

**Economic Growth, Physical Limits and
Liveability:
Can Metro Vancouver Achieve all Three?**

by
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Abstract

Can Metro Vancouver grow its population and economy while staying within physical limits and improving liveability for its citizens? I explore this question using a Business as Usual forecast, a Limits scenario and a Local Energy scenario. I model each scenario using a technology choice simulation model combined with an urban sustainability model. The BAU forecast extrapolates existing trends while the Limits scenario includes physical limits on criteria air contaminants, water use, land use, greenhouse gas emissions and solid waste disposal. The Local Energy scenario adds a local energy limit. For each scenario I assume continuous economic and population growth, impose the physical limits and then simulate household and firm responses to policy and assess the resulting implications for liveability in the region. I measure liveability using 24 indicators of environmental conditions, mobility, housing and costs.

I find that Metro Vancouver can grow its population and economy while staying within physical limits, but there are tradeoffs to aspects of liveability. I find for the BAU forecast that environmental conditions degrade with economic and population growth with similar mobility and housing choices as today. In the Limits scenario, environmental conditions are protected but costs increase, people drive 20 per cent less and 40 per cent of existing detached homes are replaced with apartments and attached houses. In the Local Energy scenario, environmental conditions remain protected and all energy is generated locally, but people travel 50 per cent less, drive 80 per cent less, 40 per cent of existing detached homes are replaced with apartments and attached houses and these living spaces cost 50 per cent more than in business as usual or the Limits scenario.

Keywords: urban sustainability, sustainability policy, quality of life, scenario analysis, urban energy, physical limits

Dedication

I dedicate this work to my parents, Richard Moorhouse and Jean Simonton, for all their support and encouragement over the years. I couldn't have done this without you.

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List of Acronyms

Term	Definition
B.C.	British Columbia
BAU	Business as Usual
CAC	Criteria Air Contaminants
CO ₂	Carbon Dioxide
CO _{2eq}	Carbon Dioxide Equivalent
CFC	Chlorofluorcarbon
CO	Carbon Monoxide
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
LCC	Life cycle cost
LEED	Leadership in Environmental Design
MARPOL	International Convention for the Prevention of Pollution from Ships
NO _x	Nitrogen Oxides
PEOPLE	Population Extrapolation for Organizational Planning
PM	Particulate Matter
SO _x	Sulphur Oxides
TEC	Technical Economic Cost
UBC	University of British Columbia
VOC	Volatile Organic Compounds

1. Introduction

A popular sustainable development joke starts with: “Why is sustainability like teenage sex?” A nervous audience – likely questioning the credibility of the speaker – waits expectantly for the punch line: “Because everyone talks about it and no one’s doing it!” This joke is prevalent because it speaks to an underlying truth – sustainability is great to talk about because we all know it is important, but its realization remains elusive. Acting on sustainability is hard because: 1. defining it is a challenge; 2. sustainability involves difficult trade-offs between economic, environmental and social interests, and; 3. it requires coordinated action at regional, national and international levels of governance.

The Brundtland Commission’s definition of sustainable development, “development which meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987), remains a common reference in sustainable development literature and is at the heart of many sustainable development plans. However, it elicits many questions such as: How do we define needs today and in the future? What resources will be required in the future to satisfy needs? Where will they come from?

Both conceptually and in models, environmental economists link resources including land, capital, labour, material, energy, waste assimilation, and productivity with economic growth (Hanley, Shogren, & White, 2001). The economy in turn generates products and services that support people’s needs. Meeting these needs sustainably therefore depends on the same elements that support a healthy economy, such as the availability of material and energy resources, innovation and healthy, educated people (Jaccard, 2005). An alternate definition for sustainable development is thus development where material and energy supplies endure, and the production, use and disposal of these supplies do not negatively impact both people and the environment.

This definition of sustainable development can help identify some threats to sustainability and also suggest policies and mechanisms for addressing them. Government policies and market forces can encourage more efficient use of resources, stimulate the transition to more abundant resources, and/or ensure wastes are less harmful. For example, policy and technology developments helped to reduce sulphur dioxide concentrations in the US by 68 per cent between 1998 and 2007, while its economy and population grew (US EPA, 2013). Unfortunately, there are also many examples where policy and markets fail to protect resources or prevent waste build-up. For example, in 1967 the cod harvest from the Grand Banks fishery was 227,000 tons, but has since collapsed to produce only 1,100 tons and full stock recovery remains uncertain (Rideout, Murphy, Brattery, & Power, 2013). The industry supported 40,000 people in Canada, generated \$500 million a year and its collapse is estimated to have cost the Canadian Government \$3.9 billion dollars (Anderssen & Sopova, 1998; Standing Senate Committee on Fisheries and Oceans, 2005). In seeking to develop effective policies, the relationship between physical limits and economic growth must be better understood.

The extent to which living within physical limits such as resource scarcity or GHG emissions will ultimately limit economic growth is an ongoing debate. On the one hand, economic growth generates wealth that can be directed towards solving sustainability issues and improving quality of life. On the other hand, economic growth today involves increasing energy and material consumption, and produces dangerous wastes that threaten both people and ecosystems (Matthews, 2000; Steffen et al., 2009; Victor & Rosenbluth, 2007a). There is increasing evidence that human activity has met or is exceeding some planetary limits; the Intergovernmental Panel on Climate Change has concluded that “continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system” and the majority of the environmental systems upon which nations depend are being used unsustainably or are being depleted (Intergovernmental Panel on Climate Change, 2013; Millenium Ecosystem Assessment, 2005; Rockstrom & Stefen, 2009). It is difficult to measure the value of natural systems in part because of our limited understanding of these systems and limited tools for assigning value. However, if governments did incorporate these valuations into their economic models, they may find that the global economy is already

shrinking, and that protecting natural systems would actually limit economic growth as they measure it today (Daly, 1996). Equally troubling are the indications that economic growth in many countries may not even be contributing to quality of life improvements (Easterlin, McVey, Switek, Sawangfa, & Zweig, 2010). Studies that consider the relationship between physical limits, economic growth and quality of life can help identify some of the trade-offs between these competing priorities.

Communities have generally been more successful at navigating these trade-offs when considering local physical limits such as air quality, water supply and water quality. Issues that depend on coordination between multiple levels of government such as climate change have met with less success. For example, a local jurisdiction may want to act on climate change, but may not have the power to enact the necessary policies or the funds to develop needed technologies. Even if the local initiative does succeed, global emissions may only decrease slightly. Yet while global challenges such as curbing GHG emissions require coordinated efforts by nation states, cities are beginning to organize and implement climate change policy (Rosenzweig, Solecki, Hammer, & Mehrotra, 2010). Some speculate that a sustainable city is only possible if its material and energy sources are under its control, otherwise the city must wait until the world is operating sustainably (Rees, 1996). However, because municipal-based action requires less coordination and collaboration than international initiatives, cities may be able to make a contribution even to a global challenge like climate change if, in reducing their emissions, they also consider the full cycle implications of their efforts.

Metro Vancouver represents a regional district comprised of 22 municipalities, one electoral area and one Treaty First Nation (Aboriginal) government in British Columbia (B.C.), Canada. It serves as the political body and corporate entity responsible for delivering regional services, setting policy and providing a forum for its members. As a growing urban region, it is an ideal location for studying the application of sustainable development policies at a local level. This is especially so because Metro Vancouver's population is growing quickly; it has been voted one of the most liveable regions in the world, and; its regional planning initiatives are focused on a sustainability framework – *The Metro Vancouver Sustainability Framework* (Metro Vancouver, 2010a, 2011a). This framework, supported by various planning documents, aims to maintain air quality, reduce GHG emissions, ensure a clean water supply, reduce waste and prevent urban

land expansion. However, it remains unclear what policies Metro Vancouver can use to meet these goals and what impact such policies might have on the liveability of the region. To focus this analysis I ask three questions:

1. Can Metro Vancouver grow its population and economy while staying within physical limits and maintaining a liveable region?
2. What are the trade-offs that individuals will make if Metro Vancouver stays within its physical limits?
3. What are the implications of this case study on broader discussions of physical limits to economic growth?

I answer these questions using a business as usual (BAU) forecast and two scenarios. In the BAU forecast, I assume historical trends related to population and economic growth continue regardless of Metro Vancouver's specific population goals. The Limits scenario implements regional policies to meet air quality, water use, GHG emission, land use and solid waste disposal limits that match or exceed Metro Vancouver goals and targets. The Local Energy scenario adds a local energy constraint. I include this scenario to explore the trade-offs inherent in the supposition that sustainability must include local energy self-sufficiency.

Developing the forecast and two scenarios is challenging because they must account for feedbacks, inter-linkages and long timelines in relation to growth, physical limits and liveability. For example, municipal planners in major Canadian cities attempting to eliminate traffic congestion in the 1950s and 1960s might have questioned their extensive road building plans if they could foresee that only 20 years later congestion would re-emerge, they would be re-expanding transit networks, and smog would arise as a new issue (Hodge & Gordon, 2003). Quantitative modeling is a useful way to keep track of these inter-linkages and potential unintended consequences. But quantitative modeling is challenged by the inherent complexity of those systems (Oreskes, 2003). I attempt to mitigate this by combining scenarios and a technology choice simulation model known as CIMS community (CIMS), which I will explain in further detail in Section 2. Using these quantitative approaches to understand the links between sustainability policy and quality of life within the context of economic growth can

help with understanding how the concepts of physical limits can be operationalized at an urban scale, and how citizens may respond to such efforts.

The remainder of my study has four sections. *Section 2 – Background* - explains the rationale for the study, describes Metro Vancouver and introduces the tools I will use to answer my research questions. *Section 3 – Methodology* - outlines economic and population assumptions, and defines physical limits and liveability. This is followed by scenario descriptions and the model details. In *Section 4 – Results and Discussion* - I explore the trade-offs between growth, physical limits and quality of life arising from the BAU forecast and the two scenarios, including the policies I implement and some likely responses of households and firms. I also speculate on what my results may imply for broader debates on limits to economic growth. Finally in *Section 5 – Conclusions and Recommendations* - I summarize the final outcomes and propose actions and policies to address emergent sustainability challenges.

2. Background

Since 1987, people from varied occupations have tried to operationalize the Bruntland Commission's definition of sustainable development in terms of today's policies and actions such as how we produce, use and dispose of energy and materials (Jaccard, 2005). One way of conceptualizing the issue is to consider the global economy as a social system that exists within the natural environment. The "economy" refers to all the products and services that we produce and use. At a simple level, we extract material and energy resources from the natural environment and then convert those resources into products and services. None of our activities occur outside of the environment, yet we use resources as economic inputs within the defined limits of our economy as if we were acting in pseudo-isolation from the broader environment. We use these products and services to sustain and perhaps improve our quality of life, and then we dispose of our wastes in the natural environment. Figure 1 depicts this relationship.

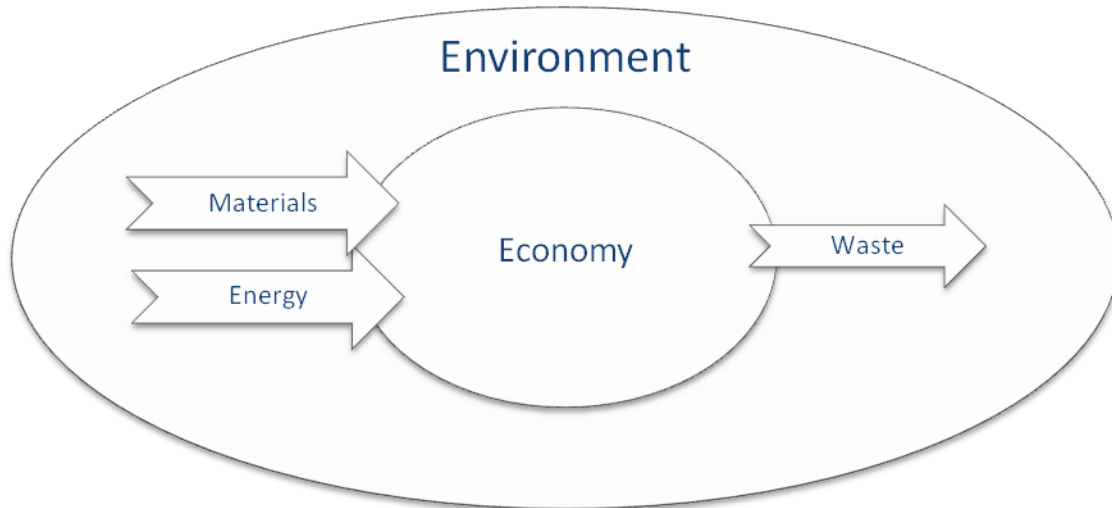


Figure 1: Relationship between economy and environment

In theory, the economy can sustain us indefinitely and even grow, so long as we do not deplete irreplaceable energy and material resources shown on the left side of Figure 1, or significantly harm or disrupt the environment with our wastes shown on the right side of the figure. For example, oil is a critical resource for our economy; if it suddenly disappeared tomorrow the results would be catastrophic. Some suspect that we are approaching a peak in oil production or at least a peak in cheap oil production (Hughes, 2009). From a waste perspective, many chemicals that our economy produces are known to harm the environment at some level of flow or concentration, possibly reducing the environment's provision of critical services like a stable climate, breathable air, productive soil and drinkable water. Examples include nitrogen and sulphur oxides that cause acid rain, chlorofluorocarbons (CFCs) that contribute to ozone depletion, and carbon dioxide (CO₂), which is increasing in concentration in the atmosphere, contributing to climate change. In this context, a sustainable economy is one that uses durable or replaceable energy and material resources, and produces wastes that do not significantly degrade the natural environment.

A sustainable economy thus implies using less material and energy per unit of economic output, switching away from limited material and energy resources or using material and energy inputs that generate wastes that are non-toxic to the environment. Market prices and public policy can signal scarce material and energy resources, and incentivize research to reduce our reliance on these resources. However, these tools only work if they provide the right signals and we are able to respond appropriately. For example, rising gasoline prices should motivate people to purchase more efficient vehicles, drive less often or even switch to vehicles that use different fuels. Related industries may also respond by designing more efficient vehicles, searching for more oil or developing fuel alternatives. Unfortunately, markets and public policy do not always provide the right signals, and we are not always able to respond appropriately. For example, two scientific papers in 1974 presented evidence that CFCs, a relatively cheap refrigerant, could threaten the ozone layer. However, concerns over the economic cost of CFC replacement and uncertainty delayed action to reduce CFC emissions. In 1984, scientists directly measured a weakening of the ozone layer and attributed it to CFCs. Countries did respond to this information, but despite CFC bans and CFC replacements, the ozone layer is not expected to recover to 1980 levels until 2068 (Newman, Nash, Kawa, Montzka, & Schauffler, 2006). Uncertainty, and trade-offs between physical limits such as the rate and cause of ozone thinning, economic growth such as the cost of CFC replacements or the cost of inaction, and quality of life such as the health impacts of ozone thinning, made it difficult for governments to adopt an appropriate response in a timely manner.

2.1. Trilemma – Growth, Physical Limits and Quality of Life

Growth is an interesting term in that it can refer to a quantitative or qualitative increase, the later being more difficult to measure and assess. In this paper, I refer to four specific kinds of growth: population growth, physical growth, quality of life growth and economic growth. Population and physical growth are quantitative measures that can be gauged using physical units such as kilograms or number of people. In contrast, increases or decreases in quality of life tend towards qualitative measures because there are no objective units by which to evaluate them. People require physical resources such as water, land and energy to survive and support their quality of life, but

improving quality of life depends on more than these physical resources alone. It also depends on qualitative factors whose measure is often based on individual perceptions and values, such as health, social connections, political voice, activity and security. Governments often presume that economic growth supports quality of life improvements, and so primarily measure it through the growth in Gross Domestic Product (GDP). GDP is “a measure of the value added to the economy by the current productive activities of individuals, businesses, governments and non-residents” (BCStats, 2012). By defaulting to GDP as a measure of quality of life improvements, governments come to rely more heavily on monetary measures in growth-related discussions.

Population, physical throughputs, quality of life and economic growth are all linked, but these links are dynamic. For example, due to a heavy reliance on fossil fuels in today’s economy, economic growth increases GHG emissions, although this could change with policy and technology. In this paper, I try to determine how quality of life, the economy and population could continue to grow while respecting physically limited resources such as water and land, and limits on the contribution made by a specific region or city to CO₂ in the atmosphere.

Regional, national and international governments and institutions generally pursue and promote policies to grow GDP in the hopes of supporting quality of life improvements (Hanley et al., 2001; OECD, 2011). One of the most compelling and early justifications for economic growth policy is that it could “do away with anything that according to present standards could be called poverty, even in the lowest strata of the population” (Schumpeter, 1942). Economic growth can help to eliminate poverty by increasing the size of the economic “cake” that society can access. Without economic growth, poverty reduction depends on redistributing wealth from the wealthy to the poor. Redistribution is difficult because those with wealth generally prefer to keep it, and often have means to do so. In theory, economic growth allows everyone to become richer, even if some benefit more than others.

Even high-income countries with little poverty pursue economic growth because forgoing it has an opportunity cost. Since growth is exponential, growing slightly less than neighbouring countries can lead to large differences in GDP per capita in a relatively short amount of time. For example, over a 20-year period an economy growing

at 10 per cent annually would grow by 250 per cent, but an economy growing at 7 per cent would only grow by 200 per cent. There is also evidence that above a certain GDP threshold, economic growth leads to little change in the happiness of the populace, but economic contraction leads to unhappiness (Easterlin et al., 2010). For these reasons and others, even affluent areas like Metro Vancouver pursue economic growth.

Despite this focus on growth, it is unclear how to sustain continuous economic growth, and to what extent economic growth could actually support quality of life improvements. In mainstream economic growth theory, economic growth is driven by a combination of savings investment, growth in the labour market and the rate of technical progress (Bannock, Baxter, & Rees, 1984). However, more recent models tend to focus on the process of technical progress, emphasizing the importance of scientific progress, growth of individual skill and incentives (Quah, 1993). However, these economic growth theories do not include tangible links to material and energy resources or waste thresholds. Therefore, they do not provide much guidance on how limiting these factors could impact economic growth.

Environmental economists explore this link by separating the drivers for economic growth into resources such as land, capital, labour, material and energy, and productivity into factors such as individual skill and scientific progress (Hanley et al., 2001). In this way the quality and availability of material and energy resources can be analyzed as contributors to economic growth. Some argue that our ability to harness useful energy – known in physics as exergy – is the only real driver for economic growth (Ayres, 2006). Energy productivity gains are presumed to be essential for economic growth because they enable more valued output from a given quantity of energy (Ayres & Vandenberg, 2005). Ayres (2005) also postulates that an economy that is incentivized to reduce waste and increase durability could sustain economic growth while also reducing absolute material and energy use. However, our current economy tends to convert efficiency improvements into additional consumption that requires more energy and material use (Ayres & Vandenberg, 2005).

Regardless of the weight one might ascribe to different economic growth drivers, there is general agreement that the economy depends on resources and the environment. Physical limits or degradation of the environment can impede economic

growth if: critical energy or material inputs become scarce, or; if environmental degradation from the economy's waste products reduces the productivity of natural capital, or requires rising investment in reclamation and treatment expenses. To convey this challenge, researchers have developed a simple equation:

Equation 1: IPAT equation

$$\text{Impact} = \text{Population} * \text{Affluence} * \text{Technology}$$

In this case, impact can be described as the change in quantity of energy and material inputs or waste outputs. Impact is a function of population growth (*Population*), economic growth measured in GDP (*Affluence*), and the use of available technology (*Technology*). *Technology*, however, can change the links between population, affluence and impact as it brings us back to the definition of sustainability and the strategies to achieve it.

Technology can be used to increase efficiency, transition to new materials or ensure wastes are less harmful. Therefore, to overcome the impacts of population and affluence while sustaining economic growth, technological development must: occur at an appropriate pace and; the cost to develop and implement the technology must be less expensive than the technology it is replacing, or less expensive than the cost of the damages it is avoiding. In the ozone layer example previously discussed, government policy prompted industry to develop new refrigerants with reduced impact on the ozone layer, thereby allowing population and affluence to grow with less impact. It did this quickly enough to address the problem of ozone depletion in human time-scales and, according to the U.S. Environmental Protection Agency, the solution cost less than the impacts (US EPA, 1987). Technology is therefore an important lever when attempting to remain within physical limits while increasing population and affluence.

In theory, if technology can address physical limits while growing the economy then quality of life should also increase. However, measuring quality of life beyond quantitative measures of GDP is an evolving field with no consistent definition and no widely-accepted theoretical model (Stiglitz, Sen, & Fitoussi, 2009). Researchers have generally agreed that subjective quality of life assessments, such as how people perceive their quality of life, are linked to supporting capacities. These include

measurable capacities such as access to health care, equality, and environmental conditions. The Commission on the Measurement of Economic Performance and Social Progress divides these capacities into eight categories: health, education, political voice, personal activity, social connection, environmental conditions, security and equality (Stiglitz et al., 2009). People who have access to these capacities are more likely, but not guaranteed, to have a higher quality of life. If economic growth is pursued in a way that protects environmental conditions, for example, then it is likely easier for people to improve their quality of life.

All of these capacities are important to Metro Vancouverites as evidenced by subjective studies of well being in the region and the priorities of regional governments (Metro Vancouver, 2011b; Vancouver Foundation, 2009). In my assessment of Metro Vancouver, I focus on mobility, costs and housing, which are a subset of security and personal activity, as well as environmental conditions. These capacities are relevant because they are key considerations in Metro Vancouver's regional growth strategy and Metro Vancouverites themselves have reported these capacities as important in surveys of subjective quality of life (Metro Vancouver, 2011b; Vancouver Foundation, 2010).

So far I have discussed an idealized model of economic growth occurring within the context of a rational policy-making process that is based on scientifically-determined sustainability limits. This approach is not without its challenges. One potential issue is that not all resources have equivalent substitutes. For example, copper is an excellent material for building electric motors, but as of yet there is no perfect substitute for this application. Aluminum could be used, but it is far less efficient, so motors would be larger, heavier, and likely more expensive (Ayres, 2007). Another issue is time. One of the primary messages from the Limits to Growth research program, first published in 1972, is that while human ingenuity can overcome many challenges given enough time and resources, the rapid rate of resource depletion or pollution can overwhelm this potential. (Meadows, Randers, & Meadows, 2004). Climate change is a primary example of this issue. It has taken several decades to establish a global target for CO₂ concentrations and global political processes have thus far failed to implement policies that would achieve the target. Another example is that while the intensity of materials per unit of economic output has decreased, absolute material and energy use has increased in nearly every case, even in countries that have attempted to reduce it (Jackson, 2009;

Victor, 2010). These challenges suggest that technological solutions to some physical limits may not exist or, if they do, may not be developed in time or may be too expensive. In my analysis I do not assume that technology development and deployment is the only means to meet physical limits; behavioural change may also be necessary and in some cases preferable.

2.2. Sustainability at the City Scale

Transitioning cities to more sustainable resource use and solid waste production requires strong public policy (Vojnovic, 2013). Cities in many countries have successfully addressed physical challenges such as water quality and limited water supply, air quality, limits on waste removal and land constraints. However, cities have been less active on measuring and considering the impact of decisions within their borders on the broader world. For example: until recently, few cities were actively pursuing climate policy because national leaders and international institutions were focused on the problem. However, these leaders and institutions have had little success in implementing effective mitigation or adaptation strategies. Yet, municipal policy decisions are critical to global sustainability, including GHG emissions. Indeed, cities represent a large and growing percentage of the world's population consuming approximately 80 per cent of global resources (Bai et al., 2012).

In Canada, for example, 81 per cent of the population lives in cities and these populations are growing by 300,000 people annually (Statistics Canada, 2011). Fortunately, Canadian cities have historically used tools that can be adapted to address sustainability concerns. Since the 1800's, urban planning in Canada has been focused on four main concerns: city appearance, housing and living conditions, the environment and efficiency (Hodge & Gordon, 2003). These concerns, and the tools used to address them, are adaptable to sustainable community planning.

Sustainable community planning distinguishes itself from other planning approaches by attempting to address global sustainability concerns at the community level, and by holistically addressing the four traditionally distinct concerns of urban planning listed above. In this way, a sustainable city must organize itself not only to

preserve its natural systems for its own people and local environment, but also contribute to preserving global natural resources and environmental systems (Jaccard, 2005; Vojnovic, 2013). A shift in municipal policy towards embracing sustainability planning at the community level has the potential to support sustainability on a global scale. As such, I would define a sustainable city as one that organizes itself to not only preserve and sustain its own environment, but also develop in a manner that is consistent with this objective at a global level.

Unfortunately, in many cities the ideal of planning for global-level sustainability concerns is not a reality and cities are often organized in a way that erodes global systems (Bai et al., 2012). Cities remain unsustainable in large part because sustainability plans are not implemented using municipal policy. In fact, “the most critical issue within the sustainability discourse remains defining environmental policies that can convert the growing global interest in preserving the environment into actual improvements in environmental well-being” (Vojnovic, 2013). Yet, municipal governments have access to an array of policies to achieve this goal since almost any municipal policy can have an impact on sustainability.

There are five general types of policies that I consider here: pricing; subsidies that include infrastructure; standards; zoning; and voluntary programs. Policy analysts often evaluate policies on political feasibility, economic efficiency, environmental effectiveness, and administrative ease (Button & Pearce, 1989; Goulder & Parry, 2008; Jaccard, 2005). Since it is often the case that no single policy ranks highly in all criteria, sustainability policy frequently requires some combination of policy options. In many cases, sustainability policy is based on voluntary actions, education campaigns and research initiatives. These types of policies are politically feasible and easy to administer; unfortunately, they must be paired with mandatory policies to change decisions – at least where the economic and political cost of a more sustainable path is substantial (Button & Pearce, 1989). In my assessment, I therefore especially focus on pricing, standards, zoning and infrastructure investment because of the significant economic and political trade-offs that some of my proposed sustainability objectives entail.

Municipal governments that implement the policies outlined here can change the material and energy intensity of their cities. But cities also depend significantly on global trade networks for food, energy and materials, and these may come from regions where production entails significant environmental and/or social costs (Rees, 1996; Swart, Raskin, & Robinson, 2004). To address this issue, some groups and individuals advocate that cities should focus on energy efficiency and local resource extraction, energy production, food production and resource recovery (Grewal & Grewal, 2013; International Energy Agency, 2009; Rees, 2009). This implies reducing trade and severely restricting material and energy supplies. This is a drastic change since energy demand in cities ranges from 10 to 100 times higher than available energy in renewable forms such as sunlight and wind (Bai et al., 2012). Some people contend that energy self-sufficiency for any particular locale, including an individual city, is an essential part of sustainability. In this report I explore this contention by simulating a scenario of energy independence for Metro Vancouver and then assessing the implications in terms of costs and other trade-offs.

2.3. Sustainability in Metro Vancouver

The growth, physical limits and liveability challenge is at the heart of many debates in Metro Vancouver, and tension exists between levels of government operating in the region. While Metro Vancouver aspires to develop compact, transit-oriented communities, other levels of government are pursuing initiatives that are, at times, inconsistent with this goal. The provincial government plans to expand road infrastructure, such as replacing the Massey Tunnel with a bridge that can accommodate more vehicle traffic (Office of the Premier, 2013). At the municipal level, the Delta Council recently approved a housing development with little access to transit in land zoned for agricultural use. This tension is apparent on other sustainability issues; the region aspires to reducing GHG emissions while Metro Vancouver ports are attempting to expand both coal and oil exports.

Such decisions are complicated by the decision making structure in the region. Municipal, regional and provincial governments and several additional regional authorities, such as Translink that is responsible for transportation in the region, have

jurisdiction over different parts of development decisions, and sometimes jurisdiction overlaps. The provincial government has delegated certain powers to Metro Vancouver, including the provision of core services such as drinking water, sewage and drainage, and solid waste management. Metro Vancouver also has planning and regulatory authority for regional growth, utilities, air quality and parks. It also acts as a political forum for regional discussions by its member municipalities. While the provincial government has authority over important policy levers like building codes, other regional authorities such as Translink have authority over decisions regarding Metro Vancouver's transportation network. Addressing issues such as land use, air quality, GHG emissions, water use and solid waste disposal requires negotiation and coordination between these actors.

Metro Vancouver's response to the growth, physical limits and liveability challenge is a sustainability framework, *the Metro Vancouver Sustainability Framework*, and growth strategy, *the Metro Vancouver Regional Growth Strategy* (Metro Vancouver, 2010a, 2011b). Metro Vancouver grounds its sustainability framework in three principals: Protect and enhance the local natural environment, provide for ongoing prosperity and build community capacity and social cohesion. These principles then bound its current growth strategy which it adopted in 2011. The growth strategy outlines goals, strategies and projections to "create a region even more liveable for future generations than it is for those who live here today" (Metro Vancouver, 2011b). Implementing the sustainability framework is challenging because: it requires coordination with multiple tiers of government, Metro Vancouver has little control over the source of its material and energy resources, and it has yet to define policies necessary to achieve the goals of its framework. The latter is challenging because in defining and designing policies that effectively bridge likely trade-offs between growth, physical limits and liveability, Metro Vancouver must account for the region's governance structure and address the challenges of sourcing material and energy resources.

My definition of a sustainable city requires that physical limits be established for air emissions, water use, GHG emissions, land use and solid waste disposal. As I discuss in Section 3, I prescribe these physical limits within the context of Metro Vancouver in my Limits scenario. I also adopt an energy limit to demonstrate the trade-offs of local energy dependence in my Local Energy scenario. Metro Vancouver's

approach to air emissions, water use, GHG emissions, land use and solid waste disposal are as follows:

- **Air Emissions:** The air emissions of concern in Metro Vancouver are known as criteria air contaminants (CACs) and include: nitrogen oxides (NO_x), sulphur dioxides (SO_x), particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs) and ammonia (NH₃). CACs are produced by human activities like burning fuels, such as wood and gasoline; construction and driving that can produce dust; using chemicals contained in materials such as paint and solvents, and; agricultural activities. The environment also contributes to CACs. For example, trees produce VOCs and forest fires produce PMs and other CACs. CACs negatively impact human health by limiting lung capacity, aggravating lung and heart diseases and increasing cancer rates while degrading the environment. For example, NO_x emissions alone aggravate respiratory diseases like asthma and contribute to acid rain, while also combining with VOC's to produce smog.

To protect human health, air visibility and the environment, Metro Vancouver has set maximum concentration targets for each of the CACs based on World Health Organization standards. Many factors, such as the quantity of each CAC, sunlight, humidity, temperature and the ratio of CACs, influence their impacts on human health and the environment. However, the quantity of CACs, and to a certain extent the ratio of CACs, are the only factors Metro Vancouver can control. Since 1990, Metro Vancouver and other levels of government have successfully used regulations to reduce CAC emissions in the region. These regulations require, among other things, that sulphur be removed from fuels and that vehicles include pollution control technologies.

Unfortunately, without further regulation all CACs are expected to increase in the region by 2035 (Wakelin et al., 2007). For example, PM emissions are already increasing, while NO_x emissions are expected to increase starting in 2020. The expected increase in CACs is driven by a combination of factors, including increased shipping and more CAC producing activities in the region resulting from population and economic growth. Metro Vancouver has

developed air emission policies to meet the air quality limits. However, the majority of policy actions outlined in Metro Vancouver's management plan are voluntary, educational, or stated commitments to develop further policies or requests to other governments to develop policy. Without further mandatory policies, these emission targets are unlikely to be achieved.

- **Water Supply:** Metro Vancouver owns and operates the regional watersheds, water supply and treatment facilities, while local municipalities own local distribution systems (Metro Vancouver, 2011e). Metro Vancouver states that it “currently has sufficient quantities of water from its source watersheds to meet the region’s needs until mid-century” (Metro Vancouver, 2011e). This seems reasonable since per capita water use has decreased at the same rate as population growth since 1991, resulting in no increase in absolute water demand over the past 20 years (Metro Vancouver, 2010b). However, there is no certainty that these reductions will continue. There is likely still room for water conservation in Metro Vancouver because its per capita water use rates are higher than many municipalities in Canada (Environment Canada, 2011). Researchers in California studying the effectiveness of water conservation policies found that per capita water reductions of 15 per cent could be achieved using voluntary policies, but that further reductions required stricter policies like water restrictions (Renwick & Green, 2000).
- **Land Use:** Like all growing cities, Metro Vancouver’s growth has been at the expense of surrounding agricultural and forestry lands. Since 1973 a provincial policy, the Agricultural Land Reserve, has had some success in slowing the rate of land conversion in the region, at least when compared to Seattle as a similar sized city with no land reserve (Smart Growth BC, 2002). As part of its sustainability efforts, Metro Vancouver has defined an urban containment boundary that aligns with the Agricultural Land Reserve in order to protect remaining farmland and encourage new development within existing areas (Metro Vancouver, 2011b). Metro Vancouver and University of British Columbia (UBC) studies have demonstrated that it is physically possible to accommodate future population within current urban areas, and

that this has many benefits beyond protecting agricultural and forest land. Such benefits include reduced infrastructure costs and communities that are more amenable to transit (Metro Vancouver, 2009; University of British Columbia, 2012). However, implementing strategies such as these requires coordination between multiple levels of government and regional authorities such as Translink.

- **GHG:** The B.C. *Local Government (green communities) Statutes Amendment Act* requires municipalities and regions to have GHG reduction targets, policies and actions to reduce GHG emissions from all sources in the community (BC Government, 2008). Metro Vancouver's targets are to reduce GHG emissions by 15 per cent by 2015 and 33 per cent by 2020 from 2007 levels, and many adjacent municipalities have also developed emission inventories and policies to reduce emissions (Metro Vancouver, 2011c). In addition, the provincial government has implemented a carbon tax, a low-carbon fuel standard and low-GHG electricity requirements. However, no public reports demonstrate exactly how Metro Vancouver will achieve its GHG targets.
- **Solid Waste Disposal:** Metro Vancouver's Integrated Solid Waste and Resource Strategy includes a target to reuse and recycle 70 per cent of solid waste by 2015 and Metro Vancouver aspires to reuse and recycle 80 per cent of its solid waste by 2020. Currently, Metro Vancouver reuses and recycles 55 per cent of its solid waste, a figure which has remained relatively constant despite efforts to increase it (Metro Vancouver, 2010c, 2012a). In addition, Metro Vancouver's solid waste forecasts show that, without policy intervention, solid waste disposal will exceed permitted disposal capacity by 2020 (Metro Vancouver, 2012b). Metro Vancouver is investigating several options such as additional landfill capacity and waste-to-energy facilities to address this issue (AECOM, 2009). Many Metro Vancouverites would also like to see waste decreased, so this issue may influence liveability as well (Vancouver Foundation, 2010).

- **Energy:** Metro Vancouver uses just under 250,000 TJ of energy per year for services such as heating, transportation and lighting (Wolinetz, Groves, Goldberg, & Baji, 2012). Approximately 2/3 of this energy is provided by fossil fuels and the remaining 1/3 from electricity, which is primarily hydro electric in B.C. The Collaborative for Advanced Landscape Planning estimates that local energy from waste, sun, biomass and small hydro could generate 72,000 TJ – less than 1/3 of current energy use (Tooke et al., 2013). Metro Vancouver has no plans to restrict energy supply to local sources, but does support district energy, energy recovery, renewable energy systems and energy efficiency where appropriate (Metro Vancouver, 2011b). Limiting energy supply to local sources could seriously impact quality of life in the region, but there are no current studies that show what level of service local energy supplies could provide and the implications for life in the city.

The physical limits described above may have important implications for sustainability and liveability in the region. The Vancouver Foundation has conducted surveys and generated statistics on what Metro Vancouverites feel makes Metro Vancouver liveable (Vancouver Foundation, 2010). They polled 1,200 people on four key aspects of community life: people, economy, place and society. Of those polled, 37 per cent cited housing affordability and 21 per cent cited apartment affordability as critical issues. When considering “place”, 29 per cent of respondents wanted more frequent transit service, 12 per cent wanted less reliance on cars and 12 per cent wanted to see waste reduced. They also found that 87 per cent of Metro Vancouverites feel they have an excellent or good quality of life and 92 per cent feel they are happy or somewhat happy. I have highlighted these results because they align with indicators that I consider in my analysis. The Vancouver Foundation’s analysis helps to understand what people are concerned about in Metro Vancouver today, and what they feel the top priorities should be. It also shows that economy and environment only partially contribute to quality of life in the region. The study also highlighted belonging, safety, education and health as important contributors.

2.4. Scenario Analysis and Modeling

Policies attempt to influence complex, dynamic and poorly understood economic, environment and social systems, and often have unintended consequences. Because the system is complex and outcomes are uncertain, analysts often develop scenarios to ask “what-if” questions (Alcamo, 2008a; Oreskes, 2003; van Vuuren, 2009). I ask three what-if questions in my analysis:

- What if historical trends continue?
- What if Metro Vancouver set policies to meet a set of physical limits?
- What if Metro Vancouver added a local energy supply requirement to these other physical limits as an objective?

Modern scenario analysis evolved from strategic exercises during World War II and became popular during the 1960’s and more recently when considering climate change impacts and mitigation options (IPCC, 2000). It lacks a codified methodology but it is usually defined as “a description of how the future may unfold based on if-then propositions” (Alcamo, 2008b). I use what is defined in the scenario analysis literature as a combination of descriptive and explorative approaches to answer my what-if questions. Explorative approaches typically determine what should or could happen, while descriptive approaches present the researcher’s best guess as to what will happen under certain conditions (Alcamo, 2008b). I follow the descriptive approach because one of the major gaps in urban sustainability analysis is the operationalization of sustainability policy, and the assessment of how households and firms react to these policies. It is relatively easy to presume people will drive less or buy electric cars in the future, but finding acceptable policies that will trigger changes like these is more difficult. While at the aggregate level I set physical limits and stipulate that Metro Vancouver *should* meet them, at the decision making level of firms and households my analysis does not usually force a particular outcome. Instead, I simulate, using a behavioural technology-choice model, the likely response to policies seeking to achieve these physical limits. Thus, my focus is on determining how individuals would likely respond to policies rather than the response that I might like to see.

I use a BAU forecast and two scenarios to explore a range of possible futures. The BAU forecast is my best guess of the future if historical trends continue. For example, Metro Vancouver may wish to protect agricultural and forestry land and promote density, but some developers will find ways to circumvent these restrictions, as they have for the past 40 years. I therefore assume that agricultural and forestry land will disappear at the same rate in the future as it has in the past, in spite of political statements to the contrary.

The Limits scenario largely reflects Metro Vancouver's stated sustainability and liveability aspirations, setting firm physical limits on CAC and GHG emissions, water use, land use and solid waste disposal. And I believe that the specific limits I have chosen to study are ones that best align with sustainability requirements and political feasibility. Governments – at any level – have some success in restricting emissions, water pollution, energy choices, and waste. They have not had much enthusiasm or success in trying to control population or economic growth.

The Local Energy scenario intensifies the Limits scenario by including the requirement for energy self-sufficiency. Energy production and use is the primary contributor to global GHG emissions and also a major contributor to air quality degradation, water use and land use change, but regions have little control over energy production in other jurisdictions (Bai et al., 2012). Thus, urban sustainability advocates often argue that for a region to be sustainable it must generate the majority of its energy. The local energy limit also acts as a surrogate for sustainability challenges outside Metro Vancouver's borders other than climate change, because the development of energy supply elsewhere could have significant environmental implications far from Metro Vancouver. For example, much of Metro Vancouver's electricity comes from large hydropower facilities that required the flooding of valleys in distant parts of B.C., and much of its vehicle fuels come from the massively disruptive oil sands development in Alberta.

For each scenario I use a regional technology choice simulation model, called CIMS. CIMS is a type of economic model that combines the features of top-down and bottom-up models. Bottom-up models are built with representations of many technologies, and their capital and operating costs. This type of model excels at

describing technological solutions to environmental issues, but is poor at describing human behaviour. Bottom-up models tend to underestimate policy cost, and so policy analysts may recommend policies that are too weak to achieve a policy objective. Top-down models are the reverse. They are based on real-world information about human decision-making, but they lack technical realism (Murphy & Jaccard, 2011). CIMS combines both approaches in a hybrid model. The implications of these different approaches are significant when recommending policy.

Since the parameters in the CIMS model are based on empirical studies, it more realistically simulates the technology choices of households and firms than a bottom-up model, while still providing the technology detail of bottom-up models. For example, the model captures known responses to changes in energy price such as the rebound effect that bottom-up models typically exclude. While there are different kinds of rebound effect, the concept essentially explains how energy efficiency improvements rarely achieve all their expected energy savings because more efficient devices have lower operating costs, which tends to encourage greater use – a rebound.

Since bottom up models miss known responses such as the rebound effect, they can overestimate the effect of efficiency policies. For example, two studies calculated the cost of reducing U.S. GHG emission by 40 per cent; one used a bottom-up model, the other a hybrid model. The bottom-model showed that a \$50/tonne carbon tax would be sufficient to achieve 40 per cent emissions reductions, while the hybrid model showed that a \$150/tonne carbon price would be necessary (McKinsey & Company Consultants & The Conference Board, 2007; Murphy & Jaccard, 2011).

With its focus on energy using and producing technologies, CIMS only simulates some of the physical limits I include in this study. So I use an urban sustainability model to calculate and track water use, solid waste disposal, land use and CAC emissions and some of the information necessary for each CIMS simulation. For example, the housing mix in Metro Vancouver will change over time and has a significant impact on density, but it is not simulated in the CIMS model. Because my urban sustainability model is not as sophisticated as CIMS, I account for some of these aspects of human behaviour by referencing studies of policy effectiveness in other cases. For example, I check the

response of citizens in other cities to water policies that have yet to be implemented in Metro Vancouver.

According to Oreskes (2003) “all evidence suggests that long-term forecasts [of complex systems] are likely to be wrong and may very well misinform public policy” (Oreskes, 2003). This argument highlights another limitation of modelling, a weakness that stems from the complexity paradox. Simple models may not reflect the complexity of a system, but complex models have so many variables, each with its own uncertainty, that the results may say nothing meaningful about the future. The complexity paradox is compounded by the long time frames of some models. I address these challenges by using scenarios to cover a range of possible outcomes. In addition, I integrate separate analyses of physical limits, population growth, economic growth, and liveability. This approach allows me to identify some of the likely trade-offs between different policy decisions, and the types of policies that are likely to lead to changes to what living in Metro Vancouver could be like for a citizen in 2050. The quantitative results reflect the assumptions I have made and will only be appropriate if Metro Vancouver follows a similar sustainability path to the one I have simulated.

3. Methodology

To determine the growth, physical limits and liveability trade-offs for the BAU forecast, Limits and Local Energy scenarios, I use the urban sustainability model to calculate changes in the region that are the exogenous parameters in CIMS, and outputs such as CAC emissions, water use, GHG emissions, land use and solid waste disposal. CIMS simulates energy technology choices and some of the liveability measures. Figure 2 shows the exogenous parameters on the left side and the outputs on the right side. The exogenous parameters directly influence some of the outputs in the CIMS simulation and also other parameters. For example, the make-up of dwellings in Metro Vancouver, called the dwelling mix, influences the travel rate in the region.

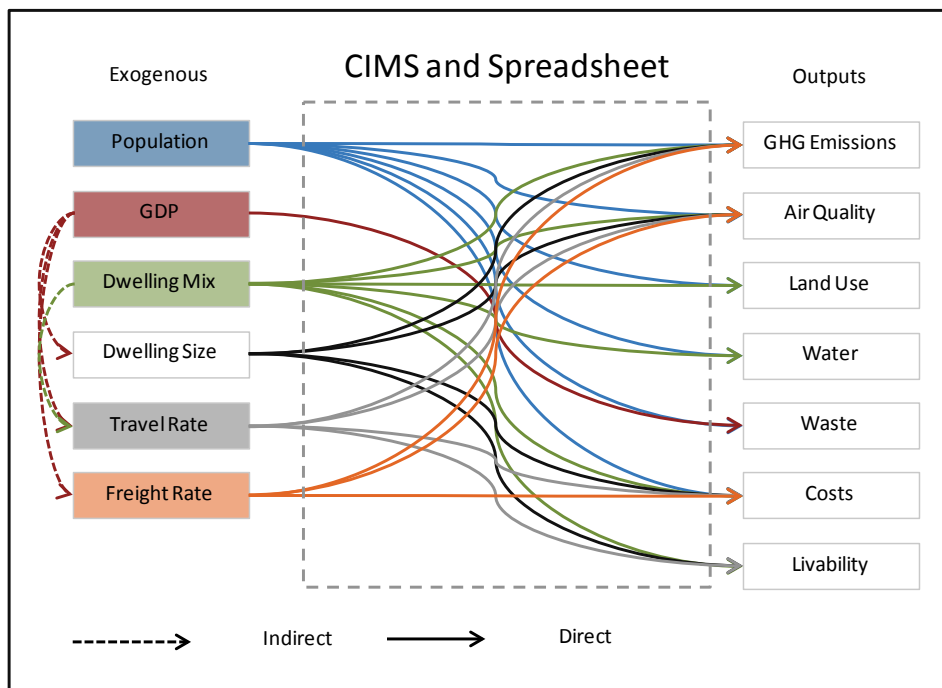


Figure 2: Model outline

I use policies to influence technology choice in the region, which also changes the exogenous parameters for each scenario and so too the outputs. I calculate exogenous parameters such as average dwelling size, travel rate and freight rate, and; driving variables such as population and GDP. I then link those parameters and variables to CAC emissions, water use, GHG emissions, land use, solid waste disposal, costs and liveability measures. Some of these connections are direct. For example, total water use partially depends on the number of people and the dwelling type they live in, including detached homes, attached homes, apartments and mobile houses. Others are indirect. For example, dwelling mix and associated density can influence mobility and vehicle use, but as the model does not account for this dynamic, I calculate it externally.

3.1. Defining the Study Area

Metro Vancouver has a land area of 283,185 ha with 114,000 ha of protected park and recreational land; 53,619 ha of farmland; 41,000 ha of residential land; and 23,000 ha of transportation corridors with the remainder consisting of commercial, industrial and open/undeveloped land¹ (Vancouver, 2008). It is bounded to the north by mountains, to the west by the Pacific Ocean and to the south by the US border.

I consider a time horizon of 40 years – 2010 to 2050 – for three main reasons. First, meeting physical limits on some of the outputs like GHG emissions requires significant changes in technology and urban form, which can take decades (Hodge & Gordon, 2003; Smil, 2010). Second, rates of population and economic growth can seem modest in short periods, but can lead to significant change over longer periods. For example, Metro Vancouver's population is expected to grow by 1 to 1.5 per cent per year for the next 40 years, which means adding 1.4 million people, equivalent to adding one new municipality the size of Surrey every 13 years. Third, long-term change often requires near-term action because of system inertia, making it difficult to appreciate the impact of policies implemented today without considering the long term.

¹ I relax this boundary for the Local Energy scenario. This is described in more detail in the scenario description section.

By 2041, Metro Vancouver estimates its population of 2.4 million people will grow to over 3.4 million (Metro Vancouver, 2009). I extrapolate Metro Vancouver's existing population growth projections from 2010 to 2041 for an additional 9 years to 2050. In the model, Metro Vancouver's population grows at 1.5 per cent per year starting in 2010, slowing to 1 per cent per year by 2050. Metro Vancouver's population estimates are based on the B.C. Stats Population Extrapolation for Organizational Planning with Less Error (PEOPLE) model (BC Stats, 1999; Metro Vancouver, 2009). The B.C. PEOPLE model accounts for immigration, domestic migration, fertility rate and mortality by tracking age groups in the population (BC Stats, 1999).

I use GDP to indicate economic growth, using the following data and assumptions:

- Metro Vancouver's per capita GDP is equal to B.C. average per capita GDP.
- Metro Vancouver's future rate of GDP growth is equal to B.C.'s average growth rate between 1990 and 2012.

Following these assumptions, Metro Vancouver's total GDP is expected to grow 2.51 per cent/yr and its per capita growth rate is expected to be 0.95 per cent/yr.

Both population and economic growth help drive sectoral growth in Metro Vancouver, as well as its associated CAC emissions, water use, GHG emissions, land use and solid waste disposal. I account for the transportation, residential, commercial and light industrial sectors of Metro Vancouver, but not air or rail traffic, heavy industrial, or any activities that significantly occur outside the bounds of Metro Vancouver.

3.2. Outputs – Limits and Liveability

I selected physical limits that are both locally and globally relevant by doing the following:

- **Regional and local relevance:** I reviewed the Metro Vancouver growth strategies (Development, 2009; Metro Vancouver, 2011b), studies of subjective well-being

(Vancouver Foundation, 2010), individual municipality planning documents (City of Vancouver, 2011) and previous studies (Compass Resource Management Ltd. & MK Jaccard and Associates, 2005; Condon & Belausteguigoitia, 2006; Shaw et al., 2009) to determine which physical limits are of importance to Metro Vancouver.

- **International relevance:** Some physical limits in Metro Vancouver are or will be experienced by other cities around the world, or are only meaningful when considering global impacts. For example, Metro Vancouver's GHG emissions could be ignored if not considering their global implications. I determined international relevance by consulting global overviews such as the Global Energy Assessment – Urban Energy Systems (Bai et al., 2012) and the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005).

I originally intended to include some liveability limits such as commute time and distance to green space, but did not include these limits because of inadequate data.

I justify each of the limits using the criteria described above in the following sections.

Land Use

Metro Vancouver occupies 283,185 ha, with an urban area of 174,219 ha, including commercial, industrial, industrial extractive, institutional, open and undeveloped lands; ports; residential lands; transportation and communication corridors; right-of-ways; and recreation areas. I limit the urban area to 174,219 ha to protect remaining agricultural land and green space. This is in part a political decision because Metro Vancouver has room to expand its urban environment, but it would eventually consume all remaining open land and still be faced with a land constraint. By artificially defining it now, I protect green space that contributes to the character and liveability of the region. I also based my decision on the fact that the United Nations expects major urban policy changes such as zoning to protect agriculture in order to reverse urban expansion that is globally degrading food production and ecosystems (United Nations Environment Program, 2012a).

CAC emissions

I set CAC emission limits at current emission levels for CACs. Since Metro Vancouver meets most of its current air quality objectives, I assume its air quality objectives will be met if emissions of CACs remain at these levels. While I track each CAC in the model, I summarize CACs in the simulation outputs by using a smog indicator calculated using the US EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (Bare, 2011, 2012). However, in the model I do ensure no individual CACs has increased above Metro Vancouver's 2010 level for the Limits scenario.

Greenhouse Gas Emissions

I set the GHG limit at 0.43 tonnes CO_{2eq} per capita in 2050. This per capita emission value is simply a global emission limit converted into a per capita value. I use this method rather than adopt Metro Vancouver's target since its timeline only extends to 2020. I extend the projection to 2050 in order to select a target consistent with IPCC projections of the global average per-capita emissions level that prevents temperature increases from exceeding 2°C. Using this approach, North America has an average per capita emissions allowance of 4.74 tonnes CO_{2eq}/per capita in 2000 reducing to 0.43 in 2050 (Böhringer & Welsch, 2004). This per capita limit is equivalent to a Metro Vancouver limit of 1.8 million tonnes CO_{2eq} by 2050, assuming a population of 3.8 million people. Metro Vancouver's current emissions are near 14 million tonnes CO_{2eq} and it has committed to reducing these emissions to 12.75 million tonnes CO_{2eq} by 2015 and 10 million tonnes CO_{2eq} by 2020.

Water

I limit water to existing summer withdrawal rates of 224 Mm³ because reservoirs are at their lowest levels during the summer months (Environment Canada, 2011; Metro Vancouver, 2010b). This limit is potentially artificial because Metro Vancouver states that it has additional capacity; however, it does restrict outdoor water use every summer and has experienced drought conditions (Metro Vancouver, 2011d).

Solid Waste

I set a limit of no solid waste disposal in landfills by 2050. Existing scenarios show that Metro Vancouver could surpass permitted landfill disposal capacity by 2020 (Metro Vancouver, 2012b), although this capacity could be increased by either creating a new landfill in or outside Metro Vancouver (AECOM, 2009). In addition to this landfill space constraint, reducing solid wastes to zero is a goal of Metro Vancouver’s government because of other environmental implications from solid waste production and disposal (Metro Vancouver, 2012a).

Table 1 summarizes the physical limits and my justification for imposing them.

Table 1: Summary of physical limits

Land Use	<ul style="list-style-type: none"> ○ Limit: 174,219 ha ○ Why: Political decision to protect green space that contributes to liveability of the region
CAC emissions	<ul style="list-style-type: none"> ○ Limit: Current emissions of CACs ○ Why: Metro Vancouver air quality objectives are met under existing CAC emissions
GHGs	<ul style="list-style-type: none"> ○ Limit: 1.8 MT/yr per-capita by 2050 ○ Why: Consistent with IPCC per-capita projections to meet 2 C constraint
Water Consumption	<ul style="list-style-type: none"> ○ Limit: 224 Mm³ during June, July, August, September, October and November ○ Why: Reservoir system supports 224 Mm³ supply and summer water supplies are the most vulnerable
Waste Disposal	<ul style="list-style-type: none"> ○ Limit: Zero waste to landfill by 2050 ○ Why: Policy goal based on attitudes towards waste in Metro Vancouver and limited landfill capacity

3.2.1. Liveability Outputs

Meeting physical limits will both impinge on and enhance liveability in the region. Metro Vancouver’s liveability performance measures and the Vancouver Foundation’s report on subjective well-being reflect general values in Metro Vancouver. I categorized the measures from both of these reports into capacities that support quality of life: health, education, political voice, personal activity, social connection, environmental conditions, security and quality. I then focused on those capacities for which public data

existed or where I could reasonably generate data using CIMS and the urban sustainability model. The remaining capacities are affordability, housing, mobility and environmental conditions.

- **Affordability:** Metro Vancouverites place cost of living, especially rental costs and housing costs at the top of their list of concerns in *Vital Signs*, a report by the Vancouver Foundation on Vancouver's values and concerns (Vancouver Foundation, 2010). I only include some contributors to cost of living such as large household items, cost of driving and housing costs. The large household items include: dryers, clothes washers, dish washers, freezers, ranges, refrigerators and other electronics such as computers and televisions. For each item I calculate the life cycle costs, including capital, operating, energy and intangible costs. For automobiles, I calculate mobility cost using the life cycle cost of driving 100km. I include automobiles because Metro Vancouverites still highly value the automobile, as evidenced by the continuous climb in car ownership between 2004 and 2009 (Vancouver Foundation, 2009). As with household goods and driving, I calculate life cycle costs to determine building envelope costs. Building envelopes include the walls and windows of the building and contribute to how much energy is required to heat or cool a building. The life cycle cost includes the construction, operating, space heating and cooling cost and intangible costs of the building envelope. Thus the building envelope cost accounts for energy price increases. Land value, taxes, immigration, developer profit margins and other fees more broadly influence housing costs; however, all other assumptions being equal, higher building envelope costs would likely increase housing costs. Land use zoning policies like the agricultural land reserve could also influence housing costs, but I do not estimate the price impact of the agricultural land reserve because no theoretical framework exists to estimate cost increases associated with policies like the agricultural land reserve (Ley & Tutchenner, 2001; Magliocca, McConnell, Walls, & Safirova, 2012; Quigley & Rosenthal, 2005). Limiting land available for residential development is only one of several drivers of price increase, and price increases are partially mitigated by a switch to smaller houses and higher density. Details on cost calculations are available in section 3.4.1
- **Housing:** In addition to housing costs, I also comment on dwelling size and mix and qualitatively discuss the implications of density in the region.

- **Mobility:** In addition to mobility cost, I use type of movement and amount of movement as indicators of mobility because they are important to Metro Vancouverites. Metro Vancouver plans to annually collect data on both indicators to measure the performance of its regional growth strategy (Metro Vancouver, 2011b).
- **Environment Conditions:** I also report on available green space, contribution to climate change, solid waste disposal, water use, and CACs. All these measures are part of Metro Vancouver's growth strategy and reported in the Vancouver Foundation's report.

Table 2 summarises the liveability measures discussed above.

Table 2: Summary of liveability measures

	Title	Unit	Description
Affordability	Dryers, clothes washers, dish washers, freezers, ranges, refrigerators and other electronics	\$/yr	Life cycle costs with intangibles
	Building costs	\$/m ²	Building envelope life cycle costs with intangibles of the building envelope
	Cost of driving	\$/100 km	Life cycle cost of a 100 km drive with intangibles
Housing	Housing size	Avg. m ²	Housing size by type of house (e.g. apartment, detached, attached)
	Housing type	per cent Type	per cent of dwelling by type
Mobility	Mode split	per cent Type	per cent trip by type, active, single occupancy vehicle, car pooling and transit
	Distance travelled	Km/yr	Average distance travelled per year by an individual
Envir	Air quality	Smog _{eq}	Expected smog production based on CAC

			emissions
	Water Restrictions	Frequency and severity	Number and severity of water restrictions in Metro Vancouver
	Waste disposal	Kg/person	Kg of waste disposed in landfill, after reductions, recycling and recovery
	Land Change	ha of green space	ha of green space after accounting for urban expansion
	Greenhouse gas emissions	tonnes CO _{2eq} /person	Total GHG emissions divided by population

3.3. Scenarios

Each scenario defines exogenous parameters for the model and then the model simulates the impact of these exogenous parameters on the liveability outcomes.

3.3.1. *Business as Usual*

The BAU forecast represents a most likely future assuming that current trends continue and human behaviour and values are similar to today. Wherever possible I identify trends in historical data and then project those trends. However, I sometimes modify these trends to include existing policy or underlying driving forces. For example, Metro Vancouver water use policy has achieved a 2 per cent reduction per year in water use during the summer months (Metro Vancouver, 2010d). I slow this trend over the next 37 years to reflect research showing that the first 15 per cent of water reductions are relatively easy to achieve, but higher reductions are more difficult (Renwick & Green, 2000). Energy technology and its use may also change in response to energy price and innovation so I use CIMS to simulate that change. The primary assumptions for the BAU forecast are summarized and justified below.

- **Dwelling Size:** Dwelling size is the floor space per household in Metro Vancouver. The size of a house influences heating energy requirements and so GHG and CAC emissions if using combustible fuels. Average housing size in B.C. has grown by 0.4 per cent a year or 1.96 per cent every 5 years. Between 1990 and 2010 average household size grew from 128.48 to 152.5 m² per household between (Natural Resources Canada, 2013). I assume the average dwelling size in B.C. is the same in Metro Vancouver and that growth continues at the same rate.
- **Dwelling Mix:** The number of detached houses, attached houses or apartments is an important metric because the mix can influence density and consequently transit use, car use and energy use. I assume the current dwelling mix follows existing trends, which shows a switch to apartments and attached homes from detached homes. Despite this switch to apartments and attached housing, Metro Vancouver's urban area continues to grow. Between 1986 and 2002, Metro Vancouver's urban area grew by 2250 ha and the agriculture/urban mix grew by 882 ha (British Columbia Ministry of Environment, 2007).
- **Travel Rate:** I assume travel per person will grow at 0.2 per cent per year based on historical estimates². That is, every year the average person travels 0.2 per cent more in Metro Vancouver whether it is by car, transit or walking/biking.
- **Freight Rate:** I assume freight traffic grows at 3.16 per cent per year from 2010 to 2015 and then 2.48 per cent from 2015 until 2050. I derived these values from historical rates in shipping tonnage through the port of Metro Vancouver and assume that truck traffic will climb in step with ship traffic. A panel of shipping experts asked to comment on growth in the shipping fleet expects that slower economic growth in Asia will slow growth in Metro Vancouver shipping from a forecast high of 3.16 per cent in 2015 (Metro Vancouver, 2010e).
- **Land:** The Agricultural Land Reserve remains, but agricultural land continues to be lost to urban development at historical rates.

² Total travel is based on calculations in CIMS in v.1.1.2 and ultimately from (Ministry of Environment, 2012)

- **GHG:** CIMS simulates GHG emissions based on technology and energy costs and other assumptions discussed above. I include the existing \$30 per tonne CO_{2eq} provincial carbon tax and the federal vehicle emission standard which requires that new light-duty vehicles – cars and light-trucks – have a fleet average GHG emission intensity less than 160 g CO_{2eq}/km after 2015 (Canada Gazette, 2010)
- **Water:** I do not limit water use in this scenario and assume additional water will be provided by increased water supply.
- **Solid Waste:** There are no limits on solid waste disposal. I assume Metro Vancouver achieves 70 per cent waste diversion and the remaining material is either combusted in waste-to-energy facilities within Metro Vancouver or shipped to landfills. Initially, residual waste is sent to the Vancouver Landfill, and once that site is full, waste is sent outside Metro Vancouver. I found little evidence to support or detract from the notion that density decreases solid waste production, so I have not included this link in the urban sustainability model.
- **Air Quality:** There are no limits on CAC emissions in this scenario; however I included the following policies which are already in effect:
 - **Vehicle CAC emissions:** Metro Vancouver’s vehicle CAC emission program, Air Care, continues until 2015 for heavy duty vehicles with expected reductions of 0.5 per cent, 2.3 per cent and 1.7 per cent for NO_x, PM and VOC emissions respectively in 2010 and 2015 (Metro Vancouver, 2010e).
 - **Marine Vessel CAC emissions:** The International Convention for the Prevention of Pollution from Ships contains relatively strict emission reduction requirements for ships including 20 per cent NO_x reductions from a 2000 baseline, followed by a further 80 per cent reduction from a 2011 baseline. I assume that the initial 20 per cent reduction occurs but that the 80 per cent reduction does not because it is currently unclear whether these emission requirements will be followed in Canada.
 - **Sulphur in Fuels:** The Federal Government’s *Sulphur in Diesel* regulation requires reductions in the sulphur content of diesel to 15mg/kg by 2012 for

marine and road transportation diesel. This is a 97 per cent drop from 2007 required levels for marine diesel and an 88 per cent reduction for on-road diesel (Environment Canada, 2010).

- **Required upgrades for heavy-duty vehicles:** In 2007 B.C. announced a mandatory retrofit regulation for older heavy-duty vehicles to reduce their CAC emissions. The regulation is expected to reduce CO, PM and VOC by 5.2 per cent, 8.4 per cent, and 7.2 per cent respectively in 2010 and 6.9 per cent, 4.1 per cent and 6.8 per cent respectively by 2015 (Metro Vancouver, 2010e).

3.3.2. Limits Scenario

For the purposes of this scenario, I assume that Metro Vancouver successfully implements policies limiting land available for urban development, GHG and CAC emissions, water supply during the summer months and solid waste disposal; the types of policies I simulate and assumptions I make are discussed below with additional detail in Appendix B.

- **Dwelling Size:** I assume that each average size of each type of dwelling – apartment, detached house and attached house, as well as the growth rate continue as described for the BAU forecast. However, the dwelling mix alters the average housing size, because apartments and attached houses are generally smaller than detached houses.
- **Dwelling mix:** In this scenario, the dwelling mix changes so that population growth remains within urban boundaries. I first project recent dwelling mix trends between 1997 to 2006 out to 2050 and then compare these results with two recent studies: the Metro Vancouver Residential Growth projection (Metro Vancouver, 2009) and a Vision for a Region of 4 Million People (Sustainability by Design, 2006). Each of these studies assumes constant urban area and projects the likely change in Metro Vancouver's dwelling mix based on different assumptions. Finally, I check the resulting building mix with its likely footprint and required supporting services to determine if that mix could fit within existing urban boundaries. The result is a

change in dwelling mix that occurs at a pace with historical precedence in Metro Vancouver, fits within other projections and does not require additional land use.

- **Travel Rate:** The dwelling mix and density changes mean that people in Metro Vancouver could get around more easily by transit and walking because they have less distance to travel and density can allow for more frequent transit. I assume travel per person decreases by 0.34 per cent per year based on modelling results of similar changes in density for major urban centres in Canada (Jaccard et al., 2010). This assumes that transit accompanies density and Metro Vancouver experiences a gradual shift to where more people live closer to where they work and shop.
- **Freight Rate:** Freight grows at 3.16 per cent per year from 2010 to 2015 and then 2.48 per cent from 2015 until 2050, which is the same as the BAU forecast. Although land limits may increase the cost of freight by limiting port expansion and road expansion, the travel decreases discussed above reduce personal road travel and so less road expansion is required to support freight expansion.
- **Land:** Municipal, regional and provincial zoning regulations limit urban land area to 174,219 ha. This assumes the B.C. Provincial government and Metro Vancouver continue to protect the agricultural land reserve. The lack of additional land to develop then restricts road development, requiring expanded transit service. I simulate with CIMS a \$0.05 per km vehicle operating charge to realize the necessary increase in transit ridership. The \$0.05 per km charge is levied based on reported km traveled per year per vehicle. A number of technologies exist that could collect kilometre data and then send it electronically to a data processing centre. The Oregon Department of Transportation has tested these devices and plans to implement a distance based vehicle charge, replacing existing gas taxes (Oregon Department of Transportation, 2013).
- **GHG:** GHG emissions are limited to 480 kg CO_{2eq} per person per year or 1.8 Mt CO_{2eq} per year by 2050 via a number of technology and sector specific policies. To determine which policies to implement I first use CIMS to simulate a carbon tax schedule that would reduce emissions to 1.8 Mt CO_{2eq} per year - Table 3. These reductions are also the least cost to Metro Vancouver, since CIMS simulates what

reductions households and firms consider least costly. However, carbon taxes have been politically unacceptable in many jurisdictions, so I use sector specific policies to create the same reduction profile as the carbon tax simulation achieves. For example, it's possible to reduce GHG emissions by shifting people to transit and walking and biking; however, the carbon tax simulation shows that, based on empirical evidence of people's preferences, many households and firms would rather chose low-GHG vehicles than switch to transit. I simulate the following policies to reduce GHG emissions: a continuation of the \$30 per tonne CO_{2eq} tax, continuation of existing Federal Government minimum energy performance standard for space and water heating, a declining personal vehicle GHG intensity standard that starts at <160 g CO₂/km in 2015 and declines to <70 gCO₂/km after 2030, a freight efficiency standard that requires heavy duty vehicles to reduce GHG emission intensity to <150 gCO₂/tonne-km after 2035, and biodiesel requirement that starts at 5 per cent and rises to 100 per cent by 2030. CIMS does not simulate natural gas vehicles; however, I expect they would play at most a transitional role because liquefied or compressed natural gas vehicles are only 15 to 20% less GHG intense than existing diesel vehicles according to GHGenius, a Canadian fuel life-cycle model (NRCAN, 2011). These reductions are not significant enough to meet the 2050 GHG limit, but existing biodiesel could supply freight fleets with a GHG intensity 90% lower than today's diesel (NRCAN, 2011).

Vehicle standards are typically implemented by either the Federal or Provincial government. However, Metro Vancouver could require vehicles registered in the region to meet the GHG intensity standards or link vehicle registration fees to the GHG intensity of the vehicle.

Table 3: Carbon tax schedule for CIMS carbon reduction simulation

Year	2013- 2015	2016- 2020	2021- 2025	2026- 2030	2031- 2035	2036- 2040	2041- 2045	2046- 2050
Carbon Price	\$30.00	\$50.00	\$150.00	\$200.00	\$400.00	\$400.00	\$400.00	\$400.00

- **Water:** Water use is limited to existing supply levels of 224 Mm³ cumulative during June, July, August, September, October and November. The limit is met in a number of ways. First, land restrictions reduce the number of detached houses and so limit outdoor water use. Second, I assume historical water per capita efficiency gains of 1 per cent per year continue (Metro Vancouver, 2010b, 2010d). Per-capita water use has declined by 1% per year for the past 20 years, in part because of regulations to increase the water efficiency of appliances, public education campaigns and improvements in leak detection. However, there is little public data that shows the individual effectiveness of these policies or forecasts of water use in the region. Finally, I simulate Metro Vancouver's current Water Shortage Response Plan when necessary to meet the water use limit (Metro Vancouver, 2011d).
- **Solid Waste:** I assume that reducing per capita solid waste production is generally unsuccessful because this has been the global experience, so solid waste production at homes and firms continues to increase following historical trends in Metro Vancouver (United Nations Environment Program, 2012b). However, 100 per cent of waste is diverted by 2050 through a combination of recycling, composting, and combusting waste in waste-to-energy facilities, which, based on existing studies, would likely be several incinerators (AECOM, 2009).
- **Air Quality:** CAC emissions are limited to 2010 levels and include policies found in the BAU forecast such as reducing CAC emissions from ships. I also use a permit policy to limit the number of wood burning stoves in Metro Vancouver. Wood burning stoves, even the most efficient technologies, contribute to poor air quality. I introduce three policies to combat PM emission increases: comprehensive street cleaning, tire replacement and reducing construction PM emissions. Comprehensive street cleaning with water and tire replacement programs are used to reduce PM from non-combustion sources, especially during summer months. Half of all major corridors are cleaned by 2020 and all major corridors by 2050 resulting in a 7 per cent and a 14 per cent drop in PM respectively. These reductions are based on a street cleaning effectiveness study (Amato et al., 2009). I also introduce tire replacement programs to reduce non-combustion emissions by 10 per cent in 2020 and 20 per cent in 2050 using estimates of the effectiveness of this type of policy from the International Institute for Applied Systems Analysis (Borken-kleefeld, 2012). I assume dust from

construction sites can be reduced by 50 per cent starting in 2015 using dust suppression technologies, but found no academic literature on the effectiveness of this type of policy.

3.3.3. *Local Energy Scenario*

I extend Metro Vancouver's boundary to the north and east for this scenario because there are several potentially large energy supply sources just outside its border. This extended border is known as the Lower Mainland, and is 506,700 ha in area and encompasses all of Metro Vancouver's 283,185 ha. This scenario generally follows the Limits scenario but I enact policies to reduce energy use to what could be sustained indefinitely from supplies in the Lower Mainland. I discuss critical assumptions below with detailed policy descriptions and justifications in Appendix C.

Local Energy Calculation

I first developed an inventory of energy sources in the Lower Mainland including geothermal, wind, solar, hydro, wood, liquid biofuels, waste and waste heat. This information came from a number of sources, including a BC Hydro review of electricity generation, conservation, efficiency and supply options (KWL, 2010), a UBC study of energy supply options in Metro Vancouver (Tooke et al., 2013) and my own calculations using CIMS and the urban sustainability model. Generally, I use the marginal levelized unit cost of electricity values for the different sources based on literature values. Levelized unit cost is a way of comparing electricity sources based on the capital and operating costs on a single \$/kWh basis. However, levelized unit cost fails to account for important characteristics of these energy sources, such as intermittency and how easily they can be turned on or off (i.e., dispatched). Based on existing research these characteristics are extremely important in terms of economic value, yet ignored by calculations of levelized unit cost (Joskow, 2011). To address this weakness, I assume Metro Vancouver remains connected to the B.C. grid and so can access electricity from the existing hydroelectric system and contribute to it, thus taking advantage of the energy storage capacity of the hydro reservoirs, but net electricity use remains equivalent to total electricity production in Metro Vancouver. The cost for this storage is

set at two cents per kWh based on existing estimates of pumped storage construction (Poonpun & Jewell, 2008).

An additional challenge is the limited supply of liquid or gaseous transportation fuels in the Lower Mainland. The Lower Mainland could provide the energy equivalent of 3 per cent of existing gasoline and diesel sales with biofuels, including methane from waste. Intuitively, transportation costs should increase greatly; fortunately, electricity could substitute for gasoline and diesel in personal vehicles over a 40-year period. Meeting the energy needs of long-haul freight trucks is more difficult. Since fossil fuels cannot be used and there are insufficient local biofuels, freight must be powered using hydrogen fuel cells, where the hydrogen fuel is produced using electricity from local energy sources.

I met the local energy constraint by first incrementally increasing electricity and heat prices until all local energy supplies could be produced. Then, I imposed technology standards to reduce energy use by requiring energy efficient technologies in the market. The full list of technology standards is available in Appendix C. Finally, I modified assumptions about human behaviour that lead to energy conservation. For example, no combination of technologies in CIMS could allow for the same activities as occur in the BAU forecast and Limits scenario within the energy constraint. Thus, I had to constrain some activities like freight and personal mobility to remain within the energy limit. I limit these changes with reality checks. For example, if I decrease the intangible costs associated with transit, transit as a percentage of mode share should be in range of what is experienced in other cities of similar density.

While CIMS simulates how households and firms respond to transportation costs, it does not directly simulate how they respond to increased transit availability, shortened transportation distances and re-organized urban form that bring housing closer to places of employment, shops and schools. To simulate the impact of these changes I reduce the intangible costs associated with carpooling, transit and walking and biking by 10 per cent, 15 per cent and 25 per cent respectively. I compare the results of the simulation with these numbers to averages for Western European countries to ensure the results are reasonable. I also limit total kilometres travelled per person and freight kilometres travelled to 2010 levels because these parameters are not influenced by cost in CIMS

and cost is only one factor that determines the distance individuals travel (Giuliano & Dargay, 2006). Freight could be limited by zoning regulations that prevent port expansion, and limiting road construction which would increase freight transportation costs either because of greater congestion or road pricing.

Specific policies and assumptions are discussed in detail below.

- **Dwelling Size:** Dwelling size is the same as in the Limits scenario because people move into more apartments and attached houses as a result of land limits and increased density. However, building codes improve efficiency to a point where physical size contributes little to increased energy use. This result is similar to an Australian modeling study which showed that housing size had little influence on energy use for the most energy efficient houses (Clune, Morrissey, & Moore, 2012). However, there will be a higher capital cost, which I discuss in the results.
- **Dwelling Mix Type, Water, Waste and GHG:** These are set the same as in the Limits scenario.
- **Travel Rate:** Total travel per person in kilometres remains constant, which means travel per person declines at the same rate as population growth, which is 1.5 per cent. Travel, with the exception of biking and walking, consumes a significant portion of the available energy supply. I assume households and firms will respond to increased energy prices by travelling less, as well as shifting to less energy intensive travel modes. This decrease goes well beyond existing trends and what density increases alone would cause, but could result from increased driving costs and local service provision. However, it is extremely difficult to judge an individual's response to policy. Travel behaviour results from at least 11 important urban characteristics such as density, road networks and job types (Stead & Marshall, 2001). My assumptions seem reasonable in order of magnitude because UK residents with denser communities, alternative transit modes and more expensive car ownership and operation travel approximately 50 per cent less than their US counterparts (Giuliano & Narayan, 2003).
- **Freight Rate:** In this scenario truck freight remains at current levels by limiting port expansion. I had to break the freight and GDP connection for this scenario because

regardless of the freight technology, it was impossible to stay within the local energy limit while growing freight transportation.

- **Land:** Municipal, regional and provincial zoning policies limit total urban land area to 174,219 ha.
- **Air Quality:** Air emission policies in this scenario need not be as stringent because the energy limit significantly reduces local combustion of fossil fuels. I do include pollution control technologies for combustion of biomass, bio-methane and waste, but these are no more stringent than required for the combustion of those sources today.

Table 4 summarizes the assumptions for each scenario as discussed above.

Table 4: Summary of assumptions per scenario

Assumption	Business as Usual	Limits	Local Energy
Growth in Dwelling Size (m ²)	1.96 per cent / 5 years	1.96 per cent / 5 years	0 per cent
Building Mix	Existing Trends	Modified to fit land constraint	Modified to fit land constraint
Growth in Travel (km/yr)	0.2 per cent per person/year	-0.34 per cent	- 1.5 per cent
Growth in Freight (tonne km/yr)	3.16 per cent / yr (2010 to 2015) 2.48 per cent (2015 to 2050)	3.16 per cent / yr (2010 to 2015) 2.48 per cent (2015 to 2050)	0 per cent
Land	Existing trends	174,219 ha limit	174,219 ha limit
GHG	Federal emission vehicle standard	0.48 tonne CO _{2eq} / yr, suite of policies	0.48 tonne CO _{2eq} / yr, suite of policies
Water	No limit	224 Mm ³ limit	224 Mm ³ limit
Waste	70 per cent waste diversion	Zero waste landfilled by 2050	Zero waste landfilled by 2050
Air Quality	Existing policies	No increase in CACs from 2010 – targeted policies	No increase in CAC from 2010 – Existing policies
Local energy	No constraint	No constraint	Only local energy

Table 5 summarizes the policies for the BAU forecast and for the two scenarios. An “x” means the policy is included in the simulation.

Table 5: Summary of policies per scenario

Name	BAU	Limits	Local Energy
Greenhouse Gas Policies			
\$30 per tonne CO _{2eq} tax	x	x	x
Federal space and water heating standard	x	x	x
<i>Declining GHG intensity standard</i>			
160 g CO ₂ /km after 2015	x	x	x
<140 gCO ₂ /km after 2020		x	x
<70 gCO ₂ /km after 2030		x	x
Zero emission after 2040			x
Freight Standards – 150 g CO _{2eq} /tkm by 2035		x	x (declining standard)
Freight biodiesel 100 per cent standard 2030		x	
Water Policies			
Water restrictions during summer months		x	x
Waste			
Zero landfill of solid waste		x	x
Air Quality			
Marine fleet technology standards 2015		x	
Wood burning stove limit 2020		x	x
Street cleaning and tire replacement program		x	x
Construction PM		x	x
Land			
Zoning for urban land use limit		x	x
\$0.05 vehicle operating charge		x	
\$0.10 vehicle operating charge			x
Energy Efficiency			

Building code – 55 per cent increase in residential energy efficiency 2020			x
Building code – 34 per cent increase in commercial energy efficiency 2020			x
Technology standard – Zero GHG emission for new heating - 2020		x	x
Freight Limit – 9,000 million tkm 2015			x
Technology Standard – freight hydrogen vehicle requirement 2025			x
Technology Standard – most efficient household appliances 2015			x
Transit purchase policy – no gasoline, diesel, natural gas or hybrid buses 2030			x

3.4. The CIMS Community Model Simulations

The exogenous variables, parameters and policy assumptions then drive the evolution of energy producing and using technologies as simulated for each scenario in CIMS. As output, CIMS provides total energy consumption by energy form, GHG emissions, and costs associated with choices about buildings, technologies and energy forms. I measure the costs of policies in the BAU forecast and two scenarios using technical economic costs (TECs) for all the sectors covered in CIMS and life cycle costs of specific technology choices.

TECs include only the capital, operating and fuel costs associated with the simulated technology choices in CIMS, and these are calculated under the assumption that each technology in competition for a certain service presents identical capital cost risks. Using this admittedly biased estimate of costs, I nonetheless can then compare the BAU forecast with the two scenarios. Where possible, I extend this approach to estimating the costs of reducing CAC emissions and solid wastes going to landfill between BAU and the scenarios.

I calculate TEC for each scenario using the following equation:

Equation 2: Technical Economic Cost

$$\begin{aligned} TEC_{5\text{Year Period}} &= (Investment_{5\text{year period}} * Capital Cost Factor) \\ &+ (O\&M_{Annual} + Energy_{Annual}) * Annual Cost Factor \end{aligned}$$

Where:

Investment: Capital costs associated with a technology

Capital Cost Factor: Discounts 5 year capital costs

O & M annual: Annual operating and maintenance costs

Energy Annual: Annual cost of energy

Annual Cost Factor: Converts annual costs to a 5 year cost

Where:

$$Annual Cost Factor = \frac{(factor^4 + factor^3 + factor^2 + factor + 1)}{factor^5} = 4.33$$

$$factor = 1 + discount\ rate$$

Discount Rate = 5%

$$Capital Cost Factor = \frac{Annual Cost Factor}{5}$$

I chose a 5 per cent discount rate because the US Energy Information Administration also used this rate in a recent report to estimate policy costs (US Energy

Information Administration, 2010). Equation 2 represents the total five year capital, O&M and energy costs of all the technology choices in CIMS discounted to 2013 Canadian dollars.

However, TEC ignores intangible costs that arise from different operating environments, personal preferences, and capital cost risks (Jaffe & Stavins, 1994). Not all technologies perform the same in different environments, which is why the market for energy technologies is heterogeneous. Households and firms also have different personal preferences that may arise from status or values. For example, some people drive compact cars and others luxury sports utility vehicles that are more expensive to purchase and operate. TEC is obviously not the only factor when making technology decisions. The sports utility vehicle may offer status and functionality benefits above a compact car, for example. Studies also show that people make decisions based more on capital than operating costs. This means the average person may purchase a higher life cycle cost freezer than a lower life cycle cost version with a higher capital cost. There are also real costs associated with learning about and learning to use new technology, and new technologies fail more often. The result is that TEC is likely to significantly underestimate the cost of policies, especially how people perceive the costs.

While CIMS includes intangible costs when simulating technology adoption, it only calculates the TEC for the stock of technologies in any given year. To mitigate this weakness I estimate TEC and intangible – known as perceived private costs in CIMS – using a shadow price on carbon to achieve the GHG emission limit which is 0.48 tonne CO_{2eq} per person per year in 2050. I use this shadow price to create a marginal abatement cost curve and estimate the cost of carbon reductions. This is only an indication of perceived private costs because I do not account for the perceived private costs of land use, air emission, water use and waste disposal policies. In addition, the shadow price method cannot be adapted to the Local Energy scenario, so I can only speculate as to the perceived private cost of that scenario. The carbon shadow price and marginal abatement cost curve calculations are available in the appendix.

Other studies have shown that policy costs when including intangibles can range from 7 per cent to 251 per cent higher than TEC costs alone (Murphy & Jaccard, 2011; Peters, 2006; Rudd, 2012). In general, technology standards in the transportation sector

lead to low TECs but high intangible costs and GHG taxes result in the lowest discrepancy.

3.4.1. Service Cost Calculation

Another way I account for costs is by calculating the life cycle service costs for clothes washing, dish washing, food cooling (refrigerator and freezer), stove and oven, living space and driving 100km. The service costs are calculated based on specific technologies that exist in most homes (Bataille, 2007). For example, a dishwasher often provides the dishwashing service and a car provides the service of travelling 100km. This approach means I exclude other ways to accomplish these services; travelling could be done on a bus and you could wash dishes by hand. I assume most households continue to use household technologies to provide these services rather than other methods. I calculate service costs using life cycle costs that include intangible costs.

Equation 3: Life cycle cost calculation of technologies

$$LCC_{kt} = CC_{kt} * CRF_k + OM_{kt} + EC_{kt} + SC_{kt}$$

Where:

CC = Capital cost at time t and technology k

CRF = Capital recovery factor

OM = Operating and maintenance costs at time t and technology k

EC = Energy costs at time t and technology k

SC = Service costs at time t and technology k

$$CRF_k = \frac{r}{1 - (1 + r)^{-N}}$$

Where:

r = Discount rate – (diff. for each technology)

N = Lifespan of each technology

This calculation is relatively straightforward and most of the information already exists in CIMS; however, there are several important assumptions that are not explicit in the previous equations.

- **Declining Capital Costs:** Capital costs decline for new technologies in CIMS based on global production of a technology and cumulative production within the model. This feature attempts to account for measured declines in capital costs associated with learning by doing and economies of scale (Bataille, 2007). Learning by doing is the reduction in costs that comes as individuals and companies become more familiar with producing technology, while economies of scale exist when expanding an industry leads to reduced costs per unit output (Bannock et al., 1984).
- **Service Costs:** For the purpose of this report, service costs are the costs associated with hot water and heat provided by other technologies in the household. For example, some washing machines require hot water from a hot water heater that has a cost to purchase and operate.
- **Energy Price:** Energy prices vary with time and are set exogenously in each scenario. I set the price of natural gas, gasoline, diesel and heating oil using National Energy Board forecasted prices because Metro Vancouver is a relatively small energy consumer by global standards, and will have little influence on global prices (National Energy Board, 2011). Electricity, in contrast, depends on local energy generation decisions. However, I again used the National Energy Board forecast because both the BAU and Limits scenario result in the same electricity demand for Metro Vancouver. For the Local Energy scenario I develop energy prices based on the cost to develop local resources described in the Local Energy Calculation portion of Section 3.3.3. Electricity prices in this scenario rise by 324 per cent relative to BAU and the Limits scenario. Energy prices for each scenario are available in Appendix B and C.

- **Intangible Costs:** I include intangible costs in both the capital and operating cost variables in Equation 3. These intangibles represent the non-financial costs that may enter into investment or operating decisions. In general, intangible costs decline as market exposure increases and people perceive the risk or uncertainty of a technology as lessening. For example, someone buying a vehicle may be influenced by the cars their friends and neighbours drive to the point of sometimes overriding capital and operating cost considerations (Mau, Eyzaguirre, Jaccard, Collins-Dodd, & Tiedemann, 2008).

3.5. Urban Sustainability Model

I use an urban sustainability model to coordinate the exogenous parameters and variables for CIMS with projections for water use, waste disposal, CAC emissions and air quality, land use, and some costs and GHG emissions not accounted for in CIMS. The type, quality and source data varies for each of the physical limits, so each projection requires different assumptions. In addition, summarizing the projections for each limit is difficult because many of them are linked as shown in Figure 2, and so each projection is tied to other calculations in the urban sustainability model. In general, each projection is based on historical trends and extrapolation of existing models. For example, Metro Vancouver has projected its solid waste production (Metro Vancouver, 2012b). I modify these models as necessary to account for recent trends, policies and linkages that were not included in the original models. For example, I project Metro Vancouver's historical water use into the future and then link it to changes in housing type to account for reduced water use from smaller outdoor areas as the dwelling mix changes.

3.5.1. Water

I base water projections on 40 years of water data from a 2010 water use statistics report (Metro Vancouver, 2010b). Residential water use accounts for 55 per cent to 72 per cent of water use in Metro Vancouver municipalities (Environment Canada, 2011). I calculate average water use for June, July, August, September,

October and November because this is when the reservoirs are drawn down. I use the following equation to calculate future water supply requirements during the summer and early fall months.

Equation 4: Water demand equation

$$TW_t = POP_t \times (PCW_{t-5} \times (1 - WEF) \times (1 - LUF_t))$$

Where:

TW_t = Total water use for June, July, August, September, October and November at time t (Mm³)

POP_t = Metro Vancouver's population at time t

PCW_{t-5} = Per capita water use at time $t-5$ (Mm³/person/day)

WEF = Water efficiency factor that represents decline in average water use per five year period (per cent)

LUF_t = Land use factor that represents declines in water use associated with land use change (per cent)

Metro Vancouver's per capita water use has declined on average by 1.4 per cent per year since 1991. This decline has accelerated recently. Metro Vancouver has achieved these reductions by implementing lawn sprinkler regulations every summer since 1993 and, since 2005, encouraging the use of more efficient toilets, water fixtures and appliances. In addition, Metro Vancouver has implemented water conservation programs and improvements to water metering and leak detection (Metro Vancouver, 2010d). I assume these policies have achieved their reductions, and future water use reductions follow the background rate of per capita water use reductions of 1 per cent during the winter months, so the WEF term is 1 per cent. I use the winter months to indicate a background rate because winter water use is less susceptible to climate variations, and policies that would affect winter water use, such as water efficient appliances, are relatively recent.

Summer water use is also linked to outside water use, so I link housing type with outside water use and assume that every m² reduction in outdoor space results in an equivalent reduction in outside water use. The land use factor varies with the housing mix. On average, detached houses, attached houses and apartments have 172 m², 14m² and 4m² of landscape space respectively. The implication of this approach is that I assume, on average, attached houses and apartments use 92 per cent and 98 per cent less outside water than detached houses.

This equation also assumes that population drives water use, which is then curtailed by technology change, land constraints, housing type and policy. GDP could also drive water use, especially with non-residential uses. However, the data is not disaggregated by type of use so I could not calculate separate residential and non-residential water use projections.

To assess the plausibility of the causality implied by this equation, I compare its results with policy effects on water use in other jurisdictions. To acknowledge the likely increase in cost and resistance to marginal water reductions, I limit the effectiveness of existing water policies to 15 per cent of current water use per capita in Metro Vancouver. A 15 per cent reduction in Metro Vancouver's per capita water use reduces water use from 480 litres per day to 410 litres per day. I also compare the results of the equation with the lowest municipal water use achieved to date in a Canadian urban setting, which is 313 litres per person per day in Winnipeg (Environment Canada, 2011). Finally, I check total water use using a simple model of Metro Vancouver's reservoirs to determine whether the current reservoir system could maintain the projected water use levels. The results of Equation 4 change for each scenario based on changes in housing type and the water use policies I impose.

3.5.2. Solid Waste

Solid waste disposal is a combination of waste generation, type of waste generated, diversion and finally disposal. I calculate solid waste disposal using the following equation.

$$WL_t = POP_t \times (WPC_t \times (1-WRP) - WD_t - ER_t)$$

Where:

WL_t = Solid waste land-filled at time (t) (tonnes)

POP_t = Population at time (t)

WPC_t = Solid waste generation per capita at time (t) (tonnes/person - yr)

WRP = Solid waste reduction policy (per cent reduction)

WD_t = Solid waste diverted by recycling and organics collections at time (t)
(tonnes/person/yr)

ER_t = Solid waste diverted to waste-to-energy facilities at time (t)
(tonnes/person/yr)

I project waste generation per capita by correlating per capita waste generation with per capita GDP for Metro Vancouver. I assume GDP is the dominant factor because it correlates better with solid waste production than population alone. In this model, GDP drives an increase in waste, but recyclable material such as plastics and aluminum are recycled, organic waste is collected and composted (WD_t) and the residual material is incinerated in waste-to-energy facilities (ER_t). Waste reduction policy (WRP) can also reduce waste generation and so affect the quantity of waste delivered to the landfill. In the BAU forecast I do not limit solid waste disposal, but in the other scenarios I limit it so that the right hand side of the equation must equal zero or very close to it.

3.5.3. Land

I calculate land use following a simple equation.

Equation 5: Land-use equation

$$LU_t = POP_t \times (D_{t-5} + \Delta D_t)$$

Where:

LU_t = Land use at time (t) in hectares

POP_t = Population at time (t)

D_{t-5} = Density at time (t – 5 years) in people per hectare

ΔD_t = Change in density a time (t) in people per hectare

Density is generally defined as either net density or gross density (Hodge & Gordon, 2003). Net density refers to “the number of dwellings, households or persons being accommodated on a specific parcel of land” and does not include streets, laneways or other services (Hodge & Gordon, 2003). Gross density refers to “the number of dwelling units, households, or persons but this time includes the specified parcels of land and ... other community land uses considered relevant” (Hodge & Gordon, 2003). I use a version of gross density that I calculate by dividing Metro Vancouver’s population by the total area of: commercial, industrial, institutional, residential, transportation corridors, right of ways, ports, open land, recreational and protected areas.

The change in the density term (ΔD_t) is simply the increase or decrease in density as defined above during each time period. In the BAU forecast, I assume a constant increase in density based on historical trends, and that urban land area expands at historical rates. That is, the current urban area accommodates most of Metro Vancouver’s growing population, but some buildings are built in previously non-urban areas. In the Limits and Local Energy scenarios, I link the density term to changes in housing type because the housing mix changes more dramatically.

3.5.4. Criteria Air Contaminants

I calculate CACs using energy technology information from CIMS. In general, I disaggregate CACs into point sources – waste-to-energy and other, area sources – heating and other and mobile sources – light duty vehicles, heavy duty vehicles, marine sources and other. For the “other” categories I extrapolated Metro Vancouver air emission projections to 2050 using best-of-fit lines. I linked waste-to-energy emissions to outputs from the waste section and heat and light duty and heavy duty vehicles to energy use calculated in CIMS, and then calculated CAC emissions based on emission factors modified by future technology and policy assumptions.

I calculated marine emissions separately because of their relatively large contribution to certain CACs in the BAU forecast. For this sector, I assumed shipping growth rates, policies and technology change and then applied emission factors to the resulting quantity and type of marine shipping.

3.5.5. Greenhouse Gas Emissions

CIMS simulates energy technology choices by firms and households and the associated GHG emissions of these choices. The model includes the residential, commercial and light industrial sectors and includes transportation, building, household goods and heating technologies.

3.5.6. Methodology Summary

This methodology satisfies the objectives of this report because:

1. The model integrates population, GDP, GHG, CAC emissions, water use, land use and solid waste disposal for Metro Vancouver, and then links these measures to liveability measures relevant to people living in Metro Vancouver. The level of detail and assumptions are sufficient to simulate policies and calculate the impact on physical limits and liveability.
2. CIMS and the urban sustainability model determine the likely response of households and firms by simulating energy technology acquisition and, through literature research, I determined the most likely response to other policies such as water restrictions.
3. I use the three scenarios to explore possible futures for Metro Vancouver. These three scenarios cover current trends, the implications of existing goals in the region and the implications local energy production to meet the city's needs.
4. Finally, the model provides an indication of what the region's liveability in 2050 relative to BAU.

4. Results & Discussion

GDP and population increase at the same rate for the BAU forecast and the two scenarios. By 2050 Metro Vancouver's population has increased by just over 50 per cent and its economy has more than doubled. Figure 3 summarizes the GDP and population changes over time.

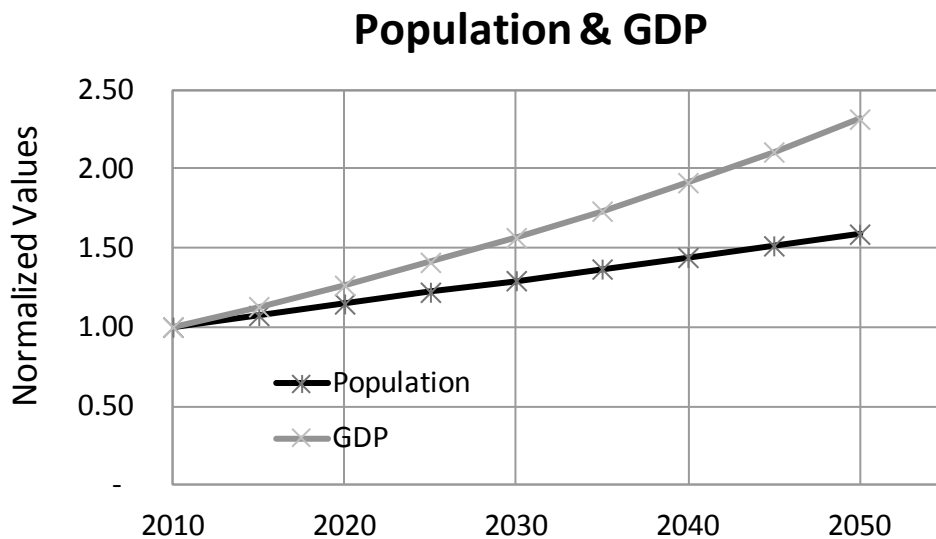


Figure 3: Change in population and GDP for BAU and each scenario

Population and GDP both grow, but at different rates. These rates are set exogenously which is why they are the same for BAU and each scenario. As the figure shows, population and economic growth continue in each scenario. Population grows by 50 per cent and the economy by 125 per cent.

In each of the following figures, the diamond markers chart the BAU forecast, the square markers the Limits scenario and the triangle markers the Local Energy scenario.

The results are normalized to 2010 to show the percentage increase and also to facilitate comparison.

In Figure 4 water use in the BAU forecast increases steadily to 30 per cent higher than current levels while water use first declines and then increases back up to the limit determined by the simulated policies and assumptions, following the same path for both the Limits and Local Energy scenarios.

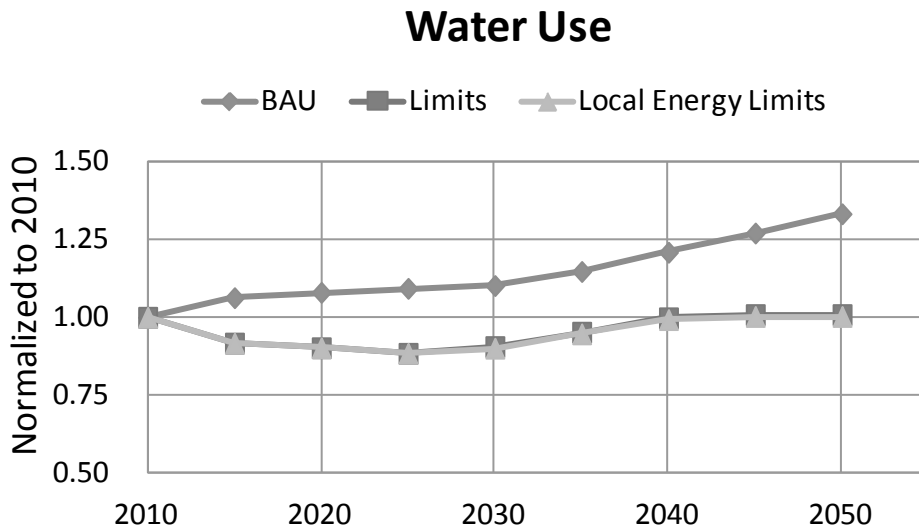


Figure 4: Change in water use for BAU and each scenario

The 30 per cent increase in the BAU forecast is a departure from recent trends. Between 1990 and 2010 Metro Vancouver’s water use remained constant because actions to increase the use of more efficient toilets, water fixtures and appliances, water conservation programs and improvements to water metering and leak detection meant water efficiency gains offset population growth (Metro Vancouver, 2010d). Future water efficiency gains at this scale will require new policies that will likely be more difficult to implement as the easy efficiency gains are exhausted. Water efficiency improvements still occur, but at a slower rate than population growth and so water use increases by 30 per cent.

In the Limits and Local Energy scenarios, households and firms use less water because residents live in houses with less outdoor space and therefore use less water

on gardens, landscaping and pools. This change, along with efficiency gains, is sufficient to keep water use at existing rates until 2040. At this point Metro Vancouver must impose outdoor water Stage 3 restrictions in its Water Shortage Response Plan which limits most outdoor water activities with the exception of hand watering and some commercial activities such as irrigating golf courses and sport fields (Metro Vancouver, 2011d). Since most people live in buildings with relatively small outdoor areas, the quality of life impacts would likely be limited to affluent neighbourhoods that still have landscaped areas to water. Water use in the agricultural land reserve would remain at existing rates; however, a significant increase in urban agriculture would have to rely on waste water, stored rain water or crops suited to Metro Vancouver's dry summers.

Part of the reason water use increases in the BAU forecast is because urban land use expands at historical rates to 5 per cent larger than today by 2050, allowing for more detached homes and outdoor water use. Growing roads, ports, and commercial land use also drives urban expansion. These land uses would expand further, but density trends partially mitigate their expansion. A 5 per cent increase in urban land area means 8 per cent of existing farming and recreational land is replaced by urban landscapes by 2050. Figure 5 shows the change in urban land area.

Urban Land Use

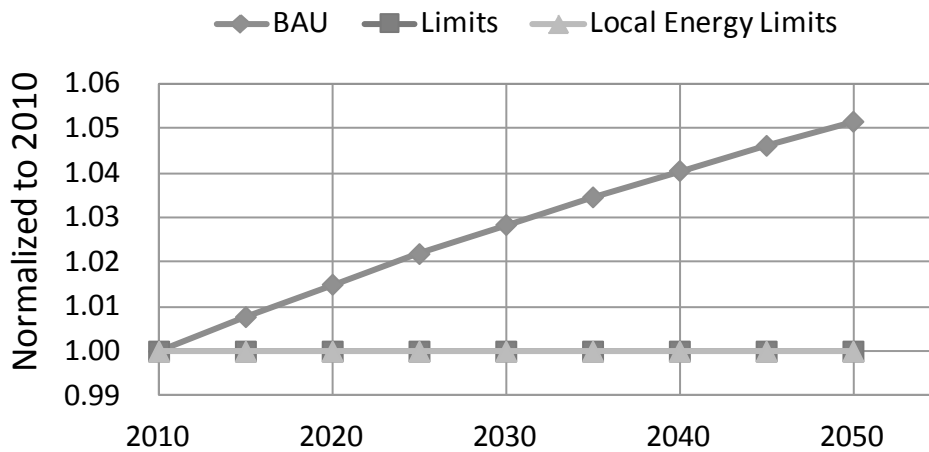


Figure 5: Change in land use for BAU and each scenario

In both scenarios, zoning protects agriculture and recreation land, which forces developers to build denser neighbourhoods to accommodate population growth. However, in the Local Energy scenario, most of the protected agriculture and recreation land is needed to grow crops for biofuels, forest lands are managed for fire wood production and solar panels cover most rooftops. This may limit some recreational uses and change the character of the region.

Land use zoning also helps reduce GHG emissions in the Limits and Local Energy scenarios. Both scenarios achieve climate targets, but initially emissions in the Limits scenario remain at 2010 levels until 2030 where they decline more rapidly to 2050. In combination, the \$30 per tonne CO_{2eq} carbon tax, declining vehicle GHG intensity standards starting in 2015, freight vehicle standards starting in 2035, heating technology standards starting in 2020 and increasing freight biodiesel requirement starting in 2015 drive down emissions. Higher density communities, resulting from land use zoning reduce travel and increase transit use, causing emission reductions. By 2050, the majority of personal vehicles are plug-in hybrid ethanol vehicles or electric vehicles, freight vehicles are primarily powered by biofuels and residential and commercial heating is primarily electric – either through heat pumps or electric resistance heating. By 2050 fossil fuels make up only 13 per cent of Metro Vancouver’s energy use, down from just under 75 per cent today. Figure 6 shows the GHG emissions

by source for 2010, BAU 2050, Limits 2050 and Energy Limits 2050 while Figure 7 summarizes the GHG emissions pathways for the BAU forecast and both scenarios.

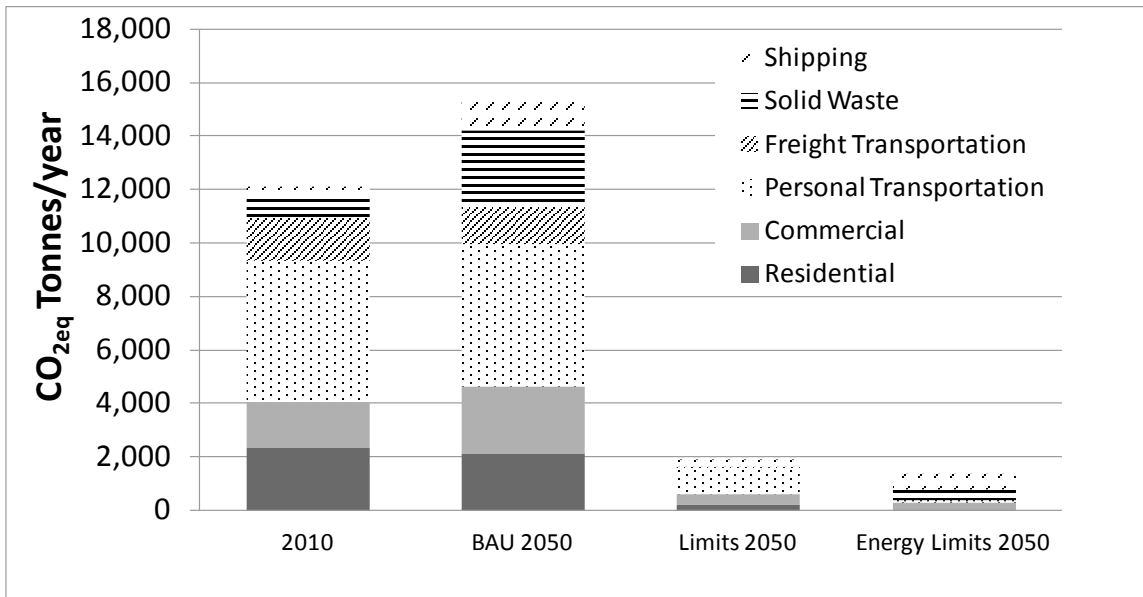


Figure 6: GHG emissions by source for 2010, BAU 2050, Limits 2050 and Energy Limits 2050.

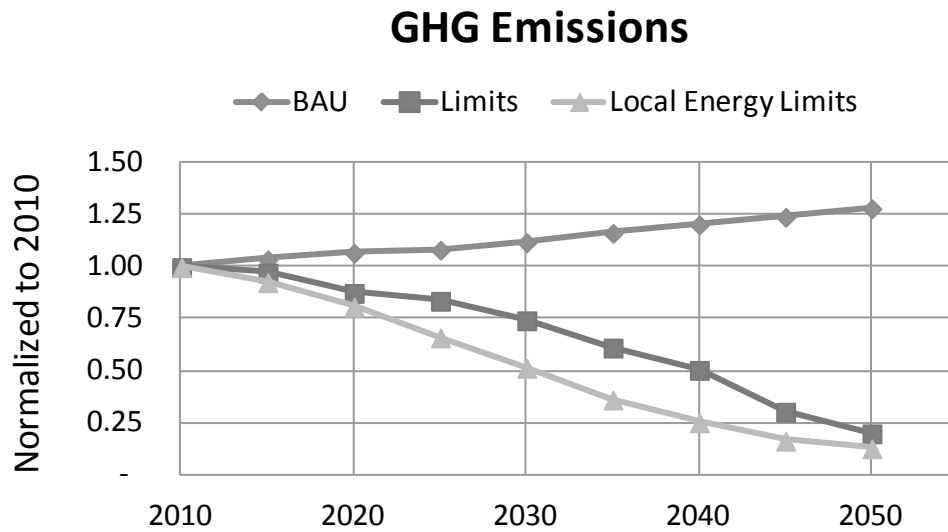


Figure 7: Change in GHG emissions for BAU and each scenario

In the Local Energy scenario, GHG emissions decline steadily from 2010 levels. This is primarily due to technology standards that require renewable energy use and minimum energy efficiency requirements complemented by policies that constrain certain activities such as a cap on freight that can be transported through the city. The Metro Vancouver government would be forced to adopt a freight limit because there is not enough local energy to support the energy requirements of a growing freight sector. Even a complete switch to electric and hydrogen trucks would leave little room for other energy services if freight growth continued.

Without the policies implemented in the Limits and Local Energy scenarios, GHG emissions increase by 25 per cent in the BAU forecast. Commercial buildings and waste are the main contributors while personal transportation emissions remain near present day values and residential emissions shrink. These emissions are far greater than Metro Vancouver’s targeted emission reductions of 15 per cent by 2015 and 33 per cent by 2020 from 2007 levels.

Air quality, summarized as smog, also degrades in BAU because CAC emissions increase. Freight and shipping increases drive NO_x increases in the model. Both marine vessels and freight vehicles become more fuel efficient and incorporate NO_x emission controls but growth in the number of vessels and vehicles outpaces both of these

improvements. PM increases primarily from road dust and dust from construction sites while solvent evaporation from paints and other chemicals, and light duty vehicle use drive VOC emission increases. All combustion sources lead to some increase in CO. The net effect of increases in each of these air contaminants is an increase in smog.

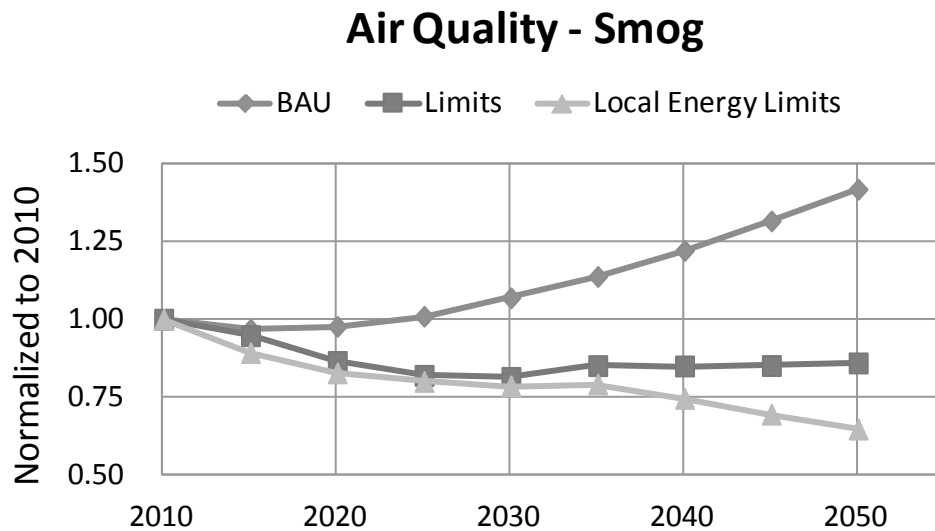


Figure 8: Change in smog for BAU and each scenario

In contrast, smog in the Limits scenario decreases slightly to 2030 but then worsens slightly and remains constant to 2050. A combination of less fossil fuel combustion driven by GHG emission policies, controls on NO_x controls on ships, and non-combustion PM policies reduce emissions, while they are increased by population growth and economic growth in the form of increased freight, increased shipping and housing size, and a shift to wood burning stoves. Air quality in the Local Energy scenario improves slightly more than the Limits scenario. However, these reductions result from significantly less combustion in Metro Vancouver as the demand for all fossil fuels are reduced through efficiency and conservation measures, and replaced by local sources of renewable energy. Combustion emissions decline to the point where additional air quality policies are unnecessary to achieve air quality objectives. Figure 9 shows the NO_x emissions per sector for 2010, the BAU 2050 forecast, Limits scenario and Local Energy scenario. This graph is an example of the scale of emission reductions and sectors covered in my analysis. Each CAC will have different emission sources and reduction pathways.

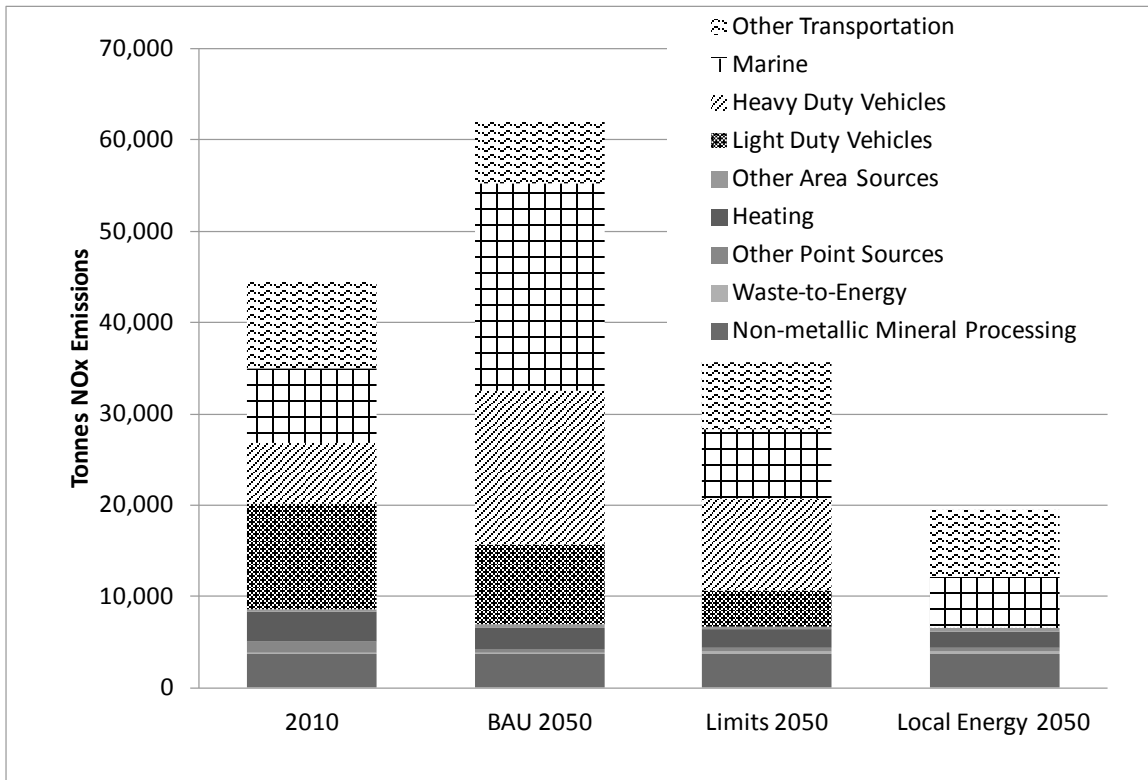


Figure 9: NO_x emissions by sector

CAC emissions are partially driven by the amount and type of energy used in the forecast and scenarios. In the BAU forecast, use of gasoline, diesel, natural gas and electricity all increase by about 40 per cent relative to 2010. This energy use explains much of the GHG and air quality changes described earlier. Gasoline, diesel, natural gas and electricity remain the dominant energy supply options in Metro Vancouver in 2050.

Conversely, both the Limits and Local Energy scenarios result in Metro Vancouverites using less energy and different types of energy. Building codes, vehicle standards, heating technology standards and land use policies mean households and firms choose more energy efficient technologies and switch to electricity and biofuels from natural gas, gasoline and diesel to meet their energy needs. By 2050 energy use is close to today's levels, but electricity and biofuels are the dominant energy carriers.

In the Local Energy scenario, stricter building codes, technology standards and land use policies result in much lower energy use and a switch to local renewable energy sources such as wind, solar, run-of-river hydro and biofuels from gasoline, diesel

and natural gas. By 2050, energy use is half of today's level despite the population growing by 50 per cent. Electricity produced from local renewable sources is the dominant energy carrier.

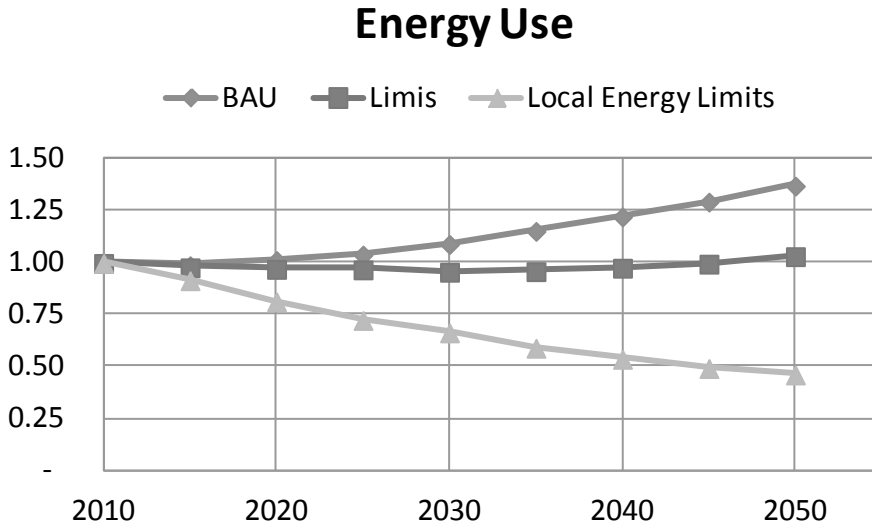


Figure 10: Change in energy use for BAU and each scenario

The forecast and two scenarios each include new incinerators that provide some additional energy and help reduce waste transferred to landfill. In the BAU forecast, Metro Vancouver recycles and composts 70 per cent of its waste while also building a 400,000 tonne per year incinerator. Until 2045, these changes reduce the amount waste going to landfill. However, population and economic growth drive increases in solid waste production, so by 2050 the amount of waste sent to landfills is greater than today.

In the two scenarios, Metro Vancouver imposes a ban on landfills and builds waste-to-energy facilities as necessary to accommodate the flow of solid waste as the population and economy grow. These facilities handle only residual waste after recyclables, organics have been removed. The result is that Metro Vancouver requires no new landfills and generates more electricity and heat from waste than today.

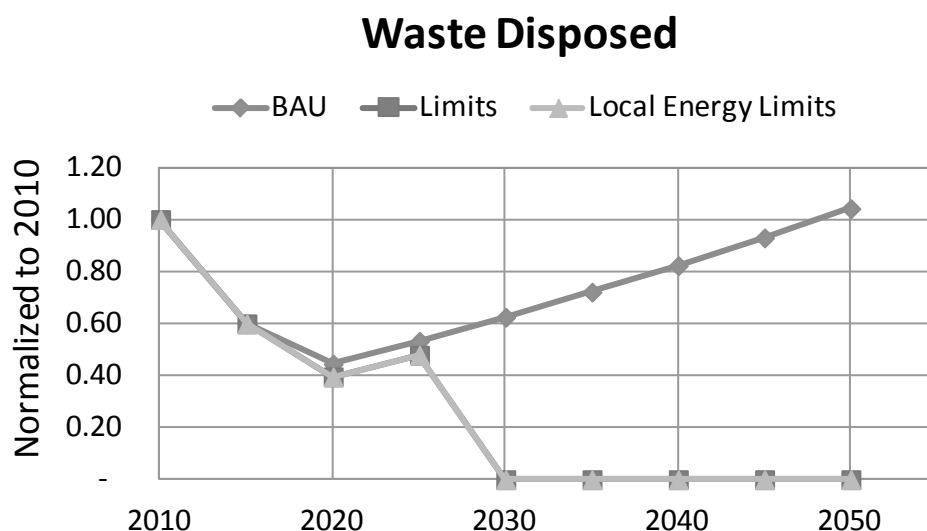


Figure 11: Change in solid waste disposal for BAU and each scenario

Regardless of which policies are implemented, individuals, firms and government must pay for new infrastructure and technologies. Figure 12 summarizes the technical economic costs (TECs) for each scenario. Recall that TECs include capital and operating costs, but not other costs like technology failure and changes in personal welfare. In the BAU forecast, TEC climbs in step with population growth, but at a slower rate than GDP. This implies that GDP increase outpaces costs, so Metro Vancouverites will have more money to spend on other goods and services; assuming everyone experiences this improvement equally. In the Limits scenario, despite seeming to follow the BAU forecast to 2050, the cost line conceals a dynamic with different implications for Metro Vancouver than the BAU forecast that I discuss later. In the Local Energy scenario TEC decreases significantly relative to the other two scenarios.

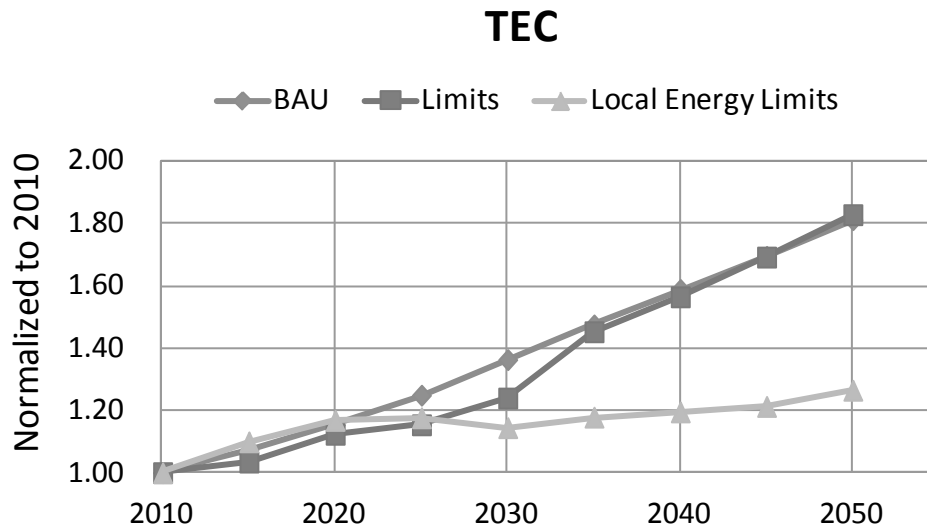


Figure 12: Change in TEC for BAU and each scenario

Metro Vancouver government policy encourages or forces firms and households to adopt a number of new technologies relative to the BAU forecast in the Limits and Local Energy scenarios. In the Limits scenario policy forces the adoption of either electric resistance or heat pumps for heating, denser communities and progressively less GHG intensive personal and freight vehicles. Some of these technologies cost more from a TEC perspective while others cost less so the net result are costs that are similar to the BAU forecast.

In the Local Energy scenario, costs are lower for two main reasons. First, people simply consume less. They drive less than in the 2050 BAU forecast and Limits scenario and there is less freight traffic in the city. Anyone could save money in this way today by simply staying at home or living within the walking limits of their community. These cost reductions would be seen as infringements by most, rather than cost savings – the very challenge with relying on TEC that I mentioned earlier. Second, new technologies allow for similar services at apparently lower costs. In this scenario, technology standards force the adoption of the most efficient technologies available. Initially these products are more expensive, but their capital costs decline as manufacturing increases.

Several studies have shown that TEC is a poor measure of cost because it does not account for costs such as technology failure, the risk of higher upfront capital costs

and intangible costs. These other costs can range anywhere from 7 per cent to 250 per cent higher than TECs depending on the specific policy and sector to which it is applied (Murphy & Jaccard, 2011; Peters, 2006; Rudd, 2012). Thus, factoring in these implicit costs will mean higher costs than just the TECs presented in Figure 12, especially in some critical areas such as housing and vehicles. Figure 13 shows an estimate of what these additional costs may be for the Limits scenario. I have excluded the Local Energy scenario from this graph because the method I have used to estimate intangible costs cannot be applied to the Local Energy scenario³.

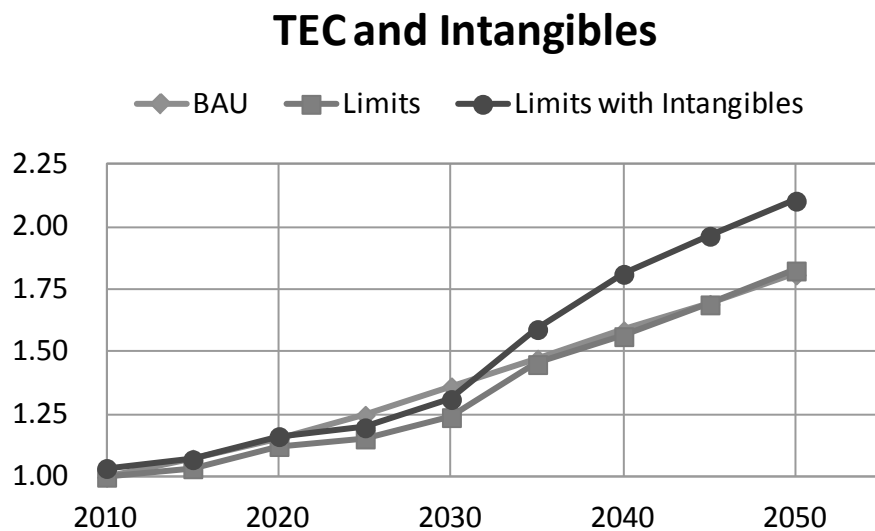


Figure 13: Intangible costs compared with TEC for the Limits scenario compared with BAU

The line with the circle markers represents the aggregate of these intangibles and the TECs and shows an additional 25 per cent increase in costs relative to BAU for the Limits scenario. The black line with the circle markers represents the costs of learning how to use and design new technologies, reflecting the higher failure rate of

³ To estimate intangible costs for the Limits scenario I determined the necessary carbon tax to achieve the GHG emission limit. I then used this information to determine a marginal abatement cost curve and estimate the total cost to Vancouver of reducing GHG emissions. However, in the Local Energy scenario meeting the energy limit would dominate intangible costs. Unfortunately, CIMS community does not have sufficient technology detail to estimate an equivalent marginal abatement cost curve for an energy limit. I expect the intangible costs would be much higher than the Limits Scenario, but did not estimate it.

new technologies and the fact that many new technologies will not be perfect substitutes. For instance, the transition from a gasoline powered automobile to plug-in electric vehicles will necessitate the development of supporting infrastructure, services, and a level of consumer familiarity with the product which currently exist for the former but not the latter.

In summary, Metro Vancouver can both increase population and its economy while meeting physical limits and a local energy limit using building codes, technology standards, taxes and zoning policies. These policies result in more investment in new technology, primarily buildings and vehicles, while also increasing density and changing the type of house in which people live. However, there will be costs to these policies especially when their full intangible costs and risks are considered.

4.1. 2050 Business as Usual Compared with 2010

The results in the previous section show that Metro Vancouver can stay within its physical limits while growing its economy and population. However, this has liveability tradeoffs in terms of environmental conditions, mobility, housing and costs for specific technologies. I show 9 liveability measures here to highlight the most significant tradeoffs for the BAU forecast and the two scenarios. Recall that I use life cycle costs (LCC) that account for the capital, operating and perceived value of the technologies.

The nine measures of liveability presented below for each scenario include: whether the physical limits have been met, energy use, kilometres of travel per person, percentage of km driven alone, the number of detached houses, average living space in m², the cost of a housing envelope per m², the average LCC of several consumer goods⁴ and the LCC of driving 100 km. Table 6 presents these results; the measure of liveability, the results for 2010, BAU 2050, Limits 2050 and Local Energy 2050. I discuss this table by first summarizing the results of the BAU scenario and then comparing each

⁴ I calculate the total LCC per household to own and operate a: dryer, clothes washer, dish washer, freezer, minor appliances – including things like televisions, a stove and a refrigerator.

measure with the Limits scenario. I then discuss the broader implications of the Limits scenario and finally discuss the Local Energy scenario.

Table 6: Summary of liveability tradeoffs per scenario in 2050

Measure	2010	BAU 2050	Limits 2050	Local Energy 2050
Environmental Conditions				
Physical Limits	-	No	Yes	Yes
Energy				
Energy (TJ)	250,000	340,000	250,000	110,000
Mobility				
Total Travel (km/person)	10,700	11,900	9,200	5,300
Driving Alone (% of total travel)	54%	60%	48%	15%
Housing				
Detached Houses	325,000	296,000	176,000	176,000
Average Housing Size (m ² /person)	140	150	140	140
Costs				
Housing Envelope Cost (\$/m ²)	\$ 8.70	\$ 8.80	\$ 8.50	\$ 12.60
Total Cost Household Items (\$)	\$ 3,100.00	\$ 3,100.00	\$ 3,100.00	\$ 3,600.00
100 km Drive (\$/100km)	\$ 15.00	\$ 15.00	\$ 22.00	\$ 32.00

In the BAU 2050 forecast, environmental conditions have worsened in Metro Vancouver relative to today. All of the physical limits, including CAC, water use, land use, solid waste disposal and GHG emissions have been surpassed. For example, 8 per cent of agricultural or forest land has been converted to urban landscape, GHG targets remain unmet, air quality deteriorates likely increasing respiratory illness and reducing visibility, landfills continue to expand and Metro Vancouver has expanded its water supply system. Rising population along with behaviour and technology choices in mobility and housing create these impacts. Assuming Metro Vancouverites would continue to value environmental qualities; these changes would likely impact liveability.

By 2050 under the BAU forecast, people travel approximately 1,000 km more than today and tend to drive alone more than in 2010. Although gasoline and diesel prices rise between 2010 and 2050, increasing fuel efficiency and decreasing costs for fuel efficient cars offsets this rise. CIMS simulates that by 2050 85 per cent of new vehicle sales will be high efficiency internal combustion engines and hybrids and the remaining 15 per cent will be electric or plug-in hybrids. In addition, the alternatives such as car pooling, transit and biking or walking do not become any more compelling. Metro Vancouver continues to build more transit infrastructure such as light rail and buses but also builds roads and bridges to accommodate increased traffic.

In the Limits scenario, the land use policy and a \$0.05/km vehicle operating charge reduce average travel per person to 9,200 km per year which is 1,500 km less than today and 2,600 km less than in the BAU 2050 forecast. In addition, driving alone decreases to 48 per cent of travel, compared with 54 per cent in 2010 and 60 per cent in the BAU 2050 forecast. The resultant split between types of mobility – known as a modal split – is close to other high-income world countries with high quality of life like Berlin and the resulting total distance travelled alone in a car is similar to Paris (Bai et al., 2012; Kenworthy & Laube, 1999). Thus, mobility in this scenario is different than today but could provide the same service as today, allowing people to get to work, go shopping, go to school and see friends and family.

Without strong policy to protect green space in the BAU forecast the number of detached homes and average living space per capita follow historical trends. Almost all new construction between 2010 and 2050 is attached houses or apartments and the detached housing stock declines by 30,000 houses, or 9 per cent compared to 2010. Despite this change, the average housing size remains close to today's level. Fewer people live in large detached homes but those houses are larger; as is the average size of attached houses and apartments. The change in housing type means Metro Vancouver is denser than today but is not dense enough to accommodate all population growth in existing developed land. A portion of new building occurs in the agricultural land reserve, which contributes to the 8 per cent reduction of agricultural land reserve discussed earlier. CAC and GHG emissions from buildings increase because of population and economic growth, which isn't offset by more energy efficient buildings or switching to less polluting forms of energy.

In the Limits scenario zoning that protects green space results in the replacement of 150,000 detached houses with apartments and attached houses. By 2050, 11 per cent of dwellings are detached houses, 55 per cent apartments and 33 per cent attached. This mix is similar to the BAU 2050 forecast where 19 per cent of houses are detached, 49 per cent are apartments and 31 per cent are attached. In addition, the average person lives in a smaller space than in the initial forecast, because attached houses and apartments are on average smaller than detached houses. However, this change is relatively small because average housing size remains equal to today. I

expect, this change in housing type would be seen as a negative impact for most, and could impact the liveability of the region.

Since few policies in the BAU forecast change energy prices and force technology adoption, firms and households experience little increase in costs. A 100 km drive in 2050 is \$15 which is virtually the same as today. Other costs such as dryers, clothes washers, dishwashers and freezers change little. Energy prices do increase slightly but don't meaningfully change the total cost of owning and operating household goods.

In the Limits scenario, driving costs, when accounting for the \$0.05/km operating charge, increase to \$22 per 100 km from \$15 in 2010. Both the operating charge and a declining GHG intensity standard on personal vehicles increase this cost. The GHG intensity standard forces the majority of new vehicles to be plug-in electric or pure electric by 2050. These vehicle types remain more expensive than today's gasoline vehicles when accounting for intangible costs. Collectively these policies drive a 70 per cent decline in GHG emissions in the personal transportation sector.

While driving costs change, other costs generally stay close to 2010 levels. The life cycle costs of building envelopes decline slightly, from \$8.70 to \$8.50 per m² in this scenario because residential and commercial building codes require buildings that are 30 per cent more efficient than today. Initially, these buildings are more expensive than standard buildings but capital costs decline with learning and familiarity as energy costs increase and by 2050 they cost less than standard construction in 2010. Other costs like refrigerators or stoves stay close to 2010 values.

The Limits scenario shows that Metro Vancouver could accommodate population and economic growth and stay within physical limits by adopting a suite of policies that include: zoning to protect the agricultural land reserve, transit investment, a \$0.05 per km vehicle operating charge, a vehicle levy on high GHG intensity vehicles, waste-to-energy facilities and technology standards for new building heating systems. The main tradeoffs by 2050 to Metro Vancouverites are shifting from detached houses to more apartments and attached houses, living in neighbourhoods where car ownership and driving alone are less necessary and adopting new and more expensive vehicle

technology. All of these processes are currently underway and have been for many years.

In the Limits scenario, households and firms respond to policy designed to meet physical limits by adopting energy efficiency technologies, conserving energy and switching from fossil fuels to biofuels and electricity generated from renewable energy resources. The result is an energy system powered primarily by electricity and biofuels that uses a similar amount of energy to today which is close to 250,000TJ. Today, 72 per cent of Metro Vancouver’s energy comes from fossil fuels and another 28 per cent from electricity. By 2050 in the Limits scenario electricity accounts for 59 per cent, biofuels 28 per cent and fossil fuels 13 per cent. Figure 14 shows for the energy mix for 2010 and Limits 2050.

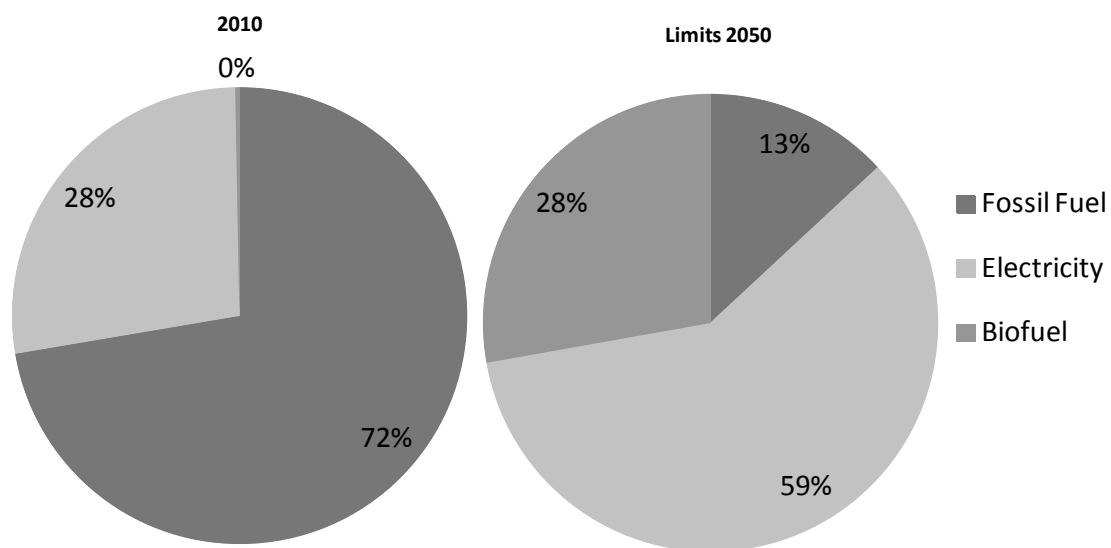


Figure 14: Energy mix for 2010 and Limits 2050

Expanding the quantity of energy consumption of the Limits scenario in 2050 to the globe also appears realistic. If everyone consumed the same level of energy as a Metro Vancouverite in 2050, global energy use would be 576 EJ. Accounting roughly for the losses to produce this energy and non-urban energy use brings this number to 1,246

EJ⁵ which is within the International Institute for Applied Systems Analysis' estimates of a sustainable energy supply of 1,050 EJ (Riahi et al., 2013). But this future is not without impact. Metro Vancouver will require an additional 15,000 GWhr (0.054 EJ) of electricity to replace existing fossil fuel use, which is equivalent to roughly 25 per cent of B.C.'s current electricity production, or three Site C dams (BC Hydro, 2013a). However, this amount of electricity is well within B.C.'s supply capacity given B.C. Hydro's current estimates of wind and hydro resources in the province (BC Hydro, 2013b).

In the Local Energy scenario, I limit energy supply to what might be produced within the Metro Vancouver area and simulate policies designed to plausibly drive the necessary technology development and behaviour to stay within the supply limit. As Table 6 at the beginning of this section shows, local energy supplies provide just over a 100,000 TJ, about 57 per cent less than existing energy use. To stay within the energy limit I use stricter energy efficiency standards on buildings, personal vehicles and freight vehicles that result in more severe mobility, housing cost and land use tradeoffs.

On average individuals travel 5,300 km per year – 50 per cent less than today – and drive alone for only 15 per cent of that travel distance. Instead of driving alone, people choose transit (35 per cent), car pooling (29 per cent), and biking and walking (22 per cent) to get around. While a significant departure from how Metro Vancouverites get around today, this mix is still within high-income country standards. For example, the mix of travel options is similar to European cities such as Copenhagen while the total amount of travel is similar to the United Kingdom (Giuliano & Narayan, 2003). Since people in other high income countries enjoy a high quality of life with these levels of mobility, it is reasonable to presume that Metro Vancouverites could as well. However, the transition to 2050 will involve very real quality of life changes for many people.

Unlike mobility, housing is relatively unchanged compared with the Limits scenario. Land use policy limits the amount of developable land, so developers and Metro Vancouverites choose denser building types such as apartments and attached houses, just as a growing percentage have been for some years. Housing size is not

⁵ Non-urban energy use is estimated at 23 per cent of the global total today, and the average conversion from primary to final energy use is 69 per cent (Bai et al., 2012)

constrained by energy limits because Metro Vancouver implements building standards that require houses that are so efficient that total floor space has little impact on total energy use. For those people who want to live in large detached houses, these changes will likely decrease the liveability of the region, but others may appreciate the diverse selection of apartments and attached houses.

Energy efficient buildings do, however, come at a cost. The energy related LCC of buildings increases to \$12.60 compared to \$8.70 per m² today. In addition, when the residential and commercial building codes are first introduced, the cost per m² is even higher than \$12.60. For example, today apartment building envelope costs – LCC with intangible costs – are \$8.70/m² while an equivalent apartment that is 55 per cent more energy efficient is 100 per cent more expensive at \$18.00/m². In this scenario I simulate a building code that requires all new buildings to be 55 per cent more energy efficient than standard buildings while concurrently imposing technology standards for local energy generation. Together, these policies increased the capital costs of new buildings while also increasing electricity cost and so the operating costs of existing and new buildings. By 2050 electricity prices are 400 per cent higher than today. However, new building LCCs decrease sharply as capital costs decline due to learning and economies of scale and intangible costs decline with technology risk and as households and firms become used to the technology. As energy efficient buildings decrease in price, standard buildings increase with increasing energy prices. By 2050, the LCC of standard building envelopes is \$15.00/m² while energy efficient envelopes are \$12.60/m². By 2050, the average person will pay \$500 per year more to live in an energy efficient building powered by local renewable energy sources. Since housing affordability for both renters and owners is a priority issue for many Metro Vancouverites, this level of price increase will likely be resisted.

Policy also increases driving costs to \$32.00 per 100 km compared with \$15.00 today. The \$0.10/km vehicle operating charge, higher costs for electric vehicles and higher electricity costs combine to create this higher cost.

Another tradeoff in this scenario is the quality of remaining green space. The quantity of green space remains the same as today but forestry land is now dedicated to providing wood and other biomass for heating and electricity generation in the city and

all crop land is dedicated to producing biofuels for the few vehicles that require them. Run-of-river hydro stations exist on every river that could sustain a 500 kW turbine and five geothermal and two wind turbine sites take advantage of local resources. Therefore, while land use technically remains the same – forest and agriculture – its character has changed considerably.

The cost of local energy dependence in terms of liveability is therefore more expensive housing, far less mobility – but potentially still within high-income world standards – and all green space is now dedicated to energy production. The only benefit is reducing energy production impacts outside Metro Vancouver's borders, which relative to the Limits scenario were limited to hydroelectricity generation and biofuel production. For Metro Vancouver, this admittedly high-level analysis suggests that there are potentially substantial costs to relying on local energy, although the benefit is less disturbance of the environment in the regions of the province, country and planet where the cities energy would otherwise have been produced.

4.2. Economic Growth and Limits

While some question whether sustained economic growth is possible for a variety of reasons (Daly, 1996; Jackson, 2009; Victor & Rosenbluth, 2007b), I assume in this study that economic growth can continue in all scenarios to the year 2050. Here I consider the implications of the policies I implement in the Limits and Local Energy scenarios on Metro Vancouver's economic growth. I focus my discussion on the implications of land, GHG and local energy policies because the costs associated with meeting air quality, water and waste limits are less significant⁶.

⁶ For example, the Canadian government expects the costs of implementing the MARPOL regulations for marine vessels at \$65 million per year from 2013 to 2032 with a benefit of \$1.8 billion per year (Canada Gazette, 2012), using landfills or incinerators to treat waste have comparable TEC (AECOM, 2009) and water reductions are primarily achieved through density changes and ongoing indoor water efficiency improvements.

4.2.1. Limits Scenario

In the Limits scenario, I attempted to meet constraints with as little departure as possible from behavioural norms assumed in the BAU forecast. I assumed that people generally want to move around in the same way, expect bigger houses and do not immediately trust new technology. Since behaviour does not change significantly, technology change is the primary way physical limits are met. Driven by policy, freight, building and vehicle technology change significantly.

Freight, shipping and ports expand as usual in this scenario. However, trucks in Metro Vancouver ultimately switch to biodiesel by 2050. Biodiesel is approximately 60 per cent more expensive than diesel in the BAU forecast, but this increased cost is partially mitigated by a shift to more efficient vehicles. In addition, the shift to biodiesel occurs over 30 years which provides time to refine vehicle technology. Shipping costs are also pushed upwards by land use zoning to protect green space, as this policy limits the amount of land for port expansion. However, this cost could also be mitigated or avoided by additional zoning to reserve land for port expansion within existing urban areas. Whether these changes would decrease economic growth in Metro Vancouver depends on whether other jurisdictions adopt similar policies, and the cost advantage Metro Vancouver ports have over other regions. All things being equal, I expect freight and shipping would likely be more expensive than in the BAU forecast and so there would likely be less economic growth in this sector.

More restrictive building codes on the other hand may increase economic growth. Assuming capital and intangible costs decline as expected, then building codes should increase energy efficiency while decreasing costs by 2050 relative to the BAU forecast. Theoretically, this suggests economic growth potential because technology and knowledge substitute for energy, and provide a service that is less energy intense. The energy savings could then lead to increased demand for other products and services. This is the energy efficiency growth engine discussed in the introduction (Ayres & Vandenbergh, 2005). However, getting to this point requires several years of experimental building design that, at least for the pioneers, will be expensive. Since most of Metro Vancouver's economy is based on services, as building costs decrease the service sector should be positively affected by these changes.

Similarly, personal vehicle technology looks less promising as a source of economic growth. Vehicles become more energy efficient and less GHG intense but at a higher perceived cost between 2010 and 2050. In this case, scientific progress and individual knowledge are unable to produce an equivalent product that uses less energy and saves money. Metro Vancouverites would then have less money to spend on other goods and services and so reduce economic growth. There are of course other ways to travel than a vehicle, and improved transit service may reduce mobility costs for many while providing a near equivalent level of service for some trips.

In the Limits scenario, weighted average energy prices increase by 25 per cent from the BAU forecast by 2050. This occurs primarily because electricity and biofuels substitutes for fossil fuels. Biodiesel is 60 per cent more expensive than gasoline or diesel while electricity is 20 per cent cheaper than these two fuels, but 60 per cent more expensive than natural gas. An immediate energy price increase would likely reduce GDP as the world experienced after energy price jumps in 1973 – 74 and 1978 – 80 (Bretschger, 2013). However, economies can adapt to energy price increases over the long-run (Gardner & Joutz, 2013). Energy prices in this scenario remain similar to the BAU forecast until 2035. In 2035, the biodiesel requirement for freight and the heating technology standard force a switch from cheaper diesel and natural gas to biodiesel and electricity. The Metro Vancouver economy does adapt to these higher energy costs by adopting energy efficient technologies and so the impact of these energy prices is less severe. For example, the cost of driving increases by only 15 per cent because of the biofuel requirement. This could slow economic growth although the specific effect is difficult to estimate because economies adjust to price changes. For example, German energy prices exceed prices in Metro Vancouver by 300 per cent for electricity, 60 per cent for natural gas prices, and 80 per cent for gasoline, yet its economic growth has been comparable (European Commission, 2013; International Monetary Fund, 2013).

I also expect that population growth would continue under the Limits scenario because the simulated costs are within historical cost increases that have had little impact on population growth. Over the past 20 years costs in Metro Vancouver the consumer price index has increased 40 percentage points and energy costs 90 percentage points (Statistics Canada, 2013). While many cities in Canada have experienced these increases, Metro Vancouver has experienced the most significant

increases. For example, Metro Vancouver is now second only to Toronto as the most expensive city in Canada to live, and is the most expensive city to own a house or rent an apartment. On average, a house in Metro Vancouver is now \$290,000 more than any other city in Canada (The Canadian Real Estate Association, 2013). Despite these cost increases and Metro Vancouver's relatively high cost of living, Metro Vancouver's population has grown by 1 to 3 per cent each year since 1990. Yet Metro Vancouver is also consistently voted one of the most liveable cities in the world, in part because of its relatively clean air, clean water, attractive communities, job opportunities, and beautiful surrounding environment.

In the Limits scenario I project energy prices will increase 25 per cent more than in the BAU forecast, and estimate total perceived costs will increase an additional 25 per cent. These cost increases are less than what the region has experienced over the past 20 years, and will occur over a longer 40-year timeframe. In addition, direct energy costs, such as spending on gasoline, diesel, natural gas and electricity, today are 5 per cent of an average family's income in British Columbia (BC Stats, 2012a). A 25 per cent increase, even assuming no increase in household income, and no technology or behavioural change to increasing energy prices, would increase direct energy costs to only 6.25 per cent of average household income.

Still, for the poorer populations in Metro Vancouver, some 20% of the population, these energy price increases would increase energy expenditures from 15% to 19%; an appreciable change with real quality of life implications. However, these policies can be modified to shelter low-income households from these increasing costs either through direct financial support or support to purchase more energy efficient appliances. For example, some of the vehicle operating charge revenues could be provided to lower-income families, or to support the purchase of energy efficient appliances. In addition, the policies lead to a denser region that requires less car travel, which for some families would limit reliance on private vehicles which account on average for 36% of a low-income family's budget (BC Stats, 2012b).

In this brief analysis, there are no obvious sectors that would decline significantly because of the imposition of physical limits on land-use, inputs and waste streams, at least not in the long-term. However, growth in some industries may be affected.

Vancouver can continue as a trade and service focused city so long as these changes do not make it uncompetitive relative to others. In the short term, those forced to adopt new technologies would likely pay more for the same service to pay for later benefits (lower capital costs and intangible costs) for others. Governments could partly subsidize these technologies during start-up using revenues from vehicle operating charges and modest fuel taxes.

4.2.2. Local Energy Scenario

While it is reasonable to expect continued economic and population growth in the Limits scenario, the Energy Limits would stiffen the challenge of sustaining economic growth. Available zero- and low-emission energy in the Lower Mainland is 57 per cent lower than today's energy use and 69 per cent lower than BAU energy use in 2050. Local energy is also limited to heat and renewable sources that can be converted to electricity, with little liquid fuels that could immediately substitute for transportation fuels. Generally, new energy efficient technologies are unable to provide the same service level that Vancouverites experience in the BAU and Limits scenario. Both personal transportation and freight are significantly curtailed by energy policies. Freight transport remains at current levels, as opposed to almost tripling in the BAU forecast and Limits scenario, and individuals are forced to travel almost 50 per cent less and 70 per cent less alone in a car than in the BAU forecast and Limits scenario. Limiting trade, an important economic driver in Vancouver, would certainly decrease economic growth. Reducing personal travel may also have economic impacts, but this depends on how effectively urban form can evolve to reduce the need for mobility. International comparisons of cities show little correlation between car ownership and economic prosperity (Kenworthy & Laube, 1999).

Staying within local energy limits is likely to require changes in building design relative to the BAU or Limits scenario. New buildings in the Limits scenario remain much more expensive than buildings today or those in the BAU forecast and Limits scenario. It is unlikely that building technology in this scenario would be a source of economic growth. Since building costs are higher, the service sector would likely be paying more for workspace than in the Limits scenario, which may further constrain economic growth.

The price of energy in this scenario is also 280 per cent higher than the BAU forecast. This increase is significantly higher than any other high-income country's energy prices. Moreover, my energy cost estimate is likely an underestimate because one would expect that with greater demand for energy than what's locally available would drive price beyond the levelized cost of the most expensive local energy source in this assessment.

Clearly, relying on only local energy supplies will eliminate or drastically change some industries in Vancouver, depressing critical drivers of economic growth like relatively low energy prices. Ayres postulates that economic growth could still continue with limited and even declining resource use so long as resource productivity and labour productivity rise enough to offset this (Ayres & Vandenberg, 2005). Essentially, the economy would grow by using intensive knowledge to reduce material and energy use while also increasing productivity. Such an economy would focus on services as opposed to material goods. This seems reasonable at a city scale because Vancouver's service sector is already dominant. Perhaps Vancouver's economy could continue to expand by delivering energy efficiency improvements to the resource sector outside its borders, or by exporting energy efficient technologies. However, Vancouver's economy would more likely suffer and as would its desirability as a city to live in.

4.3. Limitations

This study considers whether Vancouver could grow its economy and population, stay within physical limits and maintain liveability. I used a BAU forecast and two scenarios combined with a technology choice simulation model to explore this issue. These simulations were based on numerous assumptions. However, there are at least four major concerns with the approach I have chosen: 1. the arbitrary nature of a physical boundary for Vancouver, 2. the degree to which I have included critical feedback effects, 3. the estimation and treatment of costs and 4. the definition or scope of a concept like liveability. I discuss each briefly below.

1. **Physical Boundary:** Metropolitan Vancouver's political boundary acts as the physical boundary for my analysis. However, meeting regional physical limits at

the expense of increasing impacts outside the boundary may be counterproductive, especially when considering a global concern such as GHG emissions. The Local Energy scenario attempts to address this deficiency from an energy perspective, but the use of materials which originate elsewhere, such as steel, wood and consumer goods, should also be considered. I focus on energy in part because it represents the majority of Metro Vancouver's impacts according to the ecological footprint approach and globally energy is responsible for the majority of GHG emissions (IPCC, 2014; Moore, Kissinger, & Rees, 2013).

2. **Food:** I have also not required the Vancouver area to produce all of its food, and so do not account for impacts associated with food production. Incorporating these impacts outside Metro Vancouver would complement this analysis but the policies simulated in the Limits scenario would still be necessary and the resultant trade-offs would still exist. Thus excluding food does not detract from the results of this work. For example, I simulate policies to protect the agricultural land reserve that is necessary for local food production. Although, in the Local Energy scenario there is direct competition between biofuel and food production. However, the quantity of biofuels produced from this land is minimal, and it could equally remain in food production with little change to the results of that scenario.
3. **Feedbacks:** I exclude, in the modelling at least, population and economic growth feedbacks in all scenarios and energy price feedbacks in the Local Energy scenario. I assume that population and economic growth will continue primarily because I'm interested in the challenge of meeting physical limits in the context of sustained economic and population growth. However, this assumption implicitly assumes that the policies I implement do not make Vancouver a less desirable place to live, including one with a significantly lower level of economic well-being. This limitation is particularly important in the Local Energy scenario, where I do not account for the feedback of energy price increases on economic output and population.
4. **Costs:** I do not include intangible cost data for solid waste disposal, water use, air emission, land use regulations or technologies because of data limitations.

For example, water efficient appliances like showerheads or toilets may not be equivalent substitutes for existing technology for some individuals and households. Thus, I likely underestimate the costs of policies associated with waste, water, CAC emissions and land use. I also do not calculate intangible costs for the Local Energy scenario.

- 5. Scope of Liveability:** Liveability is a broad term that encompasses health, education, political voice, personal activity, social connection, environmental conditions, security and equality. I measure aspects of cost, housing, mobility and other effects which have implications for environmental conditions, health and security. However, questions of education, political voice, personal activity, social connection and equality can be considered separately from this analysis and are more a question of social policy design than whether meeting physical limits will inherently impact these other aspects of liveability. For example, policies can be designed to reduce income inequality by dedicating a portion of revenues raised from policies like a vehicle operating charge to lower-income families.

5. Conclusions and Recommendations

Urban populations are growing around the world and account for the majority of global resource consumption. Thus, implementing sustainability policies in these jurisdictions can play a key role in terms of sustainability objectives, even at a global scale. Still, while many cities espouse sustainability, they have yet to implement a comprehensive set of policies to achieve their goals. This is in part because of difficult tradeoffs between economic and population growth, physical limits and quality of life.

I used Vancouver as a case study to explore the liveability tradeoffs of implementing policy to achieve a set of physical limits on CAC emissions, water use, GHG emissions, land use and solid waste disposal in the context of sustained economic and population growth. I did this by testing a BAU forecast and two scenarios: the Limits scenario that incorporated the physical limits listed above and; the Local Energy scenario that added a local energy constraint. I used these scenarios to answer three main questions:

1. Can Vancouver's population and economy grow while meeting physical limits and maintaining a liveable region?
2. What tradeoffs must individuals make for Vancouver to stay within its physical limits?
3. What are the implications of this case study on broader discussions of physical limits to economic growth?

In short, the answer to the first question is, yes, it could. But doing so requires strict policies and a departure from BAU. In the BAU forecast, population and economic growth drive Vancouver past all the physical limits of my study, most of which are based on aspirations of municipal, regional and national governments. Under BAU, people can live similar lives to today in terms of mobility, housing and costs, but this likely means a

decline in liveability as many people would be negatively affected by the resulting loss of green space, clean air, a stable climate, sufficient water, and other amenities.

However, municipal policy can enforce physical limits at least within municipal boundaries and this will affect the technology and even lifestyle choices of households and firms. The Limits scenario demonstrates that mandatory policies, such as a declining GHG intensity standard for personal vehicles, a 100 per cent biodiesel requirement for freight vehicles, land use zoning to prevent urban expansion, and a technology standard for low-GHG heating equipment are necessary to remain within physical limits. Voluntary and educational policies are also necessary, but will probably be needed to augment and support mandatory policies. Vancouver could also produce all of its energy locally using mandatory policies, but they would have to be even stricter. For example, I impose a residential building code that requires all new buildings to be 55 per cent more energy efficient than today, and requires all heating to come from zero-GHG sources like heat-pumps and electric resistance heating. While these scenarios demonstrate that policies can be used to stay within physical limits and even energy limits, there are tradeoffs.

In the Limits scenario, land use policies drive people to purchase attached homes and apartments, while the number of detached houses declines relative to the BAU forecast. The result is denser communities that can involve less mobility, especially driving in a personal vehicle. And when this is combined with policies, such as vehicle operating charges and transit infrastructure, at some point people will drive considerably less and use more transit, walking and biking. Additionally, the vehicles that people would drive are hybrid or electric because a declining GHG-intensity standard has pushed other types of cars out of the market. The primary loss will be less opportunity for people to live in detached homes and less willingness to drive alone in one's car because of the high cost. These tradeoffs, though, are partially mitigated by alternatives to driving alone such as better transit, and denser neighbourhoods with closer services and a more diverse attached and apartment building stock.

Economic growth and population growth would likely continue under the Limits scenario. Vancouver's economic base is primarily service-oriented and this analysis shows that energy related building costs remain relatively close to today's levels.

However, economic activity at the port may shrink relative to BAU because there are fewer options for increasing the energy efficiency of its freight truck fleet, and so costs will likely increase. Still, port activities may continue to expand, assuming this cost increase does not constrain operations.

Population growth should also continue despite these policies, since population growth has occurred over the past 20 years despite significant cost increases in housing and energy. Simulated energy costs increase by 25 per cent relative to the BAU forecast; however, Vancouver will still have the attributes that make it a desirable place to live: clean air and water, accessible communities and beautiful surrounding environment.

However, the Limits scenario does not account for changes outside its borders. In the Local Energy scenario I use policies to constrain energy use to the type and quantity available in the region. Because of these policies, people travel 50 per cent less and drive alone 70 per cent less, while also spending 20 per cent more on the building envelope portion of their houses. Pursuing local energy dependence results in the same GHG emissions, CAC, land use, water use and solid waste disposal, but is a more drastic departure from BAU.

Even constrained to local energy limits, Vancouver's economy could theoretically continue to grow, but it would be much more challenging than under the Limits scenario. To depend exclusively on locally-produced energy requires the adoption of extremely efficient building and vehicles. While such technologies exist, it is unlikely that they will be exact substitutes for existing buildings and vehicles.

It appears that within Vancouver at least, economic and population growth could continue within physical limits and provide similar to better liveability than today. But, the ultimate purpose of these policies is to help achieve sustainability where national and international policies have failed. So do these policies make Vancouver sustainable? Recall the definition I use; a sustainable city must organize itself to not only preserve its own natural systems for its own people and the local environment but also preserve global natural resources and environmental systems. In both scenarios, Vancouver protects its own natural systems to the benefit of its people and environment while

organizing itself in a way that reduces its current impact on the natural environment. Based on CAC emissions, water use, GHG emissions, land use, solid waste disposal and energy measures, Vancouver could sustain itself for the next 40 years and likely beyond. However, continued economic and population growth necessitates continuous innovation to improve the resource efficiency of the economy, and stringent policy to establish and enforce physical limits.

Over the next 40 years, policy can encourage efficiency gains that may support continued economic growth and maintain or improve liveability. But even over the next 40 years, my modeling shows some innovation limits when it comes to the costs of a more sustainable path. In the Local Energy scenario, Vancouver buildings and vehicles become significantly more efficient, but remain more expensive than today. Given the limited technologies in CIMS it appears that some services we enjoy today may not be compatible with an energy limit. For example, driving alone in a car for the majority of our trips.

In summary, I believe it is possible, and in Vancouver's best interest to implement policies that enforce physical limits. Achieving limits does not mean Vancouver is sustainable, and this is virtually impossible to define definitively anyway, but it will support liveability in the region while also making it easier to pursue meaningful sustainability policy at a global level. Pursuing Local Energy on the other hand appears to be an unnecessary hardship for Vancouver; still, developing cities around the world may find this path more appealing. Table 7, on the following page, summarizes the near and long-term policies, and trade-offs for each scenario.

Table 7: Summary of primary near and long-term policies and tradeoffs for each scenario relative to 2010

Scenario	ACTIONS		TRADEOFFS by 2050	
	Near Term Policies - 2020	Long Term Policies - 2040	Negative	Positive
BAU	No additional Policy	No Additional Policy	<ul style="list-style-type: none"> • Exceed all physical limits 	<ul style="list-style-type: none"> • \$0 per km driven increase • Consistency
Limits	<ul style="list-style-type: none"> • Zoning to protect ALR • Transit investment • Vehicle operating charge: \$0.02/km • Vehicle intensity standard: <140 gCO₂/km • Waste-to-Energy 	<ul style="list-style-type: none"> • Vehicle GHG intensity standard <70gCO₂/km • Vehicle operating charge: \$0.05/km • Freight 100% biodiesel requirement • Wood-burning stove limit • Zero-GHG heating: new builds 	<ul style="list-style-type: none"> • \$7 per 100 km driven increase • 40% fewer detached homes • Changing technologies 	<ul style="list-style-type: none"> • Similar to better environmental conditions
Local Energy	<ul style="list-style-type: none"> • Zoning: to protect ALR • Zero-GHG heating for new builds • Transit investment • Freight limits • Building codes: 55% increase in energy efficiency 	<ul style="list-style-type: none"> • Personal electric vehicle standard • Freight hydrogen vehicle standard • Vehicle operating charge: \$0.10/100 km • Technology standard: all consumer goods most efficient available • All energy sources produced in Lower Mainland 	<ul style="list-style-type: none"> • \$17 per 100 km driven increase • 40% fewer detached homes • 300% increase in energy price • Significant change in moving patterns • \$4/m² increase in building envelope cost 	<ul style="list-style-type: none"> • Similar to worse environmental conditions relative to Limits

5.1. Recommendations – Metro Vancouver

Metro Vancouver can implement a small number of policies today that will help align individual decision making consistent with the Limits scenario. The first three policies; zoning, transit investment, vehicle operating charges work in concert to protect greenspace, reduce GHG & CAC emissions, and reduce water use. However they do little to reduce waste to landfill in the region, and so must be complemented by investments in waste-to-energy facilities. These policies are discussed below:

1. **Zoning, transit investment and vehicle operating charges:** Metro Vancouver should continue to align individual municipal growth plans with a regional growth strategy that protects the agricultural land reserve. Investing and constructing new transit lines supports this goal by creating environments that are more conducive to high density development and requires less space to move people in the region compared to roadways. Investment capital required for transit can be raised from vehicle operating charges and vehicle registration fees based on the GHG intensity of vehicles. Combined these policies should rise to the equivalent of \$0.05/km driven over the next 10 years. These policies both raise revenue to invest in transit, while also reducing vehicle use and encourage the adoption of lower GHG vehicles. These policies could start as tolls on bridges and small registration fees for higher GHG intensity vehicles in Metro Vancouver and expand overtime to area road pricing and stricter registration fees in the future.
2. **Invest in Waste-to-Energy:** Waste-to-energy appears to be a cost effective way to manage residual waste streams. Metro Vancouver should continue with existing plans to construct new waste-to-energy facilities in the region. This recommendation assumes Metro Vancouver continues to reduce waste generation, encourage reuse, recycling and compost wherever possible.

Metro Vancouver is currently discussing all of the policies described above. Meeting physical limits, which mostly align with Metro Vancouver's regional growth strategy means adopting and enforcing these policies, or some version of them.

5.2. Recommendations – Future Research

While completing this research I identified a number of areas that could benefit from further research. These are summarized below.

- 1. Population and economic feedbacks:** I excluded direct population and economic feedbacks partly because I was interested in how to achieve limits when the population and the economy continued to grow. Any work building on the analysis presented in this report should explicitly link population and economic growth to the policies I'm implemented.
- 2. Policy Analysis:** I have demonstrated that existing policy tools and technologies can be used to meet physical limits; however, I did not evaluate the political or administrative feasibility of each policy or the policy suite. Implementation is obviously a critical component and so a logical next step for this work is to analyze the implementability of the policy suite.
- 3. Boundary:** I consider only meeting physical limits within the Vancouver boundary. I implicitly assume that energy and materials in the BAU and Limits scenarios can increase and I do not consider the impacts. The critiques of continuous economic growth, or at least the presumed expansion of material and energy this growth implies, note that local physical limits are only part of the problem. The more pressing concern is reaching global physical limits on both wastes and some critical materials (Daly, 1987b; Jackson, 2009; Meadows et al., 2004; Randers, 2012; Steffen et al., 2009; Peter Victor, 2010). Future work could calculate the material and energy needs and their impacts for each scenario.
- 4. Food:** Food supply and security is a critical sustainability issue. Future analysis could consider the impacts of MetroVancouver's food impacts and, like the Local Scenario, the trade-offs of pursuing a local food supply in the Lower Mainland.
- 5. Natural Gas:** CIMS community does not include compressed or liquefied natural gas trucks or vehicles. This technology pathway could be added to explore the role of natural gas in meeting physical limits and also the risks of technology lock-in.

- 6. Link to community plans:** Vancouver and its member municipalities are attempting to implement some of the policies I simulate. My project shows the implications of these changes at a Vancouver scale, but not at a neighbourhood scale. This analysis could be used to support community plan development.
- 7. The other things that make people happy:** I comment mostly on economic security, environmental conditions and partially on health in my project; however, education, political voice, personal activity, equality and social connection are all important capacities that support quality of life. This analysis could be expanded to consider these aspects of quality of life and how to develop and implement these policies in a way that maintains these capacities as well.

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Appendices

Appendix A – Carbon Limit Equation

Carbon Limit Equation:

Use this equation to set up:

$$z_i(t) = \frac{40 - (t - 2010)}{40} z_i(2010) + \frac{t - 2010}{40}$$

Where:

$z_i(t)$ = per capita emissions at time (t)

t = year

$$CARBLIM_i(t) = z_i(t) * POP_i(t)$$

All equations from (Böhringer & Welsch, 2004).

Appendix B – Policies for the Limits Scenario

Table 8 summarizes the policies, year of implementation, reduction and justification and sources for the policy.

Table 8: Summary of policies for the Limit scenario

Name	Description	Start Year	Reduction	Justification/Source
Greenhouse Gas Policies				
Carbon Tax	\$30 per tonne CO _{2eq} Tax	2010	Applies to all GHG sources	Already in place and I assume it continues unchanged into the future.
Technology Standard	Federal Minimum Energy Performance Standards – Current standards for space and water heating technologies	2010	Existing Federal Standard	Already in place and I assume it continues for both residential and commercial applications.
Vehicle Operating Charge	5 cent/km operating charge for all vehicles	2025	Calculated in CIMS	I use the 5 cent/km operating charge to shift some vehicle transportation to transit to meet Translink expectations of required transit use to keep congestion charges down.
Declining GHG Intensity Standard	160 g CO ₂ /km after 2015 <140 gCO ₂ /km after 2020 <70 gCO ₂ /km after 2030 Zero emission by 2040	2015	Calculated in CIMS	Vehicles are an important part of Vancouver's GHG emissions. Fuel economy standards are one way to reduce emissions. This extends the current federal standard of 160gCO ₂ /km after 2015.
Freight Standards	150 g CO _{2eq} /tkm by 2035	2035	Calculated in CIMS	Forces freight vehicles to increase efficiency and so reduce GHG emissions, and use less biofuels which are more expensive than diesel.
Biodiesel 100 per cent standard for	100 per cent biodiesel requirement for freight and	2030	Calculated in CIMS	Biodiesel is the cheapest low-carbon alternative to diesel and becomes the fuel of choice when a carbon

Freight	commercial vehicles by 2030.			tax is employed.
Water Policies				
Water reduction	Vancouver's stage 3 water reductions include eliminating all outdoor sprinkling, all vehicle washing, shutting down ornamental fountains, and filling hot tubs, garden ponds and pools.	Activated when water use exceeds the Limit.	12 per cent reduction in water demand in July and August.	Summer water use is of primary concern because that's when reservoirs are being drained. Source: (Metro Vancouver, 2011d)
Waste				
No specific policies beyond the limit				The limit is met by ensuring all waste not recycled or composted is incinerated.
Air Quality				
Marine fleet NO _x reduction requirements	NO _x Emissions	2016	80 per cent reduction from 2010 levels	NO _x reductions in marine fleet are required to meet NO _x limits. Canada is considering signing onto MARPOL VI (Metro Vancouver, 2010e). Source: (Nikopoulou, 2008)
Technology Limit	Limit on Wood burning stoves	2010	Max. market penetration -2 per cent	Woodburning stoves expand significantly but then exceed air quality limits. This technology limit ensures their market share stays below a level that would surpass air quality limits.
Non-Combustion PM	Comprehensive street cleaning (with water) and tire replacement programs are used to reduce PM from non-combustion sources, especially during summer months. Tire replacement programs reduce non-combustion emissions by 10 per cent in 2020 and 20 per cent by 2050	Half of all major corridors are cleaned by 2020 and all major corridors by 2050	7 per cent and 14 per cent drop in PM respectively Tires result in 10 per cent by 2020 and 20 per cent 2050 reduction in non-exhaust PM.	Non-exhaust particulate matter grows with VKT and so grows with population growth. By 2050 non-exhaust PM are a dominates PM emissions and so policies are required to reduce them. Source: Calculated and policies from (Amato et al., 2009), (Borken-kleefeld, 2012).

Construction PM			50 per cent reduction in construction PM emissions	
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This section summarizes the model inputs for the Limits scenario. Table 9 summarizes the energy price inputs for the Limits scenario.

Table 9: Energy price for the Limits scenario

Energy Type	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity, \$/GJ	20	23	26	28	29	29	29	29	29
Natural Gas, \$/GJ	13	14	15	15	15	16	17	18	19
Heating Oil, \$/GJ	22	24	26	27	27	28	28	29	29
Propane, \$/GJ	25	28	29	30	31	31	32	32	32
Wood, \$/GJ	12	12	12	12	12	12	12	12	12
Gasoline, \$/GJ	28	33	34	35	36	36	36	37	37
Diesel, \$/GJ	25	28	29	30	30	31	31	31	31
Ethanol, \$/GJ	43	57	58	60	61	62	60	57	55
Biodiesel, \$/GJ	37	48	48	48	49	49	50	50	50

Table 10: Annual increase in housing size for the Limits scenario

Annual Rate of Change (of Average)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
per cent/yr	0.00 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent

Table 11: Change in housing type for the Limits scenario

Share of Dwelling
by Type

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Detached	32.07 per cent	27.63 per cent	24.75 per cent	21.82 per cent	19.25 per cent	17.05 per cent	14.85 per cent	13.06 per cent	11.27 per cent
Attached	26.47 per cent	29.12 per cent	30.21 per cent	31.34 per cent	32.13 per cent	32.53 per cent	32.93 per cent	32.93 per cent	32.93 per cent
Apartment	40.66 per cent	42.46 per cent	44.25 per cent	46.04 per cent	47.83 per cent	49.63 per cent	51.42 per cent	53.21 per cent	55.00 per cent
Mobile	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent

Table 12: Summary of travel inputs for CIMS for the Limits scenario

Travel

Annual per cent Change in Travel

-0.34 per cent

VKT relative to CEEI data (ratio)

100.00 per

	cent
Estimate length of transit trips relative to vehicle trips	100.00 per cent
Estimate length of walking/cycling trips relative to vehicle	25.00 per cent
per cent Change in Freight per person	1.51 per cent

Table 13: Other parameters changed in CIMS

Other Parameters

Limit Wood Furnace Technology -2 per cent Max technology penetration

Appendix C – Policies for the Local Energy Scenario

Table 14 summarizes the policies, year of implementation, reduction and justification and sources for the policy.

Table 14: Summary of policies implemented for the Local Energy scenario

Name	Description	Start Year	Reduction	Justification/Source
Greenhouse Gas Policies				
Carbon Tax	\$30 per tonne CO _{2eq} Tax	2010	Applies to all GHG sources	Already in place and I assume it continues unchanged into the future.
Residential and Commercial Building Codes	New builds and major retrofits must meet higher efficiency standards. Assume 90 per cent compliance.	2020	55 per cent increase energy efficiency – residential. 34 per cent increase efficiency commercial	Increasing energy efficiency reduces GHG emissions and CAC emissions. Source: (Wolinetz et al., 2012)
Technology Standards	Only non-GHG emitting heating sources (passive solar and heat-pumps) are allowed in new buildings.	2016– Residential 2016 – Commercial	Zero GHG emissions for new equipment	Without policy or a price signal GHG emissions for heating plateau or continue to increase. This policy forces zero GHG technology. Source: Calculated in CIMS.
Vehicle Operating Charge	10 cent/km operating charge for all vehicles	2025	Calculated in CIMS	Vehicles have many external costs not included in their operating costs. I use vehicle operating charges to reduce VKT and so road requirements. This also helps to reduce GHG emissions.

Fuel Economy Standard	<140 gCO2/km after 2015 <100 gCO2/km after 2025 <70 gCO2/km after 2030 Electric vehicle requirement after 2040	2015	Calculated in CIMS	Vehicles are an important part of Vancouver's GHG emissions. Fuel economy standards are one way to reduce emissions. This extends the current federal standard of 160gCO2/km after 2015 and progressively tightens it.
Transit Vehicle Policies	Purchase policy, no gasoline, diesel, natural gas or hybrid buses	2030	Calculated in CIMS	Required to force transit energy use to electricity and biofuels that can be provided in the region.
Freight Standard	Heavy Duty <160 gCO2/tkm 2010 <150 gCO2/tkm 2020 <100 gCO2/tkm 2025 Commercial <500 gCO2/tkm 2015 <400 gCO2/tkm 2025 <300 gCO2/tkm 2035	See timing to the left	Calculated in CIMS	Freight standards increase over time to reduce the energy intensity of freight vehicles. Concurrently fuel policies push out gasoline and diesel as fuel sources until only hydrogen for Heavy Duty vehicles and electricity for commercial vehicles remain as motor options. Ultimately electricity from local renewable sources is the fuel.
Freight Limit	9,000 million tkm total through the ports in Vancouver	2015	Calculated in CIMS	Freight consumes significant amounts of energy, and with Local Energy there isn't enough energy for continued freight growth. I set freight at current levels.
Water Policies				
Water reduction	Vancouver's stage 3 water reductions include eliminating all outdoor sprinkling, all vehicle washing, shutting down ornamental fountains, and filling hot tubs, garden ponds and pools.	Vancouver imposed when water use exceeds the Limit.	12 per cent reduction in water demand in July and August.	Summer water use is of primary concern because that's when reservoirs are being drained. Source: (Metro Vancouver, 2011d)

Waste				
No waste to landfill	No waste can go directly to landfill. 80 per cent of waste is diverted and the remainder is combusted. Some ash may end up in a landfill, but the quantities will be relatively small.	Full diversion by 2030	100 per cent diverted by 2030	Waste continues to flow to the Vancouver landfill until 2035. Vancouver landfill is expected to reach capacity by 2037 (AECOM, 2009).
Air Quality				
Technology Limit	Limit on Wood burning Stoves	2010	Max. market penetration -2 per cent	Woodburning stoves expand significantly but then exceed air quality limits. This technology limit ensures their market share stays below a level that would surpass air quality limits.
Efficiency Standard	Most efficient washers, dryers, ranges, refrigerators, freezers and other appliances required.	Phase in starting 2015	All new sales most efficient by 2050.	Electricity use in houses must be significantly reduced to meet electricity production limit in Vancouver. Source: Required to meet electricity limit and (Wolinetz et al., 2012)

Table 15: Summary of energy prices for the Limits and Local Energy scenario

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Electricity, \$/GJ	32	40	50	60	70	83	100	111	123
Natural Gas, \$/GJ	13	14	15	15	15	16	17	18	19
Heating Oil, \$/GJ	22	24	26	27	27	28	28	29	29
Propane, \$/GJ	25	28	29	30	31	31	32	32	32
Wood, \$/GJ	12	12	12	12	12	12	12	12	12
Gasoline, \$/GJ	28	33	34	35	36	36	36	37	37

Diesel, \$/GJ	25	28	29	30	30	31	31	31	31
Ethanol, \$/GJ	43	57	58	60	61	62	60	57	55
Biodiesel, \$/GJ	37	48	48	48	49	49	50	50	50

Table 16: Summary of housing size change for the Limits and Local Energy scenario

Annual Rate of Change -
Housing Size

	2010	2015	2020	2025	2030	2035	2040	2045	2050
per cent/yr	0.00 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent	0.39 per cent

Table 17: Summary of housing mix for the Limits and Local Energy scenario

Share of Dwelling
by Type

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Detached	32.07 per cent	27.63 per cent	24.75 per cent	21.82 per cent	19.25 per cent	17.05 per cent	14.85 per cent	13.06 per cent	11.27 per cent
Attached	26.47 per cent	29.12 per cent	30.21 per cent	31.34 per cent	32.13 per cent	32.53 per cent	32.93 per cent	32.93 per cent	32.93 per cent
Apartment	40.66 per	42.46 per	44.25 per	46.04 per	47.83 per	49.63 per	51.42 per	53.21 per	55.00 per

	cent	cent	cent	cent	cent	cent	cent	cent	cent
Mobile	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent	0.79 per cent

Table 18: Summary of transportation inputs for the Limits and Local Energy scenario

Travel

Annual per cent Change in Travel	-1.50 per cent
VKT relative to CEEI data (ratio)	100.00 per cent
Estimate length of transit trips relative to vehicle trips	100.00 per cent
Estimate length of walking/cycling trips relative to vehicle	25.00 per cent
per cent Change in Freight per person	-1.51 per cent

Table 19: Summary of other CIMS inputs for the Local Energy scenario

Other Parameters

Technology Standards

Max Wood Technology	-2 per cent
Max Market Pen HYD Trucks	2 per cent
Max Market Pen Efficient Appliances	2 per cent

Reduction on Intangible Costs

Carpooling	10 per cent
Transit	15 per cent
Walking/Biking	25 per cent

Table 20: Summary of local energy sources, costs and description

Name	Type	Quantity (TJ)	Cost (\$/GJ)	Description	Source
Biogas	Heat	674.34	31.50	Digestion of waste farm organic material	(Tooke et al., 2013)
Industrial Recovery	Heat	1,364.29	31.50	Waste heat from industry	(Tooke et al., 2013)
Hydro RoR	Electricity	19,377.00	41.73	Large run-of-river, weighted average 19 projects	(KWL, 2010)
Hydro RoR	Electricity	1,182.96	39.80	Small run-of-river <25 MW	(KWL, 2010)
Solar - PV	Electricity	17,616.46	42.42	Distributed PV assuming 13.9 per cent of south facing roofs, 50/50 split PV/HW and 15 per cent efficiency	Quantity: (Tooke et al., 2013) Cost: (U.S. Energy Information Administration, 2012)
Solar - DHW	Heat	58,721.55	21.00	Distributed hot water, assuming 13.9 per cent of south facing roofs, 50/50 split PV/HW and 50 per cent efficiency	Quantity: (Tooke et al., 2013) Cost: (International Energy Agency, 2012)
Biomass (non-timbre)	Electricity	12,614.40	31.32	Wood waste, excluding waste to WTE, weighted average cost	(KWL, 2010)
Biomass (timbre)	Electricity	9,578.60	32.06	Sustainably harvested wood from protected, watersheds and undeveloped land, weighted average cost	(KWL, 2010)

Wind	Electricity	1,695.96	45.24	Average two wind farms	(KWL, 2010)
Geothermal	Electricity	9,019.44	20.98	Average five geothermal facilities	(KWL, 2010)
Waste-to-Energy	Heat	8,313.20	Excluded	Heat energy will be available regardless because built for waste management	Calculated
Waste-to-Energy	Electricity	2,375.20	Excluded	As above	Calculated
Organics	Heat	-	Excluded	All organics assumed to be combusted	
Ethanol/Biodiesel	Transportation	2,852.65	Varies	Modified exogenously	

Appendix D – Abatement Cost Curve for the Carbon Tax Shadow Price

Table 21: Carbon tax schedule for the carbon shadow price

Year	2013-2015	2016-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Carbon Price	\$30.00	\$50.00	\$150.00	\$200.00	\$400.00	\$400.00	\$400.00	\$400.00

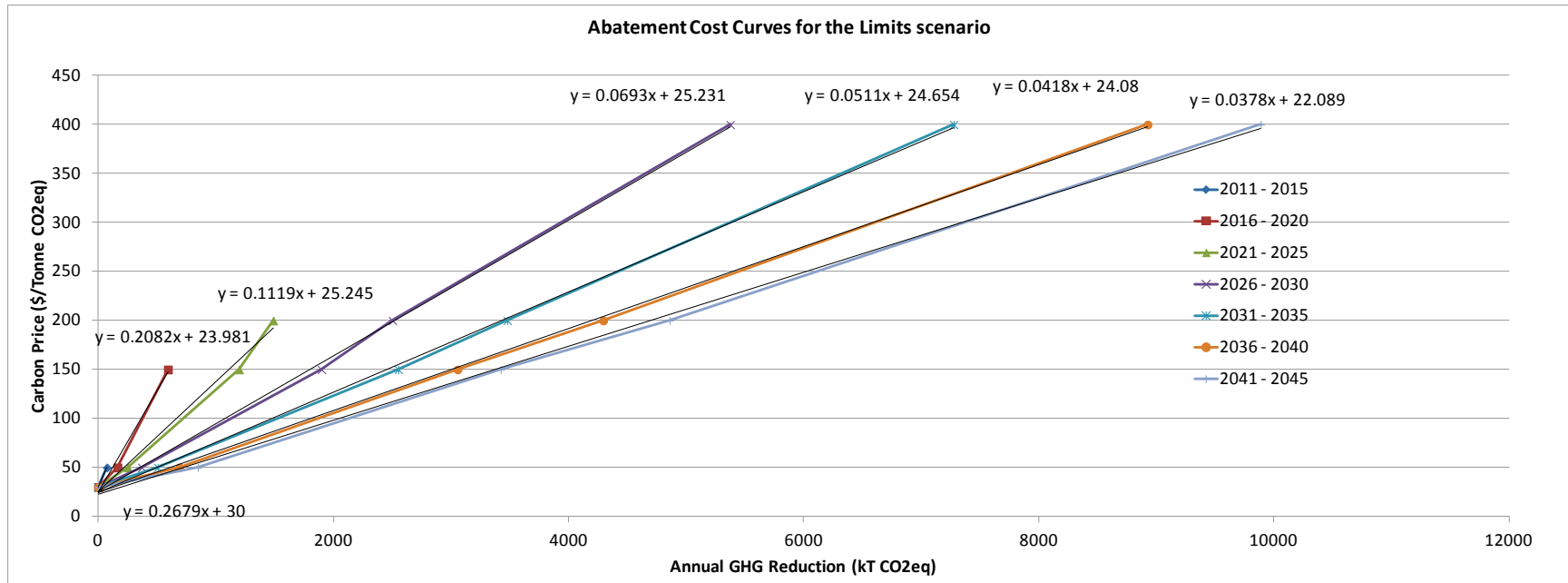


Figure 15: Abatement cost curves for the Limits scenario with line equations

Abatement costs per year, reduced to the first year of reduction using a 3.79 cost recover factor

Table 22: Summary of carbon price and abatement costs from 2015 to 2045 – cost in \$1,000s of dollars

Carbon Price (\$/tonne)	2015	2020	2025	2030	2035	2040	2045
40	\$ 4,951.47	\$ 6,474.71	\$ 16,302.93	\$ 26,343.96	\$ 36,794.16	\$ 46,248.59	\$ 55,750.90
50		\$ 8,191.64	\$ 15,241.29	\$ 24,610.39	\$ 33,375.73	\$ 40,801.44	\$ 45,119.05
100			\$ 127,010.72	\$ 205,086.58	\$ 278,131.12	\$ 340,011.96	\$ 375,992.06
200				\$ 820,346.32	\$ 1,112,524.46	\$ 1,360,047.85	\$ 1,503,968.25
300					\$ 1,854,207.44	\$ 2,266,746.41	\$ 2,506,613.76
400						\$ 3,173,444.98	\$ 3,509,259.26
Total	\$ 4,951.47	\$ 14,666.35	\$ 158,554.94	\$ 1,076,387.25	\$ 3,315,032.91	\$ 7,227,301.22	\$ 7,996,703.28

Appendix E – Vancouver Air Quality Targets

Air Contaminant	Averaging Time	Ambient Air Quality Objectives	
		$\mu\text{g}/\text{m}^3$	parts per billion
Carbon monoxide	1-hour	30,000	26,500
	8-hour	10,000	8,800
Nitrogen dioxide	1-hour	200	107
	Annual	40	22
Sulphur dioxide	1-hour	450	174
	24-hour	125	48
	Annual	30	12
Ozone	1-hour	160	82
	8-hour	126	65
Inhalable particulate matter (PM_{10})	24-hour	50	-
	Annual	20	-
Fine particulate matter ($\text{PM}_{2.5}$)	24-hour	25	-
	Annual	8 (6)*	-

* Metro Vancouver adopted ambient air quality objectives for $\text{PM}_{2.5}$ as part of the 2005 Air Quality Management Plan, based on the most stringent standards at the time and in advance of any Provincial objective. In 2009, the Provincial government adopted a 24-hour objective for $\text{PM}_{2.5}$, as well as an annual $\text{PM}_{2.5}$ objective of $8\mu\text{g}/\text{m}^3$ and a planning goal of $6\mu\text{g}/\text{m}^3$. The 2011 IAQGGMP aligns Metro Vancouver's objectives with those of the Province.