interchangeably throughout this report. They all refer to stand-alone dwellings consisting of one primary dwelling unit.

large-scale apartment buildings. *Making Room* aims to address the city's affordability issues by increasing the supply of triplexes, fourplexes, sixplexes, rowhouses, and/or small apartment buildings within the city's traditionally single-family neighbourhoods. Vancouver argues that this strategy is needed to increase affordable ownership opportunities and livable rental spaces within its residential neighbourhoods. Although secondary suites and laneways provide affordable housing rental options, they don't provide ownership opportunities, they are limited in number, and they often provide lower levels of livability and lease security than purpose-built rentals (City of Vancouver, 2018a).

In September 2018, Vancouver passed the first major policy in the *Making Room Housing Program*: nearly all single-family detached home neighbourhoods in the city were rezoned to duplex zoning. This rezoning allows for two ownership opportunities per lot, plus secondary suite rental units. According to the *Making Room* report, this rezoning is just a temporary, interim measure as zoning policies that allow triplexes and other multi-unit building forms within the city's low-density neighbourhoods will be pursued in the future (City of Vancouver, 2018a). In addition to altering building forms, *Making Room* also has the potential to alter the use rates of different transportation modes in these neighbourhoods, most of which are currently characterized by poor access to public transit and congested street parking. Though little detail is included, the report notes that improved transit and active transportation infrastructure are key for the program to be successful. Similarly, it also mentions the exploration of complementary policies for reducing or eliminating parking requirements in these future higher density new buildings to disincentivize car ownership.

2.4. Need for Analysis

In this study, I use an energy-economy-emissions model to evaluate hypothetical densification scenarios for Vancouver's low-density residential neighbourhoods. This analysis is useful because it will (1) help Vancouver understand how it's *Making Room Housing Program* could influence energy use, emissions, and affordability within the city, and (2) contribute to the literature regarding the effectiveness of densification as an emissions reduction strategy.

Although Vancouver's emissions have decreased since 2007, the city is projected to miss its current 2020 emissions target—a 33% reduction below 2007 levels—which was set before the adoption of the *Renewable City Strategy* (RCS). In an optimistic case, Vancouver will achieve 20% emissions reduction by 2020 (City of Vancouver, 2017). This likely failure follows a long line of missed GHG reduction targets at other levels of government in Canada and abroad. To help prevent future failures it is imperative that current and proposed policy choices are assessed using independent, scientifically-based methods to ensure public accountability and help policymakers weigh the effectiveness of policy options for reaching their GHG reduction targets.

One such recent assessment by Zuehlke et al. (2017) evaluated policy pathways for reaching Vancouver's RCS targets of 100% renewable energy and 80% emissions reduction by 2050. This research found that if the policies and actions outlined in the RCS were implemented, Vancouver would only reduce its emissions by approximately 30% by 2050, far from its 80% emissions reduction target. Zuehlke et al. (2017) did not evaluate densification pathways in Vancouver, leaving uncertainty as to how densifying low-density neighbourhoods could influence energy use and emissions in the context of the city's targets. Furthermore, this study did not assess home energy and transportation costs, leaving unanswered questions about how policies under the RCS and *Making Room* will influence affordability.

Investigating the role of densification on Vancouver's RCS targets also provides an opportunity to contribute to an ongoing debate in the literature regarding the effectiveness of residential densification on reducing building energy use and emissions. The modelling approach used in this study, as described below in Chapter 3, helps overcome several limitations of past research including static analysis approaches, limited policy interaction assessment, and a lack of behavioural realism.

Chapter 3.

Methods

3.1. The CIMS Energy-Economy Model

In this study, I use a city-level version of the CIMS energy-economy model to assess energy use, emissions, and affordability in Vancouver. Developed by the Energy and Materials Research Group at Simon Fraser University, CIMS is an integrated set of dynamic energy-economy models that simulates the evolution of capital stocks in an economy through retirements, retrofits, and new purchases (Jaccard et al., 2003). The model is technologically explicit, meaning it keeps track of vintages of capital stocks of different efficiencies as well as other vintage-specific characteristics. It is also behaviourally realistic in that it incorporates consumer preferences based on empirical research to better simulate how households and firms will respond to GHG policy.

In each time period, CIMS records energy consumption and costs, as well as GHG emissions. Retirement of capital stocks is based on an age-dependent function, and demand for new stocks is set exogenously or by the services demanded from the interaction between the model's supply and demand modules. When a new capital stock is required—either because an old capital stock has retired or demand has increased—CIMS fills this stock by competing technologies for market share based on a comparison of their lifecycle costs. This competition is calculated through the CIMS market share algorithm:

$$MS_j = \frac{\left[CC_j \times \frac{r_j}{1-(1+r_j)^{-n}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k \times \frac{r_k}{1-(1+r_k)^{-n}} + MC_k + EC_k + i_k\right]^{-v}\right\}}$$

where the market share (*MS*) of technology *j* is dependent on its lifecycle cost relative to the lifecycle costs of all other *K* competing technologies. CIMS does not base this comparison of lifecycle costs on financial costs alone; it also includes non-financial or "intangible" costs (*i*) that reflect technology-specific preferences (Jaccard et al., 2003). Financial costs are comprised of the technology's capital cost (*CC*), maintenance and operating cost (*MC*), and energy cost (*EC*). Capital costs are annualized using a revealed private discount rate (*r*) specific to the group of technologies being competed. Last, a *v* parameter is used to represent market heterogeneity, influencing the relationship between technology lifecycle costs and market share.

CIMS' behavioral realism comes from its three behavioral parameters, *r*, *i*, and *v*. Without these three parameters, CIMS would allocate market shares based on financial costs alone instead of accounting for household and firm behavior. The revealed private discount rate, *r*, is the weighted average time preference of decision makers for a given energy service demand (Rivers & Jaccard, 2006). While many engineering models contain social discount rates in their financial cost calculations, the inclusion of revealed private discount rates that can vary between energy sectors and services aims to improve the behavioral realism of the model.

The *i* parameter accounts for all non-financial costs or benefits associated with the use of a technology or energy service relative to a baseline conventional technology. Common examples of intangible costs include inconvenience or the perceived risks of adopting a new technology such as a ground-source heat pump or an ultra-efficient building shell. It is critical to consider intangible costs when assessing policies because individuals often do not make choices solely on financial cost minimization (Jaccard et al., 2004). For example, if financial costs were the only costs that influenced consumer preferences, then it would be likely that everyone in a city would take public transit as their preferred mode of travel. However, many people drive personal vehicles, take taxis or Ubers, or carpool with a friend or colleague even though these are more expensive modes of transport. While taking public transit may be less expensive than driving a personal vehicle or taking a taxi, it entails additional intangible costs such as wait times, less comfort, and unpredictable schedules.

Finally, the market heterogeneity parameter, *v*, accounts for variation in consumer preferences—different individuals may choose different technologies when presented with identical options. The inclusion of a market heterogeneity parameter allows CIMS to divide market share among competing technologies in a way that better reflects the diverse choices of consumers and businesses. The level of CIMS' behavioral realism, as well as the level of confidence the researcher can have in the model, is dependent on the accuracy of *r*, *i*, and *v*. It is therefore important for these parameters to be grounded in empirical evidence. Over the past two decades, researchers have estimated behavioural parameters in CIMS using revealed and stated preference techniques, literature review, and expert judgement.

CIMS has been widely used for provincial- and national-level policy analysis in Canada. With the recent trend of local governments pursuing ambitious GHG reductions, there was a need for specialized city-level versions of the model. In terms of analysis, the sources of energy use and emissions in cities differ from the provincial or national level. The high levels of energy use and emissions from large industrial operations such as mining or oil refining hold substantive weight in provincial- and national-level analysis. However, energy-intensive industrial operations tend to be outside the municipal borders of most urban areas, leaving buildings and vehicles as the primarily source of emissions in cities.

To reduce energy use and emissions, local governments must therefore influence buildings and transportation within their boundaries through policy on the built environment including land use, building stock, and transportation networks. Recognizing these differences between city- and provincial/national-level modelling, city-level versions of CIMS have been developed (Wolinetz & Goldberg, 2012). Recent projects have applied these city-level versions of the model to policy analyses in Metro Vancouver (Moorhouse, 2014), the Regional District of Nanaimo (Baji, 2015), the City of Vancouver (Zuehlke et al., 2017), and the City of Victoria (Braglewicz, 2018).

In this study, I use a scaled-down version of CIMS applied to Vancouver. This version of CIMS simulates five sectors within Vancouver’s borders from 2000 to 2050: residential, commercial, industrial, personal transportation, and freight transportation. The model does not include the solid waste sector, which only accounts for 4% of Vancouver’s current emissions profile (City of Vancouver, 2017), and unlike the study by Zuehlke et al. (2017), it does not include a GIS-based spatial component. While this

GIS-based spatial component could improve upon aspects of this research in the future, incorporating it in this analysis was outside the scope of this study.

3.2. Densification Scenario Development

My study uses the CIMS-Vancouver model to evaluate three hypothetical densification scenarios for Vancouver's low-density single-family neighbourhoods in terms of energy use, emissions, and home energy and transportation affordability. Vancouver's *Making Room Housing Program* outlines a strategy for densifying these neighbourhoods, providing a range of densification options from duplex to low-rise apartment building rezoning on current single-family lots. It does not however, provide any specific densification pathways. It is therefore currently unclear what, if any, zoning changes Vancouver might implement to foster single-family neighbourhood densification. Also unclear is where these zoning changes will occur. Will all lots be rezoned or just specific neighbourhoods, areas, or streets? Will the same level of rezoning apply to most lots or will it be highly selective based on lot size or location?

Because of this future uncertainty, my densification scenarios are intended to be illustrative rather than predictive and were chosen to show the effects of varying degrees of single-family neighbourhood densification. The densification scenarios in my model differ in terms of what is built to replace a single-family detached home during stock turnover (i.e. when it is demolished). In my first scenario, *"Detached",* I assumed Vancouver's residential neighbourhoods would continue to evolve as they have over the past decade—when detached homes are demolished, they are predominantly replaced with detached homes. In my second and third scenarios, "*Triplex"* and "*Sixplex"*, these demolished homes are instead replaced with triplexes and sixplexes respectively. The rest of the sectors in the model, including the residential sector outside of Vancouver's single-family detached home housing stock, evolve over time based on City of Vancouver, Metro Vancouver, and provincial and federal government growth projections.

3.2.1. "Detached" Scenario

In my *Detached* scenario, I modelled Vancouver's energy use and emissions under a status quo or business-as-usual policy landscape[3]. In this scenario, single-family detached stock turnover results in new single-family detached stock. The annual stock turnover rate was set at 1.5%, the average rate over the past decade according to figures supplied by the City of Vancouver. Dwelling numbers from 2000 to 2015 for all housing types were compiled using data from Metro Vancouver's Housing Data Books and the Canada Census (Metro Vancouver, 2018; Statistics Canada, 2016; Metro Vancouver, 2010).

My *Detached* scenario housing stock projection was set exogenously to align with Metro Vancouver's housing stock forecast to 2040 (Metro Vancouver, 2015). To project growth from 2040 to 2050, I assumed the same housing stock growth rate as the previous decade. To meet this projection, I had to make assumptions about the growth rates of the four dwelling types modelled in CIMS: high-rise apartments, low-rise apartments, attached dwellings, and detached homes. Detached homes, attached building dwellings, and low-rise apartment dwellings were set to grow in number at rates of 0.002%, 0.03%, and 0.024% respectively per year to 2050, rates equivalent to the average rates of growth for these housing types from 2005 to 2016. From 2015 to 2020, the number of high-rise apartment dwellings was set to grow at an annual rate equal to the average annual rate observed from 2011 and 2016 (1.17%). To align with Vancouver and Metro Vancouver housing projections, this rate then slows to 1.1% from 2020 to 2025, slowing further to 1.05% from 2025 onward.

My study also includes secondary suites and laneway houses in its residential sector, making it the first CIMS study to fully account for these housing types. The creation of a secondary suite does not increase the floor space of a building; instead, it increases the level of services within the building. My model reflects this effect: when a secondary suite is added to a detached home, the level of many services in the building

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[3] This study does not take into account Vancouver's new duplex rezoning policy that was adopted as part of the *Making Room Housing Program* in September 2018 because model analysis was performed before this policy was passed.

increase proportionally to the population growth in the building including cooking, dishwashing, refrigeration, clothes washing, hot water, and other minor appliance services. In my model, whether a detached home contains a secondary suite bears no influence on its likelihood of it being demolished and replaced. In other words, both detached homes with secondary suites and detached homes without secondary suites are demolished at rates proportional to their frequency. For example, if in a given year 40% of detached homes contain a secondary suite, then 40% of the detached homes torn down that year will contain a secondary suite.

For the 2000 to 2015 time period, the number of secondary suites was set by compiling data from several City of Vancouver sources (City of Vancouver, 2018b; City of Vancouver, 2009), while the number of laneway homes was aligned with data in Metro Vancouver’s Housing Data Book (Metro Vancouver, 2018). To 2050, the number of secondary suites increases based on the average annual growth rate observed from 2005 to 2016. The number of laneway houses grow in a similar fashion, based on the average annual growth rate observed from 2009 to 2016. For housing projection simplicity, it is assumed that when a detached home with a secondary suite is torn down, a detached home with a secondary suite is built in its stead. It is also assumed that laneway houses are not torn down throughout the model simulation.

Like the number of residential dwellings, residential floor space is also calculated exogenously in my CIMS-Vancouver model. Total floor space for a given year for each housing type was calculated by multiplying the number of dwellings by the average floor space of that building type (detached home: 221 m^2; dwelling in attached building: 154 m^2; dwelling in apartment building: 78 m^2; laneway house: 59 m^2) (City of Vancouver, 2016).

For population growth figures, the model uses Canada Census data for the period from 2000 to 2015. To project population growth forward, I used Metro Vancouver's high regional growth estimate for 2015 to 2040, the same data source used to project the total number of dwellings in my study (Metro Vancouver, 2015). To project population growth from 2040 to 2050, I assumed the same population growth rate as the previous decade. In my model, population growth influences growth in three other sectors including commercial buildings, light and medium freight transportation, and personal transportation.

For the 2000 to 2015 time period, commercial floor space was estimated using data provided by the City of Vancouver. Moving forward to 2050, commercial floor space was set exogenously to grow proportionally to population. This results in approximately 1.2 million square metres of new commercial floor space by 2025, which fits the City of Vancouver's current projection. The shares of different commercial building types (accommodation and food services, retail trade, offices, etc.) were set from 2000 to 2015 using data provided by the City of Vancouver and were projected forward at near constant shares, although the share of office space was set to increase slightly over time as in Wolinetz (2017). The model's light and medium freight truck activity from 2000 to 2015 was estimated using data supplied by Metro Vancouver. The sector grows proportionally with population to 2050.

As in Wolinetz (2017), in my model personal transportation activity from 2000 to 2015 was derived from estimates calculated by Shakouri et al. (2015). The estimates include all transportation within the city plus out-of-boundary transportation activity that is driven by activities within the city; for example, trips to and from airports or seaports. Projecting activity forward exogenously, as in Zuehlke et al. (2017), I conservatively accounted for road congestion travel demand effects by assuming that total person kilometers travelled would grow slightly slower than the population growth rate. This assumption is based on the estimated decrease in per capita travel demand for contained growth in a mid-sized city in Bataille et al. (2010). Transportation mode splits from 2000 to 2015 follow City of Vancouver data and are exogenously projected to 2050 by slightly decreasing the share of personal vehicles over time to account for a growing city (City of Vancouver, 2017). I assumed that the SkyTrain share of transit travel would remained unchanged to 2050.

3.2.2. "Triplex" and "Sixplex" Scenarios

In my *Triplex* and *Sixplex* scenarios, starting in 2021, when single-family detached homes are torn down, they are not replaced with single-family detached homes. Instead, in the *Triplex* scenario they are replaced with triplexes and in the *Sixplex* scenario they are replaced with sixplexes. This stock turnover occurs at the same annual rate as in the *Detached* scenario, 1.5%. These scenarios simulate simplified and idealized densification pathways of what could occur if Vancouver rezoned single-family properties to triplex or sixplex zoning under the *Making Room Housing Program*. These zoning changes would include altering the allowable setbacks, building height, and floor area ratio (FAR) of these properties. FAR is an important land zoning metric as it dictates the total allowable building floor space on a lot. FAR is calculated as the gross floor area of a building divided by its lot size. Most single-family homes in Vancouver were built at an FAR of 0.6. In the *Triplex* scenario it is assumed new triplexes are built to maximize a 0.9 FAR and in the *Sixplex* scenario, it is assumed new sixplexes are built to maximize a 1.5 FAR.

Triplex and *Sixplex* scenarios experience increased dwelling numbers relative to the *Detached* scenario. In the *Detached* scenario, one detached home is replaced with one detached home during stock turnover. However, in *Triplex*, one detached home is replaced with three dwellings, and in *Sixplex*, one detached home is replaced with six dwellings. By 2050, relative to the *Detached* scenario, this densification effect results in *Triplex* having over 36,000 more dwellings, increasing the number of dwellings in Vancouver's low-density neighbourhoods by nearly 25% (Table 1). *Sixplex* gains nearly 105,000 more dwellings than *Detached* by 2050, increasing low-density neighbourhood dwelling stock by nearly 70%. The rest of Vancouver’s residential building sector in these scenarios evolves in an identical manner to the *Detached* scenario; in other words, the only change to Vancouver’s residential sector in *Triplex* and *Sixplex* relative to *Detached* is the conversion of single-family detached homes to triplexes or sixplexes during single-family detached home stock turnover.

Table 1. Total number of dwellings in *Detached*, *Triplex*, and *Sixplex* scenarios.

	Total Number of Dwellings		
	2015	**2035**	**2050**
***Detached* scenario**	282,602	346,666	388,469
***Triplex* scenario**	282,602	366,891	425,015
***Sixplex* scenario**	282,602	404,711	492,983

In the *Detached* scenario, when a detached home is torn down, it is replaced with a detached home of the same size. The 0.9 FAR and 1.5 FAR zoning changes assumed in *Triplex* and *Sixplex* result in considerably larger buildings, as well as increased total floor space for these scenarios. The average dwelling size in these buildings, however, is smaller. In my model, an average new triplex unit under 0.9 FAR zoning has a floor area of 110.5 m^2, while an average new sixplex unit under 1.5 FAR zoning has a floor area of 92 m^2. Detached homes have an average floor area of 221 m^2.

Due to growth in the number of dwellings, population was assumed to grow more rapidly in *Triplex* and *Sixplex* scenarios relative to *Detached*. Using average dwelling occupancy data for Vancouver derived from Statistics Canada (2016), when a triplex replaces a detached home in the model, population increases according to the average occupancy of three triplex units minus the average occupancy of a detached home (and a secondary suite when applicable). Population increases in a similar manner for new sixplexes. In 2050, relative to *Detached*, *Triplex* has a population over 89,000 larger and *Sixplex* has a population over 301,000 larger (Table 2). This population effect increases city-wide population density from 77 people/hectare in *Detached* to 85 people/hectare in *Triplex* and 103 people/hectare in *Sixplex*.

Table 2. Population growth assumptions in *Detached*, *Triplex*, and *Sixplex* scenarios.

	Total Population Size		
	2015	**2035**	**2050**
***Detached* scenario**	625,889	760,772	880,689
***Triplex* scenario**	625,889	810,308	970,152
***Sixplex* scenario**	625,889	927,920	1,181,958

Increased population growth in the *Triplex* and *Sixplex* scenarios results in increased commercial, light and medium freight, and personal transportation activity. As in the *Detached* scenario, activity in these sectors grows proportionally to population, except for personal transportation activity which grows slightly slower than population to account for constrained traffic growth within a land-constrained city.

3.3. Transportation Mode Shift Sub-Scenario

In *Triplex* and *Sixplex* scenarios, the increase in density relative to *Detached* has no influence on per capita personal transportation activity as the version of CIMS I used in my study does not endogenously calculate the impact of densification on personal transportation travel demand or mode shifting. Holding current infrastructure constant, it is likely that increased population density would worsen road congestion in Vancouver, which in turn could lead to a negative feedback effect on vehicle use, reducing travel demand and promoting mode shifting. I was unable to incorporate this relationship in this study and it is an area where this research could be expanded upon in the future[4].

Therefore, implicit in my model is the assumption that increased density in *Triplex* and *Sixplex* scenarios does not lead to changes in per capita travel demand and mode shares relative to *Detached*. While this assumption is likely not realistic for reasons explained above, it provides a conservative baseline for densification's effect on energy use and emissions. As explained in section 2.2., density alone does not tend to have large personal transportation energy use and emissions effects (Kim & Brownstone, 2013). Instead, research finds that increases in density need to be paired with mixed-use development and improved public transit and active transportation infrastructure for meaningful reductions in energy use and emissions to result. Although *Making Room* mentions that research will be conducted on how transit networks can be improved to support densification, no specific plans or policies have been outlined. Further, the program makes no mention on combining future residential densification with commercial land uses. My densification scenarios therefore represent densification without any coordinated mixed-use development, public transit and active transportation network improvements, or accelerated road congestion feedbacks.

Densification, however, can provide the impetus for improved transportation networks and new commercial areas by stimulating demand and helping local governments fund such actions. It is likely that densification under *Making Room* would

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[4] A city-level spatial version of the CIMS model that can calculate the effects of density and mixed land use on transportation activity is currently under development by the Energy and Materials Research Group at SFU. An earlier version of this model was developed and applied to the City of Vancouver in Zuelhke et al. (2017).

be paired with transportation improvements and additional commercial areas along corridors, although the degree to which is uncertain. To evaluate emissions, energy use, and affordability under a scenario where densification does influence mode shifting, I applied a transportation mode shift sub-scenario (+*ModeShift*) to *Triplex* and *Sixplex* scenarios. In this sub-scenario, transportation mode shares shift over time to meet Vancouver's *Transportation 2040* target of two-thirds of trips by transit, cycling, or walking by 2040 (City of Vancouver, 2012b). *Transportation 2040* is the City of Vancouver's foremost sustainable transportation plan. Currently, over 50 percent of trips in the city are by foot, bike, or transit (City of Vancouver, 2017).

In +*ModeShift*, it is assumed that Vancouver meets its *Transportation 2040* target through two measures: (1) densification provides the city—with likely support from the Province—with the impetus to improve public transit and active transportation networks, which promotes mode shifting away from personal vehicles; and (2) a parking policy is instituted that limits the availability of parking spaces by two-thirds for new triplex and sixplex residents. The *Making Room Housing Program* report outlines that steps should be taken to explore parking policies for limiting vehicle ownership in new buildings. Such parking policies could include limiting the amount of on-street parking permits and limiting the number of parking spaces allowed on new building lots.

In +*ModeShift* scenarios*,* parking is restricted such that only one out of every three units can legally access a parking spot. This policy could be implemented through strict on-street parking permit systems as often seen in large European cities and zoning changes that only allows the development of one parking space per triplex lot and two parking spaces per sixplex lot. In non-ModeShift scenarios, adequate on- and off-street parking is assumed to be available to accommodate the rise in density and thus vehicle use. This +*ModeShift* parking restriction policy was modelled by increasing the intangible costs of vehicle travel until vehicle kilometers travelled (VKT) for residents of new triplexes and sixplexes declined by nearly two-thirds, instead shifting these residents' person kilometers travelled towards transit and active transportation. The individuals without a parking space were still assigned a small amount of VKT based on the 2011 Metro Vancouver Regional Trip Diary's average VKT for individuals who do not own a car. With the popularity of vehicle sharing rising, this assumption is likely very conservative but for model simplicity, exogenous assumptions about future vehicle sharing scenarios were not included in this study.

After increasing intangible costs to model the parking restriction policy, mode choice market shares were aligned with *Transportation 2040* targets to represent public transit and active transportation investments. These market shares were aligned by decreasing the intangible costs of transit and active transportation over time to represent network improvements.

3.4. Zero Emissions Building Plan Sub-Scenario

It is important to gauge how effective densification is as a strategy for reducing energy use and emissions by comparing it to other policies, such as those that regulate efficiency or emissions in new construction. To compare the levels of densification modelled in this study to other potential emissions reduction strategies, I modelled densification scenarios both with and without the full implementation of Vancouver's Zero Emissions Building Plan (ZEBP).

Since adopting the *Renewable City Strategy* in 2015, Vancouver's most significant policy effort for reducing building operational emissions came in 2016 with the approval of the ZEBP. Recognizing that reducing emissions through indirect approaches such as regulating energy efficiency was not having the desired emissions outcome, Vancouver put forward a plan to tie building regulations directly to emissions through the ZEBP (City of Vancouver, 2016). The plan itself does not change building policy in Vancouver. Instead, it establishes GHG intensity (GHGI; kg CO_2/m^2 annually) and thermal energy demand intensity (TEDI; kWh/m^2 annually) targets by building type and outlines a stepped reduction timeline for meeting these targets through maximum permitted limits in Vancouver's Building Bylaw and other building policies. The plan is quite novel, as no jurisdiction in North America at the time of adoption had specific building code requirements for limiting emissions. The targets in this plan as modelled in this study are listed in Table 3.

Table 3. Zero Emission Building Plan parameters used in this study (GHGI = greenhouse gas emission intensity; TEDI = thermal energy demand intensity; MURB = multi-unit residential building).

	Maximum after 2015		Maximum after 2020		Maximum after 2025	
	GHGI	TEDI	GHGI	TEDI	GHGI	TEDI
Detached	12	84	7	55	2.5	30
Low-rise MURB	6	35	6	35	0	10
High-rise MURB	6	32	5	18	0	10
Office buildings	3	27	1	21	0	21

In *Detached*, *Triplex*, and *Sixplex* scenarios, I model current GHGI and TEDI targets listed in the ZEBP ("Maximum after 2015" column in Table 3), as these have been implemented through regulatory policy in the Vancouver Building Bylaw and Green Buildings Policy for Rezoning. The future rollout of the ZEBP's higher stringency GHGI regulations is highly uncertain. However, because the ZEBP is currently one of the most ambitious building-focused GHG reduction policy plans proposed by a local government in North America, I modelled an additional sub-scenario where full implementation of the ZEBP occurs. In this sub-scenario—titled *+ZEBP* for the remainder for this report—regulatory policy to meet 2020 and 2025 Zero Emissions Building Plan targets are introduced. To model this regulatory policy in CIMS, I phased out specific building shell, water heater, and furnace technologies in accordance with Zero Emissions Building Plan GHGI and TEDI targets over time, closely following the methodology used to model this policy in Wolinetz (2017).

It should be noted that the ZEBP has no effect on existing building stock as it only applies to new buildings. Moreover, the regulations outlined in the plan do not prevent households from switching space and water heating systems after a building has been built and passed all necessary inspections. The plan states that compliance mechanisms will be implemented throughout the lifecycle of the building including design, construction, and occupancy. The details of these compliance mechanisms are uncertain, and implementation is not guaranteed. Nonetheless, this study assumes that electrical heating systems are not switched to natural gas after building construction. This assumption is reasonable because most new buildings that are required to be zero-emission do not undergo furnace or water heater replacement during the timeframe of my model simulation. This is because most of the buildings that are built to a zero-emission standard in the model are built post-2030, and space and water heating equipment usually have lifespans of 15 to 20 years.

3.5. Summary of Model Scenarios

To summarize, in this study I model three densification pathways for Vancouver's low-density residential neighbourhoods—*Detached*, *Triplex*, and *Sixplex*—to evaluate the effect of densification on energy use and emissions. These scenarios assume no mode-shifting effect occurs from increased densification. To evaluate energy use and emissions in a scenario where densification has a considerable mode-shifting effect, I modelled an additional *+ModeShift* sub-scenario within *Triplex* and *Sixplex* scenarios. This sub-scenario assumes that densification combined with additional parking policies and public transit improvements leads to Vancouver's personal transportation mode shares shifting over time to meet its *Transportation 2040* target of two-thirds of trips by walking, cycling, and public transit. Last, to compare how the full implementation of Vancouver's ZEBP interacts with densification and influences energy use and emissions, an additional *+ZEBP* sub-scenario was applied. In this *+ZEBP* sub-scenario, Vancouver implements regulatory building policies to meet the ZEBP’s 2020 and 2025 targets. A summary of the model scenario and sub-scenario runs performed in CIMS is listed in Table 4.

Table 4. Summary of Vancouver CIMS model scenarios compared in this study.

	Densification scenario		
	Detached	***Triplex***	***Sixplex***
Runs in CIMS	– *Detached* – *Detached+ZEBP*	– *Triplex* – *Triplex+ZEBP* – *Triplex+ModeShift* – *Triplex+ModeShift+ZEBP*	– *Sixplex* – *Sixplex+ZEBP* – *Sixplex+ModeShift* – *Sixplex+ModeShift+ZEBP*

3.6. Additional Model Inputs and Assumptions

In the sections above, I outlined my scenarios and sub-scenarios and how they differ regarding assumptions and inputs. However, many assumptions remain constant across all scenarios and sub-scenarios including energy price projections, technology costs, industrial, freight, and district energy activity, and senior government policy. In this section, I overview these assumptions as well as briefly discuss model calibration.

3.6.1. Energy Price Projections

Because Vancouver's energy consumption has little impact on overall national and sub-national energy demand and prices, energy prices in my model simulations were set exogenously rather than being calculated through CIMS' macro-economic and energy supply and demand feedbacks.

My gasoline, diesel, and natural gas price projections follow Wolinetz (2017). Gasoline and diesel retail price projections are based on the EIA's *2017 Annual Energy Outlook* reference scenario West Texas Intermediate spot price. This spot price was adjusted to account for the price spread between WTI and Western Canadian Select, and then average Vancouver marketing and refining adders were added, as were federal, provincial, and Metro Vancouver taxes. Projections for residential, commercial/industrial, and transportation sector retail natural gas prices were calculated by adding current Fortis BC adders and relevant taxes to the Sumas gas price forecasted in the Northwest Gas Association's *2015 Gas Outlook*.

My ethanol price projection is based on the high corn ethanol production cost used in Wolinetz (2017). As in Zuehlke et al. (2017), my ethanol price grows at an average of 2% every five years, and to account for the current lack of ethanol refueling stations in the Lower Mainland, I added a declining intangible cost starting at $0.35/L and ending at $0.20/L in 2050. My biodiesel and HDRD price projections are based on the high production cost scenarios for these fuels in Wolinetz (2017).

My wholesale biogas price projection reflects an average of the high and low biogas production cost scenarios in Wolinetz (2017). The high-cost scenario is based on the price estimate produced by Hallbar (2017) for the B.C. Government, where the marginal supply of biogas comes from forestry waste thermal production. The low-cost scenario reflects more anaerobic biogas supply in Canada, as estimated by the Canadian Gas Association (2014). By averaging high and low-cost scenarios from Wolinetz (2017), my biogas price projection is aligned with Zuehlke et al. (2017), which assumed that by 2050, large supplies of biogas would not be available to the Vancouver region at a cost that is competitive with electricity for building end-uses.

My model uses the electricity price projection in Wolinetz (2017). BC Hydro's announced increases to 2020 are included in the projection. After 2020, electricity prices are held constant in real dollars. The average residential electricity price in 2015 was found by taking the average electricity consumption per year in BC from the NRCAN Comprehensive Energy Use Database and apportioning it across BC Hydro's two rate steps. Commercial prices are based on BC Hydro's Medium General Service rate, and industrial prices are based on the Large General Service rate.

3.6.2. Technology Parameters

The costs of specific technologies (e.g. furnaces, water heaters, vehicle motors, etc.) in this study were aligned with those used in Wolinetz (2017). However, intangible costs of technologies were aligned with those used in Zuelhke et al. (2017) and Vass & Jaccard (2017). Technology fuel consumption and efficiency parameters were aligned with those used in Wolinetz (2017).

3.6.3. Industrial and Freight Sector Assumptions

In my model, across all scenarios, I assume that the activity of the Molson/Coors brewery ceases after 2020 due to the sale of land. I also assume that the activity of West Coast Reduction and Lantic/Rogers Sugars continues at 2015 levels to 2050. Activity for all other small- and medium-sized industry in my model is assumed to remain the same, an assumption that implies that residential and commercial land use continues to dominate Vancouver land-use planning.

As in Wolinetz (2017), I assume that heavy freight activity grows at an average rate of 2.65% based on a recent container traffic forecast study by the Port of Vancouver (2016). For light and medium freight activity, I assume growth proportional to population in each scenario to 2050.

3.6.4. District Energy Assumptions

I assume that the total floor space served by district energy systems within the city remains constant to 2050. I also assume that the fuels for these systems remain unchanged.

3.6.5. Senior Government Policy Assumptions

Across all scenarios, I assume that provincial and federal government policies hold constant unless a schedule of future changes has been formally announced. Policies that remain stable include renewable fuel requirements, federal vehicle emissions standards, and federal minimum energy performance standards for appliances. For the provincial carbon tax, which has a formal stringency schedule, I assume that the price rises to $50 per tonne of carbon dioxide equivalents by 2021 and remains stable thereafter. The BC low carbon fuel standard is assumed to reach its 10% emissions intensity reduction by 2020 with no future stringency increases. I also assume that the provincial subsidy for electric vehicles ends in 2020, as per the announced schedule of the program.

3.6.6. Model Calibration

The CIMS-Vancouver model I used in my study was originally calibrated by Wolinetz (2017) by running the model over years 2000 to 2015 and adjusting the activity and energy intensity by end use until the model results aligned with real-world data. Data used for calibration included the City of Vancouver's energy and emissions inventory, the BC government’s Community and Energy Emissions Inventory, electricity use data provided by BC Hydro, and gas consumption data provided by Fortis BC. These four data sources themselves were not perfectly aligned, so the model was calibrated to best fit the general trends of the data sources, relying most heavily on Vancouver's energy and emissions inventory (Wolinetz, 2017).

Most sectors in my model remained unchanged from Wolinetz (2017) for the calibration period of 2000 to 2015. However, I did significantly increase the detail of the residential housing stock during this period by accounting for secondary suites and lane way houses. I also made changes to technology intangible costs and updated energy price projections. After altering these key parameters, I ensured my model projections were still well aligned with the calibration data used in Wolinetz (2017).

3.7. Affordability Analysis

To evaluate the influence of densification on home energy and personal transportation affordability, I performed an ex-post archetype affordability analysis closely following the methodology utilized in Wolinetz (2017). In this analysis, I compared home energy and personal transportation costs from 2025 to 2050 for a typical two-person household in each densification scenario, *Detached*, *Triplex*, and *Sixplex*, both with and without additional +*ModeShift* and +*ZEBP* sub-scenarios. The household is assumed to own the dwelling they live in, so they are responsible for both operational energy costs as well as energy-related capital costs. However, the results of this analysis can also be extended to those who rent their housing units long-term, as energy-related capital costs are typically passed onto tenants through rent prices (Davis, 2012). Although the hypothetical rezoning changes are assumed to begin in 2021, results are presented starting in 2025 due to CIMS' five-year model time periods. The effects of densification on housing and rental costs are not evaluated in this analysis as they are outside the scope of this study.

Including the +*ModeShift* sub-scenario in the affordability analysis allowed me to gauge how additional parking polices and public transit and active transportation investment could affect a typical household's transportation costs. Moreover, the inclusion of the +*ZEBP* sub-scenario allowed me to evaluate how increased electrification and energy efficiency could influence both up-front and operational home energy costs. Because archetype scenario details are determined post-analysis, they are described in Chapter 4, Results & Discussion.

Chapter 4.

Results & Discussion

As discussed in section 2.4., there are two primary rationales for this study: (1) in the context of Vancouver's *Renewable City Strategy* targets, assess the potential energy use, emissions, and affordability effects of hypothetical densification pathways under the *Making Room Housing Program*; and (2) contribute to the literature regarding the role of densification in residential emissions reduction. In this chapter, I first present my city-level energy use and emissions model results and discuss how they pertain to Vancouver's *Renewable City Strategy* targets. I compare each densification scenario, with and without the *+ModeShift* sub-scenario to evaluate the effects of combining transportation policies and actions with densification.

Next, I present my energy use and emissions results at per capita levels, evaluating the link between densification and residential building energy use and emissions as commonly assessed in the literature. To determine how this relationship can change over time depending on future policy interactions, I compare this relationship both with and without the continued implementation of Vancouver's *Zero Emission Building Plan*, a policy strategy for promoting energy switching in new buildings. Last, recognizing that *Making Room* is being pursued for an affordability rationale, I discuss how densification and other combinative policies will influence home energy and transportation costs for average households.

4.1. The Influence of Densification on City-Wide Energy Use and Emissions

4.1.1. Densification Scenarios: Energy Use Summary

Total city-wide energy consumption in Vancouver increases to 2050 in each densification scenario, *Detached*, *Triplex*, and *Sixplex* (Figure 1). In the *Detached* scenario, energy use declines slightly to 2030 but then increases from this year forward. Over the past decade, energy consumption has been slowly declining in several sectors in Vancouver, including residential, commercial, and industrial. In my model, this continued business-as-usual decline in energy consumption is due to a combination of policies that increase in stringency post-2015 including federal home appliance efficiency standards, federal vehicle emissions standards, and the implementation of the first phase of the Zero Emissions Building Plan. Additionally, the industrial sector continues to shrink while public transit and active transportation continue to gain market share. After 2030, energy consumption begins to rise as population growth drives demand for greater levels of energy services in transportation and buildings. A similar business-as-usual energy consumption trajectory for Vancouver was calculated by Wolinetz (2017).

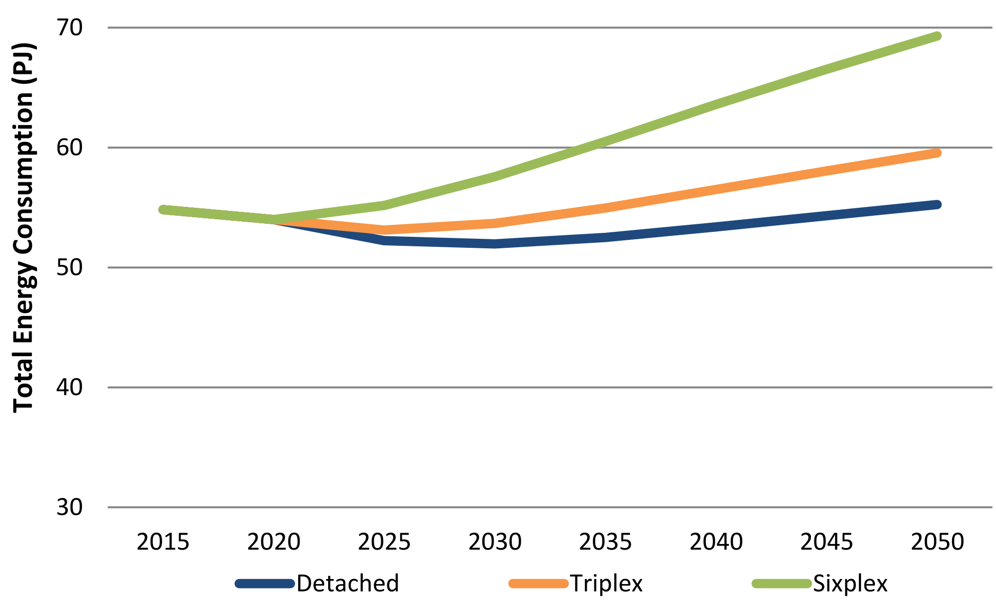


Figure 1. Total energy consumption in Vancouver across all sectors in Detached, Triplex, and Sixplex scenarios.

My model results show that by 2050, the higher the level of residential densification, the higher the level of total energy use (Figure 1). The greater number of dwellings and higher populations in *Triplex* and *Sixplex* drive up energy consumption. While *Detached* sees energy consumption increasing from 2030 onwards, energy consumption growth starts from 2025 onwards in *Triplex* and from 2020 onwards in *Sixplex* due to more rapid population growth.

The denser neighbourhoods modelled in *Triplex* and *Sixplex* scenarios contain more dwellings per unit land area, increasing residential sector energy use (Figure 2). Although the denser building forms in *Triplex* and *Sixplex* scenarios have improved thermal performance relative to their *Detached* counterparts, these efficiency gains are not enough to overcome the increase in total residential floor space per lot. While triplexes and sixplexes have less floor space than detached homes on a per dwelling basis, triplex and sixplex buildings have significantly higher floor space than detached homes. In my model, an average detached home is 221 m^2 in size while an average three-unit triplex building is 333 m^2. An average sixplex building is even larger at 552 m^2. The energy required to light and heat these additional square metres counteract the efficiency gains of these denser building forms.

The increase in energy use in *Triplex* and *Sixplex* scenarios is not only due to increased energy consumption in the residential sector. The population growth associated with a greater number of dwellings increases energy consumption in the commercial and transportation sectors as well (Figure 2). It should be noted that CIMS did not endogenously calculate this inter-sector population effect; rather growth in the number of person kilometers travelled, light freight vehicle kilometers travelled, and commercial floor space added were exogenously linked to population growth. Industrial energy use does not increase with densification because this sector's activity slightly declines across all three scenarios.

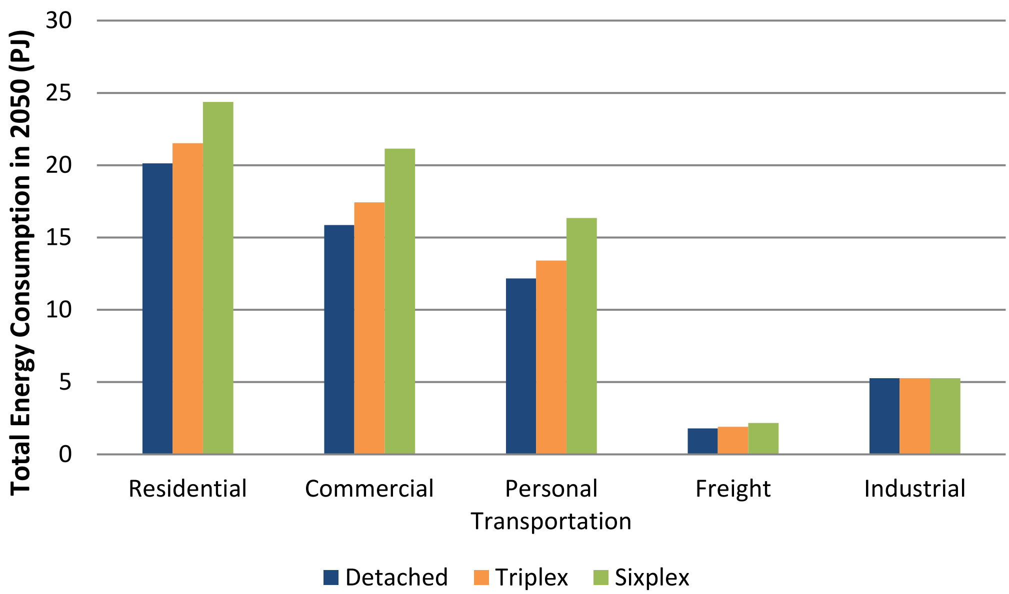


Figure 2. Total energy consumption in Vancouver by sector in 2050.

4.1.2. Densification Scenarios: GHG Emissions Summary

Over the past decade, Vancouver's emissions have declined: emissions in 2016 were down 11% relative to 2007 levels (City of Vancouver, 2017). The *Detached* scenario sees these emissions continuing to decline, stabilizing after 2030 (Figure 3). This continued decline in emissions is due to a combination of policies that increase in stringency post-2015: the provincial carbon tax and low carbon fuel standard, federal vehicle and appliance standards, and the implementation of the first phase of the Zero Emissions Building Plan. A similar emissions pattern was also present in the business-as-usual scenario for Victoria in Braglewicz (2018).

My *Detached* scenario emissions trajectory for Vancouver falls between the business-as-usual projections calculated by two recent CIMS-Vancouver studies: Zuehlke et al. (2017) and Wolinetz (2017). The former calculated that annual emissions would increase to nearly 2,500 $ktCO_2e$ by 2050 while the latter calculated emissions would reduce to 1,500 $ktCO_2e$ annually. My trajectory sits in the middle of this range with annual emissions dropping to 1,900 $ktCO_2e$ by 2050 (Figure 3). My emissions trajectory is lower than Zuelhke et al. (2017) because my study includes more detailed residential, commercial, and industrial sectors with refined exogenous assumptions, current district energy systems within the city, and the first step of the Zero Emissions Building Plan. My projection is higher than Wolinetz (2017) because my intangible costs are greater for many low-emission technologies that currently have limited market share such as electric vehicles and heat pumps. Intangible costs in my study were aligned with those used in Zuehlke et al. (2017) and Vass & Jaccard (2016).

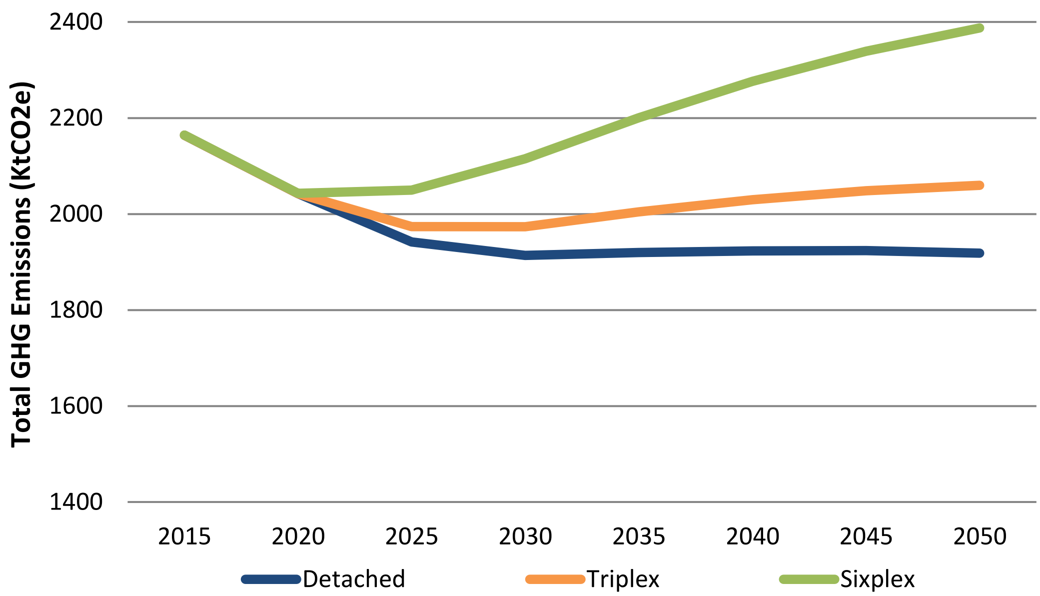


Figure 3. Total GHG emissions in Vancouver across all sectors.

Like in *Detached*, GHG emissions in *Triplex* and *Sixplex* scenarios also decline in the immediate period after 2015. However, they soon begin to increase as population growth leads to greater levels of energy use. A pattern similar to that of energy consumption is observed: the higher the level of densification, the higher the level of emissions (Figure 3). Emissions by sector also follow the same general pattern as energy consumption by sector (Figure 4). Emissions rise through increased gasoline and diesel consumption to supply higher levels of personal and freight transportation and increased natural gas consumption to supply greater levels of residential and commercial energy services.

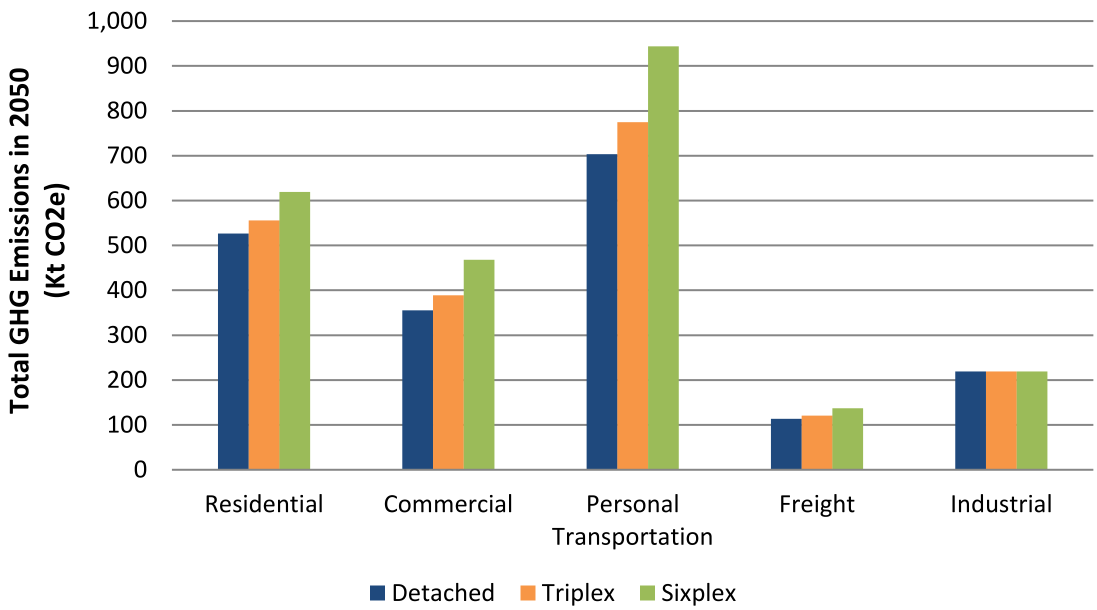
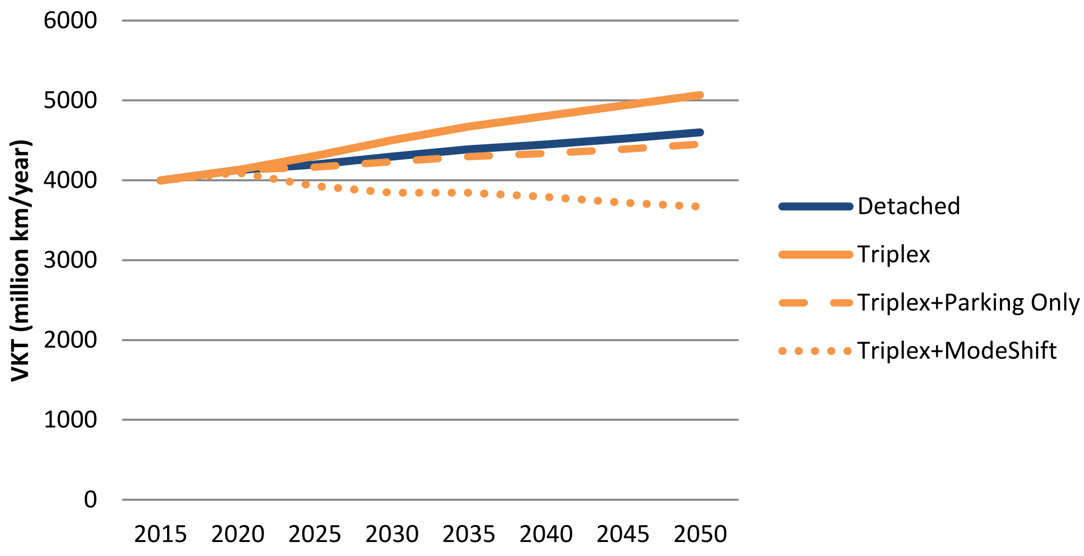


Figure 4. Total GHG emissions in Vancouver by sector in 2050.

While new triplexes and sixplexes are more efficient than new detached homes, they don't lead to significant levels of energy switching under business-as-usual policy. Detached homes, triplexes, and sixplexes utilize natural gas heating systems at near equal rates across scenarios. By 2050, 13% of new sixplexes use electricity for space heating in *Sixplex* compared to 11% of new detached homes in *Detached*. This results in a very modest increase in the proportion of renewable energy in the residential sector: from 47.8% in *Detached* to 49.2% in *Sixplex.* These results suggest that governments cannot rely on densification to promote energy switching in buildings. In my model, the relatively low retail price of natural gas combined with the higher financial and intangible costs of electric heating systems lead to natural gas continuing to dominate the home heating market, regardless of building form.

4.1.3. Transportation Mode Shift Sub-Scenario Effects

My densification scenarios—*Detached*, *Triplex*, and *Sixplex*—assume that densification has no transportation mode-shifting effect. To show how my densification scenarios influence energy use and emissions under a scenario where additional policies promote mode shifting, I applied a *+ModeShift* sub-scenario across the *Triplex* and *Sixplex* scenarios. This sub-scenario assumes that (1) a parking policy is instated that restricts parking for two-thirds of dwellings in new triplexes and sixplexes, and (2) additional improvements are made to public transit and active transportation networks in response to densification. The transportation network improvements promote additional mode shifting in households across Vancouver's residential neighbourhoods, not just those in new triplexes and sixplexes. These policies (1) and (2) have the combined effect of meeting Vancouver's *Transportation 2040* target of two-thirds of trips by walking, cycling, and transit. By 2050, the *+ModeShift* sub-scenario reduces total vehicle kilometers travelled by 30% in *Triplex* and 41% in *Sixplex* (Figure 5). The parking restriction policy accounts for 44% of this reduction in *Triplex* and 56% of this reduction in *Sixplex* (Figure 5).



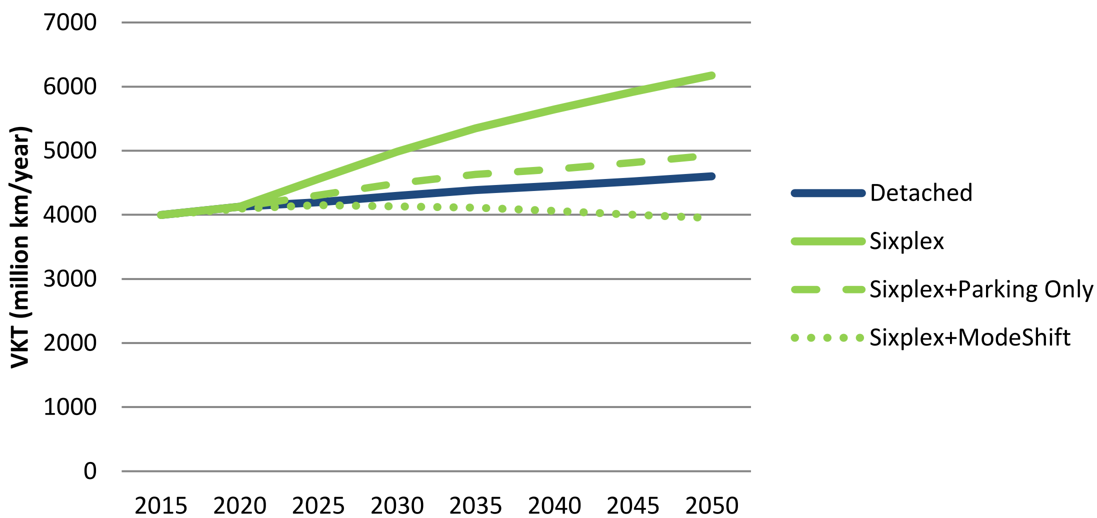


Figure 5. Total vehicle kilometers travelled (VKT) in Triplex and Sixplex relative to Detached. Scenarios are shown without additional policy, with an additional parking restriction policy (+Parking Only), and with additional parking restriction and transit improvement policies that together meet the Transportation 2040 target (+ModeShift).

The reduction in personal vehicle use in *+ModeShift* is exchanged for growth in public transit and active transportation modes of travel (Figure 6). *+ModeShift* versions of *Triplex* and *Sixplex* experience higher levels of walking, cycling, and transit, although travel demand between *+ModeShift* and non-ModeShift scenarios remains constant. This simplistic assumption implies that residential densification does not have a trip-length shortening effect and that switching modes doesn't influence an individual's total kilometers travelled per year. Future CIMS research into the interaction of land use, road congestion, mode choice, and travel demand could improve upon these assumptions.

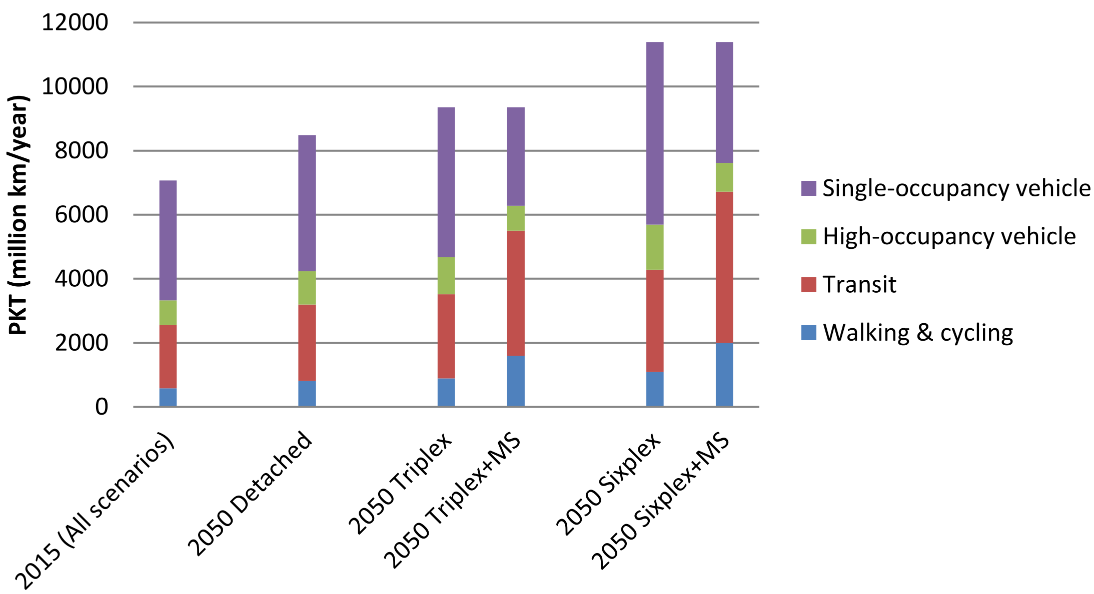


Figure 6. Person kilometers travelled (PKT) by travel mode for densification scenarios with and without +ModeShift sub-scenario (MS).

The shift in travel demand towards transit, cycling, and walking leads to lower total emissions in *+ModeShift* scenarios (Figure 7). Gasoline and diesel consumption decreases 10% from 2015 to 2050 in the *Detached* scenario as a result of improved engine efficiency, increased levels of biofuel mixing in fuels as incentivized through the Low Carbon Fuel Standard, and slight gains in market share for hybrid, plug-in hybrid, and electric vehicles. Triplex*+ModeShift* and *Sixplex+ModeShift* scenarios experience 20% less personal transportation gasoline and diesel consumption by 2050 relative to their *Triplex* and *Sixplex* counterparts. Much of Vancouver's transit system runs on electricity including the SkyTrain and several trolley bus lines, so shifts to transit result in reductions in fossil fuel use.

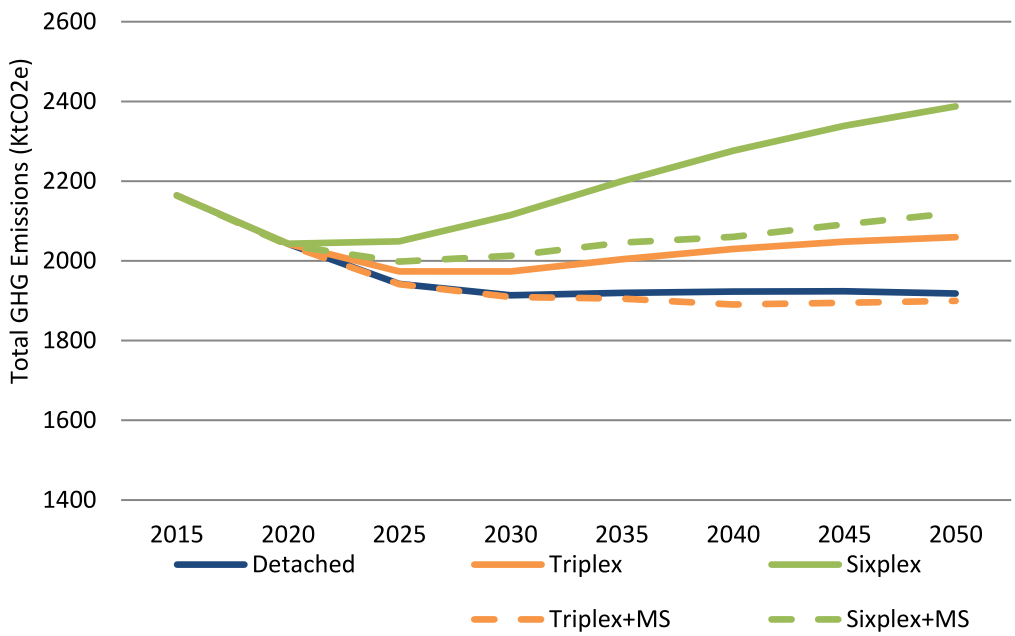


Figure 7. Total GHG emissions in Vancouver across all sectors. Emissions are compared both with and without additional policies and actions to promote transportation mode shifting (MS = +ModeShift scenario).

These results suggest that if residential densification occurs as modelled in this study and key assumptions about densification's effect on other sectors hold true—including increased population causing higher levels of commercial, light freight, and personal transportation activity—it will not help Vancouver meet its 80% emissions reduction by 2050 target. However, if densification is paired with the transportation policies and actions simulated in *+ModeShift*, my results suggest that by 2050, Vancouver will be able to accommodate the 90,000 additional people in *Triplex* while producing slightly less total emissions than under the *Detached* scenario (Figure 7). Similarly, if *+ModeShift* policies and actions are implemented, Vancouver would be able to accommodate the 301,000 additional people in *Sixplex* while producing emissions slightly higher than the non-*ModeShift Triplex* scenario.

While still a far reach from meeting its 2050 emissions reduction target of 553 annual ktCO_2e, these results highlight the potential emissions reduction role of parking restriction policies and coordinated public transit infrastructure when pursuing densification—that is, if full substitution away from gasoline, diesel, and natural gas has not yet been required by government policy. It also must be noted that if electric and plug-in hybrid electric vehicles gain higher market shares than modelled in this study, the emissions reduction effects of mode shifting would be less prominent.

4.2. Influence of Densification on Residential Building Emissions

Like my results above, past research has not found that denser areas have lower total energy use and emissions than less dense areas. Increased energy use from higher populations far outweighs reduced energy use from smaller, more efficient buildings and less vehicle use. Instead, many studies have found evidence of a negative relationship between urban density and per capita or per dwelling personal transportation and building energy use and emissions. As discussed in section 2.2., the strength of the relationship between density and building energy use and emissions has been subject to considerable debate. Similarly, the effect of densification on building emissions is not well understood due to a lack of analyses evaluating policy interactions with densification over time.

4.2.1. Residential Sector Per Capita Energy Use and Emissions

When my densification scenario trajectories are viewed per capita, there is a clear pattern of increased density leading to lower energy consumption in the residential sector (Figure 8). By 2050, the *Triplex* scenario has levels of per capita energy consumption 2.9% lower than the *Detached* scenario. Per capita energy consumption in 2050 is lowest in the *Sixplex* scenario, where it experiences levels 9.8% lower than *Detached*.

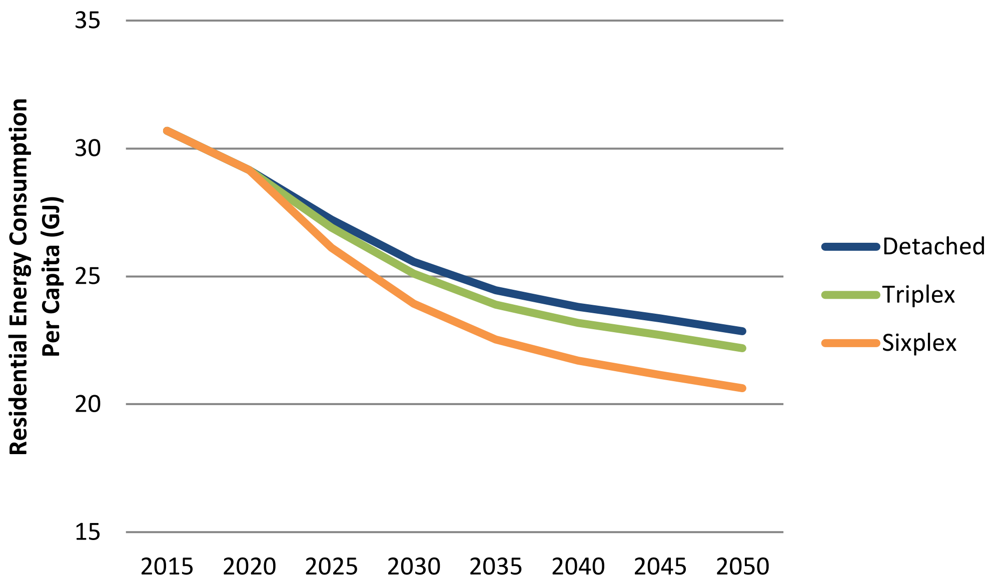


Figure 8. Total per capita residential sector energy consumption in Detached, Triplex, and Sixplex scenarios.

The decline in energy use in *Triplex* and *Sixplex* relative to *Detached* is due to the smaller floor spaces and improved thermal performance of the triplex and sixplex dwellings that replace detached homes in these scenarios. Lower floor space and improved thermal performance leads to 4.1% less natural gas use per capita in 2050 in *Triplex* relative to *Detached*. In *Sixplex*, this reduction amounts to 12.3%. This reduced natural gas use leads to lower residential emissions per capita in *Triplex* and *Sixplex* scenarios. Like per capita energy consumption, a clear pattern is evident between increased density and lower GHG emissions in the residential sector (Figure 9).

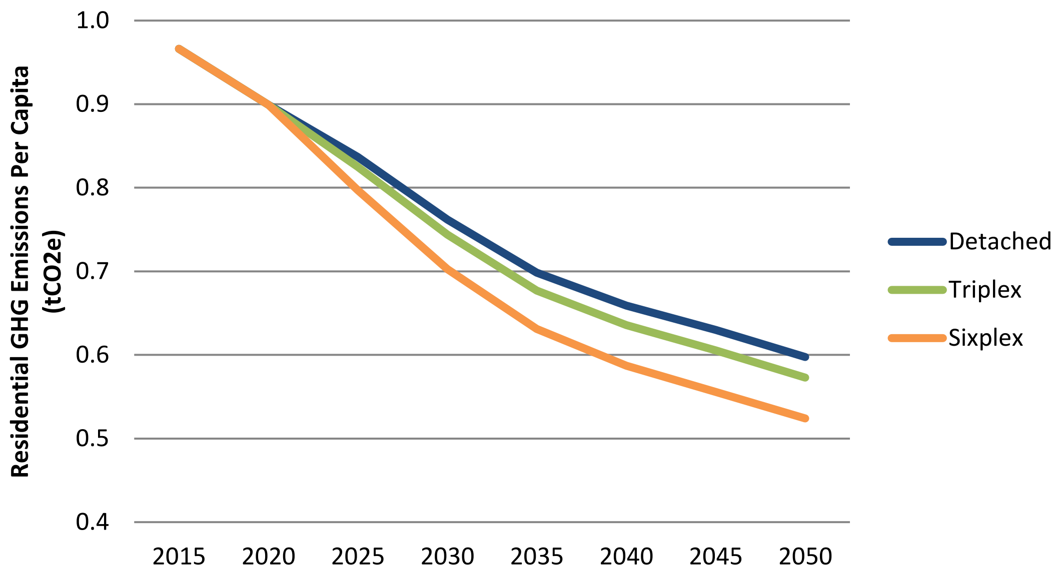


Figure 9. Total per capita residential sector GHG emissions in Detached, Triplex, and Sixplex scenarios.

These results align well with past studies that have found a moderate effect of density on current energy use and emissions in urban areas. In the *Sixplex* scenario, where population density increases 34% by 2050 relative the *Detached* scenario, per capita energy consumption declines by 9.8% and emissions decrease by 12.3%. These results are similar in magnitude to two recent studies that examined the current relationship between urban density and emissions in American cities. Lee & Lee (2014) found that a doubling in density is associated with a reduction in residential emissions of 35% while Gudipudi et al. (2016) found that a doubling is associated with a reduction of 41%.

However, direct comparison of my research to these studies is difficult. Gudipudi et al. (2016) and Lee & Lee (2014) used regression analysis of nationwide datasets to estimate the effect of urban density in cities throughout the United States, and both studies included electricity emissions in their definition of urban emissions. Households in American cities tend to receive their electricity from coal or natural gas power plants, increasing the emissions reduction effect of density-related efficiency relative to my study. Cities in the U.S. also likely have different weather conditions on average than those experienced in Vancouver as well as different average building stock ages. The complex set of factors that contributes to the link between density and emissions highlights the context-specificity of the relationship and underlines the problem of assuming that a density-induced emissions reduction in one jurisdiction will apply identically to another.

4.2.2. Interactive Policy Effects

To investigate how densification can interact with future policy changes, I compared my densification scenarios—*Detached*, *Triplex*, and *Sixplex*—both with and without the full implementation of Vancouver's Zero Emissions Building Plan (ZEBP), a sub-scenario denoted *+ZEBP*. To make this comparison, I used a version of my model in CIMS that contained only the single-family detached home properties that are replaced by new detached homes, triplexes, or sixplexes in my *Detached*, *Triplex*, and *Sixplex* scenarios[5]. In this scaled-down model of the residential sector, the *Detached* scenario sees 22,656 single-family detached homes containing 8,766 secondary suites being replaced by equivalent numbers of single-family detached homes and secondary suites by 2050 at an annual stock turnover rate of 1.5%. In the *Triplex* scenario, starting in 2021, these dwellings are instead replaced by 67,968 triplex units by 2050, and in the *Sixplex* scenario, they are replaced by 135,937 sixplex units by 2050. By 2050, in this scaled-down model, all dwellings are single-family detached homes (or secondary suites) in the *Detached* scenario, all dwellings are triplex units in the *Triplex* scenario, and all dwellings are sixplex units in the *Sixplex* scenario.

Using a scaled-down version of the residential sector was important to bind both densification policy and the ZEBP to the same set of building stock. If this analysis involved the entire residential sector, the *+ZEBP* scenario would be applied not just to the detached homes that undergo stock turnover but also to other attached and high- and low-rise apartments that are built throughout the city over time as per Metro

[5] Although this model was not formally calibrated because it consists of a hypothetical subset of Vancouver's single-family detached homes, its energy use results from 2000 to 2015 are consistent with calibration data used by Wolinetz (2017) for what one would expect for a set of detached stock this size.

Vancouver's housing stock projection. This would lead to a biased comparison of policies as *Making Room* only applies to the stock of single-family detached homes while the ZEBP would apply to all new buildings throughout the city.

The GHG results of this scaled-down model are shown in Figure 10. The first pattern to note is that the normal turnover rate of the building stock reduces per dwelling building emissions. In 2015, the housing stock largely consists of low-efficiency, pre-2000 detached homes. In *Detached*, by 2050 all of these buildings are replaced by new higher-efficiency detached homes, reducing per dwelling GHG emissions relative to 2015 by 52%. Also contributing to this emissions decline is the fact that appliances naturally become more efficient as they are replaced, regardless of the density policy.

Smaller floor space and increased thermal performance lead to lower per dwelling emissions in *Triplex* and *Sixplex* relative to *Detached*. By 2050, *Triplex* has emissions 23% lower than *Detached*, while *Sixplex* has emissions 30% lower. The difference between *Triplex* and *Sixplex* is smaller than the difference between *Triplex* and *Detached* because these building types are relatively more similar in terms of total floor space and thermal energy performance.

While these are considerable reductions in per dwelling emissions, my model shows that at the dwelling level, the policies outlined in the ZEBP would be more effective at reducing residential building emissions than *Triplex* or *Sixplex* levels of densification. By 2050, *Detached+ZEBP* has emission levels 86% lower than *Detached*. This significant emissions reduction is also 82% lower than *Triplex* and 80% lower than *Sixplex*. These results show that energy switching policies, such as the ones outlined in the ZEBP, can swamp the emissions reduction effect of triplex and sixplex densification of single-family detached properties. If a policymaker's goal is to reduce emissions, building code regulatory policies that mandate new buildings to have zero-emission energy systems are the clear choice over densification policy alone.

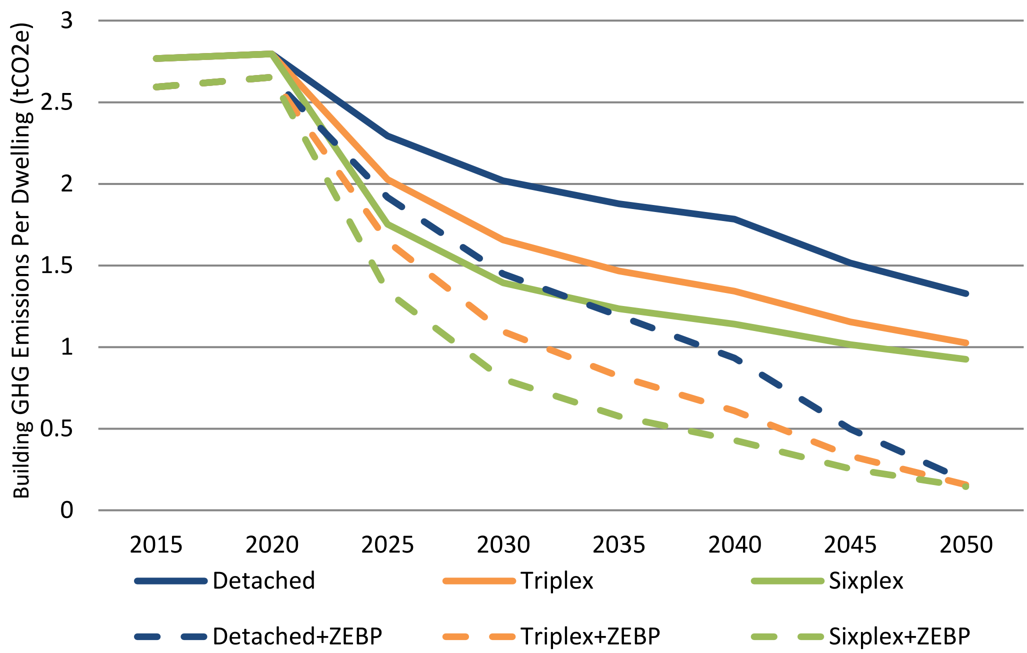


Figure 10. GHG emissions per dwelling for the subset of housing stock undergoing densification across Detached, Triplex, and Sixplex scenarios. Emissions are shown both with and without the continued implementation of the Zero Emission Building Plan for each scenario (+ZEBP).

Although the ZEBP is the more effective strategy for reducing emissions, densification scenarios still do interact with +ZEBP. By 2050, *Triplex+ZEBP* has 14% lower emissions per dwelling than *Detached+ZEBP* and *Sixplex+ZEBP's* emissions are 20% lower. However, this effect is created solely from triplexes and sixplexes built between 2021 and 2025, as these buildings can still use natural gas. Triplexes and sixplexes built after final ZEBP implementation phase in 2025 have identical emissions: 0%.

These results highlight how emissions reductions associated with densification under current conditions do not necessarily translate to emissions reductions under future conditions. Researchers and policymakers alike must be careful when assuming that a current emissions reduction observation will apply far into the future. Technology choices resulting from energy-switching policies can alter the emissions reduction potential of densification. As seen here, in the absence of building energy-switching policy, plans to densify a neighbourhood could hold a significant emissions reduction effect over the neighbourhood's per dwelling operational emissions. However, if building energy systems are mandated to be zero emission throughout this densification process, the efficiency gains from smaller buildings and more shared walls will do little to reduce emissions. The same would hold true if natural gas grids are slowly transitioned to biogas in the future.

Although densification has building energy use and emissions reduction benefits, it alone should not be viewed as a means to significantly reduce emissions. Instead, GHG building policy should be focused on regulatory mechanisms for moving building energy sources away from fossil fuels and towards zero-emission sources. This is not to say that densification should not be pursued by local governments. In addition to densification's current modest per dwelling emissions reduction benefit, there are many co-benefits of dense developments and neighbourhoods. These include improvements in livability, the preservation of green space, reduced maintenance and service costs for municipalities, and, as discussed in the next section, improvements in home energy and personal transportation affordability.

4.3. Affordability Analysis

To evaluate the influence of densification on home energy and personal transportation affordability, I performed an ex-post archetype affordability analysis of my model results closely following the methodology utilized in Wolinetz (2017). In this analysis, I compared home energy and personal transportation costs from 2025 to 2050 for a typical two-person household in each densification scenario, *Detached*, *Triplex*, and *Sixplex*, both with and without additional *+ModeShift* and *+ZEBP* sub-scenarios.

In *Detached*, this archetypal household moves into a new single-family detached home in 2025 that contains an R-2000 shell and a high-efficiency gas furnace and water heater. The household owns one gasoline-powered car, which they drive 12,000 km per year, and purchases one annual transit pass per year. They replace their car every 10 years, water heater every 15 years, and furnace every 20 years. In *Triplex* and *Sixplex,* the household instead moves into a triplex unit and sixplex unit respectively—reducing the floor space of their dwelling and improving thermal performance—while all other parameters remain the same.

+ZEBP sub-scenarios are applied across densification scenarios to evaluate the influence this policy strategy would have on home energy costs. In *+ZEBP*, this household instead moves into a dwelling with a high-efficiency building envelope that contains an electric heat pump for space heating and a high-efficiency electric water heater. Additionally, *+Modeshift* sub-scenarios are applied on top of *Triplex+ZEBP* and *Sixplex+ZEBP* to evaluate the influence that parking restriction policies and improved public transit would have on personal transportation costs. In *+ModeShift* sub-scenarios, the household does not own a car and instead purchases two annual transit passes per year.

Both upfront capital costs and operational costs were included in the analysis. Building shell capital cost premiums were added to *+ZEBP* scenarios to account for the higher upfront costs of high efficiency building shells. Because, +ZEBP households do not use natural gas for space or water heating, their building operational costs are comprised solely of electricity, while non-ZEBP scenarios include both electricity and natural gas. Cooking, refrigeration, dishwashing, clothes washing and drying, and minor appliance costs were assumed constant across scenarios. The household does not use space cooling. Vehicle operational costs included fuel, maintenance, and insurance costs. Key affordability analysis parameters are listed in Table 5.

Table 5. Key archetypal affordability analysis assumptions (H. Eff = High Efficiency; NG = Natural Gas; VKT = vehicle kilometers travelled; TEDI = thermal energy demand intensity).

Scenario:	Single-Family Detached House		Unit in a Triplex			Unit in a Sixplex		
Sub-scenario:	None	*ZEBP*	None	*ZEBP*	*+ZEBP+MS*	None	*ZEBP*	*+ZEBP+MS*
Dwelling:								
Floor area (m^2)	221	221	111	111	111	92	92	92
Building TEDI ($kWh/m^2/year$)	84	30	84	30	30	35	10	10
Space heating equipment	H. Eff NG furnace	Electric Heat pump	H. Eff NG furnace	Electric Heat pump	Electric Heat pump	H. Eff NG furnace	Electric Heat pump	Electric Heat pump
Water heating equipment	H. Eff NG	H. Eff Electric	H. Eff NG	H. Eff Electric	H. Eff Electric	H. Eff NG	H. Eff Electric	H. Eff Electric
Transportation:								
Number of vehicles	1	1	1	1	0	1	1	0
VKT/year	12,000	12,000	12,000	12,000	0	12,000	12,000	0
Fuel type	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline
Number of public transit annual passes	1	1	1	1	2	1	1	2

Here, I present and discuss the results of my archetypal affordability analysis. I first discuss differences in annualized energy-related costs between *Detached*, *Triplex*, and *Sixplex* households. I then discuss the effect that living in a *+ZEBP* household has on home energy costs. Last, I show the cost effects of not owning a vehicle in the *+ModeShift* households. Annualized energy-related costs are comprised of (1) operating costs such as electricity, natural gas, gasoline, maintenance, and insurance, and (2) annualized energy-related capital costs such as furnaces, water heaters, and vehicles. Capital costs were annualized over the lifespan of the technology using a 6% discount rate. A 6% discount rate characterizes a financial perspective, representing the cost of not investing the capital spent on energy-related costs in some other low-risk investment.

The *Detached* scenario household experiences higher annualized costs than *Triplex* and *Sixplex* households (Figure 11). By 2050, annualized energy-related costs for the *Triplex* household are 7% lower than for the *Detached* household, resulting in a cost savings of $770 ($2015 CAD) that year. Annualized energy-related costs for the

Sixplex scenario in 2050 are 9% lower than for the *Detached* household, resulting in a cost savings of $935 ($2015 CAD). *Triplex* and *Sixplex* households have lower costs than *Detached* households due to their operational energy use savings promoted by smaller floor spaces and increased thermal performance, but also due to their slightly lower energy system capital costs. Because triplex and sixplex dwellings are quite similar in size and efficiency, annualized costs between *Triplex* households and *Sixplex* households do not differ to a large degree. In 2050, *Sixplex* households spend $164 ($2015 CAD) less than *Triplex* households on home energy and transportation. In each scenario, costs increase over time due to rising electricity, natural gas, and gasoline costs.

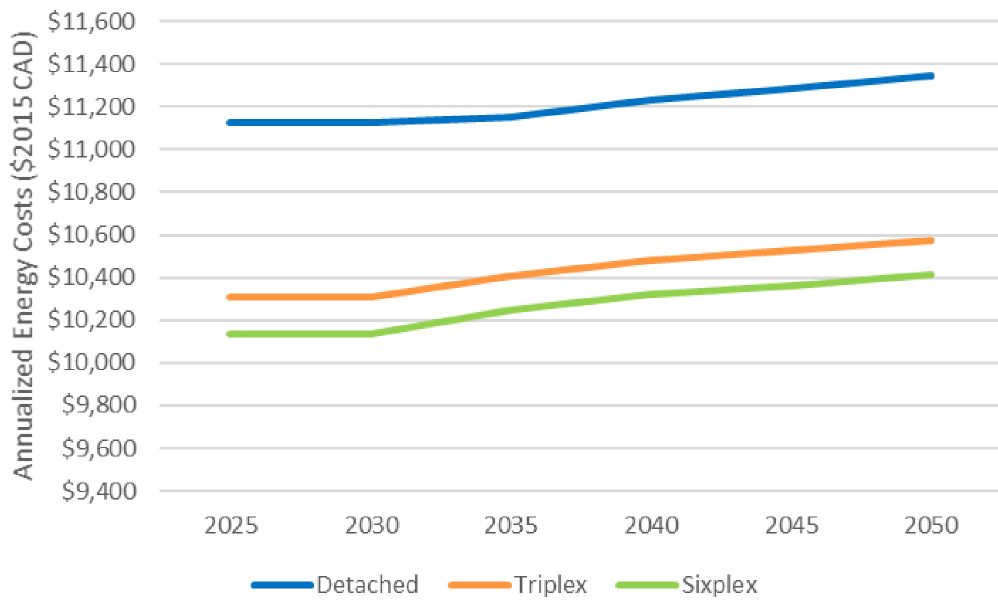


Figure 11. *Annualized energy-related costs for* Detached*,* Triplex*, and* Sixplex *households. Annualized energy-related costs consist of operational energy costs and annualized capital costs using a 6% discount rate.*

Households that live in a *+ZEBP* dwelling experience higher annualized energy-related costs (Figure 12). In 2050, *Detached+ZEBP* spends $750 ($2015 CAD) more than *Detached*. The additional costs imposed by Zero Emissions Building Plan building regulations are less prominent in *Triplex* and *Sixplex* scenarios. In 2050, *Triplex+ZEBP* spends \$500 more than *Triplex* and *Sixplex+ZEBP* spends \$400 more than *Sixplex*. These higher annualized energy-related costs are primarily due to higher upfront capital costs for more efficient buildings shells and home space and water heating equipment. Instead of using a high-efficiency gas furnace, *+ZEBP* households use electric heat pumps for space heating, which entail higher capital costs. *+ZEBP* households also use electricity for home water heating, which has relatively higher operational costs than natural gas for providing the same service. The additional costs of *+ZEBP* is less prominent in *Triplex* and *Sixplex* households than Detached households because space and water heating equipment is less expensive for these smaller dwelling forms. These smaller, more efficient attached dwellings also consume less energy for space heating and lighting.

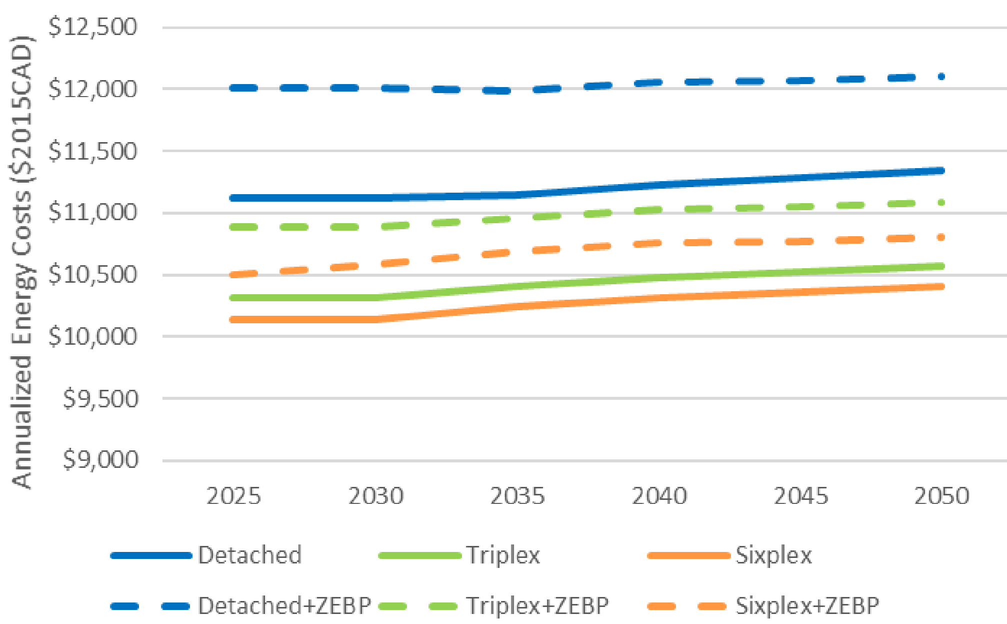


Figure 12. Comparing annualized energy-related costs between +ZEBP and non-ZEBP households (ZEBP = Zero Emissions Building Plan).

Reducing the number of cars owned by the household results in considerable cost savings (Figure 13). While non-ModeShift households spend approximately \$30,000 (\$2015 CAD) twice during this analysis for new vehicles, *+ModeShift* households forgo this large capital expense. *+ModeShift* households also save over $1,000 per year ($2015 CAD) on transportation operating and maintenance costs. In 2050, *+ModeShift* households have annualized energy-relate costs $5,500 to $7,000 ($2015 CAD) lower than the non-ModeShift *+ZEBP* households.

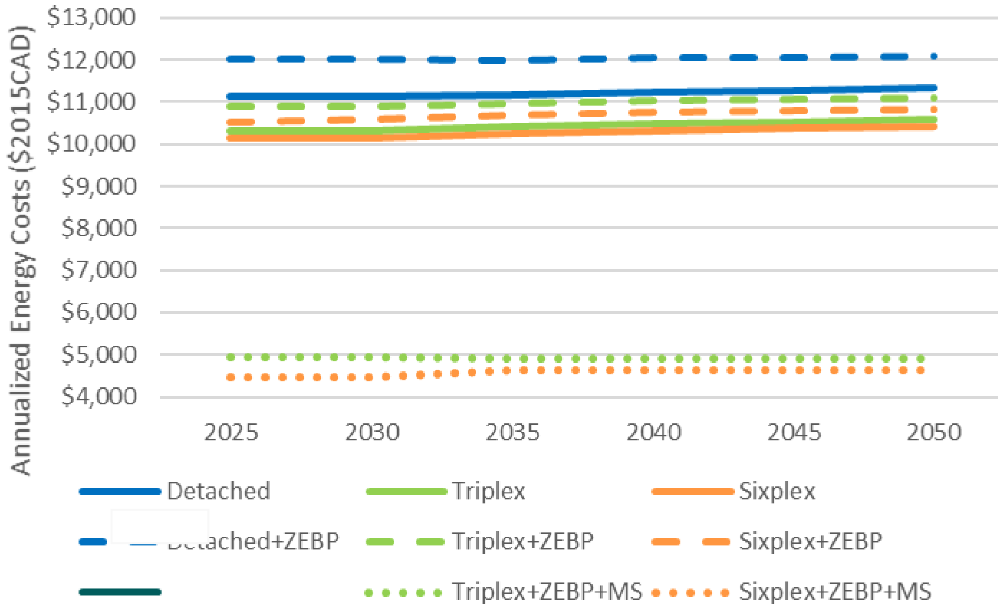


Figure 13. Comparing annualized energy-related costs between +ModeShift (MS) and non-ModeShift scenarios.

This analysis suggests an affordability co-benefit to policies that encourage densification and transportation mode shifting. Residential densification through the *Making Room Housing Program* is being pursued to improve the affordability of dwelling ownership and renting, but based on my results, home energy and personal transportation affordability are also a co-benefit. Although these energy-related costs are a small portion of total household expenditure, they still contribute to affordability. Households in British Columbia spend 5% of their total household spending on electricity, natural gas, and gasoline, and these operational costs are just a component of total energy-related costs (Green et al., 2016). If densification policy is implemented in conjunction with improved transit infrastructure and parking restriction policies, substantial cost savings can result. By 2050, my *Sixplex+ZEBP+ModeShift* scenario household had annualized energy-related costs $6,700 ($2015 CAD) lower than the *Detached* scenario household.

It is important to note that by focusing solely on financial costs, this analysis makes an assumption that living in a smaller attached dwelling gives the same value as residing in a larger detached dwelling on its own lot. Similarly, it implies that using a combination of public transit, car shares, and taxis provides the same value as a personal vehicle. However, living in small, attached dwellings may not provide the same value as living in a large detached home on a private lot. Moreover, taking public transit may entail higher intangible costs than driving your own private vehicle; stated preference research finds that this is indeed the case (Horne et al., 2005). Thus, this analysis makes claims about financial costs only. A cost-benefit analysis would be more appropriate for weighing both financial costs and other real or perceived benefits and costs.

Chapter 5.

Conclusions

5.1. Summary of Findings

My study sought to evaluate different densification pathways of Vancouver’s low-density residential neighbourhoods in terms of energy use, emissions, and affordability. This objective was sparked by Vancouver’s 2018 adoption of the *Making Room Housing Program*, a strategy for increasing the availability of medium-density housing in the city’s single-family neighbourhoods.

I found evidence of a negative relationship between density and per capita building energy use and emissions. My model results show that in 2050, a 36% increase in population results in a 12% reduction in GHG emissions. However, my results also highlight the importance of considering future policy interactions when assessing this relationship. Under the full implementation of the Zero Emissions Building Plan, which promotes energy-switching in new buildings, the strength of this relationship drops significantly. Densification has little effect on reducing emissions when home space and water heating are switched to zero-emission sources. Policymakers and researchers alike should not assume that a densification-induced emissions reduction observed under today's policy landscape will result in a similar reduction in the future.

Applying this analysis at the city-level to assess how densification could affect Vancouver's success in meeting its *Renewable City Strategy* goals, I found that by increasing the number of dwellings and thus population, densification increases energy use and emissions, potentially making it more difficult for Vancouver to reach its target of 80% emissions reduction by 2050. However, my study finds that energy use and emissions can be affected by implementing additional transportation-focused policies and actions along with densification. If triplex-level densification is combined with policies to meet Vancouver's *Transportation 2040* mode-shift target, triplex-level densification can be accommodated in the city at detached neighbourhood-level emissions. However, as my analysis of the interaction between densification and ZEBP implementation showed, efficiency measures are not technically necessary for reducing emissions. If our current carbon-based fuels are switched for zero-emission varieties, combustion emissions will be eliminated, leaving little work for efficiency-focused strategies. Therefore, to meet GHG targets, local and senior governments should focus first and foremost on policies that promote energy switching.

Although the modest building emissions reduction benefits of densification don't justify its use as a leading GHG policy for reducing building emissions, local governments still may want to pursue it for a suite of other rationales such as livability, health, decreased municipal costs, and increased green space. My study evaluated how densification influences another potential co-benefit: home energy and personal transportation affordability. I found that smaller, more energy efficient dense dwellings reduce annual energy-related costs relative to detached homes, especially when coordinated with policies and actions to limit vehicle ownership.

5.2. Study Limitations and Opportunities for Future Research

Several limitations of my study stem from the fact that the version of CIMS I utilized does not endogenously calculate the effect of increased density on personal transportation demand or mode shifting. Because of this model limitation, I was unable to account for mode-shift and travel demand effects as well as congestion feedbacks imposed by densification. I was also unable to account for how mixed-use developments paired with densification could influence both mode shifting and travel demand. My study therefore makes limited claims as to the role of densification on reducing energy use and emissions in personal transportation.

To partially overcome this limitation, I modelled two sub-scenarios: one where density had no effect on promoting mode shifting, and another where Vancouver meets its *Transportation 2040* targets of two-thirds of trips by walking, cycling, and transit. In reality, the effects of triplex- and sixplex-level residential densification on transportation emissions could lie anywhere in between the results produced by these two scenarios, leaving much uncertainty of how residential densification could influence transportation in Vancouver.

To better incorporate the effects of density, mixed-use development, improved active transportation and public transit networks, and congestion feedbacks, a new GIS-based spatial version of the CIMS model is currently being developed by researchers in the Energy and Materials Research Group at SFU. An early version of this model was used in Zuehlke et al. (2017), a study that addressed the effectiveness of policies outlined in Vancouver's *Renewable City Strategy* both with and without senior government policy support. In this previous research, the CIMS spatial model was used to calculate how public transit and active transportation network improvements influence the intangible costs of walking, cycling, and taking transit.

The spatial model is currently undergoing further development to more sophisticatedly calculate how density and mixed-use development influence the intangible costs of these mode choices. Key parameters used by the model in its intangible cost calculations include: trip length, distance to transit stop, and transit frequency for public transit; trip length, distance to path, and path quality for cycling; and trip length for walking. In all three mode types, trip length is calculated as the distance from a residential area to a commercial/employment area, capturing the influence of mixed-use development. Furthermore, distance to transit stop and bike path parameters incorporate the importance of having integrated land-use and transportation planning. In addition to these mixed-use and improved transit effects, road congestion model feedbacks are also being explored.

My study advances our understanding of the effect of residential densification on building energy use and emissions while accounting for future behavioral, technological, and policy change. However, similar research is needed to better understand how this densification influences the personal transportation sector. Future research could employ the new urban-level spatial version of CIMS to evaluate how low-density residential neighbourhood densification influences personal transportation demand and mode shifting under different associated policies including mixed land use developments, transit-oriented land use patterns, and public transit network improvements.

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