

Vancouver's Renewable City Strategy: Economic and Policy Analysis

by

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Abstract

Vancouver's Renewable City Strategy aims for 100% renewable energy and lower greenhouse gas emissions by 2050. To see if Vancouver's policies will achieve this, I used the CIMS energy-economy model to evaluate the impact of potential policies.

I simulated Vancouver's energy use and greenhouse gas emissions under different policy scenarios: (1) current policy, (2) renewable city scenario-specific policies Vancouver has proposed, and (3) additional policies focusing on fuel switching.

My results show that fossil fuel use and emissions increase relative to 2015 under current policy by about 10%. The renewable city scenario policies decrease fossil fuel use and emissions by 30% and 25% respectively, but fail to meet Vancouver's targets. Only additional stringent policies reduce fossil fuel use and emissions to near zero, thereby meeting the targets. These results show that to meet its targets, Vancouver must implement policies that specifically focus on fuel switching in buildings and vehicles.

Keywords: climate policy; urban sustainability; urban energy modelling; spatial modelling; renewable energy

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List of Acronyms

100RE	100% Renewable Energy Scenario
CEEI	Community Energy and Emissions Inventory
CNG	Compressed Natural Gas
CurrentPol	Current Policy
DA	Dissemination Area
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GJ	Gigajoule
HDRD	Hydrogenation Derived Renewable Diesel
HVAC	Heating, Ventilation and Air Conditioning
ICBC	Insurance Corporation of British Columbia
LNG	Liquefied Natural Gas
NEB	National Energy Board
NRCAN	Natural Resources Canada
RCS	Renewable City Strategy
VanRen	Renewable City Strategy Scenario

Chapter 1. Introduction

The recent (2016) signing of the Paris Agreement on climate change has signaled a renewed push in Canada and globally to act to reduce greenhouse gas emissions: national and municipal politicians have promised to move swiftly to implement climate-focused policies. Unfortunately, despite a history of political promises for climate action, many implemented policies to fulfill these promises have been ineffective or misguided. It is difficult to evaluate the level of sincerity or expertise of the politicians proposing these policies; however, it is possible to estimate the likely effectiveness of their policy choices using independent, scientifically based, analytical methods. This evaluation is important both for public accountability and for developing more effective policy.

When it comes to climate policy, not all policies are created equal – some policies, while easy to implement, are less effective than other more controversial policies. Municipal governments have outlined various actions they claim can reduce greenhouse gas emissions in response to what some perceive as a lack of willingness of senior governments to address climate change. The municipal government of Vancouver, British Columbia, has ambitious climate targets: its Renewable City Strategy (RCS), launched in 2015, aims to move towards 100% renewable energy and to dramatically lower greenhouse gas emissions (City of Vancouver, 2015b).

This study evaluates the various policies that have come out of the Renewable City Strategy with two goals in mind: first, to examine whether they achieve their stated aims regarding the Renewable City Strategy; second, to suggest additional policies that may be used to meet the Renewable City Strategy targets. My evaluation methods emphasize an approach which considers the spatial dimension of municipal policies.

The spatial dimension of urban climate policy presents a unique challenge to researchers. Unlike national or provincial governments, municipal governments are often limited in the types of policies they have the jurisdiction to implement. Thus, urban climate policies have often emphasized areas where municipal governments have authority: land use, transportation infrastructure, and urban form – all areas which are inherently geographic, or spatial, in character. Thus, for evaluation purposes, it is important to

understand and depict urban climate policies in an analytic framework capable of realistically representing energy use in urban areas. For this study, I expanded on existing forms of analysis capable of representing energy use in our economy in order to better represent the full suite of policies being considered by municipal government, including land use changes and transportation infrastructure investments. The goal of this spatially explicit analysis is to evaluate whether specific local policies will produce changes in greenhouse gas emission in urban areas.

I applied the analytic framework developed in this study to Vancouver¹ to evaluate the effectiveness of both potential and proposed policies for reducing the use of fossil fuels and associated greenhouse gas emissions. Because Vancouver's targets imply the complete transition away from our fossil fuel-dominated energy system, I had to examine not just policies directed towards changing land use and transportation infrastructure, but also policies to phase out the use of conventional natural gas in buildings and the use of diesel and gasoline for transportation. Furthermore, because Vancouver has committed to a 100% renewable energy target without a guarantee of support from senior governments, it is important to evaluate whether reaching the Renewable City Strategy targets is possible without additional senior government climate policy.

In undertaking this analysis, I hoped to achieve two objectives:

- Determine whether the policies Vancouver has implemented as part of its Renewable City Strategy are sufficient to meet its ambitious goals for 100% renewable energy and for steep greenhouse gas reductions;
- Investigate a broad suite of policies, not limited to those currently proposed, to explore whether it is feasible for a municipal government, such as Vancouver, to drastically reduce its dependence on fossil fuels without policy support from senior governments.

¹ In this report, the term Vancouver refers to the City of Vancouver unless otherwise specified

In pursuit of these objectives, I simulated Vancouver's energy use and greenhouse gas emissions under six different policy scenarios using energy-economy analysis. This type of analysis allows me to estimate energy and emissions under different levels of municipal and senior government climate policy. I explored three different levels of municipal government policies: (1) the current policies in Vancouver (i.e., those before the Renewable City Strategy was approved), (2) the policies that have been proposed by Vancouver in an effort to achieve its Renewable City Strategy targets, and (3) additional policies that fall within municipal government jurisdiction, which have the potential to eliminate the use of fossil fuels. Since the level of climate policy effort by senior levels of government is uncertain and beyond the control of municipal governments, I investigated energy and emissions under current and more ambitious policies of the provincial and federal governments.

To address these research objectives, I first discuss urban climate policy and other climate policies that are being proposed by municipal governments such as Vancouver (Chapter 2). I then describe the existing methods for representing my six different policy scenarios within an energy-economy framework, as well as the extended spatial model I developed for this study (Chapter 3). In Chapter 4, I present and discuss the results of my analysis. After summarizing my key findings, I offer policy recommendations and possible directions for future research (Chapter 5).

Chapter 2. Background

2.1. Types of Climate Policy

Various types of policies are available to reduce carbon pollution. These range in their approach, scope, and the degree to which they are compulsory. Some policy options rest on mainly voluntary actions by households and firms, other options call for strict regulation on technologies, fuels or emissions, and some types of policy fall between these extremes. This range of compulsoriness is outlined in Figure 1.

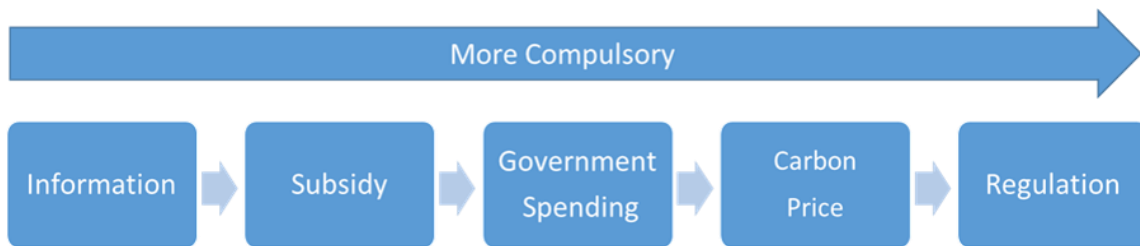


Figure 1: Level of policy compulsoriness

Information campaigns fall towards the voluntary end of the spectrum, while regulations are the most compulsory.

A completely voluntary policy is something that seeks to inform people of ways they can reduce their emissions. An example of a voluntary policy is an advertising campaign to turn down indoor air temperatures in winter to reduce energy use. At the other end of the spectrum are regulations – the most compulsory of policies. There are different types of regulations that vary in their flexibility. Command-and-control regulation is the most restrictive and seeks to enforce a specific action. An example of such a regulation would be a policy banning the use of coal for generating electricity. Flexible regulations allow for more than one way to achieve a target. For example, niche market regulations can be used to require vehicle makers to sell a certain number of zero emissions vehicles. A flexible niche market regulation does not specify exactly how many electric, ethanol, or other type of vehicles a manufacturer must sell, but instead dictates the total percentage of zero emissions vehicles that must make up sales and allows vehicle manufacturers to determine the best mix of vehicles to meet that target.

In between the two policy extremes are a variety of other policies. Subsidies, such as a rebate for purchasing an electric vehicle, fall towards the voluntary end of the spectrum, as individuals are not required to take part. Subsidies can be attractive to the public, but can be prone to “free-ridership,” where individuals who were already planning to take an action without an incentive (such as purchase an electric vehicle) benefit from the subsidy. A more compulsory policy is carbon pricing, such as a carbon tax. Carbon pricing is not optional the way a subsidy program is, but it still gives individuals or businesses some flexibility: they can choose to either emit carbon and pay the full tax, or reduce their emissions and avoid paying part of the tax.

A more compulsory policy is not necessarily more controversial. For example, research has shown that in some cases a regulation—even one which prescribes greater reductions in emissions—is often less controversial than a carbon price, even though a carbon price offers more flexibility to individuals and businesses (Rhodes, Axsen, & Jaccard, 2014).

Not all policy types are available to municipal governments due to their limited jurisdiction. Thus, discussion on urban climate policy tends to focus on areas where municipal governments have jurisdiction: municipal government investment and municipal regulations. These jurisdictional challenges are discussed in more detail in Section 2.2. Government investment falls in between voluntary and compulsory policies on the scale of compulsoriness. Municipal government spending on infrastructure (such as on transit and electric vehicle charging stations) and command-and-control regulation (such as land-use zoning and the setting of building codes) tend to make up a large portion of municipal government climate policy. However, in addition to government spending and regulation, there is also the potential for more creative policies, in the form of flexible regulations for vehicles and buildings.

2.2. Jurisdictional Challenges

It is not unusual for different levels of government in Canada to act in different ways on climate change. For example, in 2008 during a period of little climate action from the Canadian federal government, the British Columbia government implemented several

ambitious pieces of legislation aimed at reducing greenhouse gas emissions (Government of British Columbia, 2008). This legislation was possible as the province of British Columbia had the legislative authority based on its powers for taxation, licensing, and control over natural resources, as outlined in the Constitution (Hsu & Elliot, 2009).

More recently, there has been renewed federal interest in climate policy, with the federal government under Prime Minister Justin Trudeau proposing a minimum national carbon price, beginning in 2018. In this case, if a province does not want to implement a carbon price, the federal government claims that it has the jurisdiction to implement one in that province (Hsu & Elliot, 2009).

While the provincial and federal governments are both able to implement policies like carbon prices to influence decisions on energy using equipment, the ability of municipal governments to set taxes is much more limited. Under Section 92(8) of the Constitution, powers to regulate municipal governments are delegated to the province (The Constitution Act, 1867, 30 & 31 Vict, c 3). In British Columbia, the Local Government Act and the Community Charter are among the pieces of legislation that describe the powers of municipal governments (Community Charter, SBC 2003, c 26, Local Government Act, RSBC 2015, c 1). In the case of Vancouver, the Vancouver Charter is used in place of the Community Charter (Vancouver Charter, SBC 1953, c 55).

While municipal governments do not have the jurisdiction to implement a city-wide carbon price, there are various other policies available to municipal governments. Municipal governments can levy certain types of taxes, such as property taxes, and collect fees, such as parking fees. Furthermore, while municipal governments cannot regulate utilities within their boundaries, they can establish and operate their own energy utilities, allowing them to set policies for district energy systems, which can potentially shift to renewable energy.

Municipal governments also have considerable jurisdiction over land use and transportation policy within their boundaries. For example, they can zone for high density mixed-use developments around transit stations, reduce road space on roads they own, construct bikeways, and impact urban form using their full land-use zoning powers. Due

in part to the jurisdictional challenges discussed above, these types of policies often dominate the GHG reduction policy proposals of municipal governments.

In the next section, I review some of the main types of urban climate policy and discuss which policies are the most effective in terms of transitioning to renewables and reducing GHG emissions. I also explore whether there are other options for climate policy within municipal government jurisdiction.

2.3. Urban Climate Policy

I define urban climate policy as climate policy that is specific to urban areas and that is under the control of municipal governments—for example, zoning or transportation planning. In this section of the report, I discuss the types of policies that are often proposed by municipal governments and, in later sections, I model these policies and others that are specifically designed to reduce fossil fuel use.

Many of the policies in this section are proposed by municipalities to meet a variety of goals (in addition to reducing GHG emissions), such as providing housing diversity and reducing traffic congestion. The Renewable City Strategy also discusses the role of efficient buildings, density, transit, cycling, and walking in reducing energy use and greenhouse gas emissions. I evaluate the role of policies such as mixed-use development and transit because they are likely to be pursued by municipal governments for their other benefits, regardless of the impact they have on GHG emissions. While the Renewable City Strategy's ultimate goal is a reduction in fossil-fuel use and greenhouse gases, it presents policies that target not only fuel-switching but also a general reduction in energy use. I will discuss and evaluate these policies because they are part of the strategy.

I also discuss additional policies directly focused on reducing greenhouse gas emissions, as opposed to energy use, in later sections of this report. These additional policies are capable of reducing greenhouse gas emissions without reducing total energy demand. The effectiveness of policies focused on fuel switching can help address the misconception that climate policy must reduce the total energy demand to be effective.

2.3.1. Density and Mixed-use Development

Municipalities often present densification as a method of reducing urban energy use both by providing more energy efficient buildings and by providing a different neighbourhood design, which can reduce transportation demand. However, the effect of density on building energy use and transportation demand is difficult to evaluate as issues of low data quality and high uncertainty have presented barriers to fully understanding how land use and transportation infrastructure determine urban energy use (Keirstead, Jennings, & Sivakumar, 2012).

Some studies have demonstrated a link between higher densities and lower energy use (Chester, Nahlik, Fraser, Kimball, & Garikapati, 2013; Ishii, Tabushi, Aramaki, & Hanaki, 2010); however, such a link is insufficient to show that policies to increase urban density will result in a substantial drop in energy use. In addition, the mere fact that density may play a role in energy use does not mean the effect is sufficiently large to justify policy based on densification. To be effective as a strategy for reducing energy use, increasing density should not just have a statistically significant link to lower energy use, but the decrease in energy use from a change in density should be proportionate to the degree of densification. Specifically, a policy of densification is of little use if a major increase in density only results in very small decreases in energy use. Unfortunately, research has found that while density increases do help decrease energy use, the impact is modest (Kim & Brownstone, 2013). The modest change in energy use for a given change in density means that, to achieve meaningful energy use reductions, aggressive infill and substantial density increases are required. It is often difficult, impossible, or undesirable to achieve such ambitious increases in density in an established urban area (Brownstone & Golob, 2009).

The relatively modest effect large density increases have on energy use may limit the usefulness of densification as a climate policy. However, there are many benefits to densification that are not related to energy efficiency, such as preservation of greenspace and reduced infrastructure maintenance costs for cities (Clark, 2013). Given the uncertain impacts of density on energy use, densification should likely be pursued for the other benefits that it offers rather than as a climate policy.

Mixed-use development is a policy that can be pursued in conjunction with or independently from densification. Mixed-use development refers to a variety of land uses (for example commercial and residential) in the same area and sometimes even the same building. Some research finds that areas of more varied land use are often associated with lower vehicle ownership (Potoglou & Kanaroglou, 2008), while other research has produced mixed results, noting a complex set of interacting variables (Badoe & Miller, 2000). Indeed, when researchers have tried to separate different effects, such as walkability, mixed-use, and density, they have generally found that most of the reduction in vehicle ownership and use that is attributed to higher density is actually driven by other aspects of the urban built-environment and that density, when viewed in isolation, likely has a limited impact (Hachem, 2016). This result underscores the importance of taking a broader view of cities instead of focusing solely on population density; factors such as walkability, street design, employment density, and nodality should be considered (Clark, 2013).

A more nuanced view of the role played by land use and urban form is critical, as it allows us to recognize that sprawl is not the same as suburbanisation (Ewing, 1997). While sprawl typically refers to a development pattern of large areas of a single land-use type and a disconnected road network pattern, it is possible for suburban neighbourhoods to be designed in a way that reduces energy demand without drastic increases in population density by emphasising mixed-use and connected road networks. It also follows that the design of neighbourhoods of all densities may be improved to reduce energy demand. Policy should therefore allow for increased density as required by societal values, such as preservation of greenspace, but should focus climate and energy policy on urban form and mixed land uses, where there is clear evidence for emissions reductions and less potential for negative consequences.

2.3.2. Transit

Improved transit service is often proposed along with mixed-use or high density development to help reduce vehicle use and emissions in urban areas. Together with density and urban form improvements, better transit service can lead to reduced private vehicle use and a reduction in associated greenhouse gas emissions (Bento, Cropper,

Mobarak, & Vinha, 2005; McIntosh, Trubka, Kenworthy, & Newman, 2014). However, while such reductions are likely possible, in practice it is often difficult to co-ordinate density and new transit infrastructure (Filion & Mcspurren, 2007).

A focus on providing a variety of transportation options is important as it allows individuals mobility and the ability to choose the transportation mode that is most appropriate for their trip. While there is some potential to reduce overall travel, individuals derive substantial benefit from travel and will continue to demand ways to travel around and between cities (Banister, 2011). Instead of restricting travel options, there should be a focus on improving the options available to those wishing or needing to travel. Research demonstrates that those using modes of transportation where they have the most control over their trip tend to have the highest levels of satisfaction (St-Louis, Manaugh, van Lierop, & El-Geneidy, 2014; Thomas, Walker, & Musselwhite, 2014). For example, travellers using active modes (walking or cycling), using rail transit services, or driving when there is not substantial traffic congestion tend to have higher satisfaction levels than those who use the bus or who drive on routes where their commute is subject to unexpected congestion or delays (St-Louis et al., 2014; Thomas et al., 2014).

One potential way to improve bus travel as an option is through infrastructure improvements that increase reliability or provide users with information (for example, with better information on estimated wait times), helping to increase their feeling of control (Thomas et al., 2014). When urban rail and bus services with the same frequency, convenience, and reliability are compared, users show no preference for rail over bus (Ben-Akiva & Morikawa, 2002). It is possible, then, that the lack of autonomy and control often felt by bus users (compared to rail users) could also be reduced by making bus services more like rail in their frequency and reliability.

A focus on frequency and reliability is important, as research has demonstrated that the public is averse to moving to services they perceive to be lower quality. In this respect, public education campaigns for transit are generally wasteful and money would be better invested in improving service quality (Poudenx, 2008)

Along with service improvements, transit fare reductions are often extolled as a way to get people out of private vehicles and onto transit, thus reducing transportation

emissions. Unfortunately, while reducing transit fares may provide a benefit as a social policy, there is limited evidence that lowering transit fares will reduce emissions from private vehicles (Liddle, 2013). However, this result does not mean transit riders are insensitive to fare changes: there is an asymmetrical response to fare changes as transit riders are much more sensitive to fare increases than decreases (Chen, Varley, & Chen, 2011). It is also possible that decreasing transit fares may attract new riders, but many of these new riders may have previously walked to their destination, meaning the impact on private vehicle use is less than expected.

Overall, the literature suggests that policy to attract people to transit from private vehicles should focus on increasing transit frequency and reliability to improve the convenience and autonomy of travellers and should be undertaken in conjunction with improvements to the urban form, such as building mixed-use transit-oriented developments.

2.3.3. Walking and Cycling

Improved pedestrian and cycling infrastructure is often proposed in conjunction with mixed-use and transit for urban areas. Cycling is growing rapidly in developed countries and is promoted not just as a sustainable means of transportation, but also for its public health benefits (Woodcock et al., 2009). In addition to increases in urban cycling in industrialized countries, there has also been a rapid growth in bike shares in cities around the world (Fishman, Washington, & Haworth, 2014; Pucher, Komanoff, & Schimek, 1999). However, a growth in urban cycling does not necessarily translate to decreased transportation emissions. This is especially true with bike shares, which often rely on trucks to reposition bikes throughout the day. While bike shares do result in reduced private vehicle use in most cities where they operate, the majority of the trips taken on bike shares are not replacing private vehicle use and are therefore not reducing emissions (Fishman et al., 2014). Furthermore, while cycling has been increasing in most cities, it is unlikely that cycling will continue to grow at such a rapid pace without continued infrastructure and other improvements (Pucher et al., 1999).

While establishing bike share programs may not lead to a substantial decrease in private vehicle use, there is evidence that building safe cycling infrastructure and expanding bicycle networks leads to the reduced use of private vehicles and a net reduction in greenhouse gas emissions (Zahabi, Chang, Miranda-Moreno, & Patterson, 2016). In addition to infrastructure directly aimed at cycling, improvements to urban form and improved walkability also correlate with higher cycling (Nielsen, Olafsson, Carstensen, & Skov-Petersen, 2013). Furthermore, more mixed land uses, shorter distances between commercial areas, and high quality transit services also increase the rates of cycling (Nielsen et al., 2013).

The policies needed to reduce the average travel distance and to encourage more walking, cycling, and transit often overlap. While these three modes of transportation often compete for market share, there is also substantial opportunity to identify policies which can increase the attractiveness of all three modes. These policies, such as building safe walking and cycling routes, zoning to increase pedestrian-friendly mixed-use development, and public investment and management practices that improve transit quality, are closely linked with reductions in private vehicle use and transportation-related greenhouse gas emissions. Conversely, policies such as lowering transit fares or bike share subsidy programs often have merit for social or economic reasons, but are unlikely to result in a substantial decrease in greenhouse gas emissions.

2.3.4. Other Policies

The above policies are potential components of urban-specific climate policy. However, as discussed, there are sometimes mixed results when it comes to the realized impact of these policies on energy use. Many of the policies discussed above focus strongly on reducing *energy* use, even though the stated policy objective is to reduce greenhouse gas emissions and the use of fossil fuels. For example, reducing the use of electricity while allowing continued use of gasoline and natural gas will do little to meet the Renewable City Strategy's targets.

Later in this study I discuss the impact of other policies that are not urban-specific and explain how these can be used to encourage fuel switching—that is, replacing fossil

fuel use with renewable energy. Many of these policies, such as building code or vehicle regulations, fall under the category of government regulation, rather than government spending.

2.4. Vancouver's Renewable City Strategy

Vancouver is implementing policy to reduce greenhouse gas emissions and the use of fossil fuel. It has a population of about 650,000 and makes up the urban core of Metro Vancouver, a region with a population of over 2.5 million (BC Stats, 2016a). Vancouver has relatively low per-capita greenhouse gas emissions for a North American city, due in part to its compact urban form, mild climate, and the dominance in the provincial energy mix of hydroelectricity from B.C. Hydro, the provincially owned electric utility (City of Vancouver, 2015b).

Vancouver has committed to meeting its climate action goals and has set the following two targets as part of its Renewable City Strategy:

- Derive 100% of the energy used in Vancouver from renewable sources before the year 2050
- Reduce greenhouse gas emissions by at least 80% below 2007 levels before the year 2050

Unlike many past plans that have been put forward by all levels of government, the Renewable City Strategy does not focus solely on reducing energy use, but also emphasizes increasing the supply and use of renewable (non-fossil fuel derived) energy. Currently just over 30% of the energy used in Vancouver comes from renewable sources, mainly hydro-powered electricity. The remaining 70% is dominated by natural gas, which is used for space and water heating in buildings, and gasoline and diesel, which are used for personal and freight transportation (City of Vancouver, 2015b).

The Renewable City Strategy does not present specific policies that the City will use to meet its ambitious targets, but rather outlines “priorities” that will guide future policies. For example, one priority is that all new buildings be zero emissions by 2030, but the Renewable City Strategy does not provide a detailed policy to achieve this target. The Zero Emissions Building Plan was released in 2016 to provide the policies needed to

achieve this goal (City of Vancouver, 2016b). Renewable City Strategy priorities focus on both reducing total energy use and moving to renewable energy. For example, the City strives to have all new buildings use drastically less energy than the existing building stock, while also moving away from fossil fuels in both new and existing buildings.

Unlike the priorities for new buildings, as covered under the Zero Emissions Building Plan, many of the priorities outlined in the Renewable City Strategy are not yet supported by policies designed to achieve sector-specific targets. For instance, the Renewable City Strategy requires currently existing buildings to perform like new buildings by 2050, mandating efficiency improvements and increased use of renewable energy by consumers; however, at the time this study was conducted, no policies had been enacted to support those goals. In some cases, the City acknowledges its lack of jurisdiction over some areas the plan covers, such as setting the renewable content of fuels supplied to the city, and in these cases the Strategy proposes partnering with utilities to achieve the City's priorities.

Transportation priorities in the Renewable City Strategy focus on land use planning, cycling infrastructure, transit, and zero emissions vehicles. While these priorities haven't been specifically converted into policy, several plans support the same priorities. For example, Transportation 2040 outlines Vancouver's plan to improve infrastructure to support more walking, cycling, and transit use.

At the time of this report, the City was still in the process of developing a strategy to increase the availability of electric vehicle charging stations. Aside from this, no strong policy based on the Renewable City Strategy priorities currently exists to increase zero emissions vehicles for personal or freight transportation.

2.5. Need for Analysis

A prudent policy maker will attempt to understand the impacts of a policy approach before committing to it. This is especially true in the case of policy that may change a practice that is widespread across an economy, such as burning fossil fuels. Many economists argue that the most efficient policy options are those which put a price on

carbon emissions (Nordhaus, 2011); however, as discussed, carbon pricing is unlikely to be an option for a municipal government. The other policy options range in effectiveness and efficiency as well as in their acceptability to politicians and their constituents (Bristow, Wardman, Zanni, & Chintakayala, 2010; Goulder, 2013).

The range in policy cost, effectiveness, and political acceptability demonstrates the importance of carefully evaluating policy options. However, properly evaluating different policy packages is not an easy task. Simply listing available policy options and the estimated reductions from each is insufficient to properly evaluate which policies will be most effective, because different climate policies often interact, with unexpected effects. For example, improving transit and promoting zero-emissions vehicles are both a means to reduce greenhouse gas emissions and fossil fuel use; however, if both policies are pursued at the same time, the reductions from both policies combined will likely be less than the sum of the reductions achieved from each policy when enacted individually.

There is further interaction between emissions policies applied at different levels of government. For example, the emissions reductions from a municipal policy promoting electric vehicles will be amplified by a provincial policy for renewable electricity. Such policy interactions can make it difficult to identify the effectiveness of any one policy and to understand how a policy might perform in the presence of policy from another level of government. Furthermore, while reductions are often possible in a variety of different areas, it is important to pay attention to the cost of emissions reductions. The most efficient climate policy will focus on ensuring the lowest-cost reductions occur first, while the more difficult, higher cost reductions are left to last.

It is therefore essential when evaluating policies to employ an analytical method that takes into account the potential for policy interaction and does not simply add up the potential reductions achievable through individual policies. Furthermore, it is important to understand how the costs of reducing emissions vary across sectors and to make these cost differences explicit in analysis. Thus, such an approach should consider reduction costs, real-world constraints on available policy options, and the interplay among proposed policies.

2.6. Energy-Economy Analysis

This study uses energy-economy analysis to simulate the effect of policies designed to lower greenhouse gas emissions and reduce the use of fossil fuels. Energy-economy analysis is an important evaluative tool because it includes evidence-based assumptions about decision-making behaviour: since the government does not directly control the entire economy, many decisions on energy-using technology are made by individual households and firms. These households and firms make their decisions based on the cost, benefits, convenience, and perceived risk of a new technology, as well as their personal values and beliefs. Such complexity necessitates a tool with an economic, technical, and social basis for predicting how people will choose to acquire and use a variety of energy technologies in the future and for evaluating how these choices may be impacted by government policy.

The energy-economy analysis used in this study is referred to as a hybrid analysis because it draws on what were traditionally two different types of analysis: bottom-up analysis and top-down analysis. Bottom-up analysis is technically detailed and focuses on the emissions and life-cycle costs of specific energy-using technologies serving specific energy end-uses, such as space heating, lighting or personal mobility. Unfortunately, the life-cycle costs in bottom-up analysis typically include only the financial costs of a technology, specifically capital costs and operating costs, and ignore the intangible costs (Jaccard, Murphy, & Rivers, 2004).

Intangible costs are non-financial costs, such as inconvenience or the real or perceived risk from an unfamiliar technology. Intangible costs are important when considering true policy cost and policy uptake, as individuals often make their choices based on criteria other than simple financial cost minimization (Jaccard et al., 2004). Furthermore, variation in consumer preferences means that intangible costs will not be the same for every individual. Because bottom-up analysis traditionally includes only financial costs, it tends to predict high adoption of technologies with the lowest life-cycle costs and ignores other factors such as risk or inconvenience, which may play a significant role in how some individuals make decisions (Murphy & Jaccard, 2011). For example, a bottom-up analysis may predict that because apartment living is, on average, a lower cost

housing option than single family homes, most people would switch to living in apartments if made available in their area. High density apartment living is sometimes associated with lower greenhouse gas emissions, so this switch could lead to substantial greenhouse gas reductions (Norman, MacLean, & Kennedy, 2006). The problem is that there may be an intangible cost of high density living (such as the loss of private yard space) that makes the uptake of the lower cost (and lower greenhouse gas emissions) option less than predicted (Warszawski, 2003).

Conventional top-down analysis focuses on the historical relationship between energy use and energy prices to simulate the effect of policies that change the costs of using certain forms of energy. Because consumer preferences are implicit in this relationship, top-down analysis avoids some of the drawbacks of bottom-up analysis. However, top-down analysis often lacks technological specificity: estimates in top-down models are produced on aggregate figures and do not include data broken down by specific technologies, thus preventing the simulation of policies targeting specific new technologies (Rivers & Jaccard, 2006). Top-down analysis also does not perform well when applied to situations where policies aim to substantially change energy prices (to move them outside historical ranges) or to encourage a future very different from the past (for example, 100% renewable energy use).

Hybrid analysis is one solution to the shortcomings of solely bottom-up and top-down approaches. Hybrid analysis models include specific technologies, much the way bottom-up models do; however, they also include data that incorporates consumer preferences, much the way top-down analysis models do (Rivers & Jaccard, 2006). By combining the techniques of bottom-up and top-down models, hybrid models are able to simulate policies that target a specific type of technology in a bottom-up fashion, but are also able to produce more realistic results since they are based on real-world data and therefore reflect human behaviour more realistically.

Chapter 3. Methods

3.1. The CIMS Model

For this study, I use the CIMS model. CIMS is a hybrid energy-economy model and is therefore both technology specific and behaviourally realistic. Furthermore, CIMS takes into account market heterogeneity—that is, the model can represent how consumers' preferences vary from person to person (Murphy & Jaccard, 2011). Because CIMS is technologically explicit, it simulates the purchase and retirement of specific energy-using technologies and records their energy consumption and greenhouse gas (GHG) emissions. CIMS achieves this detailed technology representation by including the lifespan of current technology and allowing for uptake of new. These qualities allow the CIMS model to represent how energy-using technology may be impacted by various compulsory and voluntary government policies.

In the cases of cities, energy use and emissions come mainly from buildings and vehicles, as large industrial operations are often located outside municipal boundaries. Through policy, cities can affect building types, density, and urban form, as well as transportation options. It is therefore important that these urban policy elements be well represented within the energy-economy analysis. Fortunately, the CIMS model can be deployed on many scales, and this study employs a version of CIMS designed for community-level analysis, called CIMS Community (Wolinetz & Goldberg, 2012). CIMS Community is designed to perform community-level forecasts and help inform the crafting of effective municipal government GHG reduction strategies. It includes community-level data on transportation and buildings (Wolinetz & Goldberg, 2012). CIMS Community can represent policies that impact the financial cost of different energy using equipment found in cities, such as commercial and residential heating and cooling systems and personal and freight vehicle types. However, many policies proposed by municipal governments impact the intangible costs of energy-using technology, by decreasing the inconvenience or risk of different technology. When the impact of these policies is not spatially uniform, they cannot be easily simulated in most integrated economy-wide models including CIMS. The impacts of policies which have a spatial dimension often present the most difficult challenge when modelling city-level dynamics: at finer spatial scale, the impact of policies

which are not spatially uniform cannot be easily averaged out and the specific details of individual projects (for example, where a rapid transit line is located) become important.

CIMS is not a spatial model and therefore it is difficult to model spatially variant costs. In urban settings, spatially varying tangible and intangible costs are important. For example, a policy that seeks to increase the convenience of transit by building a new rapid transit line will not change the intangible cost uniformly across the city, but instead will cause a greater decrease in intangible cost for those living near the new transit line. Similarly, a policy that builds separated bikeways to lower the risk of cycling near busy traffic will have more of an impact on the intangible cost of cycling for those near the proposed cycling infrastructure. Changes to the built environment can also impact intangible costs; for example, a mixed-used development can decrease the distance of many residents to a commercial area and therefore reduce the intangible cost of walking for some errands. In order to model these types of policies, a spatial extension to CIMS was developed for this study. The spatial extension is discussed in detail in Section 3.3

3.2. CIMS Input Parameters and Calibration

The CIMS model uses a variety of input data including the costs of fuels and energy-using equipment and estimates of population growth. For this study, I updated the key parameters that I anticipated would differ from the model defaults, either due to updated estimates from external agencies or from areas where Vancouver differs from the provincial averages already in CIMS.

For population growth figures, I used estimates provided by B.C. Statistics for Vancouver until the year 2040 (BC Stats, 2016b). For the years 2040 to 2050, I assumed the same population growth rate as in the previous decade. For the number of individuals per dwelling and the breakdown of residential housing types, I used estimates for Vancouver produced by Metro Vancouver using their projections and data from Statistics Canada (Metro Vancouver, 2011). For commercial, institutional and light industrial floor space, I assumed a growth rate proportional to the growth of employment in Vancouver. For commercial, institutional, and light industrial floor space, I assumed the percentage of

total floor space dedicated to different activity types (e.g. education, office, retail, warehouse, etc.) would not change.

I assumed that the demand for freight in tonne-kilometres travelled would grow proportionally to population. I assumed that the personal transportation demand (in total person-kilometres travelled) would grow more slowly than population. I based this assumption on the estimated decrease in per capita travel demand for contained growth in a mid-sized city (Bataille et al., 2010). Lastly, based on current travel patterns, I assumed that transit trips are 15% longer than private vehicle trips, whereas walking and cycling trips (as a weighted average) are 70% shorter than private vehicle trips (TransLink, 2013).

Energy price forecasts are another important parameter in CIMS Community. I used price forecasts for electricity, refined petroleum products, and natural gas from Canada's National Energy Board (NEB) *Canada's Energy Future 2016* report (National Energy Board of Canada, 2016). This report covers only the period to 2040, so I extrapolated the 2040 prices to 2050 for my simulations. I adjusted the prices of all fuels used for transportation in Vancouver to have a regional transportation levy equivalent to \$0.17/L.

Personal and freight vehicle prices, including intangible costs, can also change frequently, so I chose to update these parameters within CIMS Community. Vehicle prices in CIMS are divided into vehicle shells (which I did not adjust from default values) and vehicle motors, which I set to the values in Table 1. I based my estimates on data from the U.S. National Research Council cost data and checked my prices against market prices for vehicles to make sure cost differences were within reason. I co-ordinated my vehicle prices with the work of another researcher, Tiffany Vass, in the School of Resource and Environmental Management at Simon Fraser University to make them consistent with national level modelling (Vass, 2016). Intangible cost values are values for the start of simulations. Intangible costs can decline during simulations as the market share of a technology grows. This declining cost, sometimes referred to as the "neighbour effect", represents decreased risk and unfamiliarity as a technology gains prominence (Axsen, Mountain, & Jaccard, 2009). For example, an electric vehicle may have a high initial

intangible cost for many consumers, but as these vehicles become more common in the city, consumers will be less averse to considering them. Vehicle fuel use is a parameter that may also change with time as the standard vehicle motors become more efficient.

Table 1: Vehicle motor costs (2000 \$)

Sub Sector	Motor	Capital Cost	Intangible Cost
Passenger Vehicles	Gasoline (Standard)	\$5,000	0
	Gasoline (High Efficiency)	\$6,000	0
	Gasoline (Hybrid)	\$10,500	\$5,000
	Diesel	\$8,000	\$4,100
	Ethanol	\$6,250	\$3,000
	Ethanol (Plug-in hybrid)	\$22,650	\$2,000
	Hydrogen	\$65,000	\$5,000
	Electric	\$24,600	\$3,000
Light Freight	Diesel (Standard efficiency)	\$50,000	0
	Diesel (High efficiency)	\$62,300	0
	Diesel (Plug-in hybrid)	\$148,600	\$2,000
	Electric	\$154,000	\$3,000
	Hydrogen	\$ 200,000	\$6,000
Heavy Freight	Diesel (Standard efficiency)	\$106,000	0
	Diesel (High efficiency)	\$122,000	\$5,000
	Natural Gas	\$151,000	\$8,000
	Hydrogen	\$411,000	\$120,000

For vehicle fuel use, I based values on what was already in CIMS Community as a default, and new data on vehicle fuel consumption, provided by NRCAN (Natural Resources Canada, 2016). As with vehicle prices, I co-ordinated vehicle fuel use with national level modelling. Fuel consumption for passenger and freight vehicles is summarized in Table 2: Fuel consumption by motor type (GJ per person/tonne 100km).

Table 2: Fuel consumption by motor type (GJ per person/tonne 100km)

Sub Sector	Motor	Gas, Diesel, or Liquid biofuel	Electricity	Hydrogen or Natural Gas
Passenger Vehicles	Gasoline (Standard)	0.0032		
	Gasoline (High Efficiency)	0.0024		
	Gasoline (Hybrid)	0.0020		
	Diesel	0.0028		
	Ethanol	0.0036		
	Ethanol (Plug-in hybrid)	0.0011	0.0009	
	Hydrogen			0.0026
	Electric		0.0009	
Light Freight	Diesel (Standard efficiency)	0.0071		
	Diesel (High efficiency)	0.0052		
	Diesel (Plug-in hybrid)	0.0014	0.0033	
	Electric		0.004	
	Hydrogen			0.058
Heavy Freight	Diesel (Standard efficiency)	0.0023		
	Diesel (High efficiency)	0.0018		
	Natural Gas			0.0022
	Hydrogen			0.0012

Lastly, the CIMS model requires calibration to run simulations. I calibrated CIMS Community to data from Vancouver, collected under the Province of British Columbia's Community Energy and Emissions Inventory (CEEI) data program (Province of British Columbia, 2014). The CEEI contains community specific data on fuel use and greenhouse gas emissions from utilities (such as FortisBC and BC Hydro), public agencies (such as ICBC), and other partners. The CEEI data covers emissions from on-road transportation, buildings, and solid waste. The CEEI data was anticipated to be updated every two years; however, the last update was for the 2010 inventory year.

3.3. CIMS Spatial Extension

I developed the CIMS spatial extension based on the outcomes of my research described in Section 2.3, the goal being to design the most appropriate tool to assess urban climate policies such as those being proposed in Vancouver. In contrast, policies that are not specifically focused on influencing the urban built environment, such as those targeting fuel switching, are not spatially determined and therefore I modelled these directly in CIMS Community.

My spatial extension model uses geographic information systems (GIS) to assess proposed changes in land-use, the built environment and the transportation network of a city and estimates the impact these changes will have on the intangible costs of different transportation modes. It is challenging to estimate how such infrastructure investments may impact intangible transportation costs because there are a variety of factors that determine the intangible costs. Some of these are within the control of government, such as transportation network quality, and some are beyond its control, such as demographics and individual preferences. To understand the interplay among these factors, it is necessary to compare areas with different intangible transportation costs with the urban form and transportation network quality in each of these areas.

For this comparison, I first estimated intangible transportation costs in different neighbourhoods of the city and then attempted to quantify the urban form and transportation network quality in these neighbourhoods. I used the intangible cost estimates and network quality estimates to estimate how much the intangible costs of different transportation modes are determined by the quality of the transportation network, and how much of the intangible cost is determined by other factors. Thus, as City policies change the transportation network, for example by building new bike routes or improving transit service, it is possible to estimate the effect on the intangible costs of different transportation modes. This structure is summarized in Figure 2.

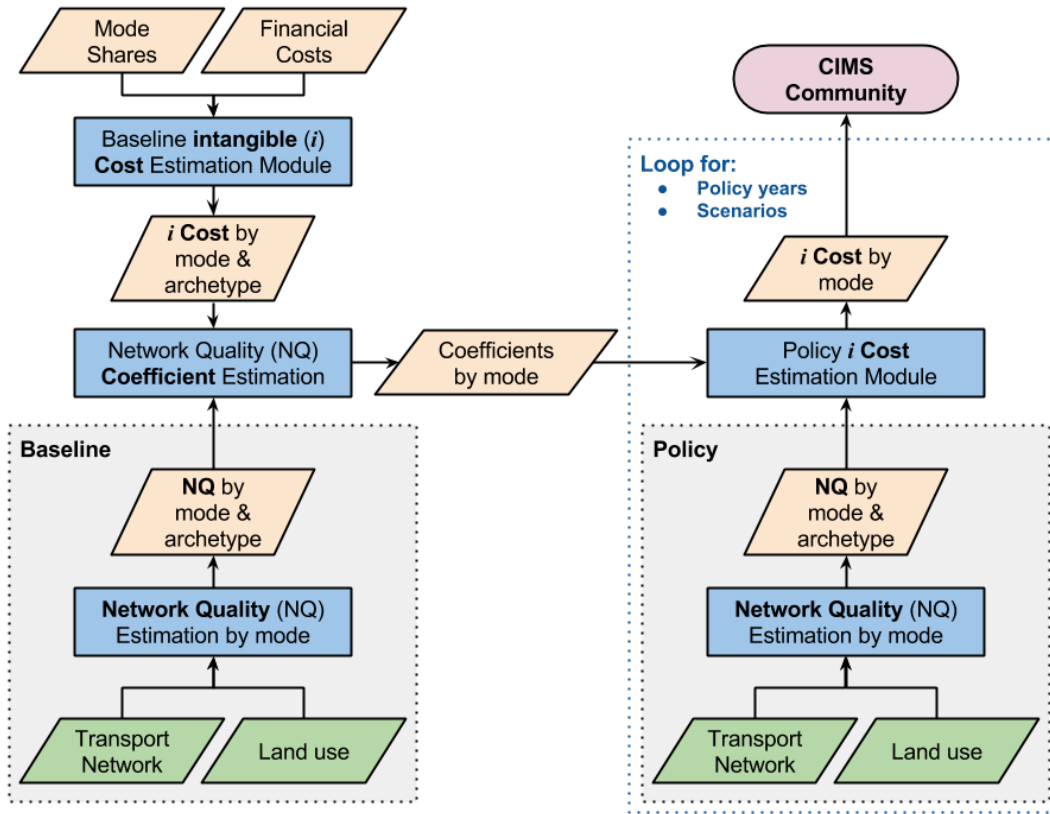


Figure 2: Spatial model structure

Spatial model begins by estimating baseline network quality and intangible costs, and then uses a similar process to estimate how intangible costs change under transportation and land use policy.

3.3.1. Baseline Intangible Cost Estimation

The intangible cost of a transportation mode is, by definition, not an easily quantifiable value. In the CIMS model, the market share of a transportation mode is assumed to be a function of the intangible and financial costs of that transportation mode relative to the intangible and financial costs of all other transportation modes. This relationship is illustrated in the CIMS Market Share algorithm (Equation 1).

Equation 1: CIMS Market Share Algorithm

$$MS_j = \frac{[CC_j + MC_j + EC_j + i_j]^{-v}}{\sum_{k=1}^K \{ [CC_k + MC_k + EC_k + i_k]^{-v} \}}$$

The CIMS market share algorithm determines the market share (MS) of a technology (j) out of a total of K different technologies that could perform a given service. For transportation, different modes are viewed as different technologies competing to provide the mobility service. Thus, the technologies in the transportation mode competition are private vehicles, transit, et cetera. This competition takes into account the total costs of operating a specific technology. The total costs are the intangible costs (i) and all financial costs, which include the annualized capital costs (CC), the maintenance costs (MC), and the energy costs (EC). Lastly, a parameter ($-v$) is used to represent market heterogeneity. This parameter represents variation in consumer preferences and perceptions of risk. Market heterogeneity means that different individuals will make different choices even if presented with the same options.

From the CIMS market share algorithm, it is possible to estimate the intangible costs associated with various modes of transportation if the mode shares and financial costs are known. However, it is not possible to solve the CIMS market share algorithm algebraically for the intangible cost of a single technology, which therefore must be solved analytically. I used the Nelder and Mead optimization technique (Nelder & Mead, 1965) in R (R Core Team, 2016) to solve for an intangible cost value for each transportation mode, in each of the three neighbourhood archetypes in Vancouver.

As discussed above, I required the financial costs and market share for each transportation mode in order to determine their intangible costs. For this study, I assume the financial cost of transportation varies among modes, but is constant across the city for each mode. For walking and cycling, the financial costs are already low enough relative to the intangible costs that any error in this assumption is likely to have a negligible effect. For transit, all of Vancouver is in the same fare zone, so this assumption is also likely to be largely true. The costs of commuting by car could vary slightly among areas of the city, but I am assuming this variation is small in comparison to the sunk costs (the car itself, insurance, maintenance, etc.), which are the same across the city. The most important factor for calculating intangible costs of transportation is therefore the market share of each transportation mode. Thus, in order to investigate differences in intangible costs, I had to compare parts of the city with different transportation mode market shares.

I looked at several neighbourhood archetypes within Vancouver to identify patterns of transportation use. For this analysis, I defined neighbourhoods to be the same as Vancouver's 23 planning neighbourhoods and grouped these neighbourhoods into three archetypes: Downtown (including the West End), Inner City (neighbourhoods bordering Downtown, plus the Grandview-Woodland neighbourhood), and Suburban (the remaining neighbourhoods). For each of these three neighbourhood archetypes I compared Statistics Canada data on transportation mode market share to an index of transportation network quality by mode.

Transportation mode share data consisted of mode of transportation to work for the employed labour force from the 2011 National Household Survey (Statistics Canada 2011). I used dissemination area (DA) level data and summarized it for each of my neighbourhood archetypes. In addition, I performed a qualitative comparison between the transportation mode in my neighbourhood archetypes and those in Vancouver transportation panel surveys (City of Vancouver, 2015c, 2016a) and the TransLink Trip Diary survey (TransLink, 2013). I did this comparison because both of these survey methods, although conducted on a coarser spatial scale, contained more detailed data on the trip purpose. Specifically, while the census data only provided data on mode of transportation to work, the survey data also provided data on trips for purposes such as shopping and entertainment.

Once I had data on transportation mode shares in each neighbourhood archetype, I was able to take transportation cost data (for example, the average cost of vehicle ownership and the annual cost of a bus pass) and estimate the intangible cost of each transportation mode in each archetype.

3.3.2. Network Quality Estimation

I evaluated transportation quality separately in four different categories: road quality (assumed to have the greatest impact on private vehicle users), mixed-use/pedestrian friendly urban form (assumed to have the greatest impact on walking), bike route and greenway quality (assumed to have the greatest impact on cyclists), and transit quality (assumed to have the greatest impact on transit users). Transportation quality

calculations were conducted within the GIS using current road network, land use, bike route, and transit network data for Vancouver.

For GIS calculations, I used PostGIS 2.1 (The PostGIS Development Group, 2015) in a PostgreSQL 9.4 database (The PostgreSQL Global Development Group, 2016). The GIS database software configuration is similar to what has been used in previous research mapping and modelling greenhouse gas emissions and is flexible enough to be expanded to larger applications (Gkatzoflias, Mellios, & Samaras, 2013).

For the spatial data, I relied on a variety of sources. I used land use data from Metro Vancouver's open data catalogue to identify commercial, institutional, and industrial areas within Vancouver (Metro Vancouver, 2015). I used road network data from the Province of B.C.'s Digital Road Atlas (GeoBC, 2015) and transit data from TransLink's Open API Google GTFS data (TransLink, 2015). For bike routes and Vancouver's local neighbourhood areas, I used Vancouver's open data catalogue (City of Vancouver, 2015a). Lastly, for the smaller sub-neighbourhood regions in my analysis I used Statistic Canada's Dissemination Areas (Statistics Canada, 2011a).

I calculated road network quality on the neighbourhood scale. A high quality road network yields a lower intangible cost to driving in a private vehicle, whereas a low quality road network yields a high intangible cost. I assume that all public roads in the city contribute to the road network, but their contribution is not equal – a kilometre of limited access freeway contributes to the road network more than a kilometre of local road or an alleyway. Quality contribution coefficients for different road classes can be found in Appendix A. In CIMS Community the intangible cost of driving a private vehicle is assumed to be zero, with the intangible costs of all other modes of transportation presented as relative to the intangible cost of driving. As a result, I assumed an initial average intangible cost of zero for driving in my baseline representation, but allowed the model to add different intangible costs to driving in different areas of the city, depending on the policy. For example, a particular policy could increase the intangible cost of driving into downtown, but not in more suburban areas of Vancouver or vice versa.

I calculated transit, walking, and cycling network quality on a finer spatial scale than road quality, as individuals walking or cycling are more sensitive to distance than

those driving. For this finer spatial scale, I used 992 Statistics Canada Dissemination Areas (DAs), rather than the 23 Vancouver planning neighbourhoods. Using DAs as the unit of analysis also allows for a direct comparison between predicted intangible costs of transportation modes and mode shares for commuting to work. I excluded DAs located within the downtown Vancouver Central Business District as the small number of residents in this high traffic area could bias results. In these calculations, I define “distance” to be the average distance of the furthest and closest points of the DA to the feature (e.g., bike route, bus stop, or train station) being analyzed. I used straight-line distance for all calculations. For these modes, the longer the distance, the less a network feature would contribute to the network quality of an area. For example, a SkyTrain station would contribute to the transit quality of a DA 100 metres away and to a DA 800 metres away; however, the contribution to the DA 100 metre away would be higher. The quality contribution of the network feature did not drop linearly, but instead declined with increasing distance according to a distance decay function specific to each mode and network type being analyzed.

I assumed the largest factor of the neighbourhood walk quality was the distance to mixed-use commercial and employment areas. Because almost all roads in Vancouver have safe sidewalks to accommodate pedestrians, I assumed distance, rather than sidewalk quality, would have a much greater impact on the choice to walk and therefore I did not include the road network properties as a factor in walk quality. I assumed that while all commercial and employment areas in the city contribute to a neighbourhood being walkable, the contribution from closer destinations is much greater than that from destinations further away. Thus, areas with many different commercial and employment areas nearby score high for walkability, while those with few nearby commercial and employment areas score poorly. I used a logistic decay function as I felt it best described how distance initially would have a relatively small impact on walk quality, but would grow in importance once individuals had to walk more than just a few minutes. The parameters for all equations were developed empirically to produce results reflective of how far the average person will generally walk to a destination. For example, most people are likely willing to walk about 5 minutes to a bus, or 10 minutes to a store other business, or rapid transit.

The walk quality (Q_w) is averaged across all DAs and is determined using Equation 2, where d_{min} describes the minimum distance between the DA being analyzed and each walk destination.

Equation 2: Network quality algorithm for determining walk quality

$$Q_w = \frac{1}{nDA} \times \sum_1^{nDA} \frac{1}{1 + e^{\left(\frac{\ln(19)}{200}\right) \times (d_{min}) - 200}}$$

Cycling quality is heavily dependent on the quality of bike routes, so I included distance of each dissemination area to Vancouver's cycling network to help determine the cycling quality of an area. However, as with the road network, not all elements of the cycling network contribute the same amount to the overall network quality. For example, a separated bikeway contributes more to the cycling network than a major road with only bike sharrows (shared lane markings). The contribution coefficients for the cycling network are in Appendix A. Furthermore, as with walk quality, distance matters—a separated bike lane will contribute more to the cycling quality of an area directly beside it than to an area several kilometers away. The overall cycling network quality is determined based on an average of all DAs in Vancouver. The distance–impact relationship for cycling follows a form described in Equation 3, where cycling quality (Q_c) is a function of the closest (d_{min}) and furthest (d_{max}) point in a DA to a bike route, the length of the route (l), and the quality of the route (q). Because distances for the cycling calculation are to the closest point on a linear feature, I used a simple inverse distance relationship instead of logistic decay. I chose an inverse distance decay for distance to linear features, as this method resulted in less abrupt changes in cycling quality among adjacent DAs, which I felt was more realistic.

Equation 3: Network quality algorithm for determining cycling quality

$$Q_c = \frac{1}{nDA} \times \sum_1^{nDA} \frac{1}{0.5 \times (d_{min} + d_{max})} \times l \times q^2$$

The transit network quality is the most complex to calculate as it is dependent on both distance to a transit stop (or station) and the service level at the stop. Service level is the normalized trips per day for all routes serving the stop – stops with more trips will contribute more to the overall transit quality of adjacent areas. I weighted transit frequency

highly in my calculations to reflect the importance of high frequency transit service to customers' feelings of autonomy and satisfaction, as discussed in Section 2.3.2. The impact a stop has on the transit quality rating of a nearby area declines with distance, similar to the logistic decay function used for walking quality; however, for transit, there are two different versions of this function to distinguish regular bus service from rapid transit service. People are generally willing to walk further to rapid transit than to a regular bus line, and therefore the contribution a bus stop makes to service quality declines more quickly than the contribution from a rapid transit station. Based on the research discussed in Section 2.3.2, I did not make a distinction between rail and bus services, but rather "regular" and "rapid" transit routes, with rapid routes defined as not only fast and high frequency, but also in a dedicated right-of-way, meaning they were not subject to traffic delays.

The transit network quality equation is shown in Equation 4. Transit quality (Q_t) is determined as the sum of distance-dependent contributions from regular transit service (d_{reg}) and rapid transit (d_{rapid}). The quality contribution of regular transit declines quickly with distance from the stop, whereas the quality contribution from rapid transit extends for a greater distance. In both cases the relatively frequency (f_{route}/f_{max}) of the transit line also plays a role. Due to the extremely high density of transit in the central business area of Vancouver, I excluded DAs in this area in transit quality analysis and included only transit service in residential areas of downtown and the West End.

Equation 4: Network quality algorithm for determining transit quality

$$Q_t = \frac{1}{nDA} \times \sum_1^{nDA} \left(\frac{1}{1 + e^{\left(\frac{\ln(19)}{200} \times 0.5 \times d_{reg}\right)}} \times \left(\frac{f_{route}}{f_{max}}\right) + \frac{1}{1 + e^{\left(\frac{\ln(19)}{400} \times 0.5 \times d_{rapid}\right)}} \times \left(\frac{f_{route}}{f_{max}}\right) \right)$$

3.3.3. Network Quality Coefficients

For comparison purposes, I re-sampled the data for driving, walking, cycling, and transit quality to the neighbourhood archetype scale. This re-sampling allowed me to compare the intangible transportation costs and transportation network quality data to get an estimate of the relationship between network quality and intangible cost. I refer to the parameter that describes the relationship between network quality and intangible cost as

the Network Quality Coefficient. Network Quality Coefficient is necessary because there is not a one-to-one relationship between network quality and intangibles costs, given the many factors other than network quality contribute to intangible costs.

I calculated a distinct Network Quality Coefficient for each transportation mode, using the least-squares method to fit a trend-line to network quality and intangible cost data. In the case of transit quality, I log transformed transit quality data to improve fit. Log transforming data helped normalize the data that was otherwise dominated by a few areas of very high transit service quality, such as around transit hubs.

3.3.4. Policy Network Quality and Intangible Cost Estimation

The network quality coefficients allowed me to estimate new intangible costs based on policies that modify Vancouver's transportation network, land use, and built environment. Different policies will lead to different intangible costs and will impact model simulations differently. The different urban climate policies I simulated for transit, walking, and cycling are summarized in Section 3.4.

I calculated policy network quality estimates for years 2015 to 2050, summarised by decade, by representing transportation and zoning changes within the GIS. I then ran the same process for determining the network quality described in Section 3.3.2, but with input transportation and land use data based on policy plans instead of baseline conditions.

Using the policy network qualities, I estimated new intangible cost values for each transportation mode represented within CIMS. I did this by averaging the policy network quality values across all DAs within Vancouver for each transportation mode and for each policy year. I then used the mode-specific Network Quality Coefficients I estimated in Section 3.3.3 to produce estimates of how intangible costs change from baseline values, given the policy network changes.

3.4. Scenario Development

I compared Vancouver’s projected energy use and emissions under their Current Policies (CurrentPol) and Renewable City Strategy (VanRen) policies in several different modelling scenarios. While it is the City’s goal to have the Renewable City Strategy policies achieve 100% Renewable Energy by 2050, there is no guarantee that this will happen, so I have also developed a scenario in which I will recommend additional policies to help ensure the City reaches their 100% Renewable Energy (100RE) target. Furthermore, because policy contributions from senior governments are uncertain, I compared all three of these scenarios under two futures: (1) one in which senior governments stay on their current climate policy path, and (2) one in which senior governments (SenGov) implement stronger climate policies. These different scenarios are outlined in Table 3 and described in detail below.

Table 3: Scenario matrix outlining the six scenarios produced from different levels of municipal and senior government climate policy

		Senior Government Policies	
		Current	Additional
Vancouver's Policies	Current Policy	CurrentPol	CurrentPol (SenGov)
	Renewable City Strategy	VanRen	VanRen (SenGov)
	100% Renewable	100RE	100RE (SenGov)

As in Vancouver’s Renewable City Strategy climate analysis, I compared emissions under current and proposed policies. My results show lower emissions under current city policy than in Vancouver’s “if we do nothing” scenario, because I include recent federal government climate policies (such as the federal minimum carbon price) in my Current Policy scenario. Furthermore, the scope of the policies I am discussing do not include emissions in heavy industry, such as those on federally controlled Port of Metro Vancouver lands, and therefore my emissions trajectories will be lower than those produced from any analysis that includes port activities and heavy industry.

3.4.1. Current Policy

This scenario represents the projected energy and emissions if Vancouver maintains its current policy path without enacting new policies based on the Renewable City Strategy. It does not represent the absence of climate policy, but rather the absence of any action in addition to what Vancouver has been doing already. The building code in this scenario is the current policy for all commercial and residential buildings, prior to any changes contemplated in the Renewable City Strategy. Transportation policy assumes current policies to promote electric and zero emissions vehicles remain, but no additional policies are enacted. Similarly, transit service levels and cycling routes are maintained with population growth, but not substantially improved. Due to geographic constraints, Vancouver cannot expand in physical size and therefore all growth in all scenarios, including the CurrentPol, is assumed to be through increasing density; however, land use patterns do not change substantially.

3.4.2. Renewable City Strategy

This scenario includes many of the priorities within the Renewable City Strategy (RCS) converted into policies. For buildings, this includes Vancouver's Zero Emissions Buildings Plan. At the time of analysis (May 2016), none of the priorities for zero emissions vehicles in the RCS have been outlined in detailed policy, so they have not been included in this scenario. Road network changes, cycling improvements and new transit infrastructure investments occur as described in the RCS, Transportation 2040, and TransLink's 10-year plan. Overall, I assume investment occurs at rates similar to those observed in Vancouver over the past two decades. In many cases, future transportation projects are uncertain, especially those occurring 20 or 30 years into the future. In these cases, I simulated projects that I felt were representative of the type and scale the City would proceed with and I modelled these projects on the best planning practices and had them align with the urban climate policies described in 2.3. I simulated all transportation network and land use changes using the CIMS spatial extension. Figure 3 compares the land use and cycling networks for central Vancouver in 2015 and 2050. As one can see, in 2050 there are more thick lines indicating high-quality bike routes and more of the pink urban areas indicating high walkability. Detailed maps are provided in Appendix B.

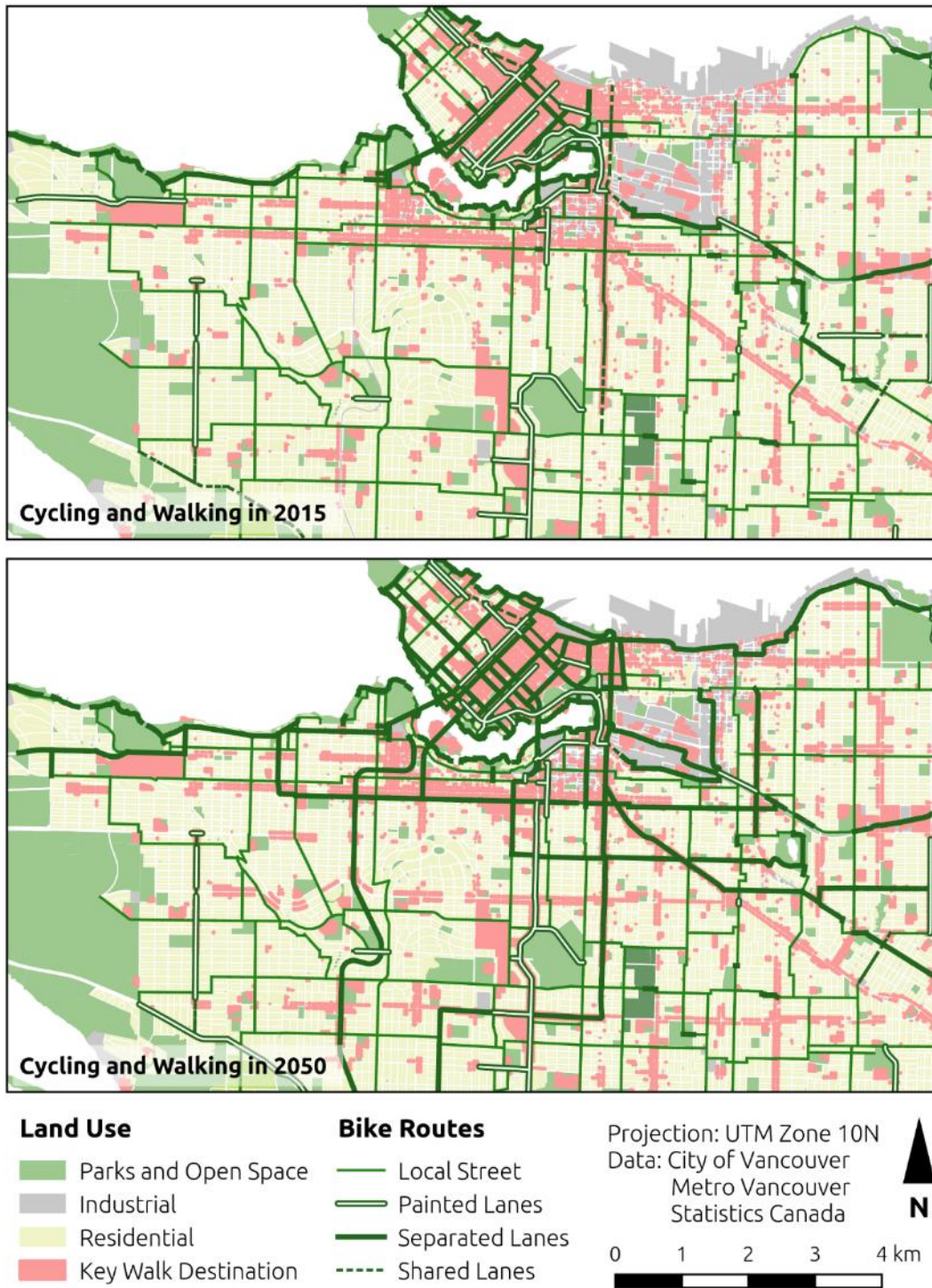


Figure 3: Land use and cycling networks in 2015 and 2050 (in VanRen and 100RE)

3.4.3. 100% Renewable Energy

This scenario includes all the policies in the *VanRen* scenario, as well as additional policies I propose to ensure the fuel switching necessary to get close to the goal of 100% renewable energy. The *100RE* scenario does not include any additional energy efficiency policies beyond those already in the *VanRen* scenario. I have selected additional policies that are potentially within Vancouver's jurisdiction. This is a necessity because the City has committed to its 100% renewable energy target without agreement with senior levels of government to intensify the stringency of their climate policies or enact new stringent climate policies or expand Vancouver's legal authority to enact its own climate-relevant policies.

For residential buildings in this scenario, I assume that fossil fuel burning hot water heaters and furnaces are not permitted under Vancouver's building code after 2030 for new buildings as well as for replacement equipment in existing buildings. Thus, all residential heating installations must use electric powered heat pumps, solar hot water, electric-thermal heat, or other zero emissions heating sources. Existing single family residential buildings are required to use renewable natural gas (RNG), which is methane produced from biological sources, in any new gas-fired furnaces installed after 2030. Thus, after 2030 in my *100RE* scenario there is policy moving both existing and new buildings to zero emissions heating equipment.

I further assume that new or existing institutional, light industrial, and commercial buildings cannot install new fossil fuel burning heating, ventilation and air conditioning (HVAC) systems after 2030, although they can continue to use natural gas for non-HVAC uses. For example, cogeneration, cooking, and other processes may use natural gas; however, businesses continuing to burn gas must demonstrate an increasing percentage of RNG through to 2050, at which time all commercial gas use must be RNG.

In addition, parking spaces for all nonzero-emissions vehicles in City-owned parking lots, on streets, and in new multi-unit buildings are slowly reduced up to 2050. Specifically, for pure gasoline or conventional diesel vehicles, available parking stalls begin being reduced in 2025 and by 2040 there are no city-controlled parking spaces available. For hybrid vehicles, the parking space reduction begins in 2035 and by 2050

there are no city-controlled spaces remaining. This reduction in spaces slowly increases the intangible cost of operating a gasoline or diesel vehicle within Vancouver, while decreasing the intangible cost of operating an electric or biofuel vehicle.

Freight vehicles are very difficult for a municipal government to regulate without senior government support. I simulate the City requiring businesses operating within Vancouver to demonstrate the use of renewably powered vehicles in order to qualify for a business license after 2030. Available freight options include electric vehicles and hybrid electric/biofuel powered light trucks, and renewable diesel powered heavy or light freight trucks, and hydrogen powered heavy trucks. Natural gas trucks are not allowed after 2030 in this scenario. Electric trucks using overhead wires are also an option on major truck routes such as Clark Drive; however, these are not simulated.

3.4.4. Assumptions about Senior Government

In the three scenarios outlined above, I assume that provincial and/or federal government policies remain stable. For example, I assume the continuance of existing federal emissions standards and that the B.C. carbon tax is frozen at its current level of \$30/tonne until after 2020, when pending federal minimum carbon pricing regulations require it to increase to \$40/tonne in 2021 and then \$50/tonne in 2022. After 2022, the carbon tax is assumed frozen at \$50/tonne under the “Current Policy” scenario for senior government.

However, it is possible there will be strong new policy at the senior government level and that this policy will complement policy at the municipal level. To assess this possibility, I ran a version of all three scenarios in which senior governments implement additional climate policy to meet Canada’s Paris Agreement commitment for national emissions in 2030 and sustain these directionally in the 2050 timeframe. From the perspective of a municipal government, such as that of Vancouver, it matters little if the key policies are implemented at the provincial or federal level. That is why I use the generic term senior government (SenGov) for these non-municipal policies.

I primarily simulate SenGov policy as a national or provincial carbon tax that rises from \$50/tonne in 2022 to \$200/tonne in 2030, where it remains constant until 2050. While

senior government could implement a carbon price such as this, they could instead choose to achieve a similar result through various flexible regulations in key sectors of the economy (Jaccard, Hein, & Vass, 2016). Either way, the implications are the same for a municipal government such as Vancouver.

3.4.5. Assumptions about Renewable Natural Gas (RNG)

I simulate RNG as a fuel option in Vancouver's 100% renewable future; however, its future supply is highly uncertain. Currently, most RNG comes from landfills and industrial composting facilities. But considerable RNG could be produced from wood waste materials. Given British Columbia's large forest industry, there is the possibility for an ample supply of input material to produce RNG. And while it is currently quite costly to produce RNG from this feedstock, technological innovation could change this situation. My base assumption nonetheless is that large supplies of RNG will not be available to the Vancouver region at a cost that is competitive with renewable electricity for building end-uses.

Thus, in the 100RE scenario, the cost of RNG rises from 60% higher than natural gas in 2020 to about 100% higher by 2050, again making it difficult to compete with renewable-derived electricity. Consequently, RNG's penetration was limited to a few niche applications: for cooking, some industrial processes, and space heating in buildings constructed prior to 2030. In the VanRen scenario, conventional natural gas could be used for these purposes, so the use of RNG, being more expensive, was limited in any case.

My base assumptions about RNG's supply and price limit its future consumption to a small amount compared to current natural gas consumption. This has major implications for the economic viability of the gas delivery network. As the number of users of the gas distribution system in Vancouver declines, more of the fixed costs of maintaining the system will fall on each individual customer. Furthermore, engineering considerations, such as the volume of gas required to keep the pipeline system functioning properly, could become an issue. A more detailed analysis is needed to understand if or how the existing gas infrastructure in Vancouver could be maintained in a 100% renewables future. For this

study, I assumed that the natural gas distribution system could provide the needed RNG until at least 2050. This assumption may have to be revisited.

3.4.6. Assumptions about Decentralized Energy

Very little of the energy used currently in Vancouver is generated locally. While there is some potential for increasing local (distributed) electricity generation, especially with rooftop photovoltaic (PV) panels, my base assumptions do not result in this source of electricity flourishing to the extent that some people believe it could. The main argument against local generation is cost. Even with a major increase in B.C. Hydro zero-emission generation over the next three decades, the price of its electricity for Vancouver's residential, commercial, institutional and light industrial customers (whether for buildings or electric vehicle recharging) is likely to remain cheaper than most applications of rooftop PV, especially when comparing the substantial difference in value of dependable (dispatchable) B.C. Hydro-generated electricity with the intermittent (non-dispatchable) PV-generated electricity. However, an argument in favour of more local generation is the intangible value that some individuals and firms place on being self-generators of zero-emission electricity. Thus, in the interpretation of my results, it is important to consider that some of the electricity used in Vancouver over the coming decades is likely to be generated locally at individual homes and commercial buildings and facilities. These locations, however, will rely on connection to the B.C. Hydro grid to address the intermittency in supply of solar power and to provide additional supply during times of peak demand.

District heating is also an option that some advocates believe will increase significantly in importance over the coming decades. Such systems improve energy efficiency, especially if heat is metered for each customer and if the central heating facility cogenerates heat and electricity. However, district energy systems require major capital investments, and these substantial costs are even higher where existing buildings and infrastructure must be disrupted and retrofitted. Furthermore, since low-cost natural gas cannot be the source fuel for district energy – when the goal is 100% renewables – such systems must use electricity or RNG or solid biomass as the energy source. Given my base assumptions about bio-energy supply availability and cost in Vancouver, district

energy must therefore compete with decentralized, electricity-driven heating sources with their lower capital cost, including resistance heating and heat pumps in efficient buildings. It is for these reasons that, even with changes to urban form that create more density, I do not assume a substantial increase in district heating in any of my three scenarios. I do, however, envision a gradual expansion of district energy at key high density nodes over the next decades. But this technology in 2050 still represents a relatively small percentage of the energy systems serving most buildings in Vancouver.

Chapter 4. Results and Discussion

4.1. Spatial Model

4.1.1. Baseline Intangible Cost Estimates

The three different neighbourhood archetypes I investigated were characterized by different transportation mode shares. The Downtown archetype had high levels of walking (40%) and lower levels of transit (20%) and driving (30%) than other areas of the city. The Inner City archetype had the highest transit (30%) and cycling (7%) use of all neighbourhoods examined and intermediate driving (40%) and walking (15%) rates. The Suburban archetype was characterized by high driving (60%) rates, lower transit (20%) use and very low levels of walking and cycling.

With these mode share values, the optimization model produced differing intangible costs for each mode in each area of the city. The mode-specific annual intangible costs (relative to intangible cost of driving, which is zero under the baseline conditions) are summarized by archetype in Table 4.

Table 4: Yearly intangible costs for different transportation modes under baseline conditions (relative to driving).

Mode	Archetype	Cost
Transit	Downtown	\$10,300
	Inner City	\$10,500
	Suburban	\$11,400
Cycling	Downtown	\$21,500
	Inner City	\$18,300
	Suburban	\$22,600
Walking	Downtown	\$13,700
	Inner City	\$17,100
	Suburban	\$22,600

These values are for commuting trips only. Qualitative comparison of these data to survey data shows that the mode shares for non-commute trip types, such as running errands, differ from commute trips (for example, there is lower transit use and higher

walking percentage for social trips than in commute trips (City of Vancouver, 2015c, 2016a). The pattern of mode shifts according to trip purpose is similar across the region (for example, more people in suburban and urban areas of Metro Vancouver carpool for social trips than for work trips (TransLink, 2013). Because these shifts by trip type occur in a similar fashion across Metro Vancouver, I assume that Vancouver follows a similar pattern and that all city archetypes exhibit a similar modal shift depending on the trip purpose. In addition, because my analysis is designed to look at changes in travel behaviour with changing intangible costs, having a range of different intangible costs across the city is more important than knowing the exact intangible cost of each transportation mode in each archetype. Thus, even though the intangible costs of different modes may differ by trip type, this characteristic is not as important as how the intangible costs change depending on the transportation network quality. Therefore, in this analysis I am assuming that the change in intangible costs from a network improvement is the same for all trip types, even if the initial mode share varies by trip type.

4.1.2. Baseline Network Quality Estimates

As with intangible costs of transportation, the transportation network quality varies by transportation mode and across archetypes. The network quality estimates were normalized to have a value of 100, on average, across the city in the baseline scenario. Any values less than 100 indicate a network quality less than average whereas values greater than 100 indicate a higher than average network quality. The baseline network quality estimates for other modes are summarized in Table 5.

The walk quality estimates of neighbourhoods varied drastically between the Urban, Inner City, and Suburban Archetypes. Both the Urban and Inner City neighbourhoods had relatively high walk quality throughout all neighbourhoods, whereas the Suburban neighbourhoods had relatively low walk quality, with a few exceptions such as along Fraser Street and Victoria Drive.

Cycling quality across the city exhibited a similar trend to walk quality, with Downtown and Inner City neighbourhoods exhibiting higher quality values for cycling infrastructure due to the high density of bike routes and their proximity safe cycling infrastructure.

Table 5: Baseline network quality estimates

Mode	Archetype	Quality
Driving (road network)	Downtown	64
	Inner City	102
	Suburban	132
Transit	Downtown	107
	Inner City	100
	Suburban	96
Walking and Cycling	Downtown	126
	Inner City	112
	Suburban	59

Transit quality is, unsurprisingly, highest downtown, with other areas of high quality transit surrounding SkyTrain stations and transit exchanges. While the extension of SkyTrain lines into suburban areas of the city provides some high-quality transit in these neighbourhoods, overall these areas are characterized by low quality transit. When the central business district is excluded from the Downtown archetype (leaving the West End residential neighbourhood), the transit quality is the same as the Inner City archetype.

4.1.3. Network Quality Coefficients

The variation of intangible costs and transportation network quality values across the city provided me with an initial indication of how much intangible costs are dependent on network quality and how much they are dependent on other factors, such as demographics. Specifically, these coefficients show the change in intangible costs for a set change in network quality. For example, the value of -130 for transit means that for every unit increase in the transit network quality the intangible cost of transit declines by \$130. These coefficients differ by mode: some modes show a strong sensitivity to network quality, whereas other modes are less sensitive (Table 6).

Table 6: Network quality coefficients for each transportation mode

Mode	Coefficient
Driving	-32
Transit	-130
Walking and Cycling	-69

Network quality explained some but not all of the variation in intangible costs of different transportation modes. Specifically, despite the high degree of correlation between network quality and intangible costs, the relationship is not directly inversely proportional. For example, a doubling of the walking and cycling network quality does not reduce the intangible cost of walking and cycling by half, but rather by about 25%. This relationship means that to drive a substantial decrease in intangible costs, strong policy to improve network quality is necessary.

Because there is substantial uncertainty around this relationship, I have designed the spatial extension of CIMS Community so that model users can try running the model with different Network Quality Coefficients to investigate how they may impact results. I used this design feature when running sensitivity analysis for my results. I found that while extreme differences in the intangible costs coefficients could lead to detectable differences in mode share, the differences in energy use and emissions for Vancouver overall were negligible.

4.1.4. Policy Network Quality Estimates

Transportation network quality changes are summarized in Table 7 and the network changes can be seen for each mode in maps included in Appendix B. After I applied the transportation policies outlined in the VanRen scenario, the road network quality decreased in the Downtown archetype neighbourhoods, beginning in 2020, and then in the Inner City neighbourhoods, after 2030.

Walk quality in all areas of the city increased as mixed-use developments were completed between 2015 and 2050. The increase in walk quality was most pronounced outside of the Downtown archetype, as the downtown neighbourhoods already had many walk destinations within a short distance of most residents and therefore an already high

walk quality index. Mixed-use developments in the southern parts of the city experienced a dramatic impact – residential areas formerly isolated from commercial areas showed increases in their walk quality index as more mixed-used development occurred along major arterials.

Table 7: Normalized network quality estimates under VanRen and 100RE policies, summarized by decade of implementation

Mode	Archetype	2020 to 2030	2030 to 2040	2040 to 2050
Driving (road network)	Downtown	51	45	45
	Inner City	105	97	97
	Suburban	132	123	118
Transit	Downtown	108	114	121
	Inner City	110	116	118
	Suburban	97	99	107
Walking and Cycling	Downtown	148	157	169
	Inner City	130	142	162
	Suburban	71	83	102

Cycling quality was also already high in the Downtown and Inner City archetypes in the baseline representation and thus experienced the greatest improvement in the southern areas of the city. Unsurprisingly, cycling quality improved most in areas where connected bike routes separated from busy traffic were constructed. When averaged together with walk quality, the overall trend was for an increase in walking and cycling conditions across all city neighbourhoods from baseline to 2050.

Transit network quality improved in all areas of the city with investment. Even the Downtown archetype experienced a substantial increase in transit quality, due to its position as a regional transit hub. Other substantial changes in transit quality occurred along central Broadway after the Millennium Line extension in the mid 2020s and along Arbutus and 41st Avenue with rapid transit installations occurring after 2040.

4.1.5. Policy Intangible Cost Estimates

The intangible costs changed over the simulation period from 2015 to 2050 in response to transportation and land use policies included in the VanRen and 100RE scenarios (Table 8). The intangible costs of driving (or carpooling) in a private vehicle rose slightly over this period, whereas the intangible costs of using transit or walking and cycling fell. The increased intangible cost of driving resulted from increasing traffic congestion brought on by population growth and no roadway expansion.

Table 8: Policy intangible costs for each mode (VanRen and 100RE scenarios)

Mode	Archetype	2020 to 2030	2030 to 2040	2040 to 2050
Driving (road network)	Downtown	\$ 1,180	\$ 1,340	\$ 1,340
	Inner City	-\$ 130	\$ 55	\$ 55
	Suburban	-\$ 800	-\$ 590	-\$ 470
Transit	Downtown	\$ 9,710	\$ 8,950	\$ 8,000
	Inner City	\$ 9,434	\$ 8,600	\$ 8,330
	Suburban	\$ 11,180	\$10, 880	\$ 9,790
Walking and Cycling	Downtown	\$ 18,400	\$ 17, 640	\$ 16,530
	Inner City	\$ 18,810	\$ 17,770	\$ 15,940
	Suburban	\$ 19,280	\$ 18,250	\$ 16,600

The intangible costs for transit, walking, and cycling vary substantially over relatively short (a few hundred metres) distances. Transit intangible costs are lowest near the SkyTrain and highest in the southwest corner of the city (Figure 4). Under VanRen policy, by 2050, transit intangible costs decrease across the city, especially along the Broadway Corridor, the Arbutus Corridor (west side of map), and 41st Avenue (along the southern portion of the map).

Walking and cycling are calculated and mapped independently and averaged when input into CIMS Community. Walking intangible costs in 2015 are low on the downtown peninsula and along commercial corridors, but high in most areas on the southern and western edges of the city (Figure 5). With policy, walking intangible costs decrease, especially along transit routes such as 41st Avenue (in the south) where I assume future mixed-use developments will be concentrated.

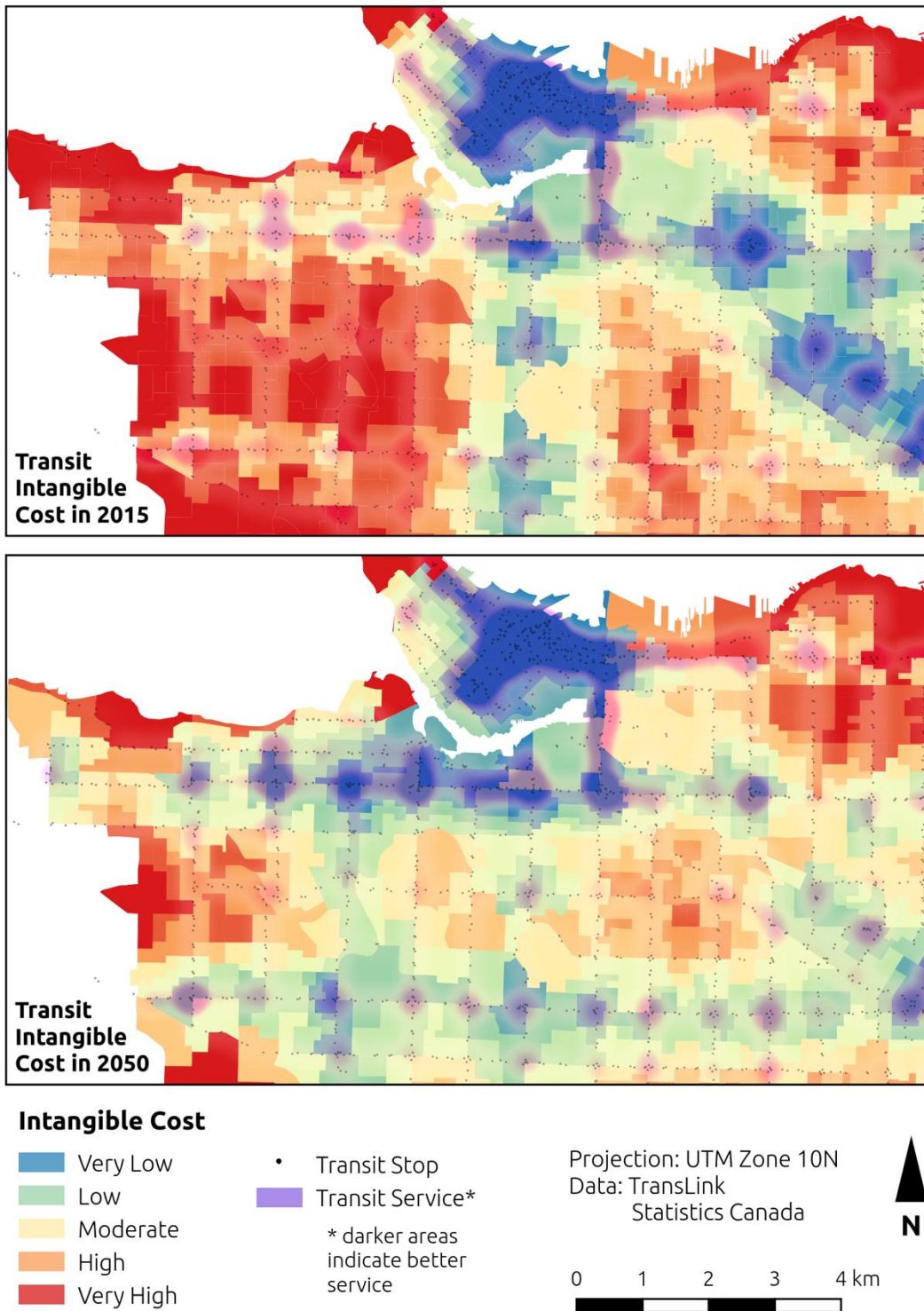


Figure 4: Transit intangible costs in 2015 and 2050 (in VanRen and 100RE)

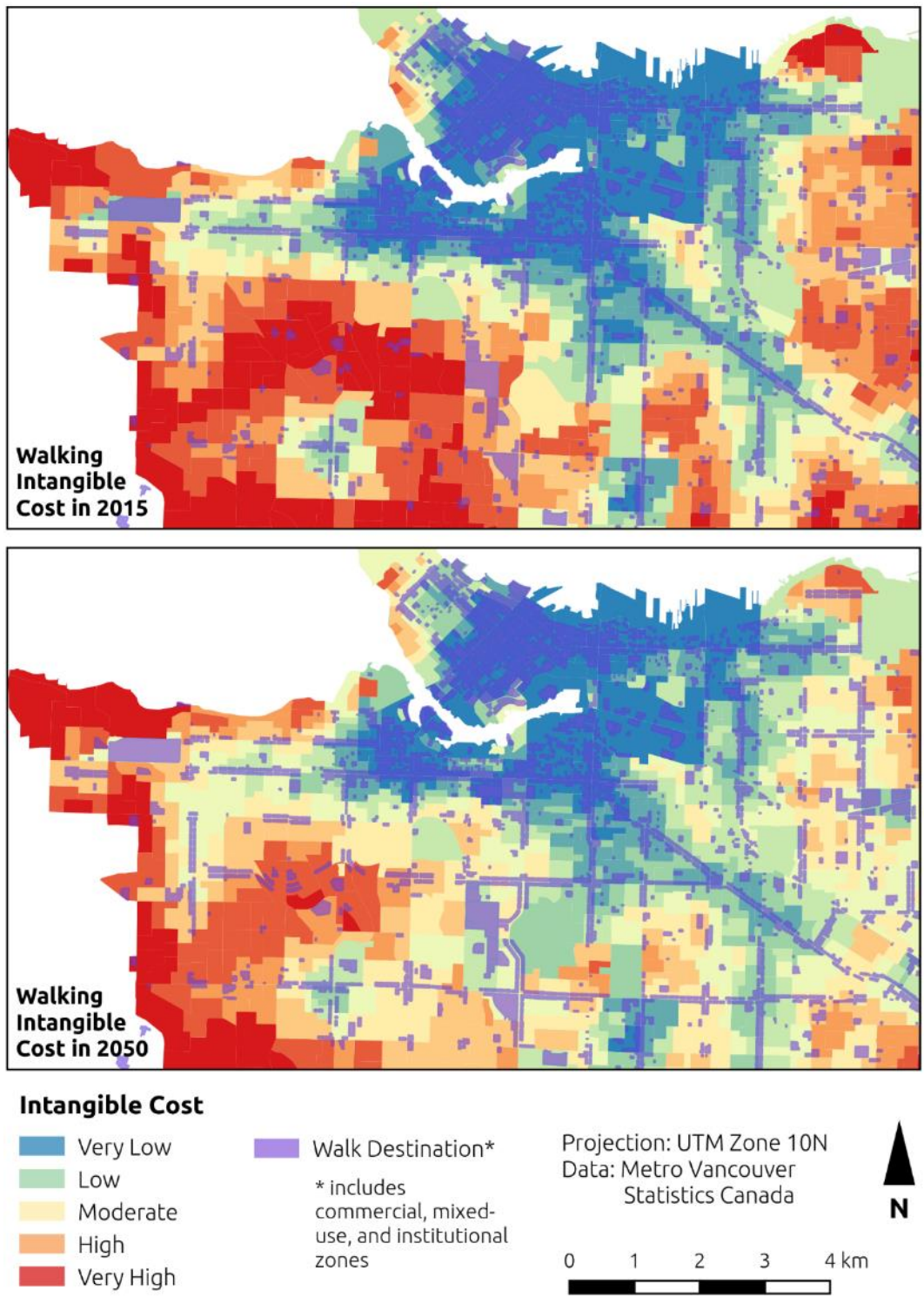


Figure 5: Walking intangible costs in 2015 and 2050 (in VanRen and 100RE)

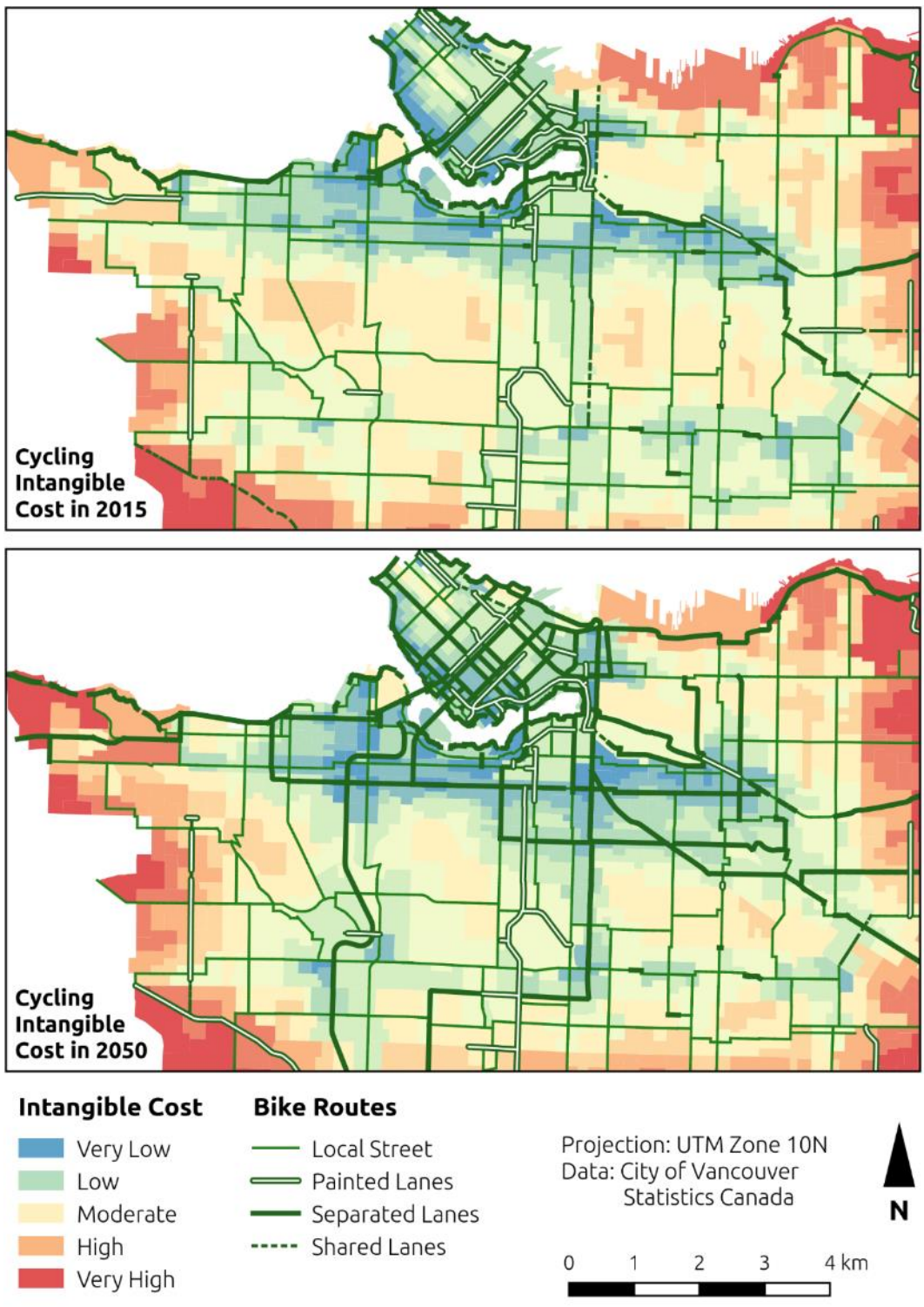


Figure 6: Cycling intangible costs in 2015 and 2050 (in VanRen and 100RE)

Cycling intangible costs in 2015 are lowest near the seawall (which surrounds False Creek, the inlet south of downtown) and along the 10th Avenue bikeway (near the map centre). This pattern is expected as these areas of the city have the greatest density of high quality cycling routes (Figure 6). By 2050, the intangible cost of cycling decreases across the entire city. Cycling improvements along the Arbutus Corridor (the new north-south route on the west of the lower map) and the Ontario Bikeway (the new north-south route in the centre of the lower map), drive a substantial decrease in the intangible cost of cycling in these areas.

Detailed maps of transportation network and land use changes along with the associated changes in the intangible costs of transit, walking, and cycling for each decade from 2020 to 2050 are provided in Appendix B.

4.2. Emissions Trajectories

Greenhouse gas emissions and energy use in Vancouver rise in the Current Policy (CurrentPol) scenario when there is no additional climate policy from senior government. The Renewable City Strategy (VanRen) policies yield a slight decrease in total energy use, fossil fuel use, and a decrease in greenhouse gas emissions; however, this decrease is insufficient to meet the City's greenhouse reduction targets (Figure 7).

Only in the 100RE scenario do emissions drop enough to meet the City's goal of an 80% greenhouse reduction by 2050. This drop in emissions is driven by a move to nearly 100% renewable energy. While emissions and fossil fuel use in the 100RE scenario drop substantially, total energy use only decreases a small amount, illustrating that much of the emissions reduction in this scenario comes from fuel switching, rather than decreased energy consumption.

For the purposes of this study, I assumed that results for renewable energy that fell within a few percentage points of 100% successfully met the Vancouver's vision of a city powered by renewable energy. Specifically, I was not concerned about a small amount of residual fuel use remaining (for example, conventional natural gas stoves) when designing the policies for the 100RE scenario.

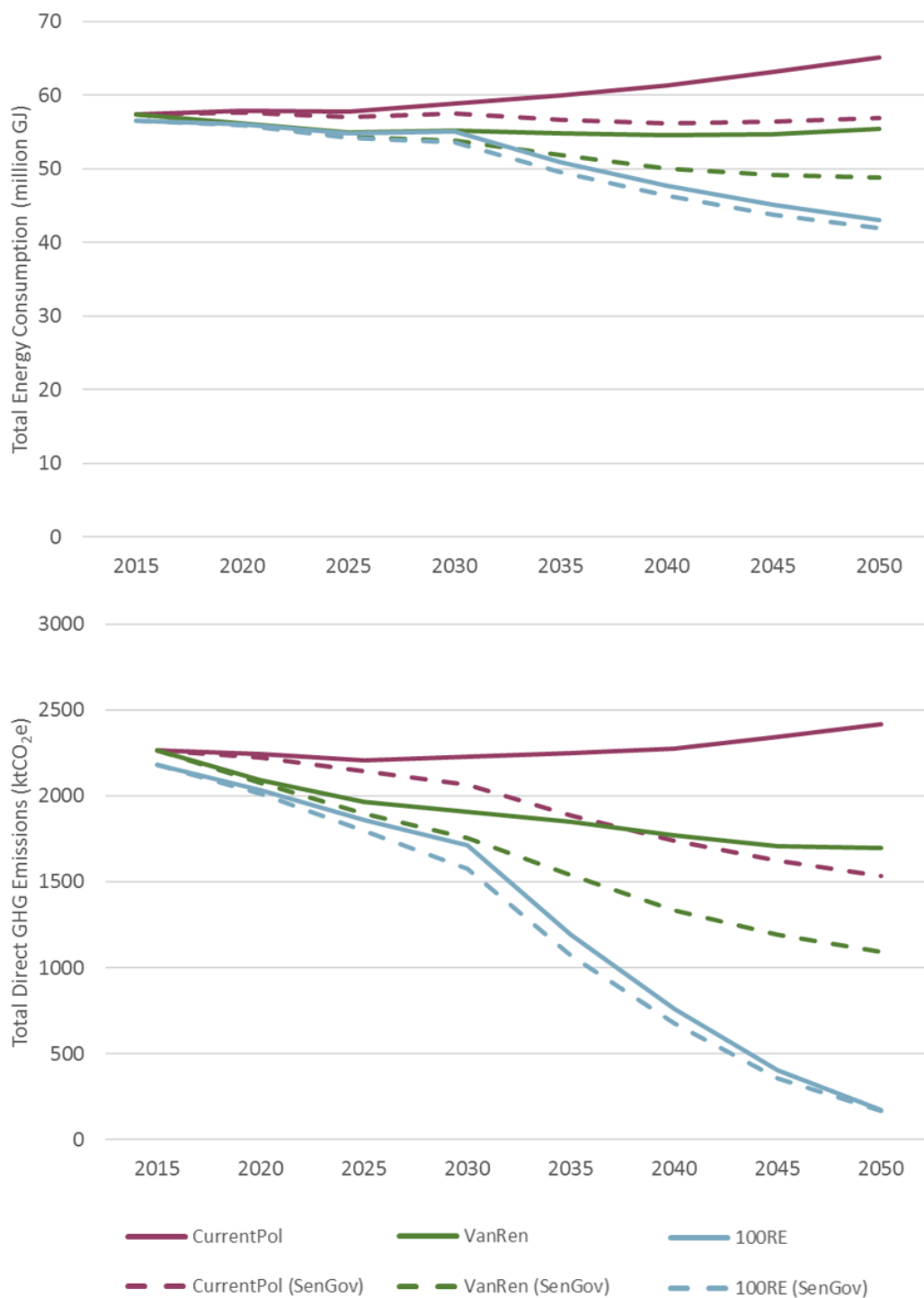


Figure 7: (a) Total energy consumption and (b) greenhouse gas emissions
 Energy and emissions under the Current Policy (CurrentPol), Renewable City Strategy (VanRen), and 100% Renewable Energy (100RE) scenarios with current senior government policy and additional senior government policy (SenGov)

4.3. Emissions by Sector

4.3.1. Current Policy

Personal transportation (blue) is the largest greenhouse emissions source for all years modelled, followed by residential buildings (green) and then non-residential buildings (commercial, institutional, and light industrial buildings; Figure 8). Under current policy, emissions in most sectors remain relatively constant, with emissions reductions from improved efficiency and fuel switching typically compensating for most of the increases caused by population growth. Emissions for residential buildings increase substantially (20% increase). This increase is driven by increasing floor space; however, greenhouse gas emissions per square metre of floor space decreases as older buildings are replaced with better insulated new buildings and as single family homes, often heated with natural gas, are replaced with multi-family buildings, which are more likely to be heated with electricity. Commercial building shell efficiency improves; however, commercial floor-space also increases substantially (30%) in the 2020 to 2050 period. The growth in commercial floor space offsets reductions in energy use from improved building shell efficiency, yielding relatively constant commercial sector emissions.

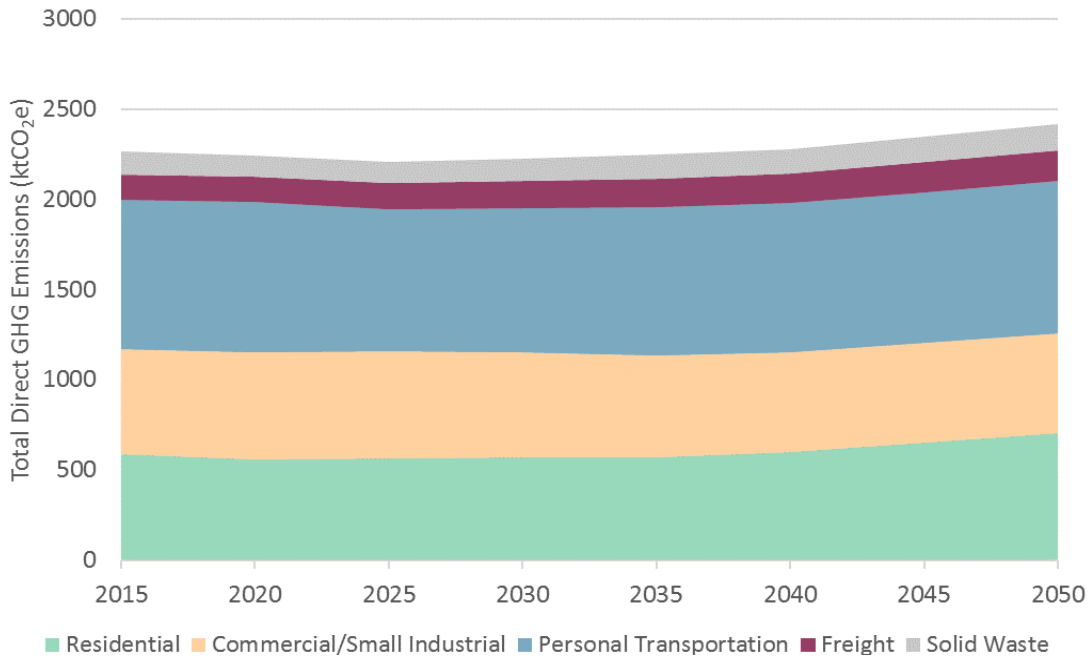


Figure 8: Emissions by sector under Current Policy

Personal transportation emissions increase only slightly (2%) as extra travel from new residents is balanced with decreased travel per capita as the city densifies. Freight transportation grows substantially (30%) in terms of tonne-kilometres travelled; however, improvements in engine efficiency mean there is a more modest (20%) growth in emissions from freight transportation.

4.3.2. Renewable City Strategy

The Renewable City Strategy scenario yields a small shift to renewable energy and a decrease in greenhouse gas emissions, compared to the Current Policy scenario, for all sectors except freight transportation (Figure 9). The Zero Emissions Buildings Plan drives a decrease in energy use in new residential buildings as well as a shift away from natural gas for heating. Commercial, institutional, and light industrial buildings also demonstrate a shift to more efficient building shells, as well a shift away from natural gas, yielding 25% decrease in conventional natural gas consumption.

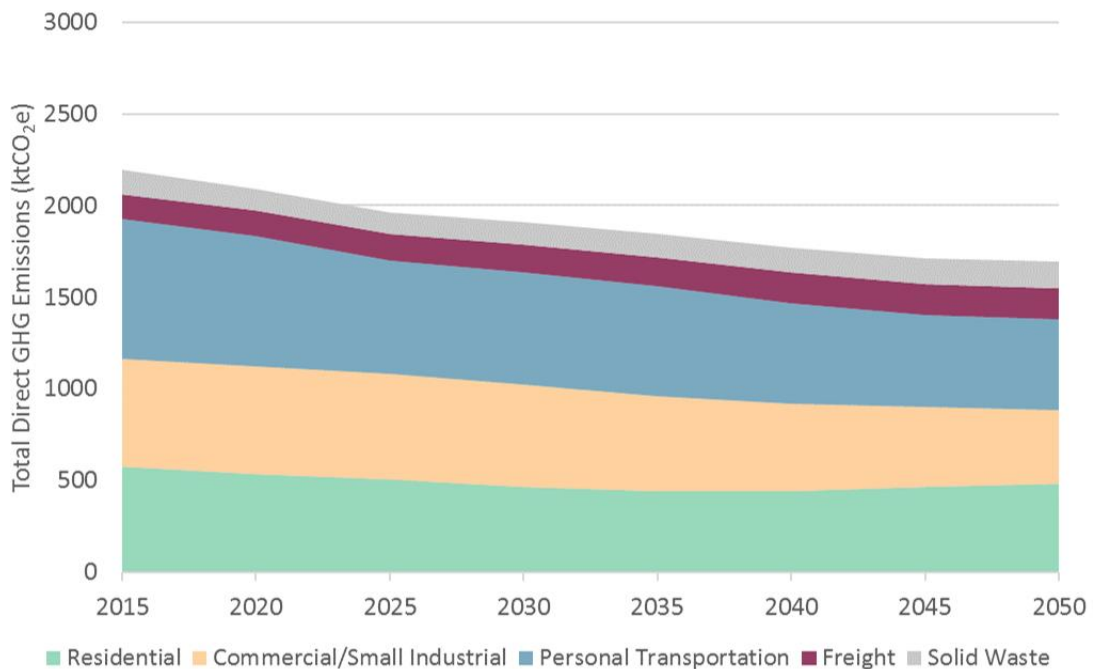


Figure 9: Emissions by sector under the Renewable City Strategy

The Renewable City Strategy scenario lacks strong policy for increasing the use of zero emissions vehicles; therefore, there is little movement away from gasoline powered personal transportation. Freight transportation in this scenario is identical to that under current policy, as there is no substantial new policy aimed at reducing the use of conventional diesel freight trucks in this scenario.

The VanRen scenario does include policy for improved transit service and investment in cycling and walking infrastructure, which helps cause a shift towards these transportation modes, especially in the later years of the simulation (Table 9). When this investment occurs along with more aggressive senior government policies or with policies for fuel switching in private vehicles (such as in the 100RE scenario) the shift to transit, walking and cycling is even more pronounced. While cycling and walking infrastructure improvements generate modest growth in these modes, transit service at first experiences a stagnation in mode share change (compared with what has been observed in the past decade). It is important to note that total ridership continues to climb, but in the period from 2015 to the mid 2020s the increase in transit ridership just keeps pace with population growth, leading to very little change in transit mode share. This effect occurs because very little additional transit capacity is anticipated in Vancouver until the mid 2020s, when the Broadway Subway is assumed to open. A lag-time between transit investment and ridership changes means transit mode share does not begin increasing substantially until beyond 2030.

Table 9: Estimated mode shares (as percentage of total distance travelled) averaged for each decade in the Renewable City Strategy

Mode	Baseline	2020	2030	2040	2050
Single Occupant Vehicle	38%	37%	38%	36%	33%
High Occupant Vehicle	20%	20%	16%	15%	13%
Transit	33%	36%	37%	38%	41%
Walking and Cycling	7%	7%	9%	11%	13%

4.3.3. 100% Renewable Energy

Emissions in all sectors, except solid waste, reach nearly zero under this scenario (Figure 10). In addition to the shifts seen for new buildings under the Renewable City Strategy, this scenario sees existing buildings moving to electricity and renewable natural gas, yielding a residential building sector powered mainly by electricity with only a small percentage (less than 5%) of renewable natural gas used. A similar result is seen with commercial, institution, and light industrial buildings; however, renewable natural gas makes up a slightly larger percentage (10%) of energy consumed in this sector. The higher energy costs under the 100% Renewable Energy scenario mean that in addition to fuel switching, there is a shift to more efficient energy use, with energy used in buildings about 20% lower than under the Renewable City Strategy and 35% lower than under current policy.

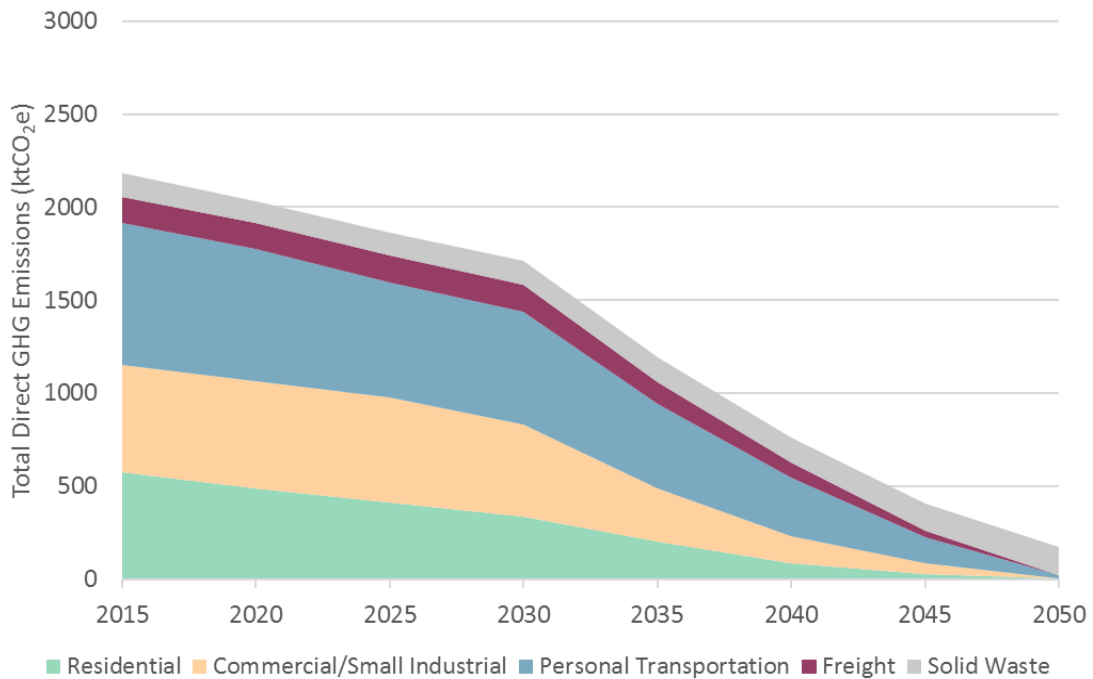


Figure 10: Emissions by sector under 100% Renewable Energy

Emissions from transportation also decrease substantially in the 100RE scenario. However, unlike under the Renewable City Scenario, most of the reductions in this scenario come not from a mode shift, but from a shift in personal vehicles to zero emissions vehicles. Electric vehicles (including plug-in ethanol hybrid vehicles) dominate personal vehicles under this scenario, making up about 80% of all vehicles by 2050; however, biofuel (ethanol or renewable diesel) vehicles make up a percentage (20%) of vehicles. A very small amount of fossil fuel use remains in the personal transportation sector as I assumed city policy for this subsector was focused on parking restrictions for personal vehicles, rather than a city-wide ban.

Freight transportation moves to almost all renewable diesel (HDRD) in the 100% Renewable Energy Scenario. A small percentage (14%) of light freight (local delivery) vehicles moves to electric (full electric and plug-in hybrid), while hydrogen fails to gain any significant market share. Natural gas vehicles, using either liquefied natural gas (LNG) or compressed natural gas (CNG) were not allowed in the 100% Renewable Energy Scenario as conventional natural gas is not a renewable fuel. While it is technically possible that renewable natural gas could be made into LNG or CNG, this would be substantially more expensive than conventional LNG or CNG, due to the higher price of renewable natural gas. Given the already low market shares of LNG/CNG heavy freight vehicles, it is highly unlikely LNG/CNG vehicles would have a substantial share of heavy freight vehicles. Additionally, heavy freight vehicles using overhead electric wires were also not simulated, but with the right policy could conceivably have some market share; however, because this outcome is entirely dependent on a very specific policy, it was not included in these simulations.

4.4. Fuel Switching

Under current policy, the consumption of different energy types changes very little—electricity, gasoline and natural gas remain the most common forms of energy used in Vancouver (Figure 11a). The Renewable City Strategy policies do very little to force fuel switching and thus the energy use is similar to what is projected under current policy (Figure 11b). One exception is the Zero Emissions Building Plan for new buildings, which does help drive a shift towards the reduced use of conventional natural gas for heating in new buildings. In the Renewable City Strategy Scenario, there are no policies to force fuel switching in personal vehicles, so gasoline and diesel use remain high. A slight decrease in gasoline use is predicted in this scenario, as new transit infrastructure and road congestion causes a shift to transit, which is not only more energy efficient, but assumed to be 100% zero emissions by 2050.

The 100% Renewable Energy Scenario is specifically designed to focus on fuel switching, in addition to energy efficiency, and can achieve about 99% renewables by 2050 (Figure 11c). The role of electricity in delivering power is greatly increased in a near 100% renewable future; electricity makes up 85% of the energy consumed in Vancouver in 2050. Electricity is the main source of energy for all building types and for personal transportation, with freight transportation being the only sector that is not dominated by electricity. Most of the liquid biofuels consumed are in the form of renewable diesel (HDRD); however, ethanol for passenger vehicles also makes up a substantial portion of liquid biofuels.

Conventional natural gas use decreases to zero in the 100RE scenario, while the use of renewable natural gas increases from 2020 to 2040. The use of renewable natural gas peaks in 2040, because there is still substantial pre-2030 building stock (old buildings are allowed to use natural gas but are mandated to use an increasingly high percentage of renewable natural gas). The overall need for either type of natural gas decreases after 2040 as a growing portion of the city's building stock is built to higher efficiency standards where heating demand is lower.

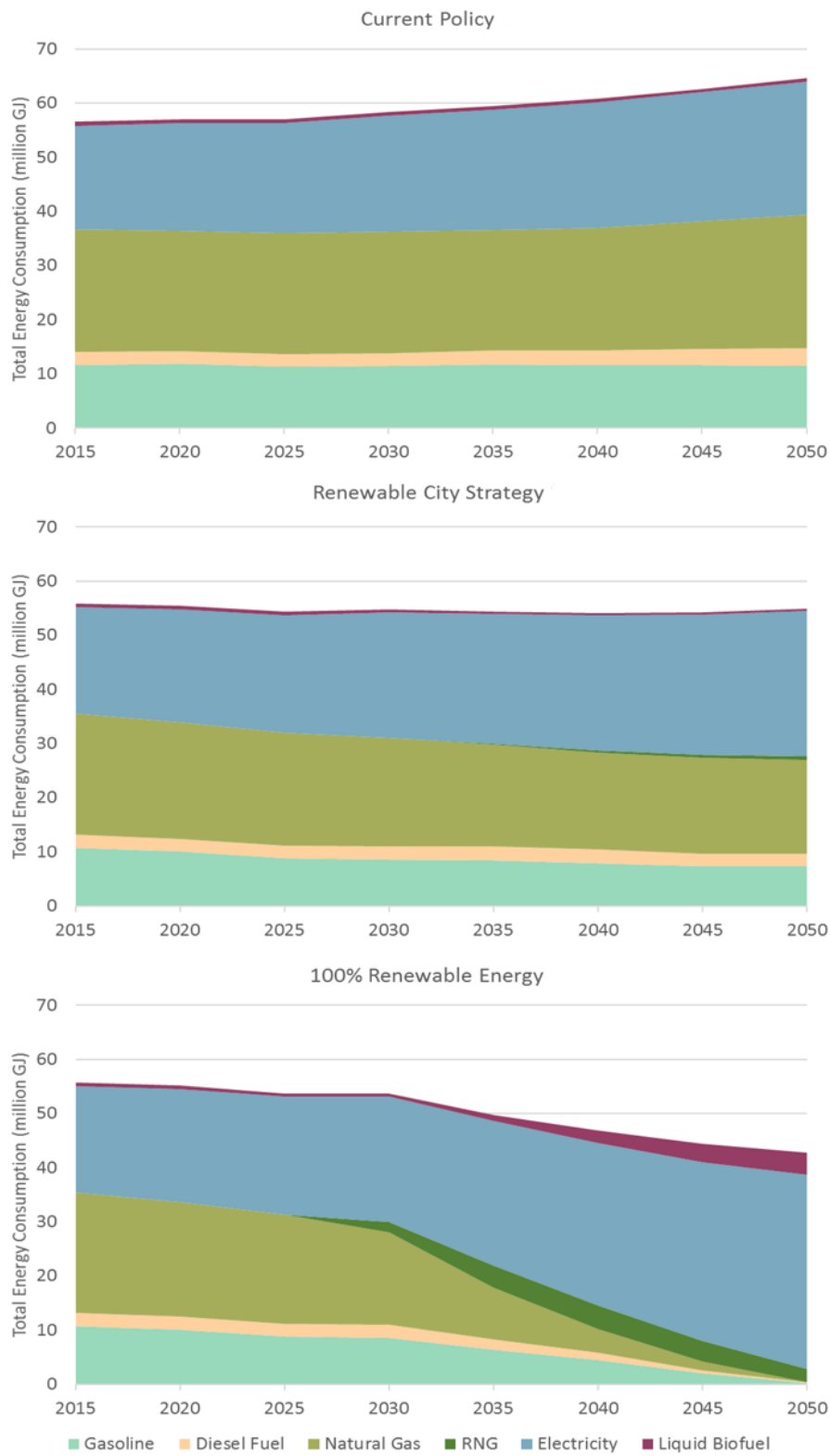


Figure 11: Energy consumed by type
 In the a) Current Policy, b) Renewable City Strategy, and c) 100% Renewables scenarios

4.5. Buildings

4.5.1. Residential Building Shells

Vancouver's Zero Emissions Building plan includes efficiency improvements to the building code and, by 2030, a requirement for new buildings to be zero emissions. Since both the *VanRen* and *100RE* scenarios include the Zero Emissions Building plan, they are associated with an increase in zero emissions buildings. Figure 12 shows the market shares of residential housing stock among different categories of building shell efficiency as policies change this over time, illustrating the shift to more efficient building shells.

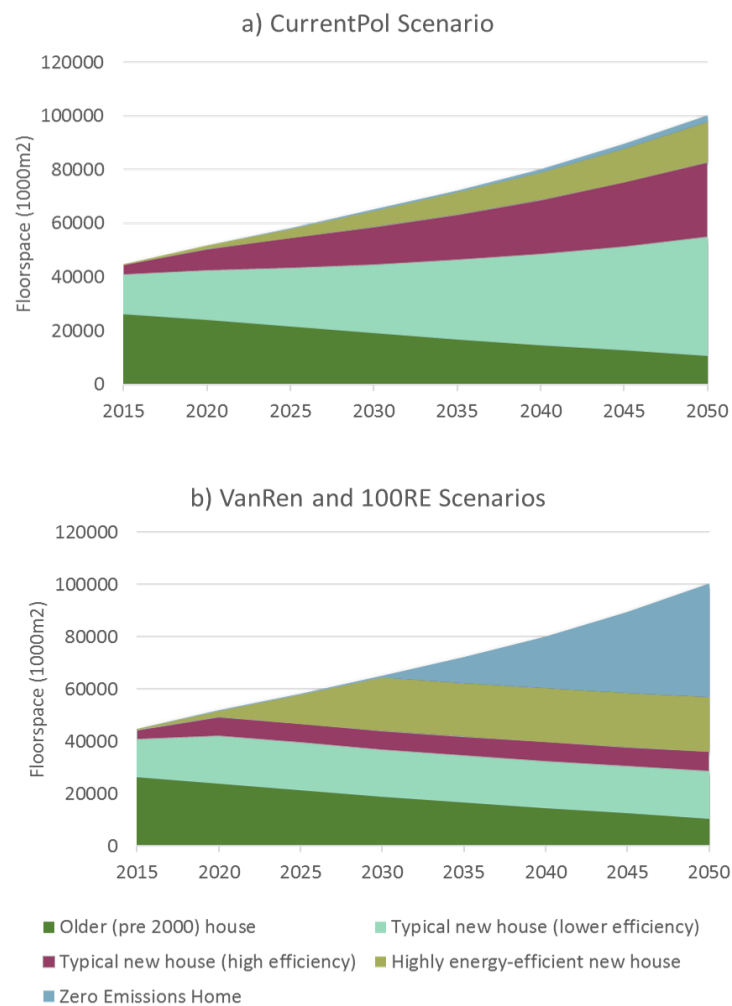


Figure 12: Market shares of residential stock

In a) CurrentPol and b) VanRen and 100RE scenarios. Zero emissions homes have the most efficient building shell and must also not use fossil fuels for heating.

4.5.2. Residential Heating Technologies

The CurrentPol scenario does not outline heating technologies that must be used while the VanRen scenario policies ensure that after 2030 all newly constructed buildings are heated with electric baseboard heaters, electric heat-pumps, rooftop solar, or other zero-emissions heating equipment. The 100RE scenario extends this requirement to existing buildings when their space or water heating equipment is being replaced or when the building is undergoing a major renovation. The differences in policy among these three scenarios yields a different mix of space (and water) heating technologies.

Figure 13 compares the space heating equipment in these three scenarios in 2050. Conventional baseboard electric heat (purple) in standard pre-2030 buildings (those without high efficiency building shells) remains relatively constant among the three scenarios whereas the use of standard combustion furnaces (green) is lower in the VanRen scenario and near zero in the 100RE scenario. In the 100RE scenario, the remaining standard combustion furnaces in existing buildings are consuming RNG. The blue column in the figure represents all new buildings constructed after 2030 and any existing buildings that have been connected to a zero-emissions district energy system, retrofitted to a passive house standard, or fitted with a zero-emissions heating technology, such as an electric heat-pump.

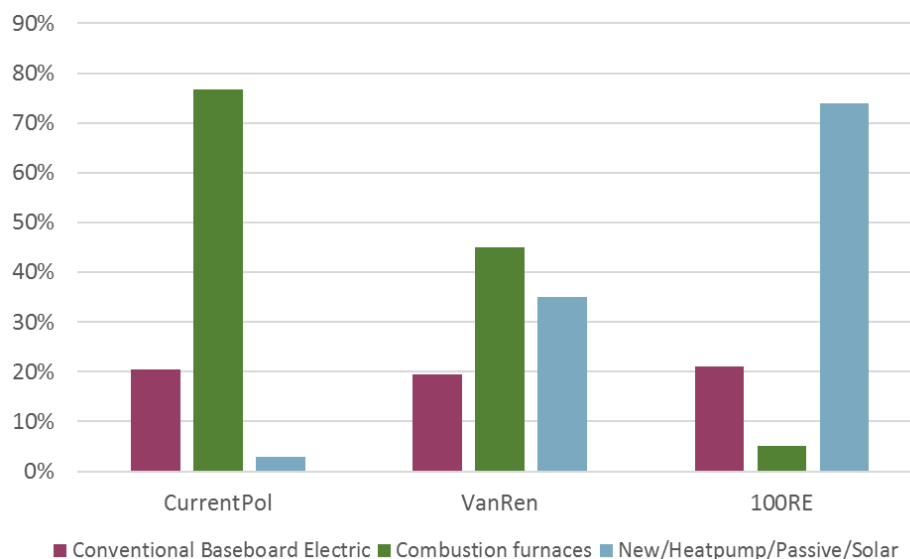


Figure 13: Market share of heating technologies

In the Current Policy (CurrentPol), Renewable City Strategy policy (VanRen) and 100% Renewable Energy (100RE) scenarios in 2050

4.5.3. Commercial, Institutional, and Light Industrial Buildings

Commercial, institutional, and light industrial (warehouse and office space) energy consumption in 2015 was evenly split between electricity and natural gas. This sector does not include heavy industries or port activities, which can have substantial electric loads and combustion demand from industrial equipment. Under CurrentPol, energy use continues to grow to 2050 with increasing floor space. However, improved building shell efficiency offsets the growth in heating demand that would otherwise be expected, while electricity demand does grow somewhat, with increasing lighting and plug loads.

Under VanRen, buildings are better insulated and require less energy for space heating. Furthermore, new buildings are required to use zero emissions energy starting in 2030. When modelling policies for this scenario, I assumed new buildings could use RNG for non-HVAC uses, such as cooking or light industrial processes.

Figure 14 shows energy consumption by end-use in the 100RE scenario. Better insulated buildings and higher costs for electricity and gas cause overall energy use to decrease with greater efficiency gains. This is especially the case with energy use for HVAC.

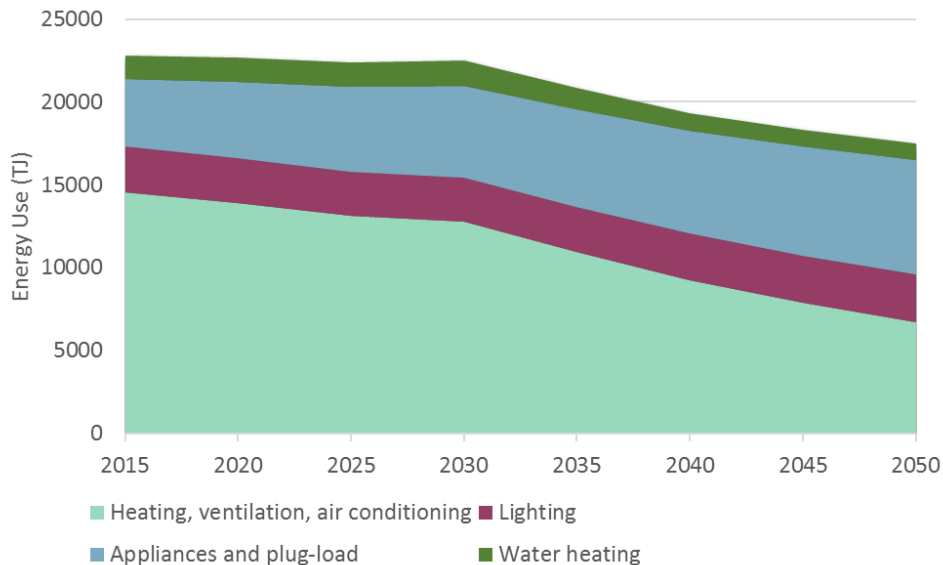


Figure 14: 100RE Energy consumption by end-use
For commercial, institutional, and light industrial buildings

4.6. Personal and Freight Transportation

The emissions stemming from transportation can be especially difficult for the City to influence without help from senior government. Transportation policies that are within the City's jurisdiction often focus on transportation infrastructure investment, which can result in mode shifting, but does not change the fuels used in private vehicles. In the VanRen scenario, this investment resulted in considerable shifts in transportation mode share, especially in later years of the policy. This mode shifting resulted in decreased emissions; however, substantial emissions in the transportation sector continued to come from personal transportation.

Under the Renewable City Strategy (VanRen scenario) policies, private passenger vehicles remain in the city and continue using fossil fuels (Figure 15). CIMS captures this dynamic by incorporating the intangible benefit some individuals attach to these fossil fuel-consuming vehicles and therefore predicts their presence into the future, despite improvements to other parts of the transportation network and incentives to use zero emissions vehicles. Furthermore, because CIMS simulates competition among transportation modes, vehicle types², and vehicle motors, it can realistically show how many of those who switch to transportation modes such as walking and cycling, will be switching from already relatively efficient vehicles (i.e., we cannot expect the shift to walking and cycling to mainly come from large gasoline or diesel vehicles).

The difference between the VanRen scenario and the 100RE Scenario shows that, to realise reductions in passenger transportation emissions, policies directly preventing the use of fossil fuel powered vehicles within Vancouver are necessary.

² In simulating vehicle choices, modeling assumes no major changes in the rest of the world. If fossil fuel demand were to fall globally it would impact energy prices and therefore the results presented here

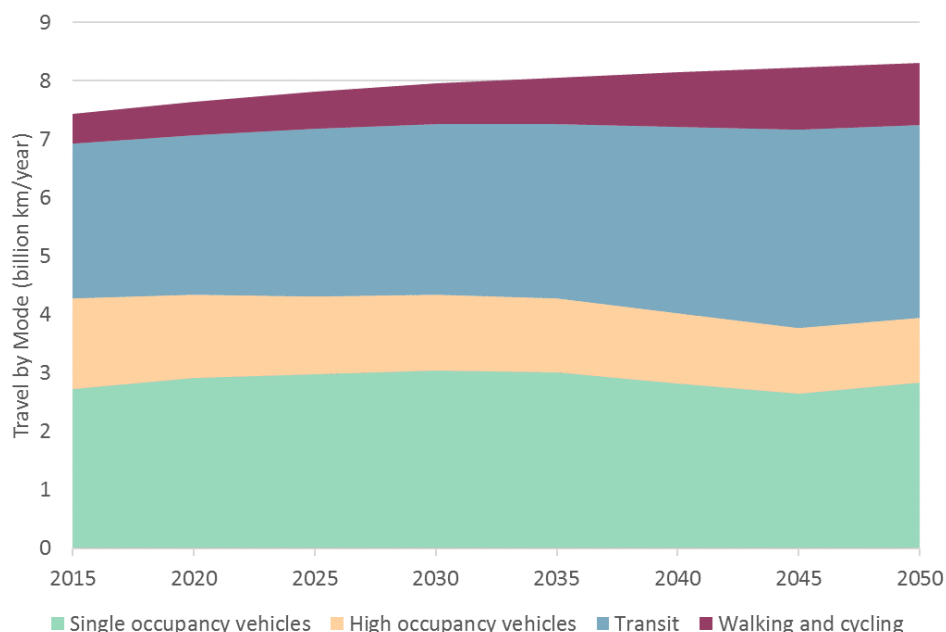


Figure 15: Distance travelled by mode under the Renewable City Strategy (VanRen) Scenario transportation policies

Even in the 100RE scenario, in which most personal transportation is powered by electricity and biofuels, a small amount of fossil fuel use and emissions from passenger vehicles is still predicted (Figure 16a). This is because it is extremely difficult to eliminate the use of gasoline in passenger vehicles with the limited policies available to municipal government, such as parking restrictions. For example, a parking restriction on fossil fuel vehicles in Vancouver would not stop a fossil fuel using vehicle from passing through Vancouver on a provincially-owned highway. Therefore, when modeling personal vehicle policies, I chose to not represent the policies as a ban on having fossil fuel using vehicles within Vancouver’s city limits, but rather as an increasingly high intangible cost to operating them. Freight transportation, which is subject to different policies than personal transportation, is powered mostly by renewable diesel (Figure 16b). The overall energy use for freight transportation increases from 2015 to 2050, despite efficiency improvements. This increase occurs as freight traffic grows with rising population and GDP more rapidly than efficiency improvements reduce energy demand.

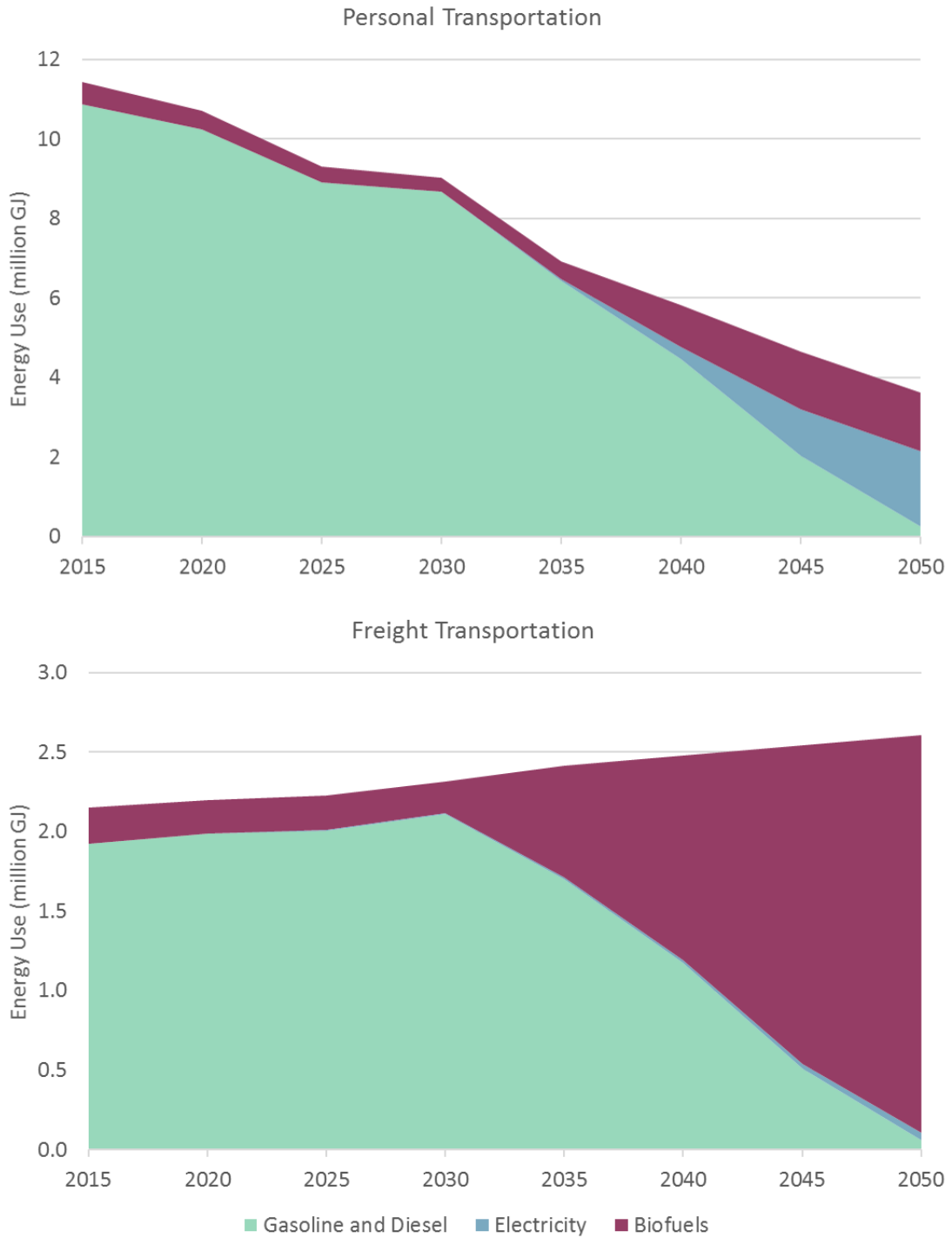


Figure 16: Transportation energy consumed by type in the 100RE Scenario
 Consumption for (a) passenger transportation and (b) freight transportation

Senior government policy, while non-binding in most sectors in the 100RE scenario, does further reduce the use of gasoline powered personal vehicles. In the absence of federal policy that completely bans the use of gasoline and diesel, efforts by the City to further reduce the intangible costs of other transportation modes (walking, biking, transit) is one way in which policy could encourage fewer trips into (or through) Vancouver by gasoline or diesel fueled vehicles.

4.7. Senior Government Policy Interaction

Additional senior government policy in the form of flexible regulations or a higher carbon price helps reduce emissions and fossil fuel use in all scenarios. The impact of senior government policy is greatest under the CurrentPol and VanRen scenarios, whereas in the 100RE the impact from senior government policy is much less since the City would have its own aggressive policies (Figure 17). The CurrentPol and VanRen scenarios are sensitive to senior government policy because there is still fossil fuel using equipment in these scenarios and the demand for fossil fuels is sensitive to an emissions price from senior government. Under the 100RE scenario, fossil fuel using technology has mostly been phased out.

The additional senior government policies were designed to be of the stringency necessary for Canada to meet its 2030 Paris target. Beyond 2030 I assumed that the federal government maintains its policies at the same stringency through to 2050. Even alongside these relatively stringent policies, the VanRen policies are insufficient to meet the targets of the Renewable City Strategy. Because the main difference between the VanRen and 100RE policies consist of the additional fuel switching policies for both existing buildings and vehicles, this finding suggests that policies specifically targeting fuel switching will be essential for the City to achieve its targets. If the City implements strong fuel switching policies for existing buildings and private vehicles similar to those already implemented for new buildings in the Zero Emissions Building plan, it is possible to achieve emissions reductions and a shift to renewable energy that is consistent with the Renewable City Strategy targets.

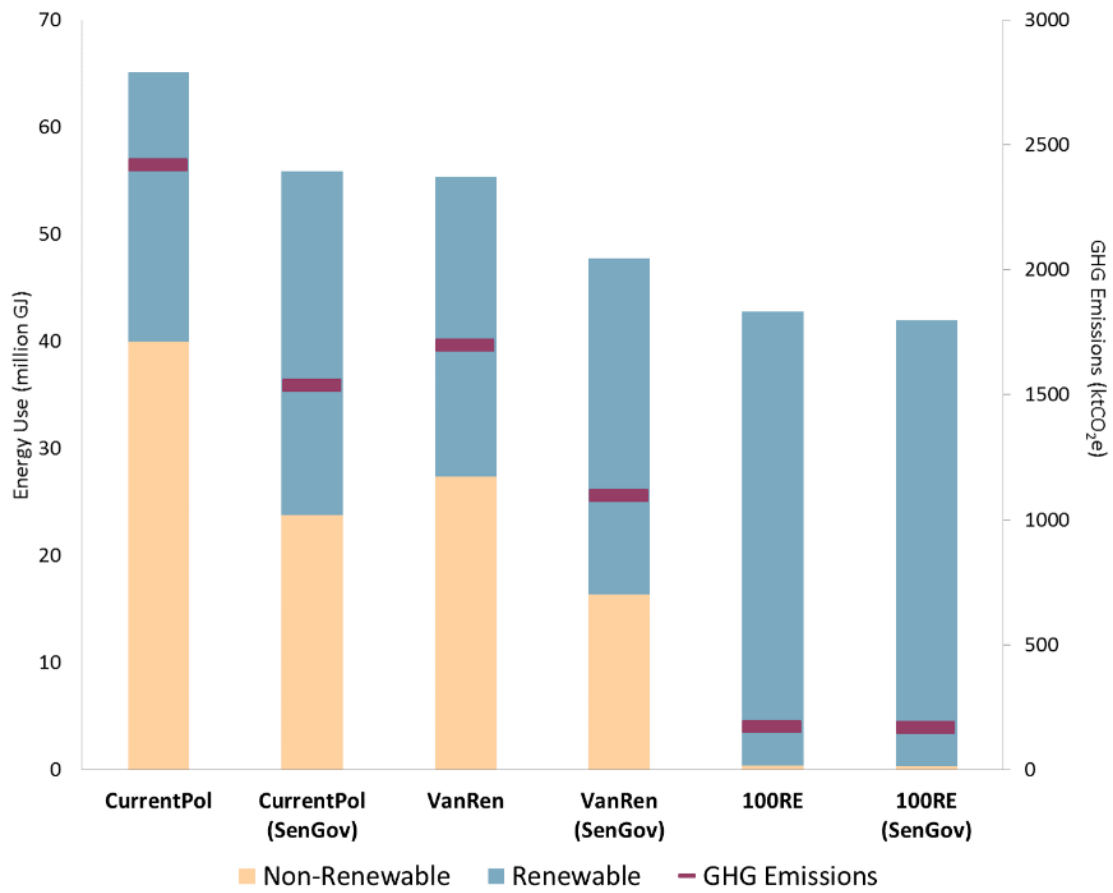


Figure 17: Energy use and emissions in 2050

Results for Current Policy (CurrentPol), Renewable City Strategy (VanRen), and 100% Renewable Energy (100RE) scenarios without additional senior government climate policy and with additional senior government climate policy (SenGov)

Chapter 5. Conclusions

5.1. Summary of Findings and Policy Recommendations

In this study, I developed a spatial extension to the CIMS energy-economy model, capable of representing land use and transportation network changes, and used it along with the model's technology and fuel choice simulation capabilities to evaluate Vancouver's Renewable City Strategy (VanRen scenario) targets. These targets call for 100% renewable energy and an 80% greenhouse gas reduction by 2050. I evaluated energy and emissions trajectories for Vancouver under scenarios where the City 1) continues the path set out by existing policies prior to the Renewable City Strategy targets, 2) proceeds with the policies it is implementing to fulfil the targets of the Renewable City Strategy and 3) proceeds with policies that will ensure achievement of the Renewable City Strategy targets, regardless of how legally and politically challenging.

My results show that the policies proposed under the Renewable City Strategy reduce the use of non-renewable energy and lower greenhouse gas emissions; however, the policies I modeled are insufficient to completely meet the Renewable City Strategy targets, even if senior governments simultaneously implement policies of a stringency sufficient to meet Canada's Paris commitment for 2030. The estimated Renewable City Strategy reductions of fossil fuel use of 30% and greenhouse gas emissions of 25% below current policy indicates a substantial gap between where we will be in 2050 and what the targets are. The Renewable City Strategy is the most effective at achieving emissions reductions for new buildings, as this is where its targets have been elaborated into specific and compulsory policy. As long as policies for existing buildings remain vague and on the voluntary end of the "compulsoriness" spectrum, substantial emissions reductions in this sub-sector cannot be expected. Likewise, compulsory policy is currently lacking in the transportation sector; transportation network improvements alone, without compulsory policy directed at vehicles or fuels, do not eliminate the use of gasoline and diesel. Many of the current urban climate and transportation policies in effect or proposed for Vancouver have been designed to achieve a wide range of objectives, but not specifically to reduce fossil fuel use. While these policies help reduce emissions, they are not a substitute for strong policies targeted at ultimately eliminating the use of fossil fuels.

In order to meet the Renewable City Strategy targets, the City would have to implement a suite of ambitious policies in addition to those it has already proposed. Specifically, the City would have to develop regulations to prevent the use of fossil fuels in existing buildings similar to what it has already proposed for new buildings. Furthermore, the City would have to implement flexible regulations to phase out the use of diesel and gasoline for transportation, while allowing residents and businesses to choose the most appropriate zero emissions replacement that meets their needs. Policies for improving transportation choice and modifying land use patterns do help to reduce energy use and emissions, but without targeted regulations on vehicles and fuels, fossil fueled personal and freight vehicles will continue to be a significant emissions source.

Many of the policies necessary to achieve 100% renewable energy are likely to be more controversial than the ones already proposed; however, with careful consideration it is possible to design these new policies in a way that still provides flexibility. For example, instead of requiring a certain type of technology, such as electric vehicles for transportation, the City should focus on increasingly stringent regulations phasing out fossil fuel using technologies without prescribing the type of technology that must be used to replace them. Creating regulations that can lead to 100% renewable energy remains a jurisdictional challenge. While the City does have jurisdiction in the areas I have discussed, substantial changes to the status quo could easily lead to legal challenges or intervention from senior governments.

There are likely less controversial pathways to 100% renewables; however, without a commitment to Vancouver's plan from senior levels of government, the City must explore options for achieving its goal without senior government policy support. Furthermore, the results presented in this study show that even if senior governments do act to implement climate policy strong enough for Canada to meet its Paris commitments, the City will not be able to meet its targets without compulsory regulations. If regulations similar to what I have presented here are not deemed politically acceptable, the City will have to advocate for more jurisdictional power within governing legislation, such as the Vancouver Charter, or it will fail to meet its Renewable City Strategy targets.

5.2. Limitations and Opportunities for Future Research

A model is, by definition, a representation of the real world. When representing complex systems such as those discussed in this study, simplification is necessary. What's more, assumptions about the future must be made and there are uncertainties inherent in these assumptions. Like all energy-economy models, CIMS has several parameters which have been estimated via other studies, expert opinion, and calibration to real-world data. Many of these were initially estimated for national level analysis and have been adjusted to an analysis of Vancouver based on calibration to city-specific data. Future research could further refine the Vancouver-specific estimation of parameters, with a special focus on areas where Vancouver may differ substantially from other parts of British Columbia and Canada, such as in building design and vehicle preferences.

Data used in this study to calibrate CIMS parameters are based on older inventory data about energy use in Vancouver. If newer data are made available, this analysis could be updated to reflect unanticipated changes since the old calibration data were produced. For example, the intangible transportation costs in the spatial model were calibrated using data from the 2011 National Household Survey (Statistics Canada, 2011b). Unlike in previous census years, these data were collected as a survey and not as a mandatory census; it is therefore potentially less reliable. More recent data are currently in the process of being analyzed as part of the 2016 Census. These are not only more current, but also likely more reliable.

In this study, I improved the estimates of several transportation parameters, such as intangible costs of different transportation modes, by making the model spatially explicit. As with other model parameters, the relationships among the parameters in the spatial model are uncertain and are based on input assumptions. I designed the spatial model to allow future researchers to test different input assumptions to see how they impact results, which provides opportunities for further exploration of the impact of land use and transportation on emissions. In addition, the spatial model is modular, so specific components can be refined or expanded. More sophisticated land use and transportation models exist; however, they cannot be integrated easily with an energy-economy technology and fuel choice model such as CIMS. Future research could investigate

improving portions of the CIMS spatial extension to add some of the more advanced characteristics of stand-alone land use and transportation models.

I conducted limited sensitivity analysis as part of the spatial model development; however, there is opportunity for more research into the sensitivity of results to input parameters and calibration data. This analysis could help future researchers better identify where to focus their attention when trying to estimate model parameters and thus improve the robustness of conclusions drawn from the modelling.

When it comes to buildings, decisions on the use of decentralized energy systems, such as rooftop PV, will largely be made by individuals based on their preferences and values. While I expect some growth in decentralized energy in the coming decades, the extent is not great in my scenarios, partly because of low-cost options for renewable electricity generated in non-urban areas of B.C., partly because of the relatively low solar incidence of Vancouver, and partly because of the trend toward higher density urban form. By 2050, only about 10 – 15% of Vancouver households will live in single family homes. Based on cost and the limited amount of roof space, I predict that electricity generated within Vancouver will play a relatively modest role in the total energy mix.

Lastly, it is important to note that in all scenarios there was at least a small amount of fossil fuel use remaining. It is very difficult to simulate a zero fossil fuel future in CIMS. Like most energy-economy models that exist today, CIMS is designed to simulate changes in our current energy system. It is therefore difficult to represent a transition to a completely fossil fuel free economy in such a framework. Similarly, while disruptive technologies, such as electric self-driving cars, may have a profound impact on transportation systems in future decades, the impact of such technologies is very uncertain and difficult to model. Future research could focus on ways to better represent the structural changes that occur when an economy shifts away from using fossil fuels altogether.

In summary, the study presented here suggests myriad opportunities for further research and investigation. My hope is that the spatial extension I have developed for the CIMS model will contribute to a diversification of tools for rigorous and on-going evaluation of the effectiveness of climate policies proposed and implemented at the municipal level.

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Appendix A. Route Quality Contribution Values

Table A1: Road quality contributions of different road types

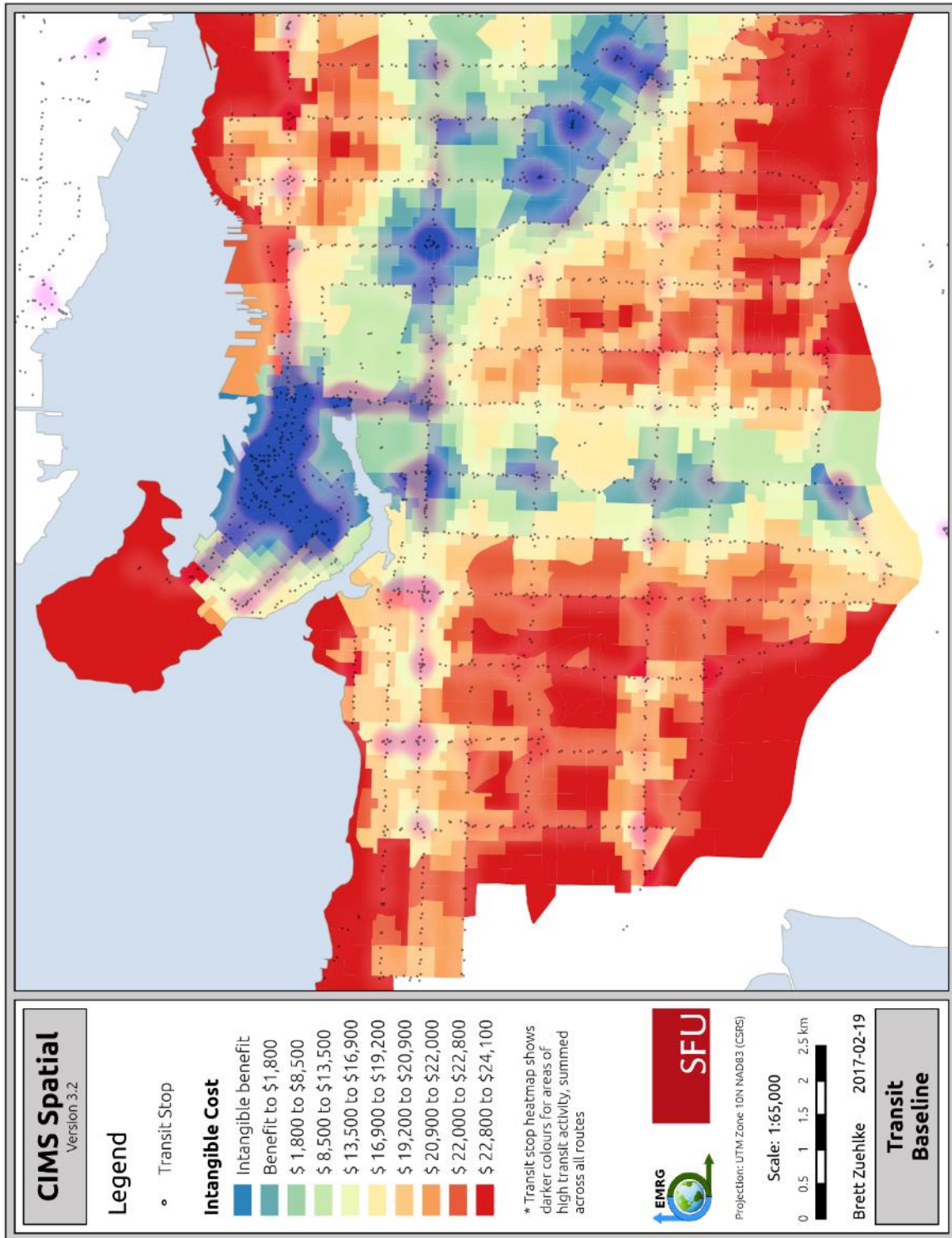
Mode	Coefficient
Freeway	20
Arterial	10
Collector	5
Local	1
Lane/Strata	0.1
Trail/Restricted/Other	0

Table A2: Cycling quality contributions from different bike route types

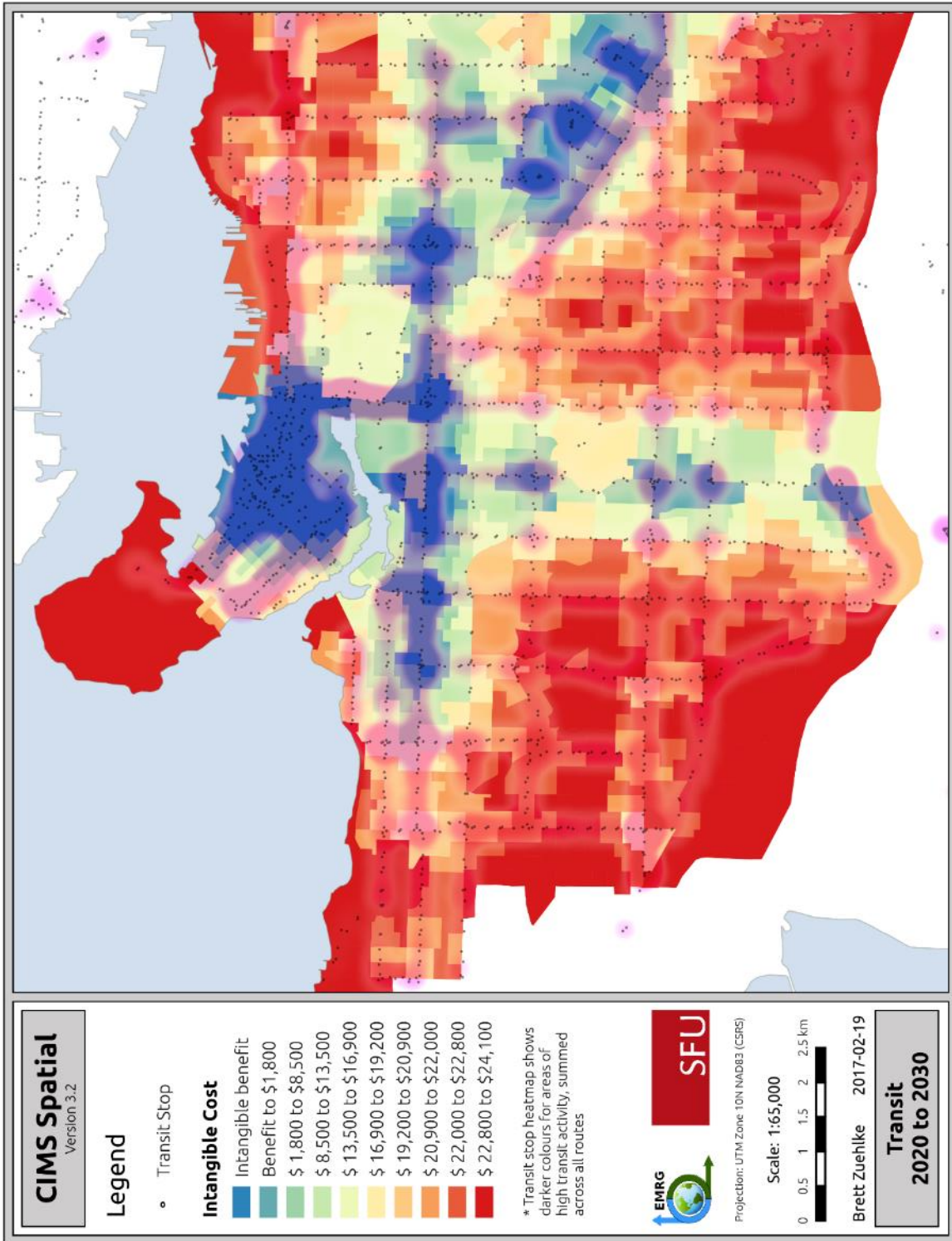
Mode	Coefficient
Shared Lane (Sharrow)	1
Local Street	3
Painted Bike Lane	3
AAA* Local Street	4
Separated Lanes or Paved Path	5

* AAA = Safe for all ages and abilities

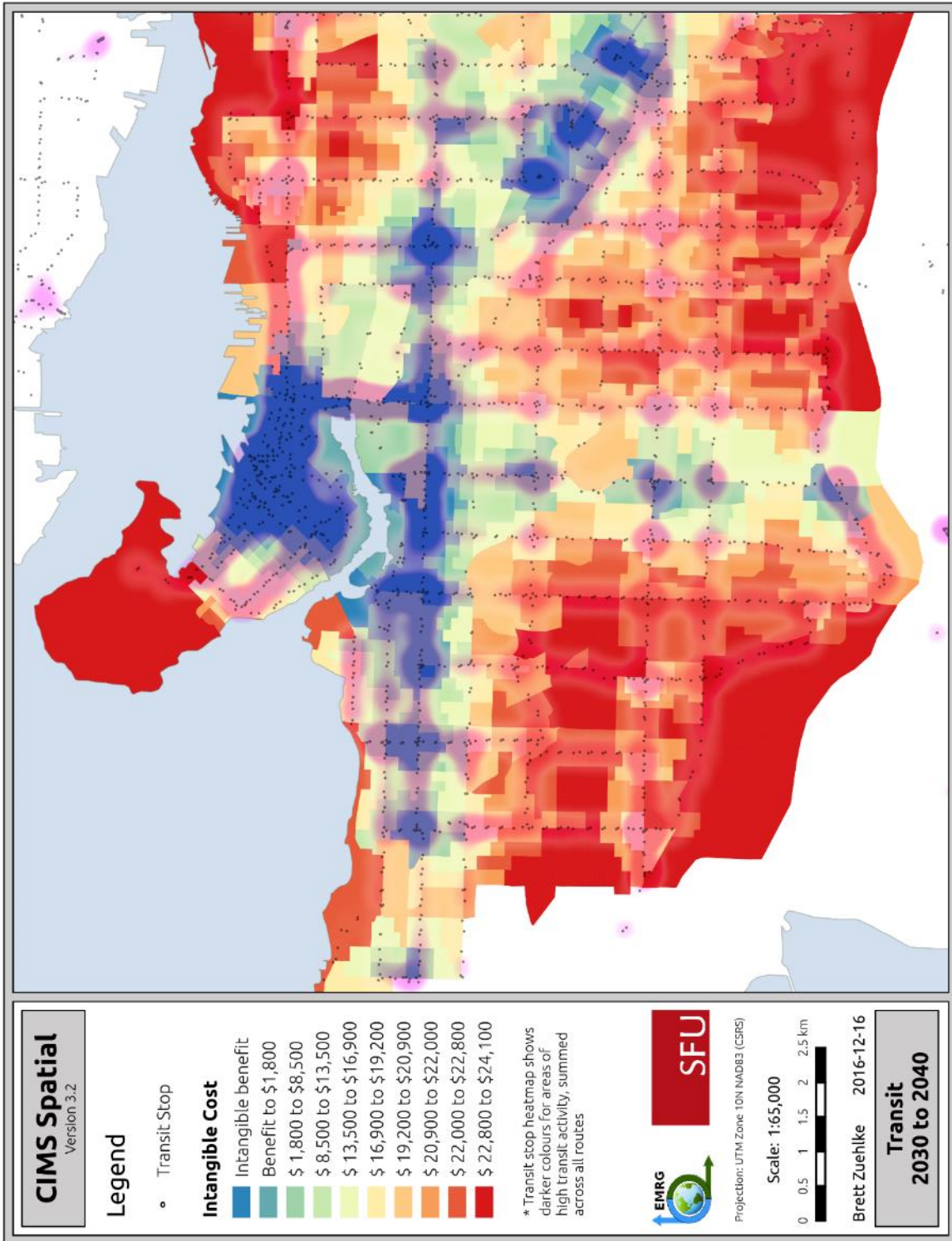
Appendix B. Transportation and Land Use Maps



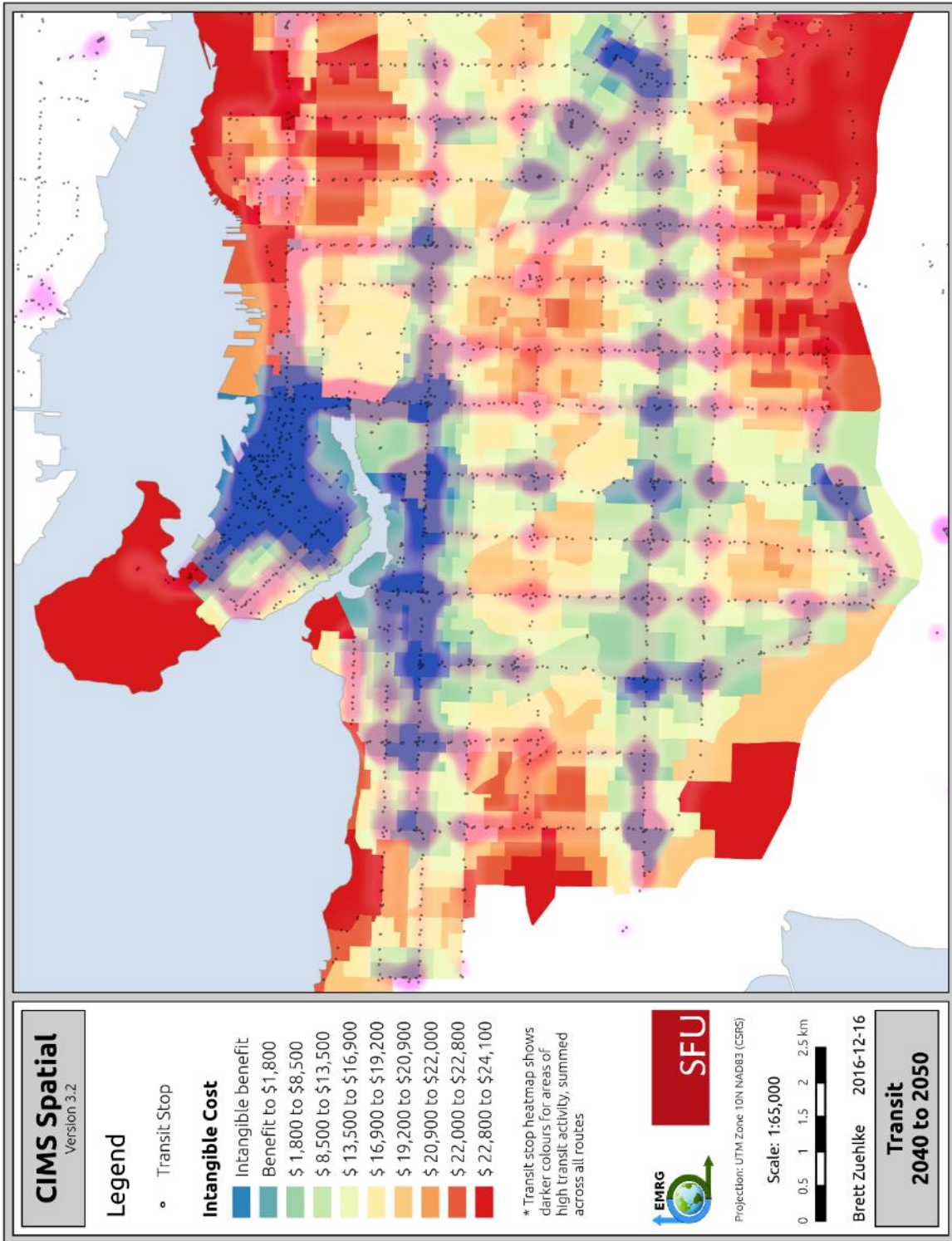
Analysis data sources: Statistics Canada, 2011; TransLink, 2015



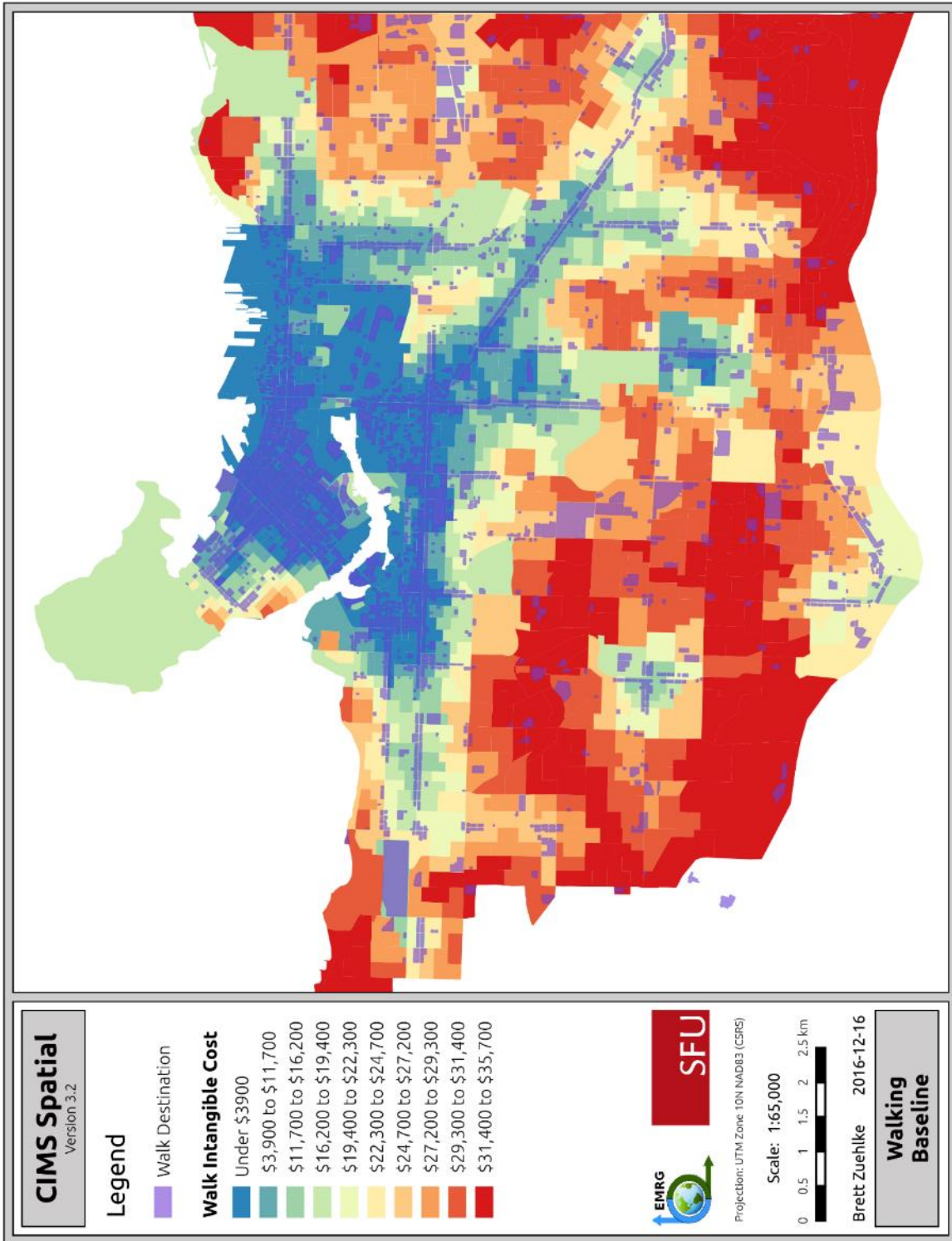
Analysis data sources: Statistics Canada, 2011; TransLink, 2015



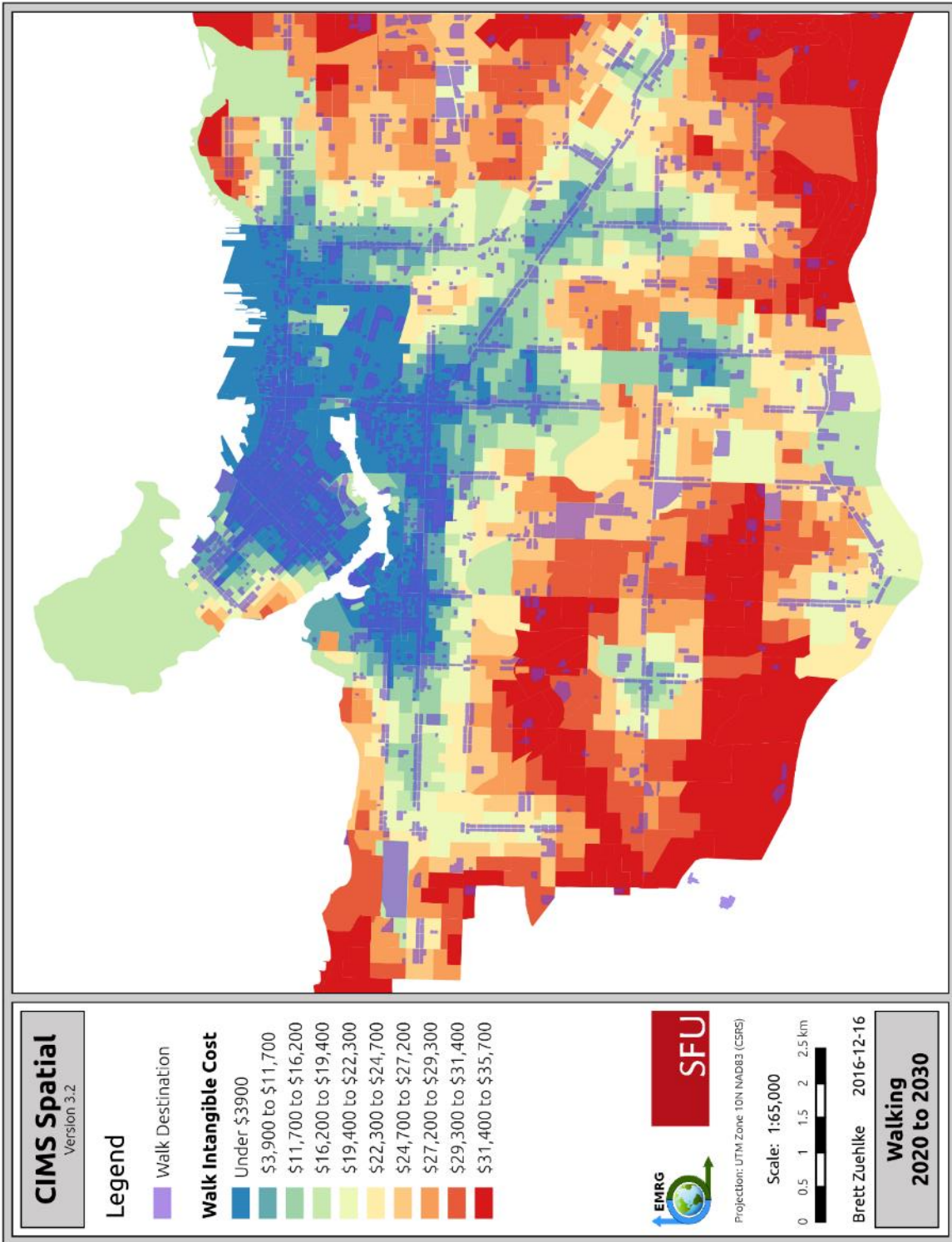
Analysis data sources: Statistics Canada, 2011; TransLink, 2015



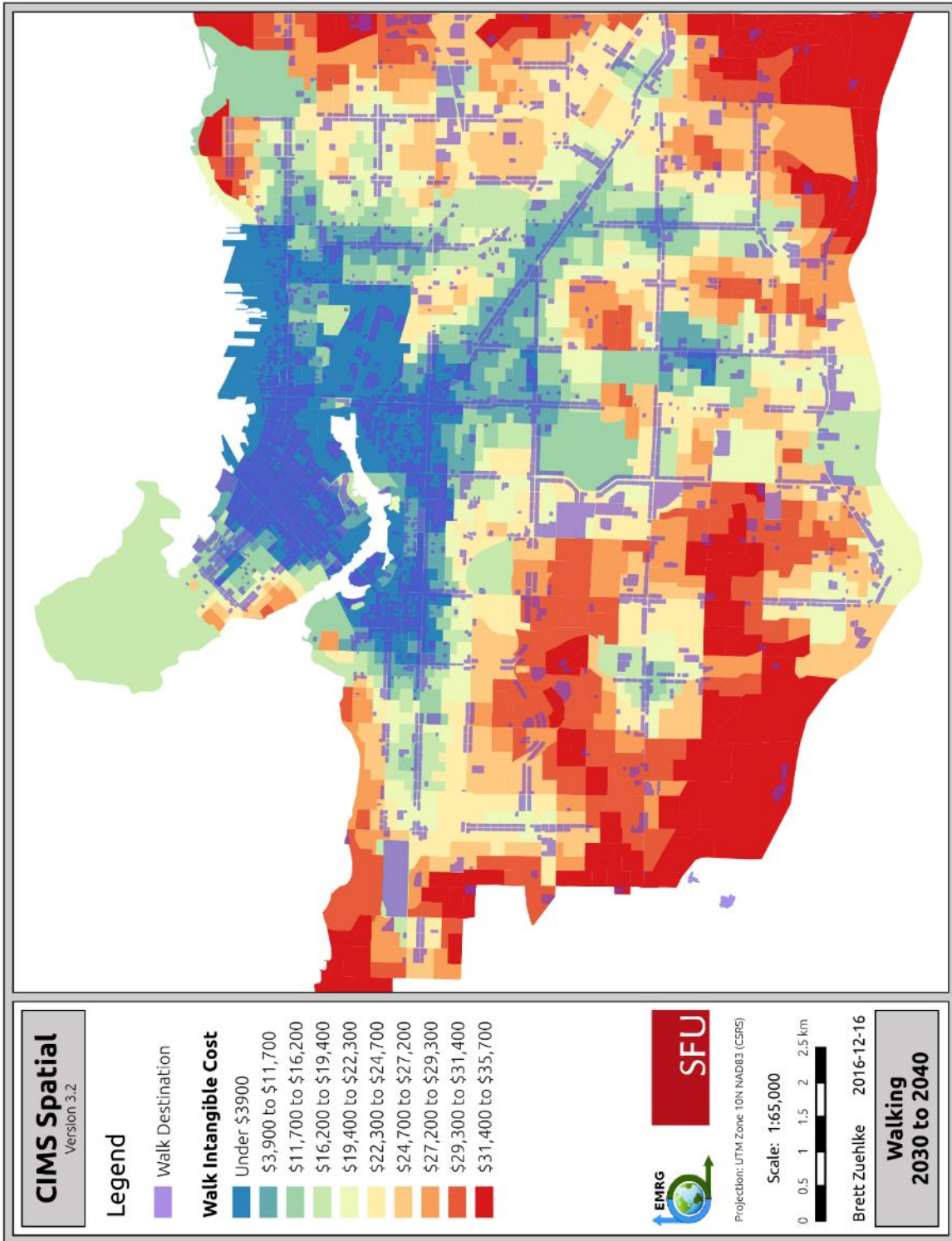
Analysis data sources: Statistics Canada, 2011; TransLink, 2015



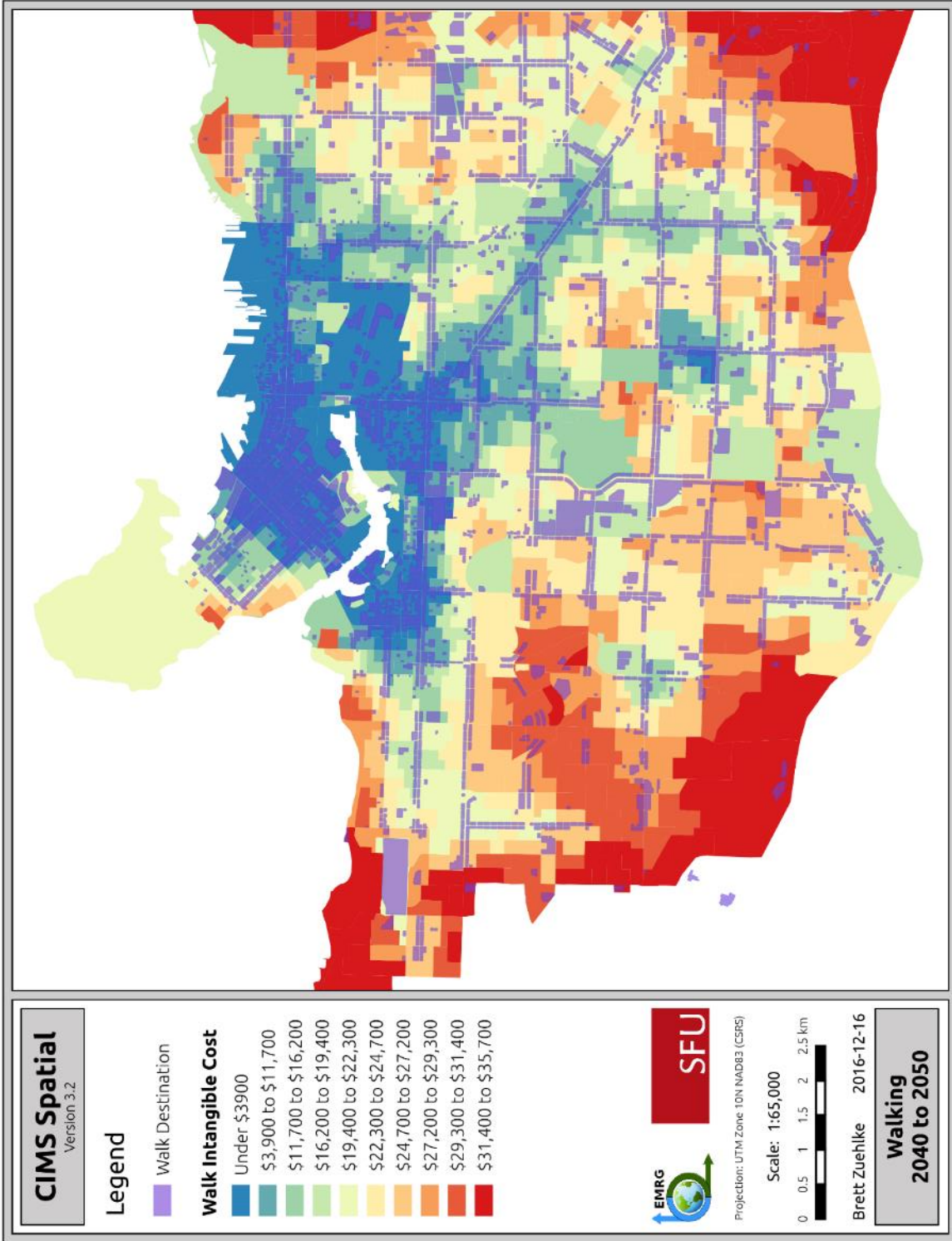
Analysis data sources: Statistics Canada, 2011; Metro Vancouver, 2015



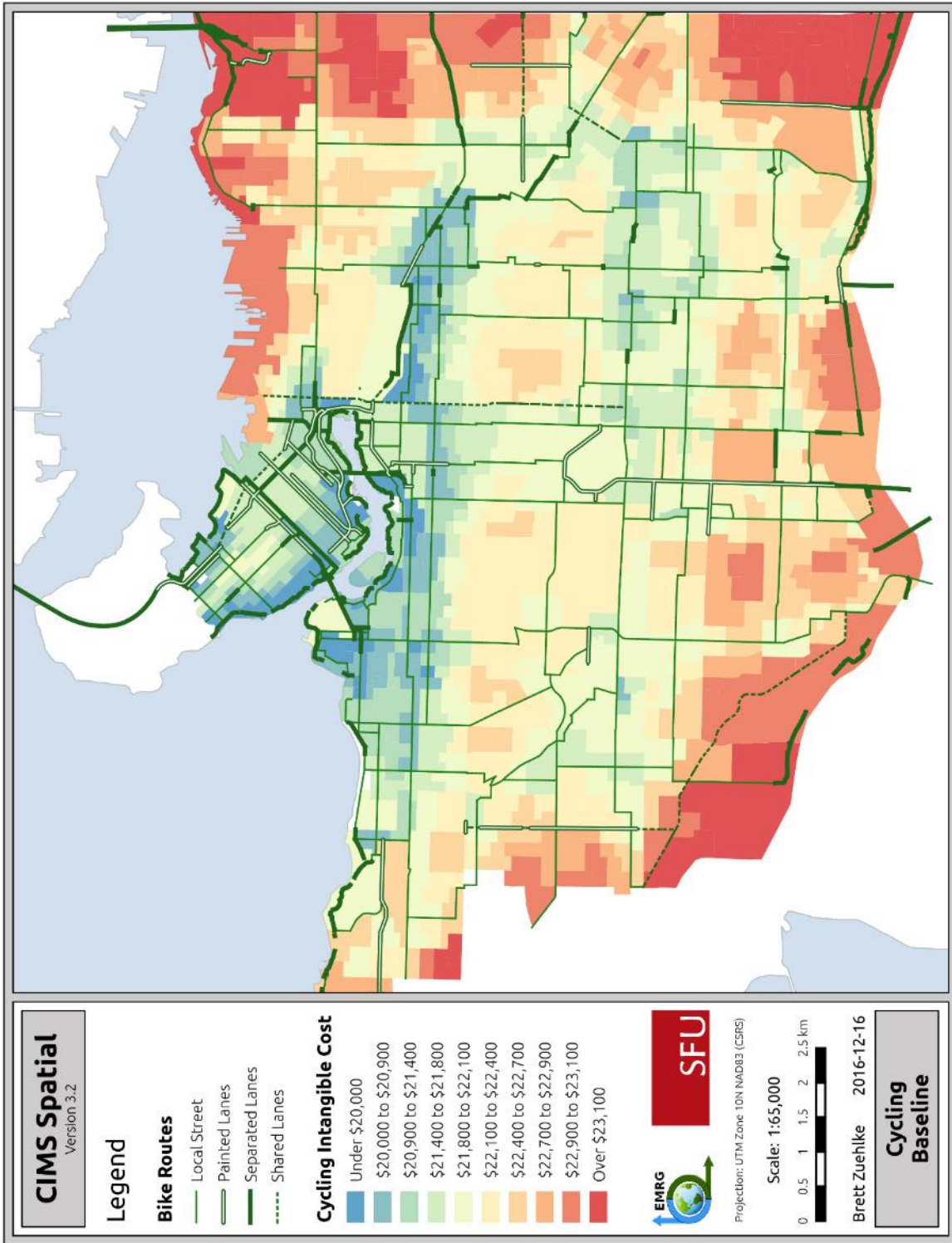
Analysis data sources: Statistics Canada, 2011; Metro Vancouver, 2015



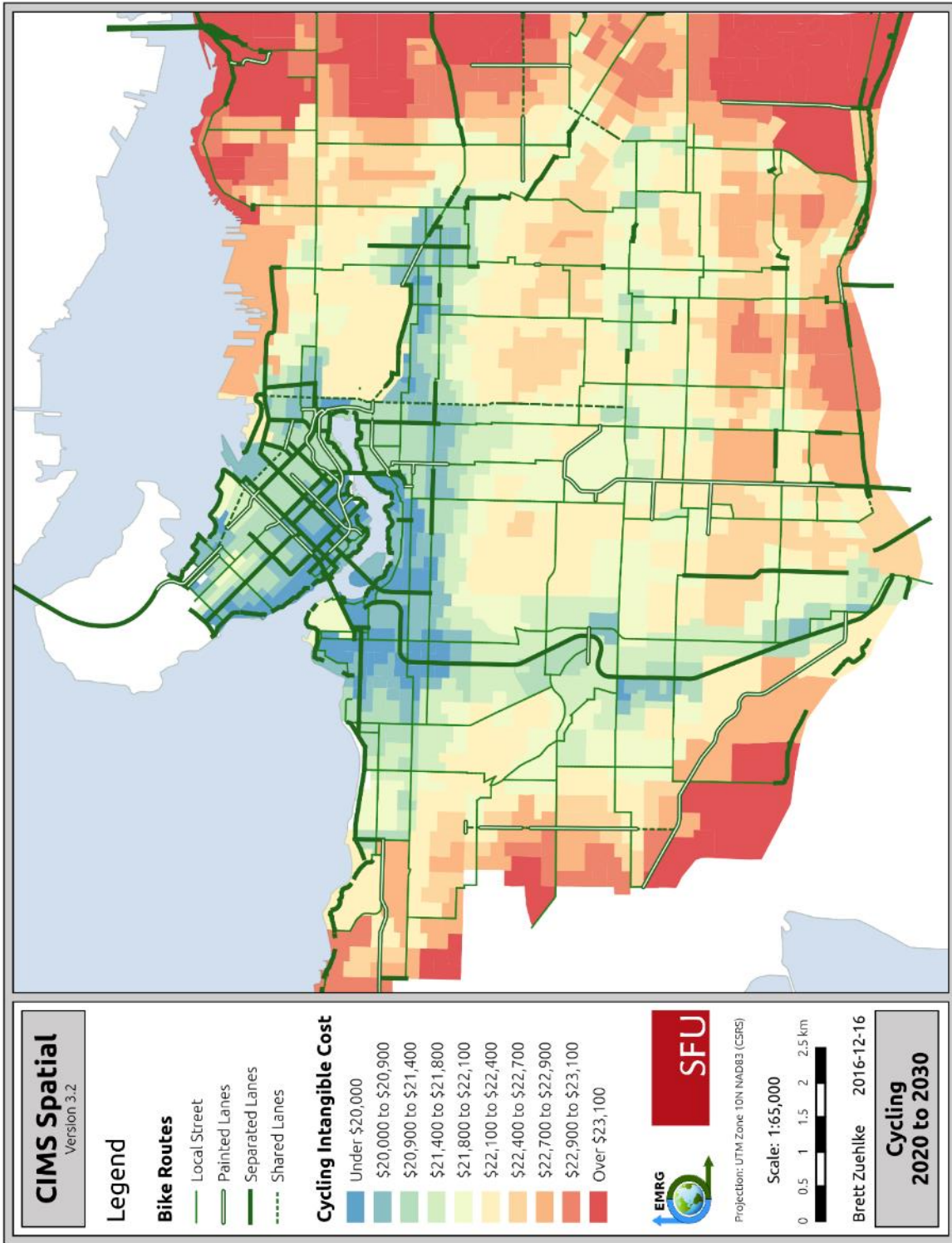
Analysis data sources: Statistics Canada, 2011; Metro Vancouver, 2015



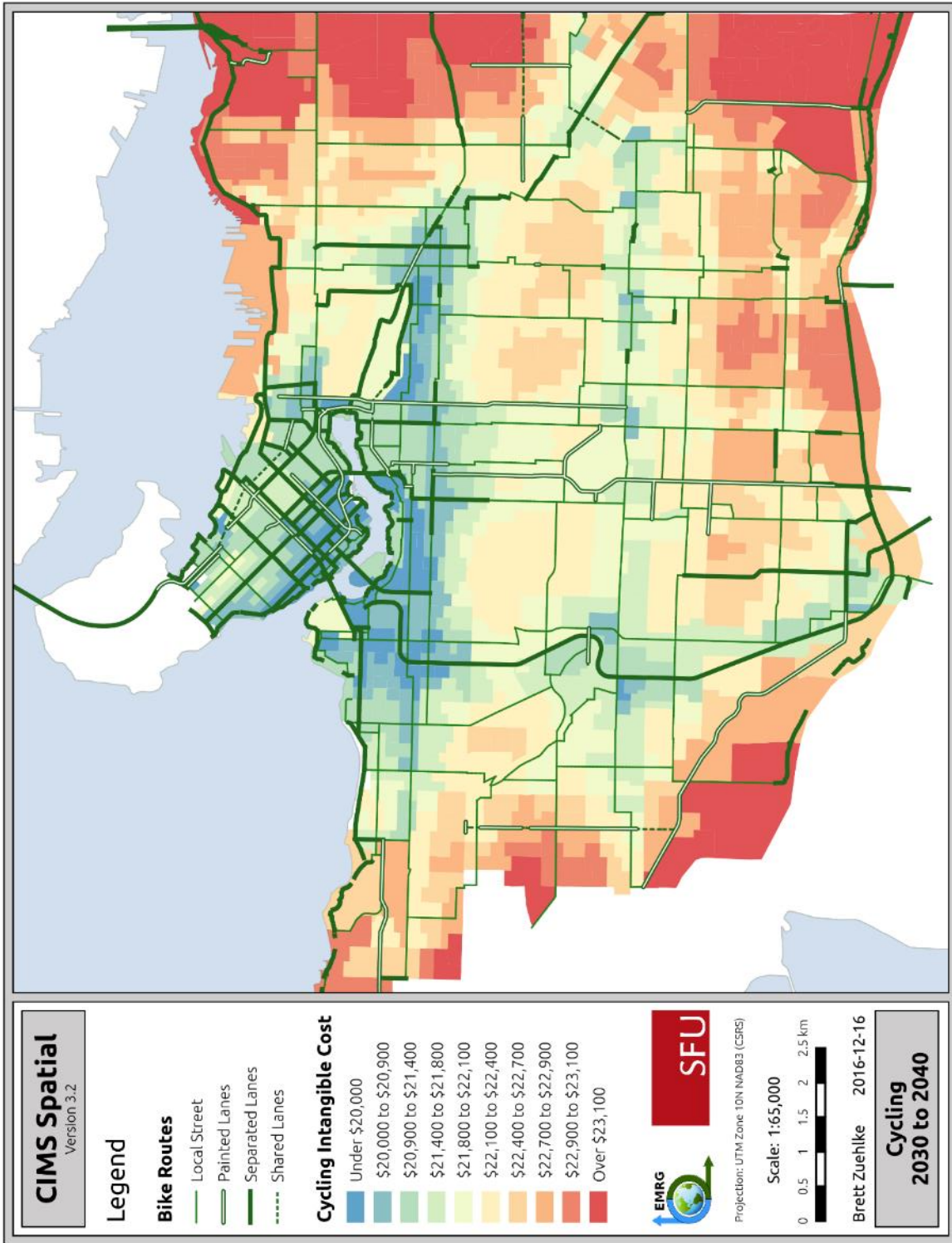
Analysis data sources: Statistics Canada, 2011; Metro Vancouver, 2015



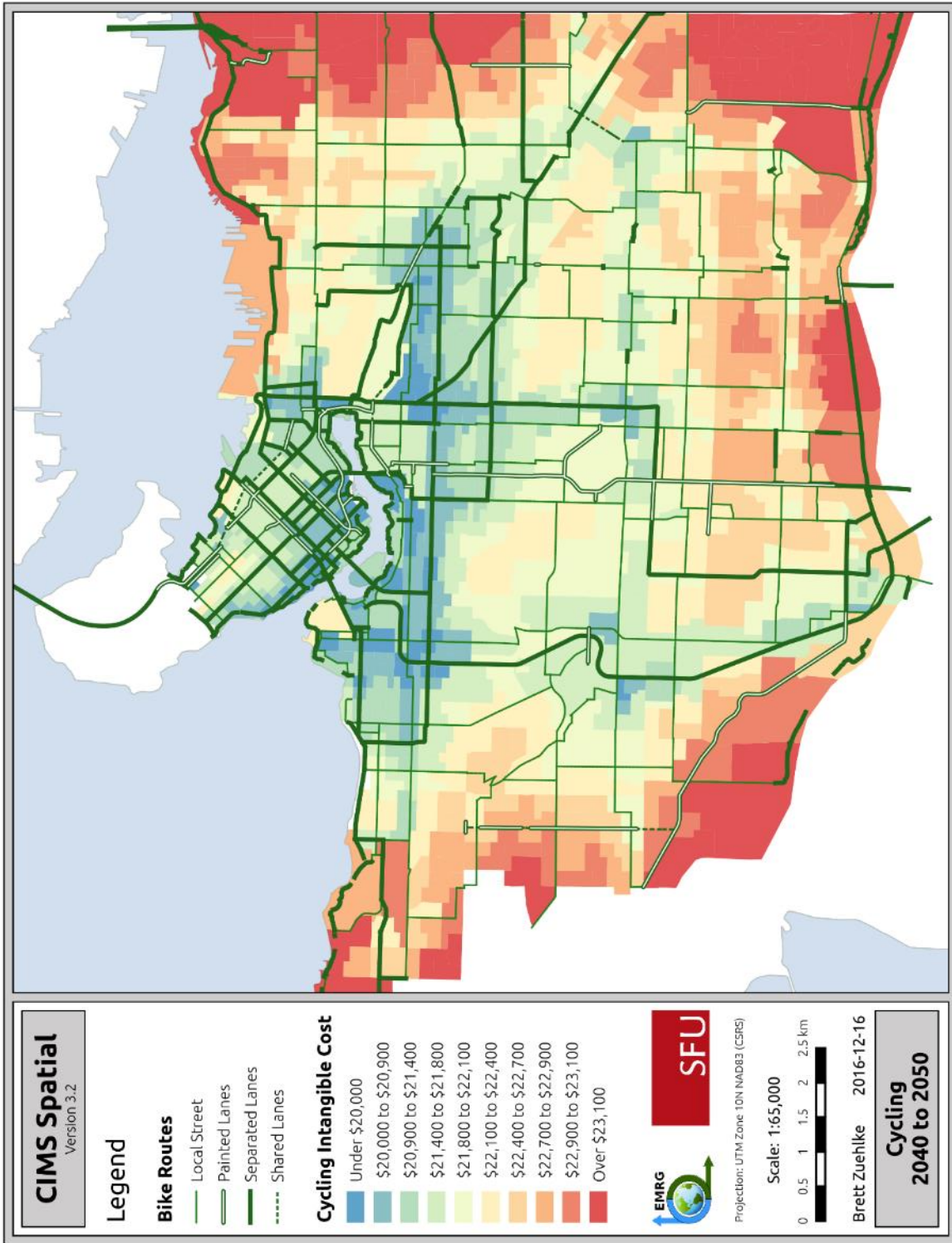
Analysis data sources: Statistics Canada, 2011; City of Vancouver, 2015



Analysis data sources: Statistics Canada, 2011; City of Vancouver, 2015



Analysis data sources: Statistics Canada, 2011; City of Vancouver, 2015



Analysis data sources: Statistics Canada, 2011; City of Vancouver, 2015