Modelling urban climate mitigation in Canadian municipalities

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1. Introduction

Sustainability Solutions Group (SSG) and whatif? Technologies Inc have collaborated in the creation of a new generation energy and emissions model -- CityInSight -- in response to the growing demand from cities for tools that integrate GHG mitigation objectives in local planning and investment strategies for land use, transportation systems, and local energy production and distribution systems. CityInSight employs a spatial systems modelling approach, relating population, employment, buildings, transportation, waste and finance. It generates quantitative analysis and visualizations that are key ingredients in local climate action planning.

The low carbon transition in cities depends on the way in which urban planning and investment strategies affect the level and pattern of energy use and greenhouse gas emissions in the community, and this in turn requires energy consumption and production data and analytics be spatially resolved at a level of granularity that is absent in the generation of post-OPEC energy models that are designed for and applied at the national or provincial level. For example, this spatial resolution is needed to specify the potential for a number of emerging low carbon urban strategies including microgrids; district energy networks; candidate combined heat and power sites; land use and zoning to reduce the number and length of trips; infrastructure investment plans for transit, active transportation, and electric, shared, autonomous vehicles (esav's).

The development of City Insight is a response to the need for a local government modeling tool that supports the integration of climate change mitigation in municipal planning, spending and operating policies and procedures. The model is being used in numerous municipalities across Canada and represents current best practice in urban energy and emissions modelling. Utilizing geocoded datasets, combined with the algorithmic structures of the well-established whatif? Canadian Energy Systems Simulation (CanESS), CityInSight helps cities develop a quantified understanding of the way the urban energy system affects and is affected by the larger urban systems for the provision of amenities and helps identify opportunities for the acceleration of the low carbon transition.

CityInSight has been deployed in municipalities of all sizes -- from 8,000 to 2.8M population, represents current best practice for supporting municipal climate action plans, and in Canada has been the model of choice for the City of Toronto (ON), City of Markham (ON), Region of Waterloo (ON), Town of Bridgewater (NS), Region of Durham (ON), City of Guelph (ON), City of Sudbury (ON), City of Edmonton (AB), City of Ottawa (ON), Cities of Hamilton & Burlington (ON), Region of York (ON), Town of Caledon (ON), City of Richmond Hill (ON), City of Saskatoon (SK) the City of Halifax (NS), the Region of Peel (ON) and the Federal Government's operations in the National Capital Region. In the summer of 2017 Toronto City Council unanimously adopted the TransformTO report, based on CityInSight analysis, which lays out a low-carbon (80% GHG reduction) pathway to 2050 with associated actions and financial analysis.

The remainder of this paper is organized as follows. The next section summarizes the urban policy and energy modeling contexts in which and for which CityInSight has been developed. This is followed by a description of the model in Section Three and with examples of its applications and results in Section Four. A final section discusses the future research and development agenda for the model.

2. The policy and modelling contexts

The need for and the design of CityInSight is rooted in the history of energy systems modelling and in the emergence of climate mitigation as a local government priority.

Urban climate mitigation

Local governments were early adopters of climate change mitigation objectives. Following the international Conference on the Changing Atmosphere hosted by Toronto in 1988, a group of North American and European cities, including Toronto, committed to targeted greenhouse gas emissions, both in their own operations and in their communities. Under the auspices of the International Council for Local Environmental Initiatives (ICLEI), they formed the Urban CO2 Reduction Project and began a collaborative effort to define the methods and strategies for urban climate mitigation, including quantitative methods and models for inventories and action plans.[1] Led by ICLEI, methods and conventions for the quantified analysis of municipal greenhouse gas emissions continued to evolve throughout the 1990's[2][3][4]and reflected a pragmatic approach for supporting local action. Although there was then and is now no mandate for local government to take on the climate issue, today over 90% of Canada's urban population reside in member communities of the Federation of Canadian Municipalities Partners for Climate Protection program.

Local government engagement in climate change mitigation is a prerequisite for a successful low carbon transition, partly because the energy transition must necessarily take place mostly in urban communities and partly because over 50% of Canada's greenhouse gas emissions are under the direct or indirect control and influence of local government.[5]

The low carbon transition is characterized by efficiency, electrification, decarbonization of the grid, and innovation that reduces the relative contribution of energy services in the provision of amenity. The technologies and techniques that characterize the emerging post-petroleum energy system tend to be distributed and matched in scale to end use needs. The centralized pattern of the prevailing system will continue to be important, but the transition to low carbon is coming with a shift in value creation toward the retail end of the generate-->transmit-->customer end of the vector, and the vector itself is giving way to a highly interconnected grid that supports the two way flow of energy and information between producers, consumers, and prosumers.

Cities will be the platforms on which the above changes play out in Canada. In the low carbon transition, the widespread and rapid uptake of new technologies for using energy more efficiently and for establishing new electricity and thermal grids will be largely located within the boundaries of urban communities. Municipalities govern the concentrated markets and relatively dense settlement patterns in which new techniques and technologies can spread quickly and in which the supporting infrastructure must be embedded. The details will vary with local culture, circumstance and opportunity, and success will require the proactive engagement of local authorities.

Beyond the role of municipalities in supporting the transition of the energy system, there is the also the question of how urban systems can themselves be aligned with and evolve in ways that contribute to the low carbon transition. Urban communities are not just the places where most fuel and electricity is consumed; they are themselves energy using organisms, and the way they are designed, built and operated has widespread and long lasting impacts on the level and pattern of energy services (heat, light, mobility, motive power, information transfer) required, which in turn drives the consumption of fuels and electricity and the associated greenhouse gas emissions.

- Perhaps the most profound, long-term impact of municipal governments on greenhouse gas sources and sinks derives from their control of land use. Urban form and spatial structure are key factors in determining why some cities are more greenhouse gas intensive than others (see Figure 1). Zoning, permit conditions, municipal ordinances, and bylaws all affect energy use through their impacts on residential density, access to goods and services, structural automobile dependence, transit mode shares, and the pedestrian and bicycle "friendliness" of the community. These in turn affect the scope for energy efficiency in the community, the feasibility of district energy systems, and the "mobility efficiency" of the community (i.e. how much travel is needed to get access to employment, recreational, shopping and other amenities). In the past, energy and emissions considerations have not been an important consideration in urban planning, but as the climate mitigation and other benefits of "community energy management" become apparent, municipalities want to take explicit account of these factors in their policies and programmes.

- Local government control and influence over both investment in and operation of transportation infrastructure provides another important connection to climate change mitigation opportunities. Investment in roads and bridges, transit, and active transportation infrastructure has always been a dominant item in local government capital and operating budgets, and the vehicle tailpipe emissions often account for more than half of community greenhouse gas emission inventories. In the past, these systems have not been planned without much regard for their energy and emission impacts, but that is changing in the face of the climate emergency.

Figure 1. A Tale of Two Cities

- Nothing gets built in a municipality without the approval of City Hall, making local governments one of the most important influences on the pattern of investment in infrastructure and the built environment. There is no pathway to an effective emergency response to climate change that does not include wide scale thermal retrofitting and conversions to heat pumps or district energy systems for new and existing buildings. In the rethinking, redesigning and remaking of the built environment, local governments have a unique interest in and responsibility for the “big picture”, of how the different systems can work together to achieve a healthier, more liveable and low carbon outcome.

- Municipalities have direct responsibility for solid waste collection and landfill management, and landfill gas recovery and utilization are important climate mitigation measures. Municipal waste reduction, recycling and composting programs deliver even greater emission reductions. In the case of energy intensive materials such as steel and aluminium, plastic, and paper products, the impact of recycling a tonne of material can result in more than a tonne of CO_2e emission reductions, sometimes many times more.[6] More generally, as electrification proceeds and the emissions from building chimneys and vehicle tailpipes decline, the emissions embedded in goods and services will become relatively more important in climate change mitigation. The “raw materials” in a circular economy are to be found in cities, and the supply chains for materials recycling and remanufacturing will be important components of urban economies in the future.
- Through their control over land use, parks and community greening programmes, municipalities have a central influence on the growth (or decline) of carbon sequestration within their boundaries. Urban greening and forestry programmes not only increase the carbon sink in the community but also moderate the “urban heat island” effect and reduce the demand for both heating and air conditioning energy by providing windbreaks and shade to buildings.

Local government policies and practices have and have always had a pervasive if mostly indirect impact on the level of greenhouse gas emissions in the community, but those impacts have not generally been considered in the design of those policies and programs. Fossil fuel dependency and greenhouse gas intensity have been coincidental consequences of an historical urban development paradigm, but there is now growing interest in understanding the linkages between urban systems and the energy system so that the low carbon objective can be aligned with the community’s social and economic aspirations and integrated with urban planning policies and methods.[7][8]

There is often alignment between the priority goals and aspirations of community planning and the objective of lowering greenhouse gas emissions. In fact, a great deal of the moderation of greenhouse gas emissions growth that has already taken place in recent years has been a side effect of trends and measures that have been driven by goals other than GHG emission reduction. For example, energy efficiency developments can be key elements of strategies for local economic development, job creation and self-reliance. Public health policy advocates promote a variety of measures that also reduce greenhouse gas emissions, including active transportation infrastructure, green roofs, urban forestry, and reduced emissions from fossil fuel combustion.

With these synergies in mind, urban climate mitigation emerges as more than energy planning *per se*, and the community of stakeholders expands to include many decision makers whose decisions are not much influenced by energy commodity prices, but whose decisions nevertheless have profound and long lasting impacts on the level and pattern of fuel and electricity consumption. Urban climate mitigation requires the integration of low carbon objectives in land use plans, transportation plans, waste management plants, housing strategies, economic development plans and all related capital and operating budgets. The key decision-makers and stakeholders in these areas will have other goals and priorities than climate mitigation; success requires identifying how the low carbon objective aligns with their objectives and motivations (see Table 1).[8]

The challenge of urban climate mitigation is exacerbated by the long-lasting impacts of municipal planning and investment decisions. Many municipal planning decisions made today will still be having environmental impacts 100 years from now. In the case of infrastructure investments and land-use plans, the environmental consequences continue for centuries. This leads to "lock-in" and a situation where past decisions limit the options and increase the costs for future decisions. In the context of community energy and emissions planning, this makes the longest-term decisions also among the most urgent.

Systems modelling for urban climate mitigation

Given the dominant role of fossil fuel production and consumption in Canada's greenhouse gas emissions, the focus here is on energy systems models and their applicability to urban climate mitigation planning and policy. Energy systems are complex, and they are embedded in and subsidiary to larger and more complex systems, including urban systems, for the provision of human needs: comfort, nutrition, health, safety, community, knowledge, and self-actualization. As explained by Hoffman, the energy system

> "has two interacting components: a bio-physical component consisting of a large number of processes that transform materials and energy into the goods providing the services needed to meet human needs, and a cognitive component consisting of large number of economic agents including individuals, households, business enterprises and governments whose decisions and actions establish the structure of economic activity. These disparate processes and agents interact with each other and the relationships among them are non-linear."[9]

Urban systems have an asymmetrical relationship with the energy system insofar as their design and operation go a long way toward determining the level and pattern of energy services and commodity demand in the community, but their design and operation has not been much affected by the attributes or internal dynamics of the energy service and commodity markets. For example, the planning of a new suburb will not be much influenced by the price of fuel or electricity, but the level of fuel and electricity consumption in that new neighbourhood will depend on how it is laid out, how big the houses are, the level of transit service, the proximity of goods and services, the extent of the automobile and active transportation infrastructures, and so on.

Table 1

<table>
<tr><th colspan="5">Connecting the Dots – Stakeholder motivations and decision-makers that affect energy use for housing and personal mobility</th></tr>
<tr><th>Sectors</th><th>Drivers</th><th>Causal Factors</th><th>Key Decision Makers</th><th>Motivations</th></tr>
<tr><td>Housing</td><td>• Population
• Household size
• Weather
• Lifestyle</td><td>• Housing preferences
• Dwelling size
• Building efficiency
• Lighting and appliance efficiency, water heater
• Fuel choice
• Appliance saturation rates
• Occupant behaviour</td><td>• Building and homeowners
• Residential developers
• Builders and construction industry
• Architects
• **Local governments (building**
• **codes, zoning, etc.)**
• Prov and fed governments
• Banks and mortgagers
• Occupants and tenants
• Condo boards
• Purchasers, investors
• Real estate industry
• Gas and electric utilities
• Banks
• Building technology suppliers</td><td rowspan="2">• Comfort
• Convenience
• Safety and security
• Client Satisfaction
• Profitability
• Competitiveness
• Reliability
• Resiliency
• Regulatory compliance
• Risk Avoidance
• Capital cost
• Operating budget
• Energy cost savings
• Public policy objectives (e.g. carbon reduction, air quality improvement, job creation, economic development, urban densification, etc.)
• Sustainability
• Knowledge and information
• Environmental health
• Reputation
• Employee retention
• Political objectives</td></tr>
<tr><td>Personal Mobility</td><td>• Population
• Demographics
• Lifestyle, demand for access to goods and services
• Urban form
• Urban spatial structure</td><td>• Trips per capita
• Trip lengths
• Mode choice
• Occupancy factor
• Vehicle efficiency
• Fuel choice</td><td>• Traveler/household
• Vehicle operator
• **Urban planners**
• Vehicle manufacturers and their suppliers
• Transit organizations
• **Infrastructure providers (government)**
• Highway operators and concessionaires
• Parking authorities
• Developers
• **Local government (land use planners)**</td></tr>
</table>

Energy system modeling developed in the wake of the OPEC initiated crisis of 1972, and the major energy system models used in Canada today for supporting long term strategic analysis are based on conceptual framings of the energy system that prevailed in the 1970's and 1980's, before climate change was a public policy priority. They include "top down" macroeconomic and general equilibrium models, "bottom up" models with structures based on energy commodity market optimization, systems dynamics models utilizing discrete choice theory, physical system-based models for supporting exploratory simulation of the energy systems, and hybrid models that combine attributes of different model types.

From the outset of urban climate mitigation, it was apparent that the databases, models and analytical frameworks for understanding the internal dynamics of energy systems would be of limited utility. Energy supply and demand statistics, for example, are not compiled at the municipal level, so even the relatively simple job of creating an inventory of community greenhouse gas emissions presented a challenge to the pioneers of urban climate mitigation.[2] Beyond that, the central issue in urban climate mitigation – the impact of changes in urban systems on the level and pattern of energy service demands -- is at best on the periphery of energy system models, if not entirely beyond the system boundary.

Bottom-up models with highly disaggregated representation of the stocks and flows of buildings, vehicles, equipment, infrastructure and electricity generation can be used to assess the impact on greenhouse gas emissions of urban climate mitigation. The addition of spatial resolution supports the analysis of the impacts on emissions of land use patterns, microgrids, district energy, personal mobility patterns, supply chains, and other factors where spatial relationships matter. It is also important to be able to simulate system behaviour with time steps that are the right size for assessing the impacts of the time pattern of energy end uses, intermittent generation, energy storage, demand response capacity, the longer thermal time constants of low-energy buildings, and other temporal dynamics of the low carbon energy system.

The need to better understand how local agency affects greenhouse gas emissions exemplifies a general need for expanding the model boundary to include the larger systems which give rise to the demand for energy services and other emission drivers (see Figure 2). Energy commodity and energy service markets occupy a relatively small region within the large, complex, self-organizing network of social and economic systems for meeting human needs. It is not an equilibrium system; while there may be some regions that remain stable for periods of time, the system is constantly evolving. In recent years, the role of energy services in providing amenity has been particularly dynamic, with factors exogenous to energy commodity markets having a greater impact on the level and pattern of energy commodity demand than the internal dynamics of those markets.[10][11]

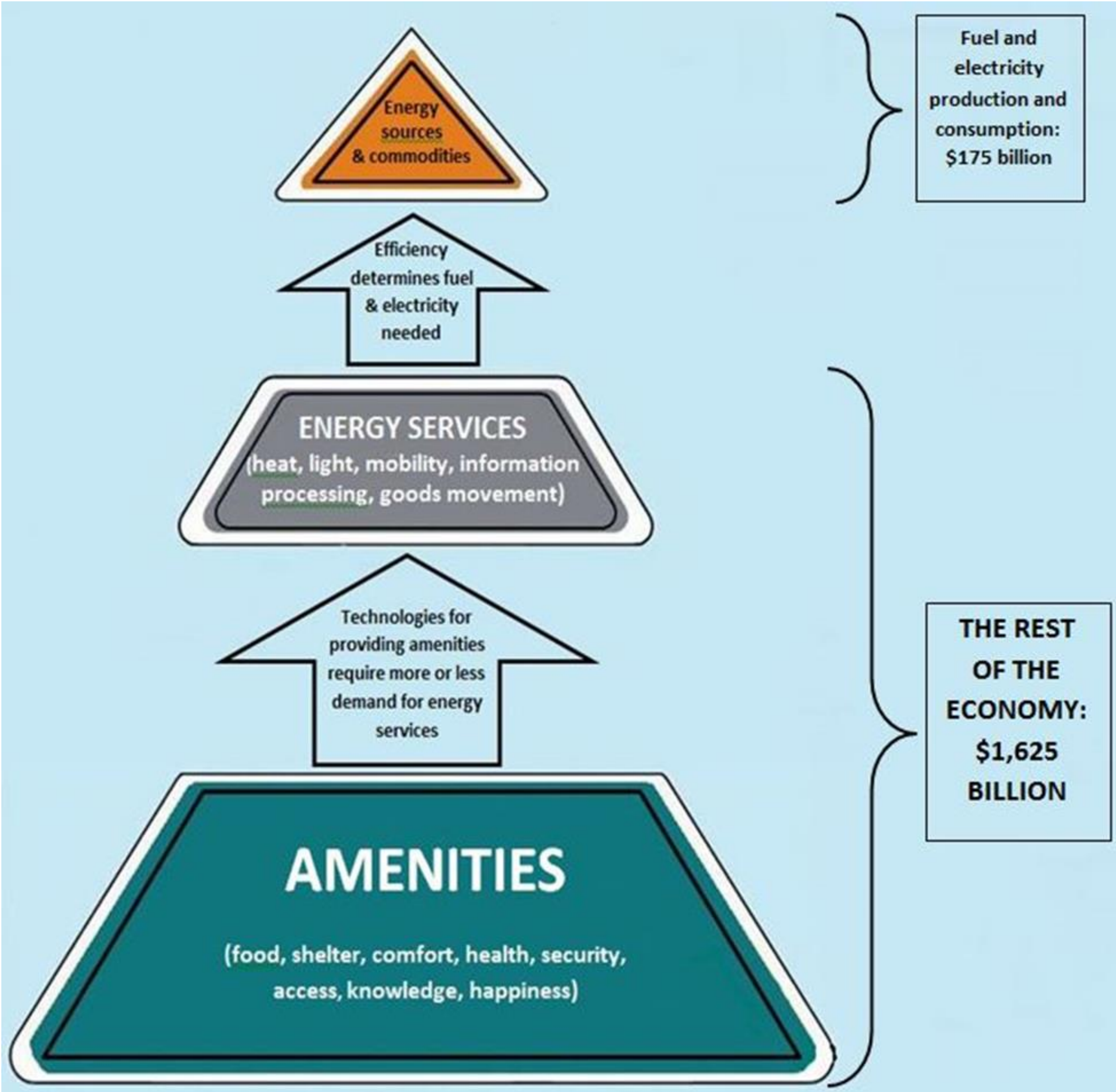

Figure 2. Energy commodities and services in the context of the larger socio-economic system (from [12])

3. CityInSight

The CityInSight model responds to the local government need for a deeper understanding of the connections between urban systems and energy systems, and of the opportunities where local agency can contribute to the low carbon transition. It is an integrated, multi-fuel, multi-sector, *spatially disaggregated* energy systems, emissions and finance model. CityInSight uses bottom-up accounting for energy supply and demand, including renewable resources, conventional fuels, energy consuming technology stocks (vehicles, appliances, dwellings, buildings, industry) and all intermediate energy flows. CityInSight incorporates a unique level of resolution, enabling, for example, the testing of strategies for a specific area of geography, for a specific vintage of buildings, for a specific type of dwelling, for a specific piece of equipment within buildings, or for a specific technology for transportation or energy provision.

CityInSight incorporates and adapts concepts from the system dynamics approach to complex systems analysis. It builds on and adapts the Canadian Energy Systems Simulation (CanESS), a longstanding bottom-up Canadian energy model for exploring energy system transformations, built on the whatif? Technologies modelling platform.[1] CanESS was first applied in 2004 and is designed to simulate stock/flow consistent technology-rich trajectories for the energy and materials transformation processes of Canada and the provinces. CanESS applies a physical economy approach to provide coherent scenarios that explore the long-term impacts of ongoing transitions in the energy system. Stocks and flows are represented in physical units and technologies are represented as discrete processes. The modeler literally draws a picture of the system being modelled, with standardized symbols for stocks, flows, parameters and processes. These model diagrams are directly linked to the underlying equations that define the relationships between the model components, thus making documentation an integral part of model development.

[1] The whatif? modelling platform includes a suite of software tools that support the design, documentation and implementation of simulation models. DOCUMENTER uses linked structural diagrams as the framework for entering and managing information about model components, variables, procedures, and flows of information among model components. This provides a single point of entry for information that can be formatted as a reference manual for the model and for the files that are used to realize the model in the Scenario and Model Manager (SAMM) software. SAMM facilitates the creation, display and comparison on multiple scenarios and automatically manages the linkages and flows of information among sub-model components. It supports customized "views" of scenario outputs. A high-level interactive language (TOOL) allows the user to apply a library over 150 mathematical operators to the manipulation of structured data objects, including multi-dimensional arrays, sets, mappings, and geometric objects such as points, lines and polygons, thereby facilitating quick and easy manipulation of very large data structures. Data import and export protocols support ASCII files, spreadsheets and GIS systems, and can be linked to graphing and mapping tools.

Table 2. Key Attributes of CityInSight Model

INTEGRATED	In contrast to a collection of individual sector-specific models, CityInSight is designed to account for and to model all sectors that relate to energy and emissions at a city scale while describing the relationships between sectors. The demand for energy services is modelled independently from the type/fuel of energy service technologies, enabling exploration of fuel switching scenarios.
SCENARIO-BASED	Once calibrated with historical data, CityInSight enables the creation of dozens of scenarios to explore different possible futures. Each scenario can consist of either one or a combination of policies, actions and strategies.
SPATIAL	The configuration of the built environment determines the ability of people to walk and cycle, accessibility to transit, feasibility of district energy and other aspects. CityInSight therefore includes a full spatial dimension that can include as many zones as are deemed appropriate. The spatial component to the model can be integrated with City GIS systems, land-use projections and transportation modelling.
ACCOUNTING FRAMEWORK	CityInSight is designed according to the accounting framework of the GHG Protocol for Cities, the international standard for emissions inventories for cities. The GHG Protocol includes guidance on reporting on scope 1, 2 and 3 emissions. CityInSight Corporate uses the Local Government Operations Protocol accounting framework to report on scope 1, 2 and 3 emissions.
ECONOMIC IMPACTS	CityInSight incorporates a full financial analysis of costs related to energy (expenditures on energy) and emissions (carbon pricing, social cost of carbon), as well as operating and capital costs for policies, strategies and actions. It allows for the generation of marginal abatement curves to illustrate the cost and/or savings of policies, strategies and actions. It accounts for the impact of policies, strategies and actions on household incomes and public and business expenditures.
ECONOMIC EQUITY	CityInSight can assess the impact of policies, actions and strategies on individual households, neighbourhoods, specific dwelling types (detached, row, apartments, etc.) and household income levels. Additional analysis from SSG's ModelHealth and Places+Spaces can be incorporated into CityInSight to enhance the analysis.
OPEN SOURCE	CityInSight is open source and can be used on an ongoing basis without additional costs such as licensing fees or otherwise.
VISUALIZATIONS	The team has worked with a data journalist to develop an online and interactive visualization tool for CityInSight. These visualizations can be used to enable staff and other stakeholders to explore the results of the scenarios. Additional visualizations can be added for health impacts and economic and social equity.

A high-level influence diagram for CityInSight is shown in Figure 3. Following the CanESS approach, CityInSight traces the flows and transformations of energy from sources through energy currencies (e.g. gasoline, electricity, hydrogen) to end uses (e.g. personal vehicle use,

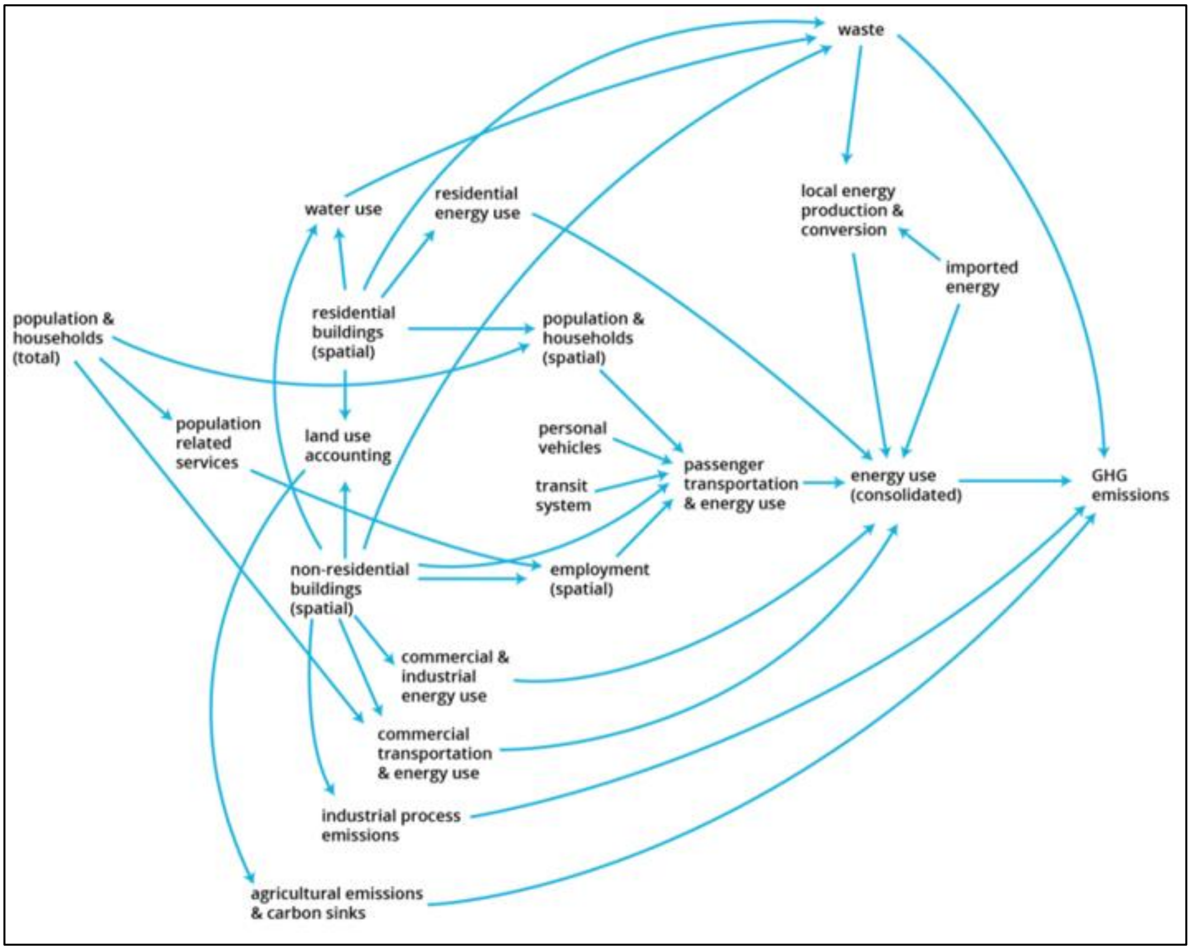

Figure 3. High level influence diagram of CityInSight components

space heating) to energy costs and GHG emissions. An energy balance is achieved by accounting for efficiencies, conservation rates, and trade and losses at each stage in the journey from source to end use. CityInSight can be used to analyze energy and emissions associated with customized policies over time and includes modelled financial information which can inform financial decision-making related to energy and emissions actions.

Model Scope

The major components of the CityInSight model represent the sectors influencing energy or GHG emissions in a city or municipality. Additional relationships may be modelled during scenario development by modifying inputs and assumptions as specified by model users and clients, or in an automated fashion by code or scripts running "on top of" the base model structure. Feedback relationships are supported, such as increasing the adoption rate of non-emitting vehicles in order to meet a GHG emissions constraint.

Key model outputs include energy and emissions by sector, subsector, fuel and location. Financial reporting includes capital costs, operation and maintenance (including fuel and electricity and carbon premiums, where applicable). The spatial resolution is determined by the granularity of input data and can extend to individual building level. The transportation planning "traffic zone" is typically used for purposes of mapping outputs, with larger cities being typically represented with hundreds of zones.

CityInSight incorporates the accounting framework articulated by the GHG Protocol for Cities. A full set of Scope 1 and 2 emissions are included and, if deemed appropriate, scope 3 emissions can also be included.

Model Components

Population and Demographics. City-wide population is modelled using the standard population cohort-survival method, disaggregated by single year of age and gender. It accounts for various components of change: births, deaths, immigration and emigration. The age structured population is important for analysis of demographic trends, generational differences and implications for shifting energy use patterns.

Residential Buildings. Residential buildings are spatially located and classified using a detailed set of 30+ building archetypes capturing footprint, height and type (single, double, row, apt. high, apt. low), in addition to year of construction. This enables a "box" model of buildings and the estimation of surface area. Coupled with thermal envelope performance and degree-days the model calculates space conditioning energy demand independent of any space heating or cooling technology and fuel. Energy service demand then drives stock levels of key service technologies (heating systems, air conditioners, water heaters). These stocks are modelled with a stock-turnover approach capturing equipment age, retirements, and additions – exposing opportunities for efficiency gains and fuel switching, but also showing the rate limits to new technology adoption and the effects of lock-in. Residential building archetypes are also characterized by number of contained dwelling units, allowing the model to capture the energy effects of shared walls but also the urban form and transportation implications of population density.

Non-residential buildings. These are spatially located and classified by a detailed use/ purpose-based set of 50+ archetypes, and the floorspace of these non-residential building archetypes can vary by location. Non-residential floorspace produces waste and demand for energy and water and provides an anchor point for locating employment of various types.

Spatial population and employment. City-wide population is made spatial by allocation to dwellings, using assumptions about persons-per-unit by dwelling type. Spatial employment is projected via two separate mechanisms: population-related services and employment, which is allocated to corresponding building floorspace (e.g. teachers to school floorspace); and floorspace-driven employment (e.g. retail employees per square metre).

Personal mobility. CityInSight includes a spatially explicit passenger transportation sub-model that responds to changes in land use, transit infrastructure, vehicle technology, travel behavior changes and other factors. Trips are divided into four types (home-work, home-school, home-other, and non-home-based), each produced and attracted by different combination of spatial drivers (population, employment, classrooms, non-residential floorspace). Trips are distributed - that is, trip volumes are specified for each zone of origin and zone of destination pair. For each origin-destination pair, trips are shared over walk/bike (for trips within the walkable distance threshold), public transit (for trips whose origin and destination are serviced by transit) and automobile. Following the mode share step, along with a network distance matrix, a projection of total personal vehicle kilometres travelled (VKT) is produced. The energy use and emissions associated with personal vehicles is calculated by assigning VKT to a stock-turnover personal vehicle model. All internal and external passenger trips are accounted for and available for reporting according to various geographic conventions.

Waste. Households and non-residential buildings generate solid waste and wastewater, and the model traces various pathways to disposal, compost and sludge including those which capture energy from incineration and recovered gas. Emissions accounting is performed throughout the waste sub-model.

Local energy production. Energy produced from primary sources (e.g. solar, wind) is modelled alongside energy converted from imported fuels (e.g. electricity generation, district energy, CHP). As with the transportation sub-model, the district energy supply model has an explicit spatial dimension and represents areas served by district energy networks.

Financial and Employment Impacts. Energy related financial flows and employment impacts are captured through an additional layer of model logic. Calculated financial flows include the capital, operating and maintenance cost of energy consuming stocks and energy producing stocks, including fuel costs. Employment related to the construction of new buildings, retrofit activities and energy infrastructure is modelled.

Stocks and Flows

For any given year various factors shape the picture of energy and emissions flows, including: the population and the energy services it requires; commercial floorspace; energy production and trade; the deployed technologies which deliver energy services (service technologies); and the deployed technologies which transform energy sources to currencies (harvesting technologies).

Some factors are modelled as stocks - counts of similar things, classified by various properties. For example, population is modelled as a stock of people classified by age and gender. Population change over time is projected by accounting for: the natural aging process, inflows (births, immigration) and outflows (deaths, emigration). The fleet of personal use vehicles, an example of a service technology, is modelled as a stock of vehicles classified by size, engine type and model year - with similarly classified fuel consumption intensities. As with population, projecting change in the vehicle stock involves aging vehicles and accounting for major inflows (new vehicle sales) and major outflows (vehicle discards). This stock-turnover approach is applied to other service technologies (e.g. furnaces, water heaters) and harvesting technologies (e.g. electricity generating capacity).

Investment Pathways

SSG's detailed financial data dictionary describes a wide range of metrics for analyzing financial impacts of community energy and emissions plans. For example, the dictionary includes fuel cost projections for each fuel type out until 2050, the capital, operating and incremental costs of different levels of energy performance for building construction and renovations (for example the incremental cost of net zero buildings), the capital and operating costs of vehicle, transit and energy generation technologies, employment implications of different actions and policies and so on.

Future Projections

CityInSight is designed to project how the energy flow picture and emissions profile will change in the long term by modelling potential change in the context (e.g. population, development patterns), projecting energy services demand intensities, and projecting the composition of energy system infrastructure, often with stocks. Stock-turnover models enable users to directly address questions about the penetration rates of new technologies over time constrained by assumptions such as new stock, market shares and stock retirements. Examples of outputs of the projections include energy mix, mode split, vehicle kilometres of travel (VKT), total energy costs, household energy costs, GHG emissions and others. Energy, emissions, capital and operating costs are outputs for each scenario. The emission and financial impacts of alternative climate mitigation scenarios are usually presented relative to a reference or "business as planned" scenario.

Spatial Disaggregation

As noted above, a key feature of CityInSight is the geocoded stocks and flows that underly the energy and emissions in the community. All buildings and transportation activities are tracked within a discrete number of geographic zones, specific to the city. This enables consideration of the impact of land-use patterns and urban form on energy use and emissions production from a baseline year to future points in the study horizon. CityInSight outputs can be integrated with city mapping and GIS systems. This is the feature that allows CityInSight to support the assessment of a variety of urban climate mitigation strategies that are out of reach of more aggregate representations of the energy system. Some examples include district energy, microgrids, combined heat and power, distributed energy, personal mobility (the number, length and mode choice of trips), local supply chains, and EV infrastructure.

For stationary energy use, the foundation for the spatial representation is comprised of land use, zoning and property assessment databases routinely maintained by municipal governments. These databases have been geocoded in recent years and contain detailed information about the built environment that is useful for energy analysis. Overlaying fuel and electricity consumption and intensity data allows mapping the intensity of stationary energy use in the community, as shown in Figure 4.

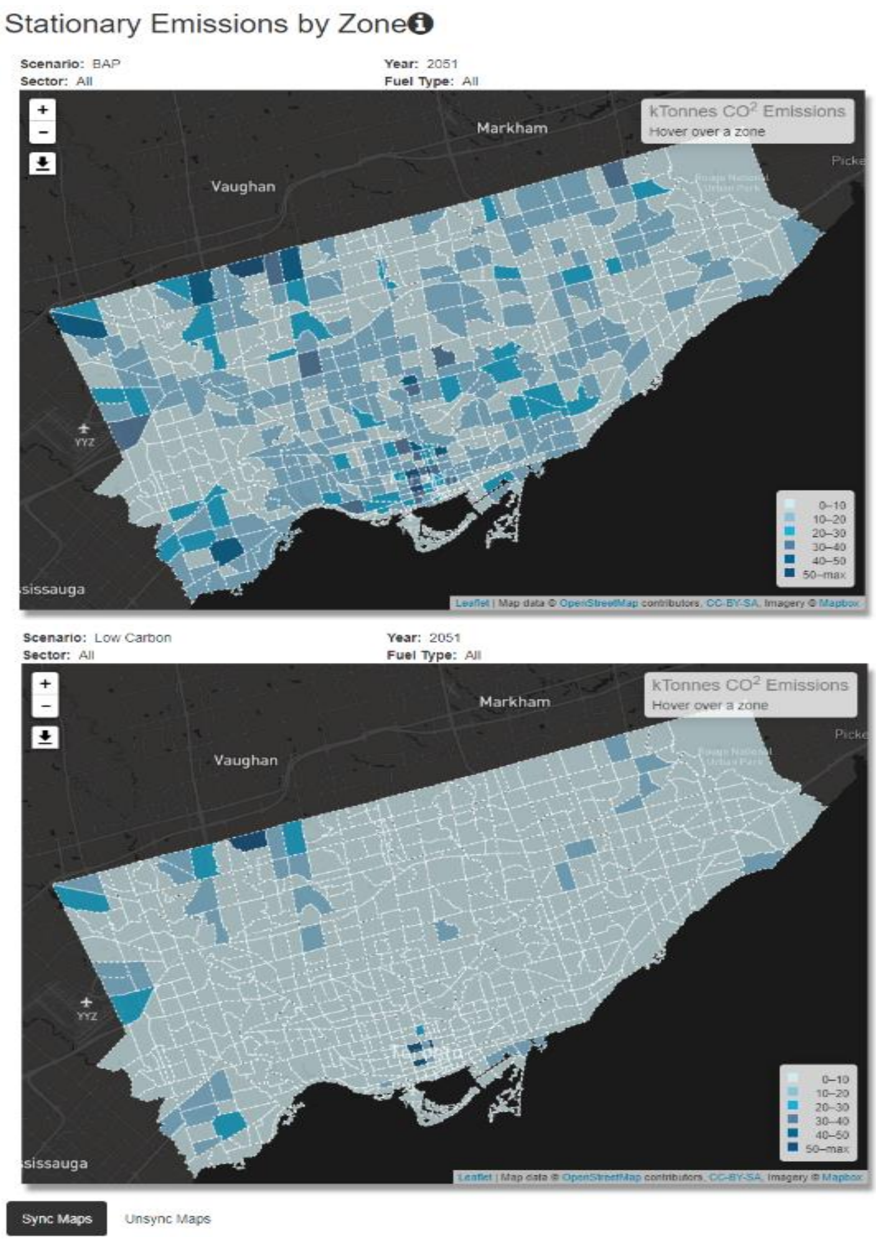

Figure 4. CityInSight map of GHG emissions from stationary energy use by transportation zone in 2051 for business-as-planned (top) and low carbon (bottom) scenarios.

For transportation energy use and emissions, urban transportation survey data characterizes personal mobility by origin, destination, trip time, and trip purpose. This in turn supports the spatial mapping of personal transportation energy use and greenhouse gas emissions by origin or destination.

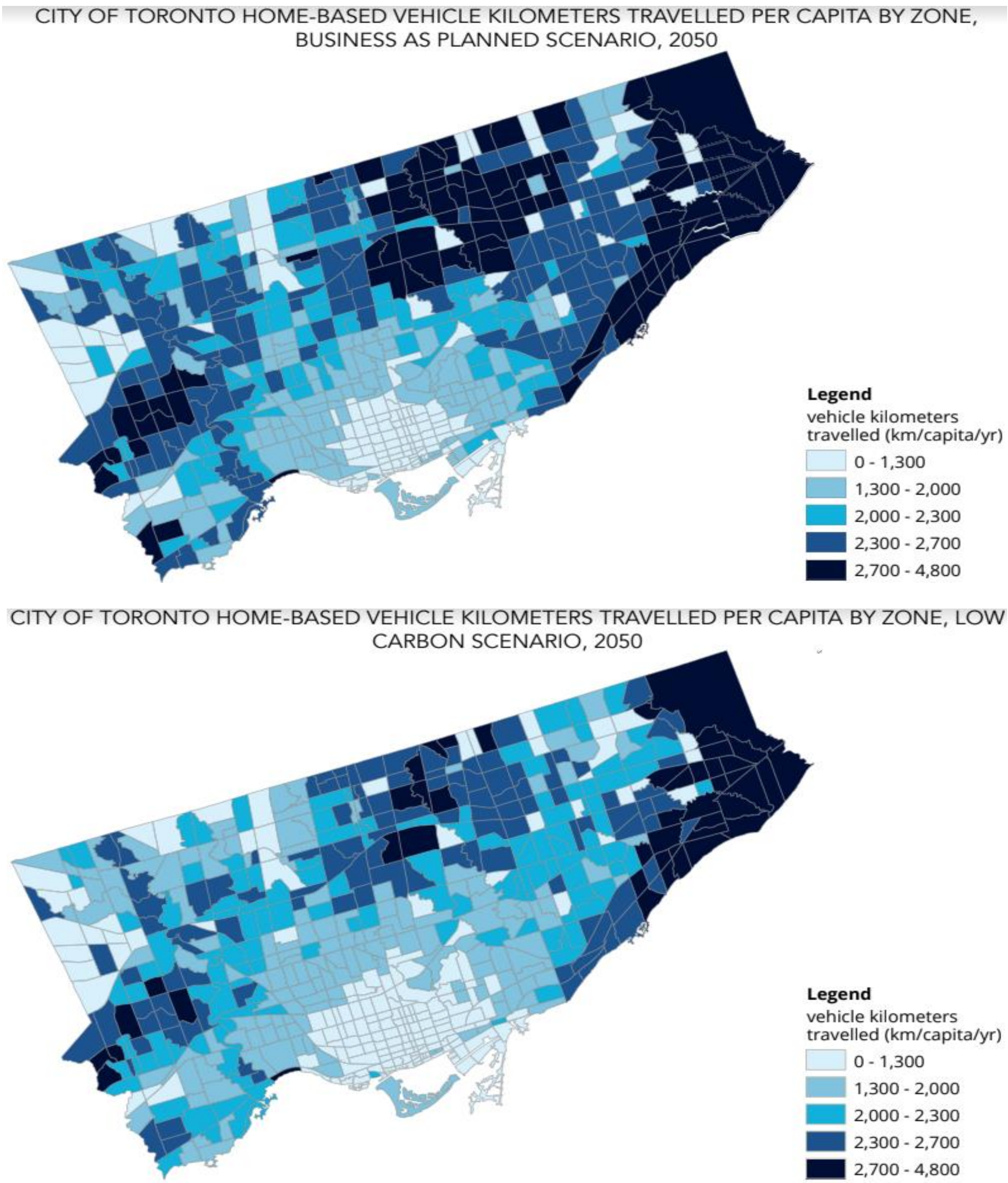

Figure 5. CityInSight map of per capita home-based vehicle-km of travel by transportation zone in 2050 for business-as-planned (top) and low carbon (bottom) scenarios.

Once the model is calibrated, there are numerous views and corresponding applications of the spatial resolution in CityInSight; a few examples are provided in Table 3. The maps are key to making the connections between urban planning and the level of energy use and greenhouse gas emissions in the community. For example, Figure 6 illustrates how the mapping of stationary energy intensity by zone in a low carbon scenario can be used to locate the areas with the best long term potential for district energy.

Table 3. CityInSight – Examples Applications of Spatial Modelling

Type	Calculation	Application
People and employment density	People and jobs per area (people and jobs/hectare)	Population and employment densities are useful in most aspects of community planning, including housing and transit.
Buildings density	Number of units or square metres per area (units/hectare or square metres/hectare)	An indicator of the density of heated and cooled space (energy use). New buildings do not necessarily increase total energy use if they are high efficiency and/or existing buildings are retrofit.
Energy Density	Energy consumed per area of developable land (GJ/ha or GJ/m2)	Can be used to compare the energy impacts of land-use for growth nodes, corridors, or other areas in the city. Areas of high energy densities are potential sites for district energy systems.
Energy Use Intensity (EUI)	Energy consumed per area of floorspace (GJ/m2 or kWh/m2)	Can show the average EUI for all buildings in a zone or parcel. If the information is granular enough, it will show over time how retrofitting and/or a change in the housing mix can improve EUIs.
Energy Per Capita	Energy consumed per person (GJ/cap)	Can be used to compare how much energy is consumed by each resident or worker. The overall energy intensity of different neighbourhoods can be compared.
VKT Per Capita	Kilometres by mode per person from the origin	Can be used to compare the extent of travel by different modes in different areas. Areas with high levels of vehicular travel can be identified for interventions such as travel planning or transit.

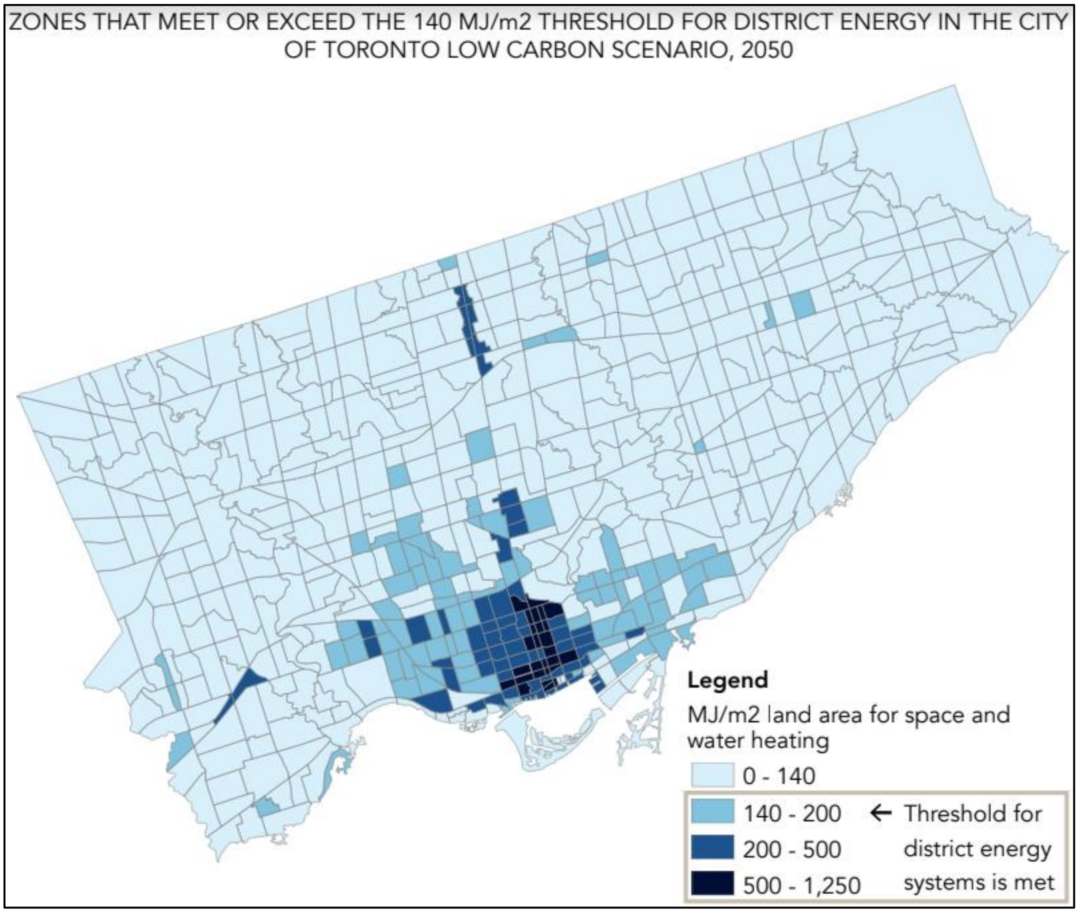

Figure 6. CityInSight map of the zones in Toronto in which the stationary energy intensity in 2050 in the low carbon scenario meets or exceeds the specified threshold for district energy feasibility.

Data Visualization

Data visualization is an integral part of the CityInSight model. The datasets being analyzed are very large and difficult to interpret without visualization. Also, the model is intended to help make connections between urban systems and the energy and emissions systems, to help the users and stakeholders “see” how their decisions and investments affect the level of greenhouse gas emissions, and to identify opportunities for alignment and climate mitigation. CityInSight is designed for scenario analysis, to help users envision low carbon futures and the pathways for reaching them.

Applications of CityInSight include a data visualization platform or “dashboard” that enables users to explore in detail the modelling results for various scenarios or actions. The dashboard is interactive, designed to support stakeholder engagement, and utilizes data journalism techniques to illustrate key trends, drivers and results of CityInSight scenarios. Users can explore the results to greater degrees of detail according to their interests. Specific data points can be identified, aspects of the charts can be enlarged, data sets highlighted, and so on. Different combinations of datasets, outcomes, time periods and geography can be selected.

4. Application and Example Results

CityInSight is designed to support the process of developing a municipal strategy for greenhouse gas mitigation. Usually the model is engaged to identify a pathway for a community to meet a greenhouse gas emissions target by a certain year, or to stay within a cumulative carbon budget over a specified period. The generalized process is show in Figure 7.

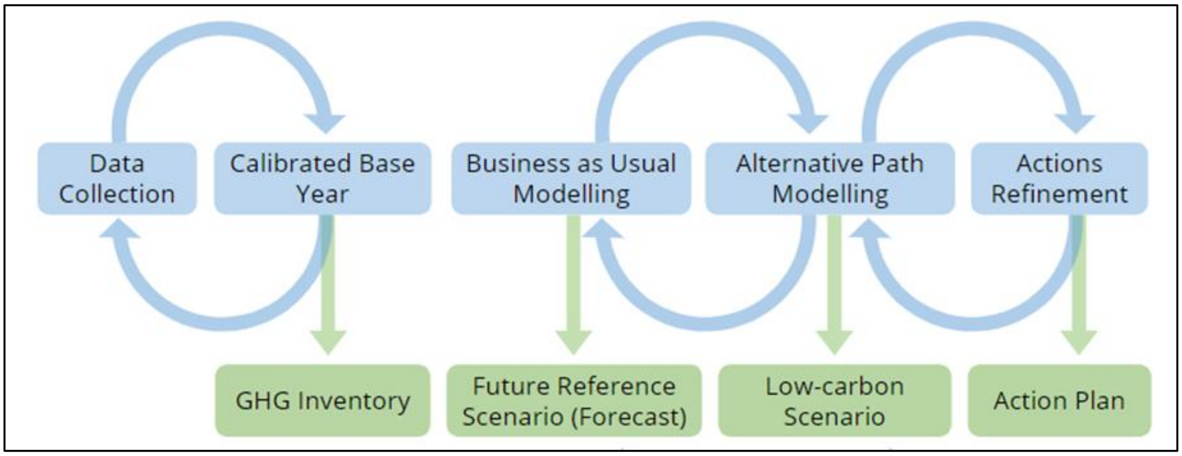

Figure 7. Schematic representation of municipal climate mitigation action plan

Data Collection and Calibration. A typical CityInSight engagement begins with an intensive data collection and calibration exercise in which the model is systematically populated with data on a wide range of stocks and flows in the community that affect greenhouse gas emissions. A picture literally emerges from this data that begins to identify where opportunities for climate change mitigation are likely to be found in the community being modeled. The calibration and inventory exercise helps establish a common understanding among community stakeholders about how the greenhouse gas emissions in their community are connected to the way they live, work and play. Relevant data are collected for variables that drive energy and emissions -- such as characteristics of buildings and transportation technologies -- and those data are reconciled with observed data from utilities and other databases. The surface area of buildings is modeled in order to most accurately estimate energy performance by end-use. Each building is tracked by vintage, structure and location, and a similar process is used for transportation stocks. Additional analysis at this stage includes local energy generation, district energy and the provincial electricity grid. The primary outcome of this process is an energy and GHG inventory for the baseline year, with corresponding visualizations.

The Reference Projection. Once the baseline is completed, a "business-as-usual" or "business-as-planned" projection to the target year or the horizon year of the scenario exercise is developed. This process involves identifying future population and employment and allocating the population and employment to building types and space. In the process the model is calibrated against historical data, providing a technology stock as well as an historical trend for the model variables. This process ensures that the demographics are consistent, that the stocks of buildings and their energy consumption are consistent with observed data from natural gas and electricity utilities, and that the spatial/zonal system is consistent with the municipality's GIS and transportation modelling. The projection typically includes approved developments and official plans in combination with simulation of committed energy infrastructure to be built, existing regulations and standards (for example renewable energy and fuel efficiency) and communicated policies. The projection incorporates conventional assumptions about the future development of the electrical grid, uptake of electric vehicles, building code revisions, changes in climatic conditions and other factors. The resulting projection serves as a reference line against which the impact and costs of GHG mitigation measures can be measured. Sensitivity analysis and data visualizations are used to identify the key factors and points of leverage within the reference projection.

Low carbon scenario and action plan.

CityInSight draws on an in-house database that specifies the performance and cost of technologies and measures for greenhouse gas abatement. These are used to develop a list of candidate measures for climate mitigation in the community being modelled, supplemented by additional measures and strategies that are identified in the calibration and reference projection analyses and through stakeholder engagement exercises. CityInSight inputs are developed for characterizing these measures relative to the reference projection for the community being modeled. Integrated scenarios are then generated in which packages of measures are analyzed together to ensure that there is no double counting and that interactive effects of the proposed measures are captured in the analysis.

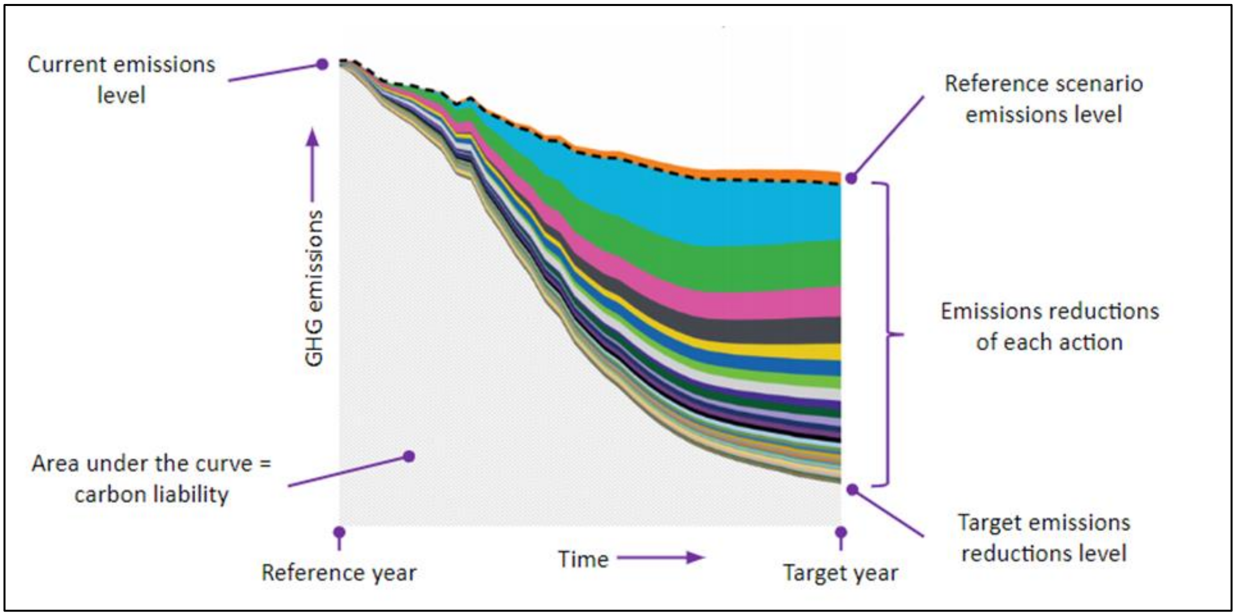

Figure 8. CityInSight "wedge diagram": anatomy of a low carbon pathway analysis

The following graphics illustrate results from several recent CityInSight engagements for Canadian municipalities.

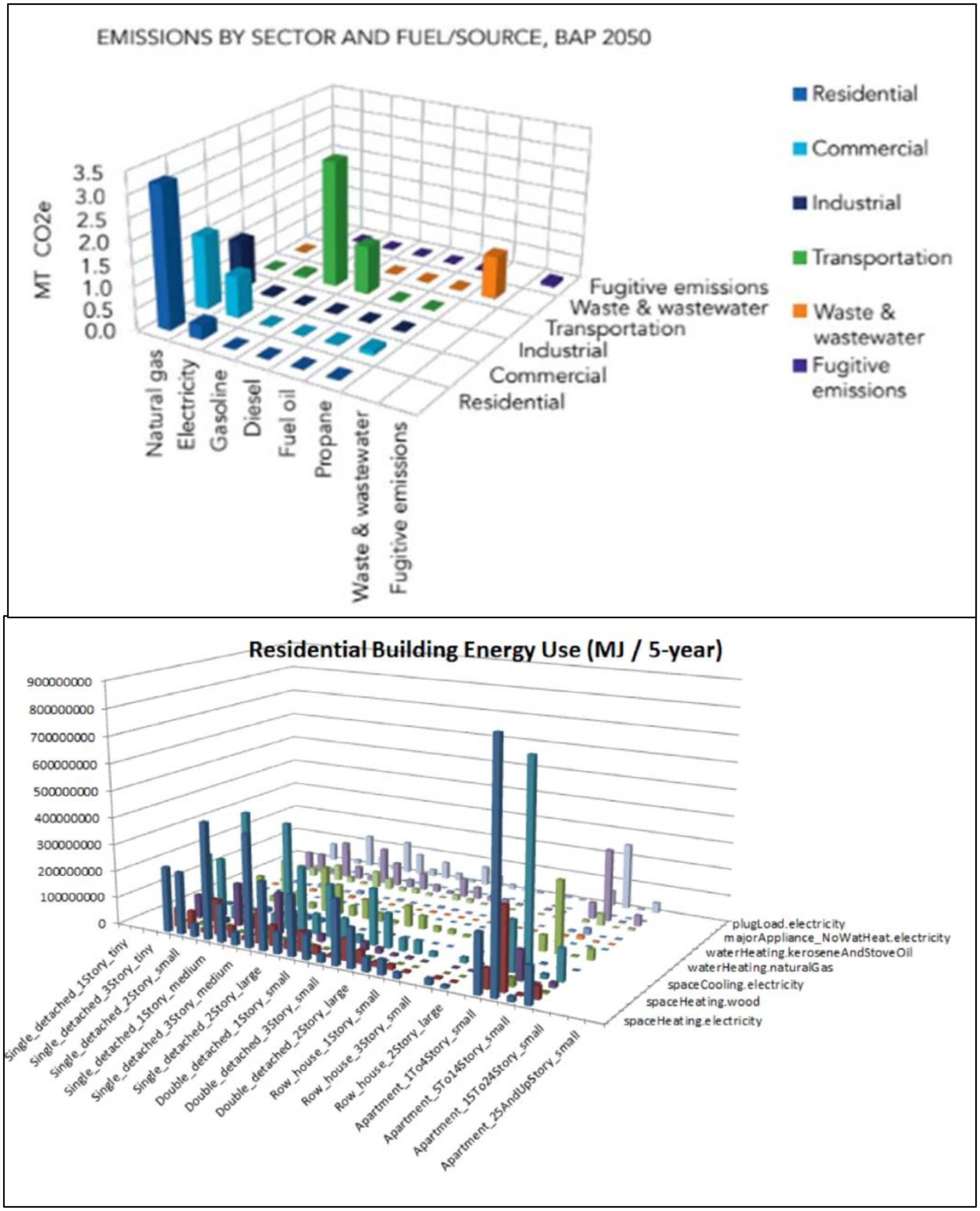

Figure 9. CityInSight calibration results: an overview of emissions by sector and source (top) and a more detailed breakdown of residential energy use by end use and building type (bottom).

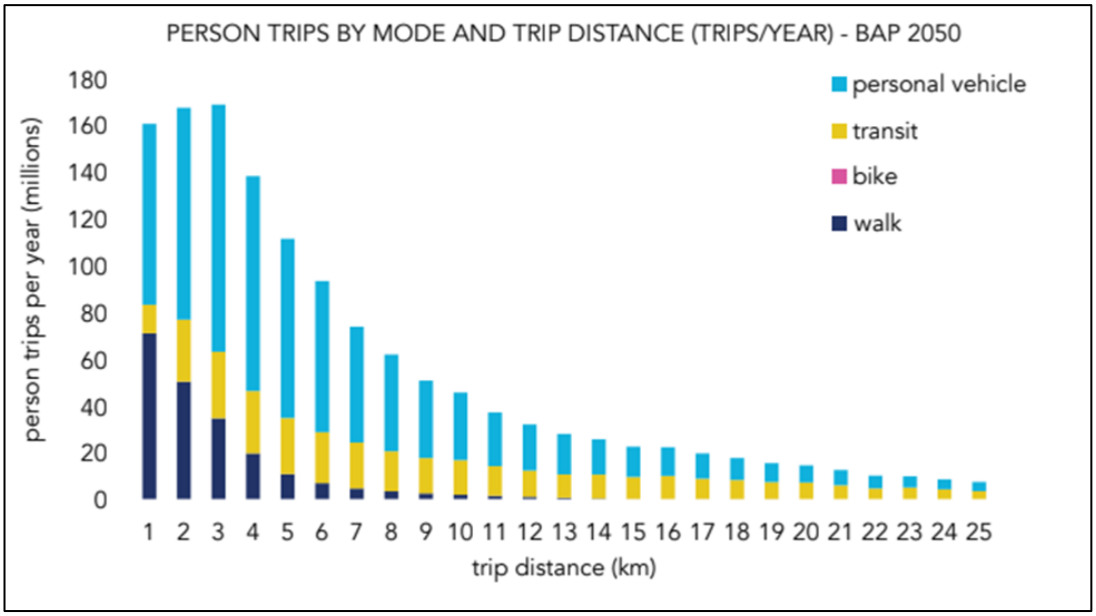

Figure 11. CityInSight spatial resolution of trips by origin-destination pairs allows a profile of trips by length and mode, supporting anlaysis of opportunities for active transportation.

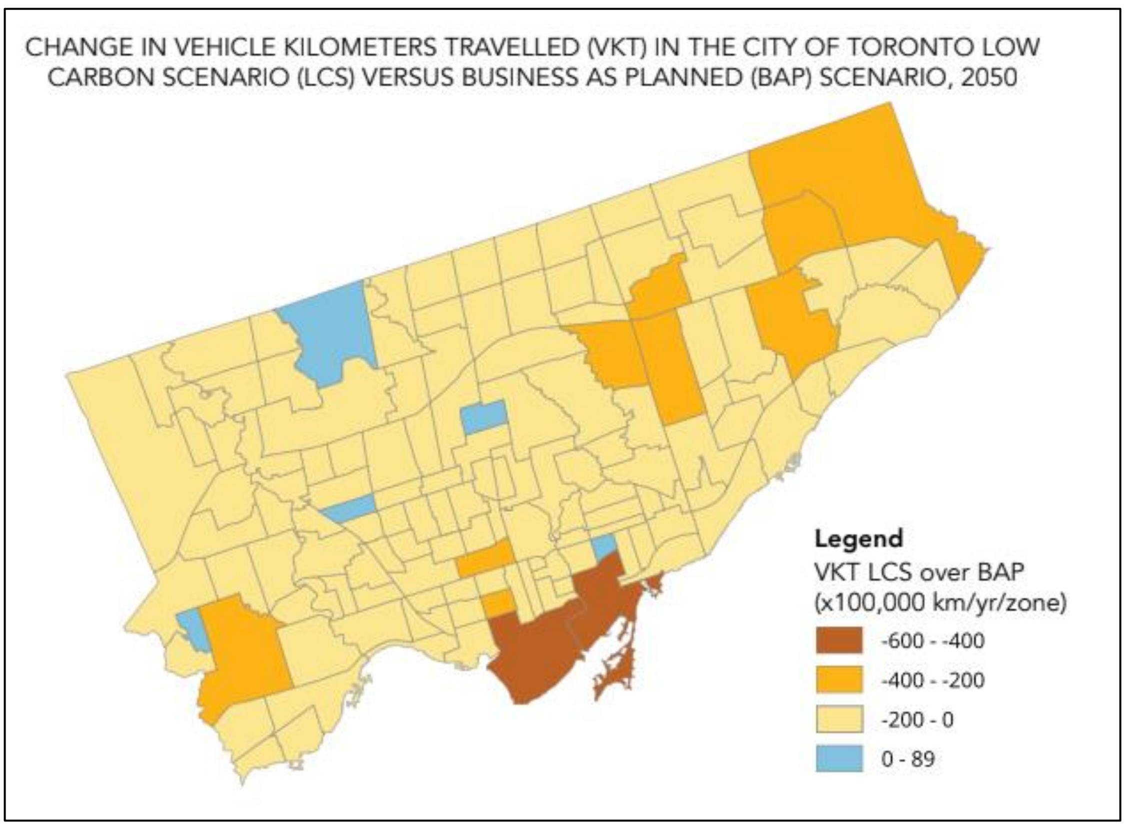

Figure 10. A CityInSight map of the impact of land use and other measures in reducing vehicle-kilometres of travel (VKT) in a low carbon scenario, compared to business-as-planned.

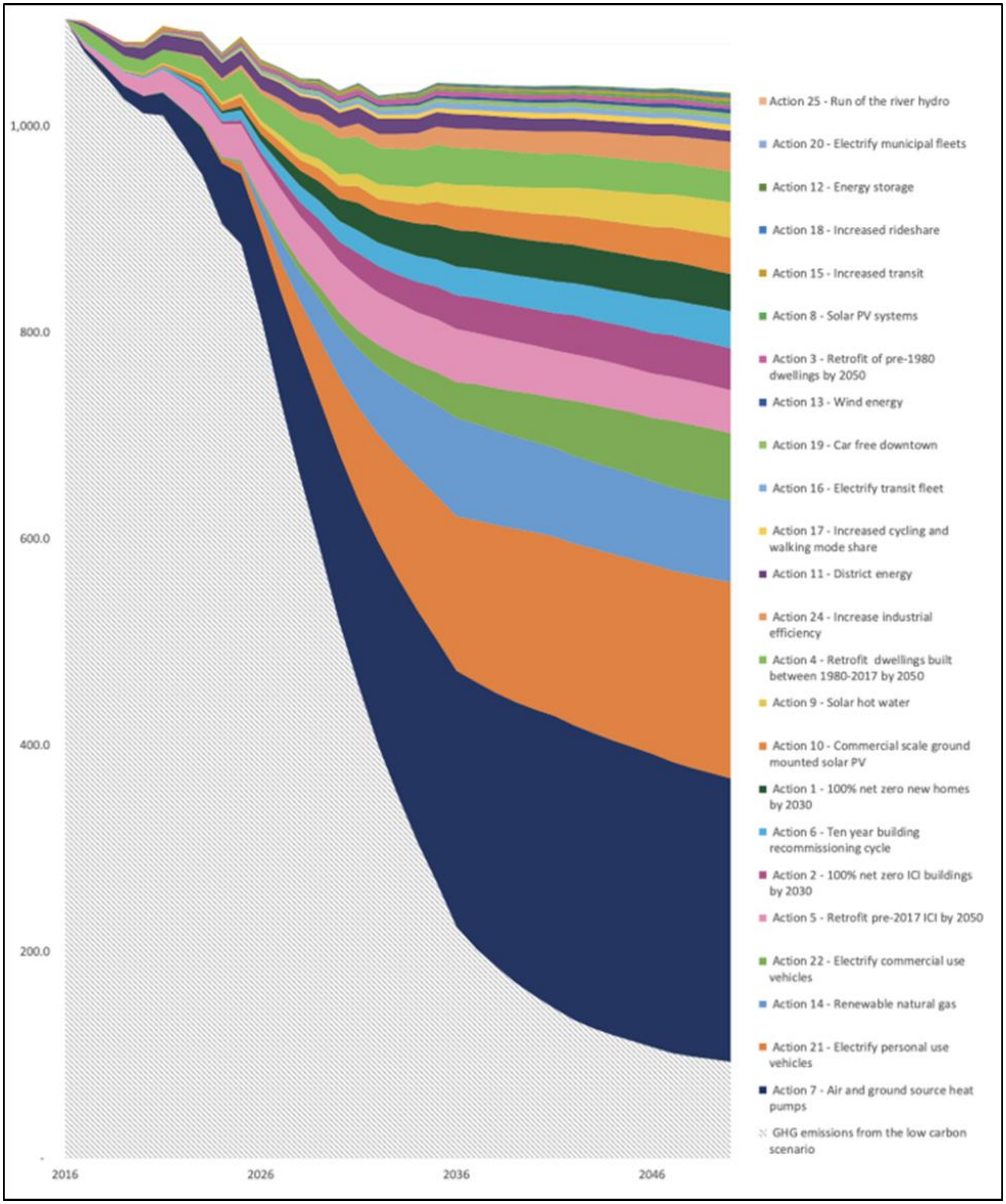

Figure 12. A CityInSight wedge diagram of the measures in a low carbon pathway analysis. The two largest measures in this scenario – heat pumps (dark blue) and electric vehicles (orange)—are consistently among the largest contributors to low carbon scenarios for Canadian cities.

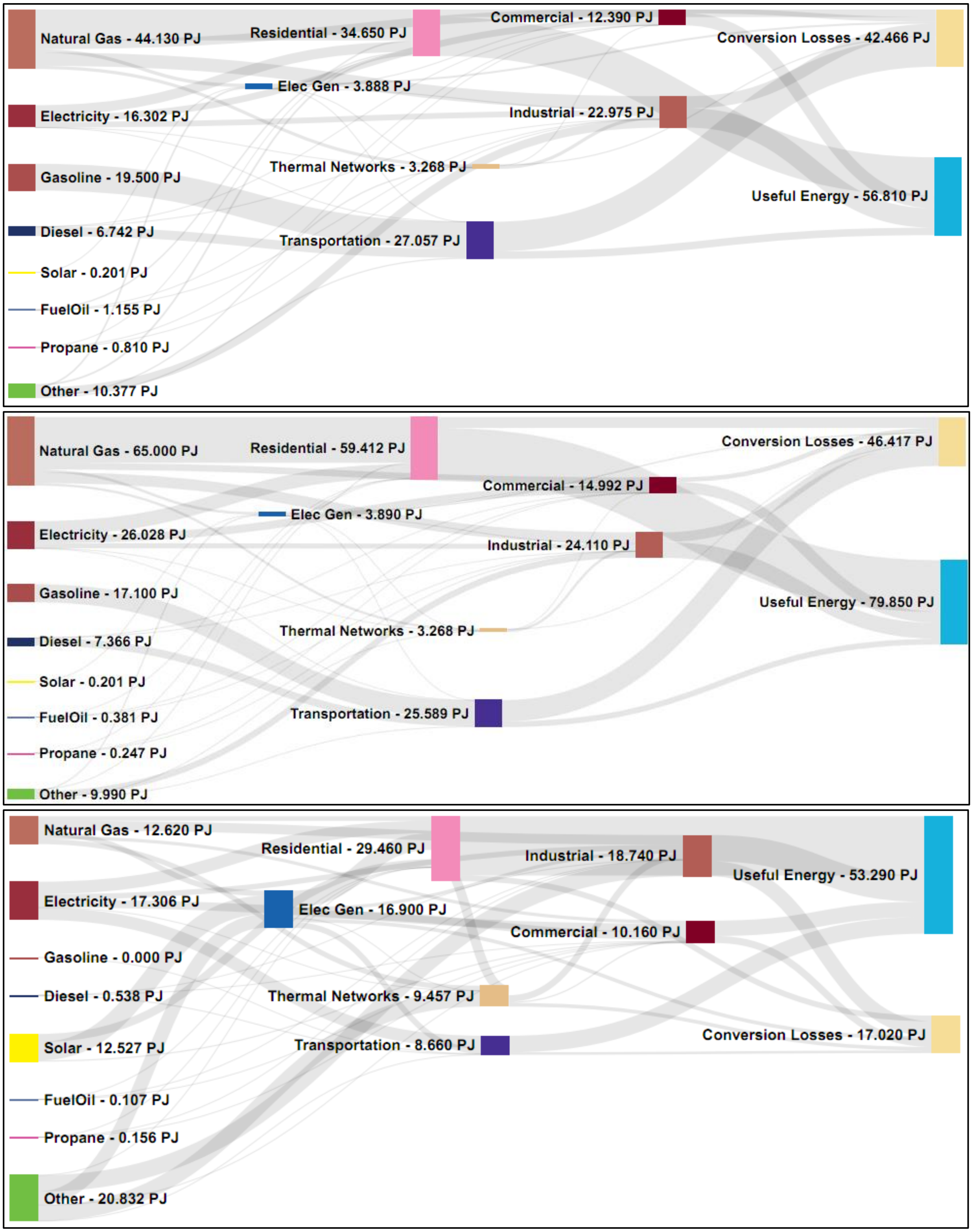

Figure 13. CityInSight generated Sankey diagrams for the Region of Durham for 2016 (top), 2050 business-as-usual (middle) and low carbon pathway (bottom). Note the increased role of electricity, the lower conversion losses, and reductions in gasoline and natural gas in the low carbon pathway, as compared with the base year and business-as-usual scenarios.

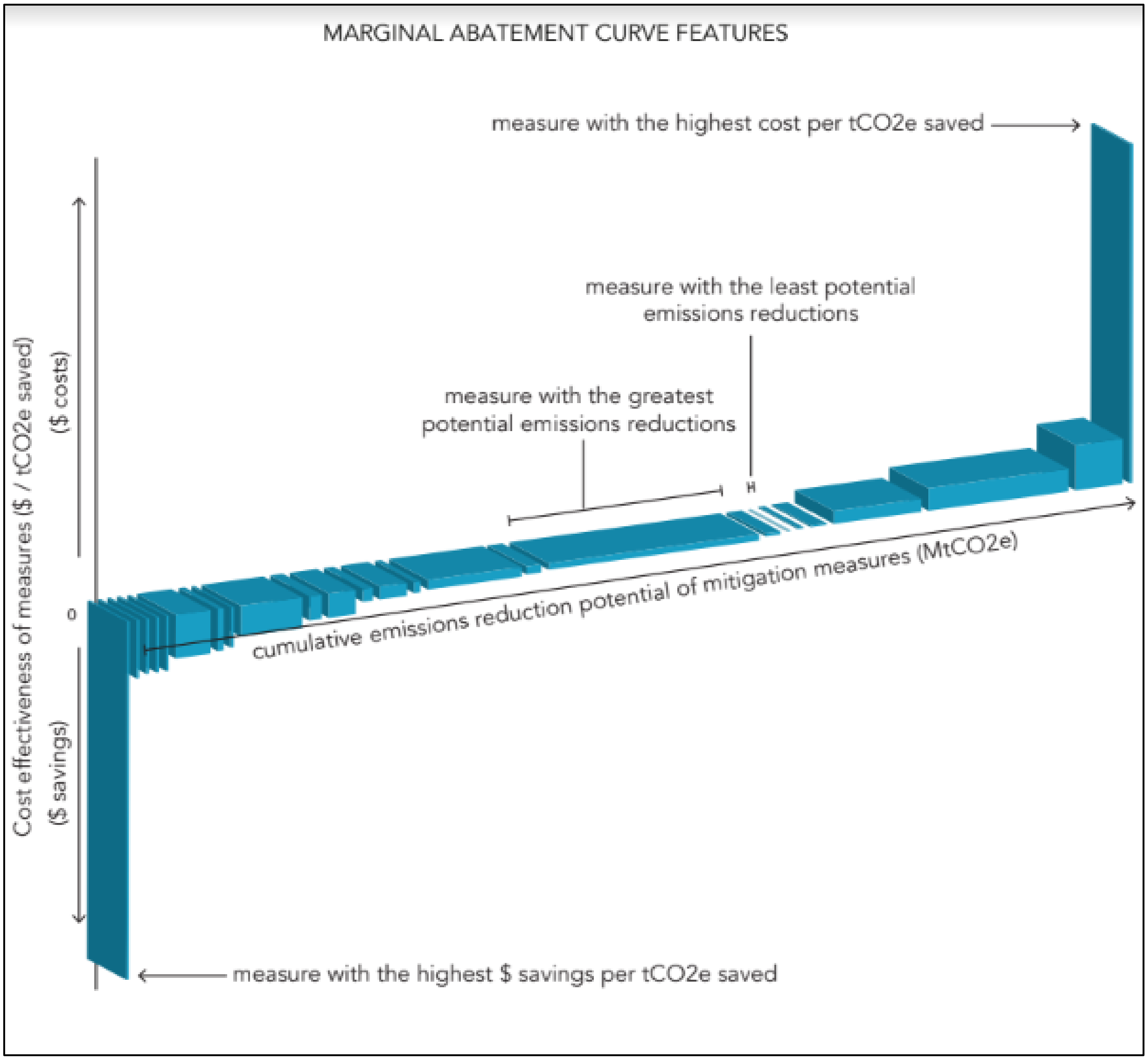

Figure 14. CityInSight generates marginal abatement cost curves. The height of each block represents the cost of the measure and the width represents its contribution to the emission reductions relative to the reference projection. Measures with negative values on the y-axis result in net savings.

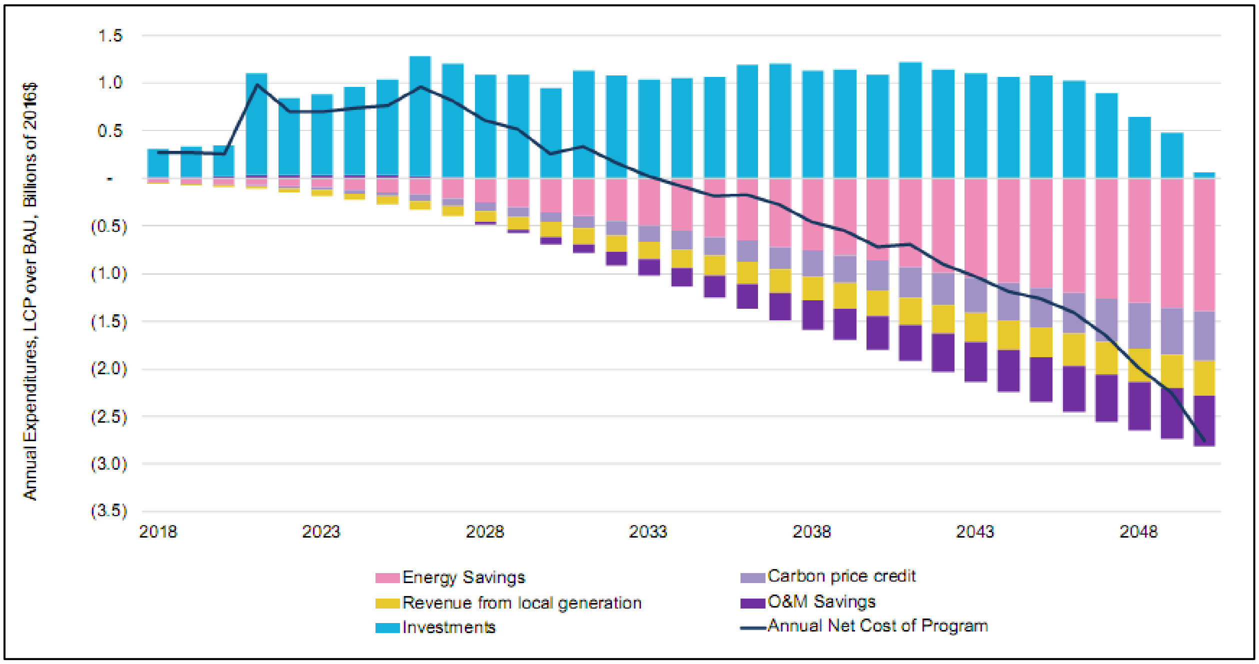

Figure 15. CityInSight's financial analysis tracks capital investments, energy cost savings, carbon price credits, operation and maintenance savings, and revenue from local energy generation. The annual and cumulative net cost of the scenario is report for each year and can be displayed on a cash or accrual basis. In this graphic, investments and costs are positive, and savings are negative.

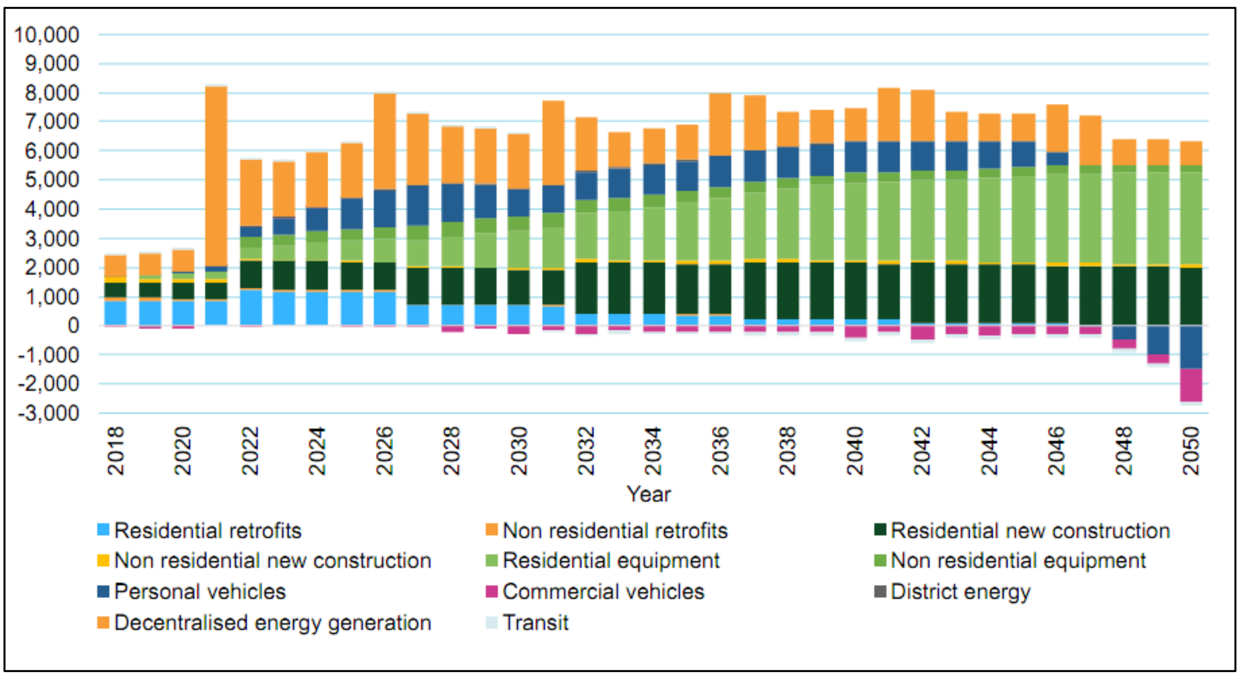

Figure 16. CityInSight tracks employment impacts of scenarios relative to the reference or business-as-usual projection. The above example is for the Region of Durham low carbon pathway.

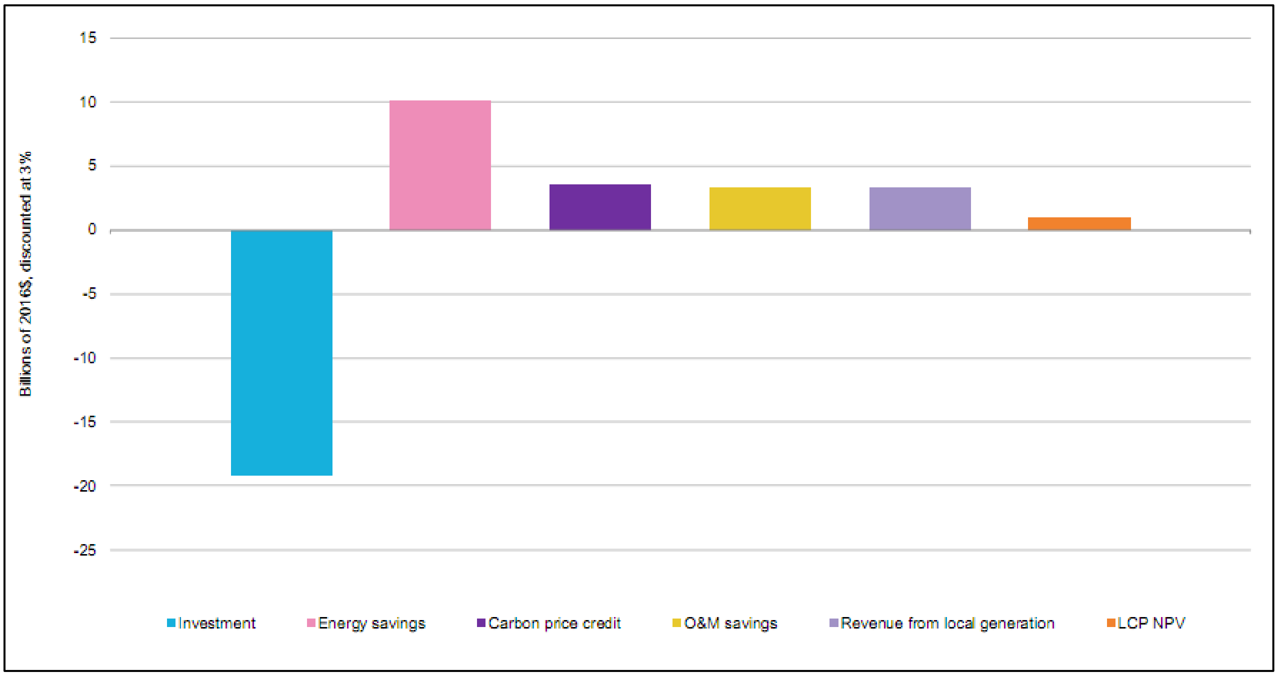

Figure 17. CityInSight tracks net present value of scenarios. This figure, from the Region of Durham low carbon pathway to the year 2050, shows the present value of expenditures, savings and revenue for a scenario with a positive net present value.

5. Research and Development Directions

The CityInSight model has been developed in the private sector with private sector resources in response to a need for modelling and analytical support for urban climate mitigation. The choice of a physical-based, systems dynamic framework with spatially disaggregated, bottom-up data structures is a direct result of the model's practical application. It has been widely deployed by municipalities large and small across Canada, and out of that experience several topics for future model research and development have been identified. Here are a few observations from our recent work with CityInSight:

- First, the model has affirmed the interest in and the value of spatial resolution in community energy and emissions analysis. We have only just begun to realize the potential for this type of modeling in the identification and development of urban climate mitigation. There has been very little investment in model development beyond the firms involved. The planning decisions and investments made in Canadian municipalities over the next decade will determine whether we make a smooth transition, or at least a less rocky transition to a low carbon economy. More support is needed for the research and development of the databases and modeling tools needed for the identification and design of urban low carbon transitions.

- In addition to spatial resolution, the role of temporal resolution is becoming more important for energy policy and business strategies. The time pattern of electricity supply and demand has always been an issue for planning and managing electricity grids, but time variations and time lags in supply and demand are a signature challenge in the low carbon transition. Energy system planning models have tended to operate with time steps of one year or more, but there are many aspects of the super-efficient, electrified energy systems of the future that require understanding and modelling on sub-annual time scales. We have been preparing CityInSight for 8760-hour simulations but there are issues of data and practicality that need to be resolved. Different modeling problems require different time steps and it will be important to match the time scale of simulation to the specifics of the system being modeled.

- There is a need to better represent energy service dynamics and/or to link to the models in those sectors that do simulate those systems (e.g. the trip making and allocation models of urban planners). We now understand that over the past twenty years about 50% of the improved energy commodity productivity in Canada was the result of behaviours and decisions outside of the normal purview of energy commodity markets and models, but which nevertheless go a long way in determining the level and pattern of energy service demand, and therefore ultimately energy commodity demand. Some of our current models are better at addressing this than others, but in general we are flying blind as energy modelers when it comes to the fundamental drivers of the system we are trying to understand.

- The economies of cities are dominated by the service sector, not manufacturing. A significant portion of the light duty vehicle traffic in large urban centres (perhaps 20% or more in some centres) is commercial traffic. We need to understand the trip-making dynamics of this vehicular activity in the same way we study the issue of personal trip making in the transportation planning models.

- As electrification proceeds and the emissions from vehicle tailpipes and building chimneys decline, the greenhouse gas emissions embodied in goods and services will become of relatively greater importance.

- The ratio of dwellings:households appears to be growing due to vacancy rates, vacation homes, and households that maintain more than one dwelling. There is a need for more research on the energy consumption implications of this trend and how best to account for it in scenario modeling.

- The efficiency of electric vehicles and heat pumps, two mainstays of the low carbon transition, vary significantly with ambient temperature. As these technologies gain in market share, energy models must account for their variable efficiency. Similarly, highly energy efficient buildings have long thermal time constants, and respond more slowly to changes in outside temperature, with implications to their demand load shapes.

6. References

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