Cite as: Mohareb, E.A. & Kennedy, C.A., 2012. Greenhouse Gas Emission Scenario Modeling for Cities using the PURGE Model – a Case Study of the Greater Toronto Area. *Journal of Industrial Ecology*, **16(6)**, 875 – 888.

Greenhouse Gas Emission Scenario Modeling for Cities using the PURGE Model - a Case Study of the Greater Toronto Area

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Acknowledgements

This study received financial support from people of Canada, through the Natural Sciences and Engineering Research Council. The authors appreciate the data provided by L. Bond, K.Crate, J. Humphries, L. Lewis, M. Nehme, R. Persaud, and J. Webster, as well as the comments provided by C. Andrews, D. Harvey, H. MacLean, and K. Pressnail.

Introduction

Cities face an ongoing challenge to decouple their growth from their resource consumption (Kennedy et al, 2007). One consequence of this is that greenhouse gas (GHG) emissions from cities will continue to rise unless the technology stock of cities no longer relies on fossil fuels to provide energy services. Technological solutions are routinely suggested as a means for reducing the emissions of GHGs contributing to climate change (e.g., Pacala and Socolow, 2004). These technological measures include fuel switching (i.e. coal to natural gas), adoption of renewable energy sources, the pursuit of carbon sequestration and the transition to higher efficiency conversion technologies. The gaps that these technologies must bridge are expansive; Meinshausen et al (2009) suggest that a peak CO_2e concentration of 450 ppm would likely limit warming to below 2^oC, avoiding some of the most severe consequences of climate change. The IPCC suggests that to achieve this concentration, Annex I nations need to reduce their GHG emissions by 80-95% from 1990 levels by 2050 (Box 13.7; IPCC, 2007). Hence, there is value in modeling the impact of technological changes from now until 2050.

This article describes an urban-scale model where temporal considerations of GHG emission reductions associated with transitions to low-carbon technologies can be examined. The Pathways to Urban Reductions in Greenhouse gas Emissions (or PURGE) model focuses on the principal sources of GHG emissions attributable to cities: buildings, transportation, and waste. The rate of building stock change, as well as the adoption of and decisions for retrofitting, are applied to the model for different eras of construction. The adoption of vehicles powered through alternate propulsion systems (i.e. those with electric motors) is also examined, reducing reliance on petroleum fuels. Total annual electricity demand is likely to increase due to the anticipated reliance on battery-powered vehicles; the net impact on GHG emissions is also explored. The emissions reduction associated with the increase in diversion of organic waste and its treatment with incinerators or anaerobic digesters are also quantified. The changing emissions intensity of the electrical grid is also factored into the emissions calculations for technologies that utilize this energy source (predominantly in buildings and transportation). Finally, the model captures the temporal change in carbon stocks in the principal means of carbon sequestration in urban areas (urban and regional forests). The PURGE model is applied to the current strategies suggested by government policy that are intended to impact GHG emissions in the Greater Toronto Area (GTA, 2011 population 6,054,191; Statistics Canada, 2012).

Table 1 provides an idea of the relative scale of these emissions for the City of Toronto (2011 population, 2,615,060; Statistics Canada, 2012). It should be noted that gasoline contributes 95% of passenger transportation-related emissions (the remainder a mixture of natural gas and diesel), while natural gas usage results in 60-80% of building energy emissions (with the rest predominantly attributable to electricity; City of Toronto, 2007a; OEE 2009).

Table 1: Proportions of Toronto GHG associated with the Four Major Sectors to be Assessed (City of Toronto, 2007a).

Sector	**% of Total Emissions**
Natural Gas (predominantly heating)	37%
Transportation [a]	27%
Electricity Generation	26%
Waste	4%

[a] Only ground-based emissions are considered

Considering the contribution that the selected sectors make to urban GHG emissions, modeling of the transition of these to low carbon alternatives would provide a representative estimate of the timeline and scale of emission reductions. Using historical data and logistic curve modeling, the methodologies for estimating these reductions are presented.

Background on Technological Change

Technological change is generally viewed as the most economically and socially palatable option for reducing GHG emissions. The IPAT equation (Holdren and Erlich, 1971) has been modified for greenhouse gas emissions using the Kaya identity (Kaya, 1990; from Raupach et al, 2007),

$$C\,emissions = P \times \frac{GDP}{P} \times \frac{E}{GDP} \times \frac{C}{E} \qquad (1)$$

where in a given year, P is population, GDP / P is gross domestic product per capita, E / GDP is energy consumption per unit of GDP, and C / E is the average carbon intensity of a unit of energy. Looking at the terms, carbon emissions are a product of population, per capita income, energy intensity of the economy, and carbon intensity of energy conversion devices; it follows that if an emissions reduction of 80-95% were to occur, significant reductions will be required in these terms. Global population reduction is likely only achievable in the long term (UN, 2008) and socio-political resistance would understandably limit reductions attainable though policies aimed at lower economic activity. This leaves technological solutions, i.e. energy conversion efficiency and demand reduction (represented by the 3rd term), and alternative fuel sources or carbon sequestration technologies (characterized by the 4th term) as the most saleable options in combating climate change. Given the likely focus placed on widespread technological change to reduce anthropogenic GHG emissions, and that this change is subject to a temporal influence, it is important that the expected shift to low-carbon alternative technologies be assessed for its expediency.

The transition to low-carbon technologies is a complex matter, with political, technological, economic and social factors influencing the rate and pathway of change. Political influence comes in the form of subsidies and financing schemes, which may favor certain technologies, in turn dictating the transitional pathway. Technological influences include technological lock-in of an energy-intense (as well as carbon-intense) technology, preventing or restraining the adoption of an alternative that is more efficient (Unruh, 2000). In the absence of carbon pricing, many transitional and disruptive low-carbon energy technologies will not be able to compete with entrenched technologies. Finally, social attitudes affect adoption in that technological selection often does not solely favor low-carbon technologies; Turrentine and Kurani (2007) explain that fuel consumption is but one factor in the decision of which vehicle to purchase, with other factors including social perceptions of the vehicle, as well as aesthetics (such as interior design and color). Additionally, the impacts of fuel consumption are often not accurately estimated by the consumer. While considering these points, we set out to examine some commonly held notions of technological change.

Cumulative technological change has frequently followed a sigmoidal diffusion curve over time (Rogers, 2003; Banks, 1994; Grubler, 1997). Initially, adoption is slow, with a period where niche applications dominate new usage (Figure 1; point #1). As barriers to adoption are overcome (such as economic or informational barriers), rate of adoption begins to increase, with a period of exponential growth (point #2; the “take-off” stage). Eventually the rate of adoption reaches a maximum (an inflection point, #3) and begins to decline to a point where adoption essentially plateaus (point #4).

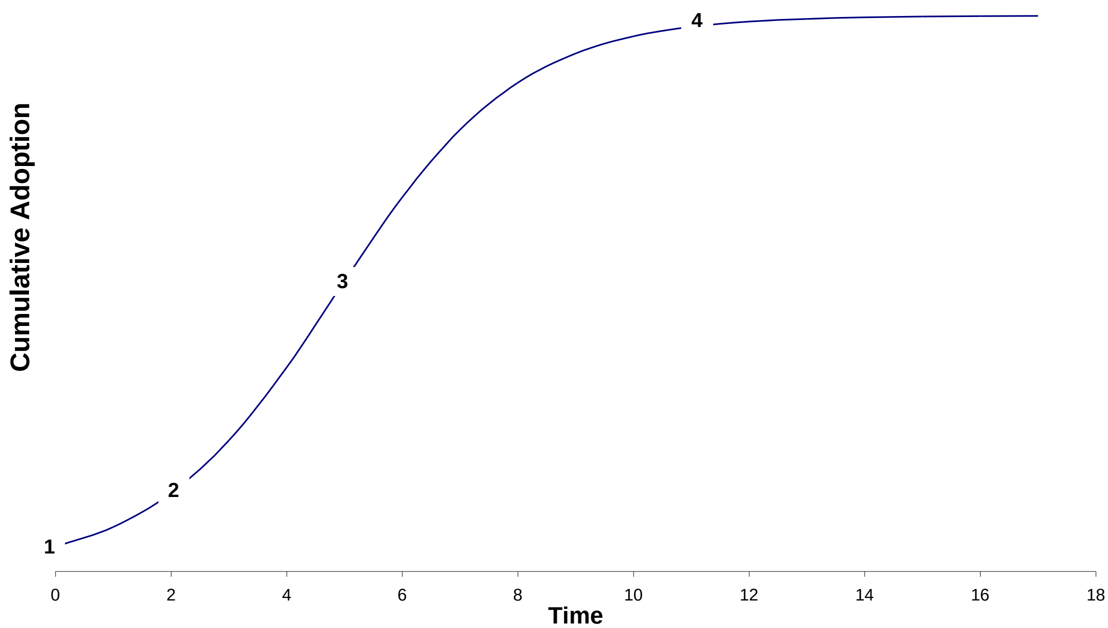

Figure 1: Typical Technological Diffusion Curve

One model for sigmoidal diffusion described in Figure 1 is the logistic equation, where the "population" of a given technology (*Y*) at time *t* is given by

$$Y(t) = \frac{K}{1 + \frac{K - Y_o}{Y_o} e^{-at}} \qquad (2)$$

where *K* is the carrying capacity (or ultimate population) of the technology, Y_o is the initial population and *a* is the growth coefficient.

Grubler et al (1999) examine technological change in the context of energy technologies. They note that in the predevelopment/exploration phase, technologies are typically not economical, but once a niche market is discovered, a shift into the take-off stage begins. After a certain amount of technological learning, further progression into the take-off phase occurs; this is due partly to production processes becoming more efficient and, hence, less costly, with greater experience in manufacturing the emerging technology. As well, information of the benefits of the new technology spreads amongst potential adopters, further increasing adoption. This has been observed with energy technologies as well, with solar photovoltaic (PV) and wind turbines experiencing exponential declines in production costs as cumulative production increases. Globally, a ~20 % decline in cost for PV and wind has been observed after each doubling of production of these technologies (or ~80% "progress ratio"; IEA, 2000).

In an effort to increase energy efficiency (in light of price volatility) and reduce carbon emission intensity (in anticipation of the internalization of the costs associated with carbon emissions), the transition to low-carbon emitting technologies has begun. Pacala and Socolow (2004) suggest that the technologies required to prevent the doubling of pre-industrial emissions already exist, many at a commercial scale. It follows that a large number of the technologies that require mass deployment in the sectors of interest in this research (electricity generation, space / hot water heating & transportation) have already reached the "take-off" stage. Alternatives to current energy provision technologies are commercially available and many are economically competitive with the status-quo.

The PURGE model focuses on the role of technological change in mitigating GHG emissions, but this approach does have some limitations in capturing a complete range of emissions reductions options. These limitations, which are principally associated with behavioral change and certain urban policy levers (e.g. date-certain policy which does not follow a sigmoidal adoption curve), restrict the user's ability to explicitly model key approaches to urban GHG emission reduction. However, these approaches can be indirectly modeled through modification of key indicators over time (i.e. reductions in vehicle kilometers travelled due to land use change policy or in energy demand per square meter due to date-specific adoption of compact fluorescent lighting). These key approaches include energy conservation behavior, urban planning strategies, and land use interventions. Additionally, one further limitation is the assumption that plasticity of adoption behaviors (the percentage of households that have not adopted energy-saving strategies, but would do so) is 100%. The PURGE model generally employs a plasticity of 100%, which is not realistic, but is used to demonstrate a best possible outcome of current policy measures.

The work of Dietz et al (2009) highlights measures that can be taken at the household level to achieve significant GHG emissions reductions, examining behaviors related to the building and transportation sectors. From a planning perspective, the National Research Council (2009) has provided a series of findings from their expert committee's assessment of the relationship between land use and transportation energy consumption (e.g. improved density, incorporating a diversity of uses in developments). Finally, Ramaswami et al (2012) have described a case study of Denver, Colorado where a number of emissions reductions wedges, which include behavioral change and policy/regulatory strategies amongst them. Ramaswami et al (2012) also suggest policy measures being tested in a few cities that can be adopted by cities that can result in a significant and relatively quick reduction in GHG emissions, such as building ordinances, carbon taxes and the inclusion of real-time residential energy displays. These literature sources highlight that behaviour and policy change must be pursued in conjunction with the voluntary adoption of more efficient end-user technologies in order to achieve deep reductions in greenhouse gas emissions.

Components of the PURGE Model

Quantification of the release of GHG emissions from the four main sectors of the model (electricity generation, private transportation, buildings and waste) is described below. Generally speaking, the model requires knowledge of the current stock of technologies contributing to a given sector's GHG emissions. The means of achieving the necessary emission reductions from technological change can follow any number of paths, requiring a model which utilizes broadly applicable parameters.

Past rates of stock change are explored in order to quantify how quickly new technologies can be adopted. These can be estimated using historical data, accompanied by contextual information associated with the timeframes and geographic area analyzed. As well, the energy requirements of the new technology and the expected carbon intensity of the fuel source utilized (not applicable for waste) are quantified based on analysis from peer-reviewed sources. The sources and methodologies used for obtaining this information varies for each sector and are described in detail below.

Electricity Generation

When examining electricity generation over a period of time for a given set of generating stations and end users, emissions intensity (EI_{Elec}) can generally be calculated as

$$EI_{Elec}(t) = \frac{\sum_{FFtype}(EG_{FFtype}(t) \bullet EF_{FFtype})}{EG_{Total}(t)} \tag{3}$$

where EG_{FFtype} is the total electricity generated using a given fossil fuel type (coal, natural gas) in MWh, EF_{FFtype} is the emissions factor of a fossil fuel generating station type (t CO_2e / MWh) and EG_{Total} is the total electricity generated. Total GHG emissions from electricity generated are given as

$$GHG_{Electricity}(t) = \sum_{End\,Use} EI_{Elec}(t) \bullet \frac{EC_{EndUse}(t)}{1 - LL(t)} \tag{4}$$

where EC_{EndUse} is the total electrical energy usage (MWh) per end-use sector and LL is the fraction of electricity lost in transmission and distribution.

Transportation

Urban transportation GHG emissions are a function of total fuel consumption and the emissions intensity of the secondary energy source used (assumed here to be either gasoline or electricity). Direct annual aggregate private transportation GHG emissions is modeled as a product of the vehicle stock, average vehicle fuel consumption and vehicle kilometers traveled (VKT) for each vehicle type in operation.

$$GHG_{Transport}(t) = \sum_{Model\ \ Year} \sum_{Vehicle\ Type} U(t) \bullet D(t) \bullet C(t) \bullet EI(t) \tag{5}$$

where U is the number of units of a given vehicle and technology type from a given model year that is currently in operation, D is annual vehicle distance travelled (or Vehicle Kilometers Travelled, VKT) of the vehicle type, *C* is the energy consumption of vehicle type (GJ/km), and EI it is emissions intensity of the energy source (tCO_2e/GJ). The efficiency must be disaggregated for vehicle type in order to allow for sigmoidal diffusion equations of alternative technologies.

Greene (2006) presents a model for estimating vehicle stock change based on life-expectancy, GDP, vehicle price, fuel price and lagged vehicle sales. The total number of vehicles sold annually (*n*) is given as

$$n_t = \left(\frac{GDP_t}{GDP_{t-1}}\right)^{\beta_1} \left(\frac{P_t}{P_{t-1}}\right)^{\beta_2} \left(\frac{p_t}{p_{t-1}}\right)^{\beta_3} \left(\frac{n_{t-1}}{n_{t-2}}\right)^{\lambda} n_{t-1} \tag{6}$$

where in year *t*, GDP_t is the regional gross domestic product, P_t is the average vehicle price, and p_t is the average price of fuel. Elasticities of demand with respect to *GDP*, *P* and *p* are given by β_1, β_2 and β_3, respectively. Effect of lagged vehicles sales is represented by λ. To determine the number of vehicles sold in a given year that rely solely on an internal combustion engine (ICE) powertrain, the following simplified approach is taken in the PURGE model

$$f_{ICE}(t) = 1 - f_{ALT}(t) \tag{7}$$

where f_{ICE} is the fraction of new vehicles sold using ICEs and f_{ALT} is the fraction of vehicles sold employing alternative powertrains. The value of n_t is then multiplied by either f_{ICE} or f_{ALT} to give the number of vehicles of each powertrain type sold in a given year.

Greene (2006) also provides a three-parameter logistic model for predicting vehicle scrappage rate (σ) based on vehicle age (*a*).

$$\sigma_a = 1 - \frac{1}{B_o + e^{B_1 + B_2 a}} \tag{8}$$

Population of a given model year (P_i) for either cars or light trucks is given by

$$P_i = P_{i-1} - \sigma_a \tag{9}$$

Annual vehicle use is presumed by Greene to exponentially decay; as vehicles age, usage declines. Annual vehicle usage (*U*) is given as

$$U_a = U_o e^{-\delta a} \qquad (10)$$

where δ is the annual exponential rate of decline in VKT for a vehicle of age a and U_o is the VKT by a vehicle in its first year of operation. The PURGE model does not take the rebound effect into account (which Greene applies in his model), where energy savings are offset somewhat by increases in use due to cost savings. U_a is assumed to be constant across each class of car. By excluding the rebound effect, a positive influence on GHG emissions is neglected; as absolute energy costs decrease, energy consumption has historically increased. In transportation, the magnitude of the rebound effect has generally been observed to lie between 10-30% (i.e. for a reduction in fuel consumption through vehicle efficiency, 10-30% of that reduction is lost due to increased vehicle usage; Hymel et al, 2010). The magnitude of the rebound effect in the future is uncertain, given potential energy price volatility and carbon pricing. Hence, this approach can be viewed as an optimistic scenario of future emissions from passenger vehicles. U_a is assumed to be constant across each class of car.

The diffusion of alternative vehicles into the vehicle stock is assumed to follow logistic diffusion (i.e. a symmetrical sigmoidal curve). In calculating the f_{ALT} (see equation 11), the following is applied

$$f_{ALT}(t) = \frac{K}{\frac{K - f_o}{f_o} e^{-at}} \qquad (11)$$

where K is the ultimate fraction of new vehicle sales for alternate powertrain vehicles, f_o is the fraction of new vehicles sold that utilize an alternative powertrain at $t = 0$, and a is rate of adoption.

The number of vehicle technologies is not fixed and can be modified as needed. This can be adjusted in one of two ways; first, by altering the quantity and/or proportion of fuel/electricity applied to vehicle energy consumption (associated with the variable C in Equation 5); second, but adjusting the emissions intensity of given fuels (electricity or fuels used; EI in Equation 5). For example, in a case where biofuel-based vehicles were to gain in prominence, the fraction of vehicles of this type would be calculated using Equation 11, while the associated value of EI would be adjusted accordingly based on the changing composition of vehicle stock.

Buildings

In many cities, buildings generally directly emit GHG emissions through the provision of heating services (i.e. water or space). However, upstream GHG emissions associated with building operations include electricity generation and material consumption / disposal. The focus of this module is on GHG emissions associated with building heating and electrical energy demand, as operating energy is the largest component of building energy use (Sartori and Hestnes, 2007).

Based on the complexity related to the factors associated with energy demand, GHGs from buildings are modeled as the sum of emissions from each type of building (single family dwelling detached, multi-unit residential (MURs), retail trade, etc.) and both electrical and fossil fuel energy usage using

$$GHG_{Buildings}(t) = \sum_{Era} U(t) \bullet \bar{A} \bullet \left[\sum_{Fuel} C(t) \bullet EI(t) \right] \qquad (12)$$

where, for a given era, U is the total number of units of a given building type, $\bar{A}$ is the average floor space of the building type (m^2), C is the energy consumption of the given building type (either electrical or fossil energy; GJ/m^2) and EI is emissions factor of the energy source used (CO_2e/GJ). It is possible to capture a change in the type of energy consumed in buildings to provide energy services (e.g. space heating, water heating), through the revision of the proportion of heating demand that is supplied through fuels or electricity (e.g. adjusting consumption data so that more energy is consumed in the form of electricity (C_{elec}) rather than natural gas (C_{NG})) and then adjusting of the electricity grid or fuel emissions intensity.

Residential Buildings

Given the total stock of buildings demanded (which can be forecasted based on population data and average inhabitants per unit type), estimations of building-type mix, and declines in housing stock, the building stock replacement rate and composition can be calculated. One can estimate the rate of energy efficiency improvement using this change in building stock composition. The cumulative number of new houses required from t = 0 can be modeled using

$$U_{Type,New}(t) = \frac{P(t)}{O_{Type}} \bullet f_{Type} - \sum_{Era} U_{Type,Era}(t) \qquad (13)$$

where for a given housing type (single family or apartment) constructed in a given year, $U_{Type\ New}$ is the number of new units, $U_{Type,Era}$ is the number of old units from a specific era, $P(t)$ is the population in year t, O is the number of occupants per unit of a particular dwelling type and f_{Type} is the fraction of the urban population living in a dwelling type.

$$U_{Type,Era}(t) = U_{Type,Era}(t-1) - D_{Type,Era}(t) \qquad (14)$$

where D is the cumulative number of units demolished (a function of building age and is assumed to be linear in the PURGE model). This is given as

$$D_{type,era}(t) = A \bullet \varphi \qquad (15)$$

where A is the building age in years and φ is the rate of demolition (units / yr).

Retrofits to existing buildings are assumed to follow a sigmoidal adoption curve (see explanation in “Projected Emissions from a Business-as-Usual Scenario – Buildings”). This applies Equation 11 with some modifications to the definition of the variables; in the case of buildings, K is the ultimate fraction of buildings to adopt the retrofit, f_o is the fraction of properties that are retrofitted in the year $t = 0$, and a is the rate of adoption. The only alternative being applied would be a retrofitted building, replacing the current average energy consumption of a given type/vintage. As a result, *C(t)* is variable over both building vintage and time. As the number of buildings retrofitted increases, the average value of C(t) will decrease for any given vintage of building.

Commercial and Institutional Buildings

While the residential building stock is suggested to be correlated with population growth, commercial and institutional buildings are assumed to be reliant on GDP growth. GHG emissions are calculated using Equation 12, with slight modifications. Averages of sector-specific intensity for a given energy source (in GJ / m^2) is multiplied by total floor area of that sector, rather than using era and number of units. Total floor area per sector is scaled from provincial data based on employment numbers in each sector in the GTA (obtained from census data; Statistics Canada, 2006) and resultant emissions are calculated for each sector. Estimates in growth in GDP provide a means to calculate increases in floor area, assuming a fixed GDP/m^2 of gross floor area (GFA). Commercial floor area growth for an individual sector in a given year is calculated using

$$\Delta A_{Sector}(t) = \Delta GDP(t) \bullet \left(\frac{f\ (t)}{(GDP\ /\ A)_t} \right)_{Sector} \qquad (16)$$

where f is the fraction of GDP growth attributed to a given sector, and $(GDP/A)_t$ represents the GDP per unit of floor area in a given sector in year t.

Waste

Residential waste production in the PURGE model takes into account population and residential building type, employing data used in the “Buildings” model module. The relationship used is described as

$$Annual\,Waste\,Generation = \sum_i W_i(t) \bullet P_i(t) \qquad (17)$$

where W_i is the waste generated per capita for occupants of a building type i (single family or apartment; single family houses were found to produce nearly 50% more waste by mass than MURs) and P_i is the total urban population dwelling in building type i. Waste is then divided into distinct categories, consistent with those used in IPCC (2006) emissions quantification methodologies: metals, glass, food waste, garden waste, textiles, nappies, rubber/leather, plastics, sludge and other inert materials. This allows for the identification of a diversion strategy for each waste material category, shaping future emissions.

Landfill gas production has been modeled using a first-order decay model with IPCC (2006) methodology. Focusing on methane (CH_4) production, landfill GHG emissions (t CO_2e) are calculated using

$$GHG_{Landfill}(t) = ((DDOC\ decomp(t) \bullet 16/12 \bullet F) - R(t)) \bullet (1 - OX(t)) \bullet GWP_{100} \quad (18)$$

where, in the year *t*, *DDOC decomp* is the mass (in tons) of decomposable degradable organic carbon decomposed, *F* is the fraction, by volume, of CH_4 in LFG, *R* is the amount of LFG that is collected (t CH_4), OX is oxidation factor of the emitted LFG and GWP_{100} = Global Warming Potential based on a 100-year timeframe (25 for CH_4; 298 for N_2O). Information on waste composition is required in order to determine *DDOC decomp* in a given year; detail on this calculation is found in IPCC (2006), with further illustration in Mohareb et al (2011).

The IPCC guidelines provide quantification methodology for incineration, bioreactor anaerobic digestion (AD) and large-scale composting. Emissions from these sources (t CO_2e) are, respectively:

$$GHG_{Incineration}(t) = MSW(t) \bullet \sum_j (WF_j(t) \bullet dm_j \bullet CF_j \bullet FCF_j \bullet OF_j) \bullet 44/12 \quad (19)$$

$$GHG_{AD/Compost}(t) = [(MSW(t) \bullet EF_{GHG}) \bullet 10^{-3}(1-R(t))] \bullet GWP_{100} \quad (20)$$

where *MSW* is the mass of wet waste treated for the given treatment type, Gg/yr; WF_j is the fraction of component *j* in the *MSW*, dm_j is the fraction of dry matter in component *j*, CF_j is the fraction of carbon in dry matter of component *j*, FCF_j is the fossil carbon fraction in of component *j*, OF_j is the oxidation factor, 44/12 is the conversion factor from C to CO_2, *EF* is the emissions factor (kg / t waste treated; 4 for $CH_{4\ compost}$, 0.3 for $N_2O_{compost}$, and 1 for CH_{4AD}) and *R* is the gas recovered (t; 0 for composting, 95% for AD).

Amlinger et al (2008) provide empirical data on GHG emissions from the degradation of waste in residential-scale composting units. This is applied to the PURGE model using the equation

$$GHG_{Backyard}(t) = \sum_{GHG} MSW(t) \bullet EF_{GHG} \bullet GWP_{100} \quad (21)$$

where the emissions factor for small scale composting is $2.2\text{x}10^{-3}$ and $0.45\text{x}10^{-3}$ (tons / ton of wet waste composted) for CH_4 and N_2O, respectively.

Of the waste treatment options described above, incineration, AD and landfilling have the capability to generate electricity through CH_4 capture, when the necessary infrastructure is in place. For landfill gas and AD, electricity generation is calculated using

$$EG\ (t) = MR(t) \bullet LHV \bullet \eta \bullet \frac{1\,GWh}{3.6\,TJ} \tag{22}$$

where *MR* is the mass of methane recovered (in tons; can be calculated using equations 18 and 20), *LHV* is the lower heating value of methane (50 x 10^{-3} TJ / t) and η is the efficiency of the conversion device. For incineration, an electrical conversion factor per ton of waste combusted of 0.480 x 10^{-3} GWh / t is used (Denison, 1996).

Forestry

Biomass, soil and dead organic matter (DOM) represent some of the principle carbon sinks for most nations. In the 2008, forestry provided 83 & 57% or (704 & 18 Mt CO_2e, excluding credits from harvested wood products) of net carbon sinks in the US and Canada, respectively (USEPA, 2010b; Environment Canada, 2010). Examining these at the urban level will provide some insight on the potential impact of municipal policy decisions in directly offsetting their carbon sources.

It is generally held that, on average, biomass growth follows a sigmoidal curve with respect to its volume/mass, and hence, carbon sequestered (Botkin, 1993). Initially, growth follows an exponential curve, but slows as time progresses. The slowing of biomass growth in forests as they mature is due to competition with other species for limited access to solar radiation at / through the tree canopy and the annual loss of litter from limbs and branches. In essence, this implies that at an equilibrium point, solar radiation utilized by a tree will simply maintain a balance between biomass growth and losses, and any gains in carbon storage will come from increases in soil and DOM stocks.

The CBM-CFS3 forest carbon budget modeling tool, based on an IPCC Tier 3 approach to carbon dynamics in forests, allows the development of carbon storage curves based on yield data for given forest species. Using Plonksi's yield curve data, carbon stock change curves were developed for tolerant hardwoods and white pines (to represent softwoods) in the case study described below (Plonski, 1974). It should be noted that these curves are species and climate dependent and would require further development for application of this model elsewhere. These curves are applied to regional forest stands (i.e. forested areas outside of settlements), for both afforestation and existing forest tracts. The annual carbon sink provided by all regional forest stands in tCO_2e is given as

$$GHG_{RF}(t) = \left[\sum_{S\tan d} [C_{DOM}\,(t) + C_{Biomass}\,(t)] \bullet A_i \right] \bullet {}^{44}\!/\!_{12} \tag{23}$$

where *RF* is regional forest, C_{DOM} and $C_{Biomass}$ are the carbon sequestered in dead organic matter and living biomass (t C), respectively, and A_i is the area of forest stand of age *i* (ha).

For urban carbon storage in forests within settlements, the IPCC (2006) approach is applied to quantify t CO_2e, using the equation

$$GHG_{UF}(t) = \Sigma A_{i,j} \bullet CRW_{i,j} \bullet 44/12 \qquad (24)$$

where *UF* is urban forest, $A_{i,j}$ is the total crown cover area of class *i* woody perennial type j (ha), $CRW_{i,j}$ is crown cover area-based growth rate of class i in woody perennial type j, (t C / ha).

Projected Emissions from a Business-as-Usual Scenario

The Greater Toronto Area (GTA) has a number of explicitly-stated GHG emission reduction strategies in place, allowing for the application of the PURGE model. These have been used to develop a business-as-usual (BAU) scenario for each sector and to quantify total emissions projected to 2050. Detailed information on assumptions made in the BAU scenario is provided in Table 2. Two key underlying assumptions are a 2.0% annual GDP growth (below the 1998-2008 average of 4.5%; Statistics Canada, 2011d) and a 1.4% annual increase in population (Ontario Ministry of Finance, 2010). GDP intensity (the second term in Equation 1) is not directly incorporated into the PURGE model; however, it may be modified is by adjusting the GDP per GFA from the commercial sector (see Equation 16) or by modifying the elasticity associated with GDP in the vehicle purchase equation (β_1; see Equation 6), perhaps by making it variable over time.

Table 2: Parameters Applied to PURGE Model for BAU Scenario

Parameter	Assumed Value	Comments on Data Source	Relevant Equations
Universal Parameters			
2006 Population	5,798,100[a]	National census data	13
Annual Population Growth	1.4%	Provincial estimates for the GTA	13
Gross Domestic Product Growth (Ontario)	2.0%	Provincial GDP growth observed between 1998-2008	16
Transportation			
# of VKT in First Year of Operation	23,000[b]	Estimate of Canadian VKT from Greene (2006)	5
Price of Gasoline, 2008	94.6[c] + 2¢ annually		6
Vehicle Purchase Price	23,000[d]	Average price of a new car in 2008 (US data)	6
Fuel Economy			
Annual Fuel Economy Increase (all Technologies)	1%	Slightly less than the observed average annual increase of 1.7% between 1975-2009[d]	5

Average ICE Fuel Economy in 2010 – Cars (MJ / km)	3.1[e]	US National Data	5
Average ICE Fuel Economy in 2010 – Light Trucks (MJ / km)	4.2[e]	US National Data	5
Average HEV Fuel Economy in 2010 – Cars (MJ / km)	3.12[e]	US National Data	5
Average HEV Fuel Economy in 2010 – Light Trucks (MJ / km)	3.77[e]	US National Data	5
Average PHEV Fuel Economy in year 1 - Gasoline (MJ / km)	1.54[f]	Literature estimate	5
Average PHEV Fuel Economy in year 1 - Electric (MJ / km)	0.48[f]	Literature estimate	5
Average BEV Fuel Economy in year 1 - Gasoline (MJ / km)	0.0		5
Average BEV Fuel Economy in year 1 - Electric (MJ / km)	1.11[g]	Literature estimate	5
Ratio of Gas to Electricity Consumption for PHEV	1:3[h]	Literature estimate	5
Final Market Share of Electric-Based Vehicles (PHEV:BEV)	70% (4:3)		5, 11
Proportion of Ontario Vehicle Sales Completed in the GTA	44%[i]	Regional data	6
First Year of PHEV Sales	2010	Release of Chevy Volt	11
First Year of BEV Sales	2010	Release of Nissan Leaf	11
β_1, β_2, β_3, λ – Cars – Obtained using historical data for each parameter and the Excel Solver tool	0.227, 3.606, 0.268, 0.679	Apply provincial GDP growth, US vehicle price, regional fuel prices and provincial vehicle sales data	6
β_1, β_2, β_3, λ – Trucks – Obtained using historical data for each parameter and the Excel Solver tool	0.316, 0.730, -0.228, 0.704		6
B_0, B_1, B_2 (cars/light trucks)	4, 5.2781, -0.3306/-0.2682[b]	Obtained from Canadian national estimates applied in Greene (2006)	8
K, a, b– Obtained using historical data for each parameter and the Excel Solver tool	1, 0.008, 0.4128[e]	Applies US historic sales data	11
	Buildings		
Proportion of Single Family Dwelling– Attached (SFDA)	20.1%[j]	Regional data	12
Proportion of SFD – Detached (SFDD)	52.2%[j]	Regional data	12
Proportion of Multi-Unit Residential (MUR)	27.6%[j]	Regional data	12
Occupants per SFD-Attached	2.94[j]	Regional data	13
Occupants per SFD-Detached	3.27[j]	Regional data	13
Occupants per MUR	2.14[j]	Regional data	13
φ_{SFDD}	-14.9[k]	Regional data	15
φ_{SFDA}	-3.6[k]	Regional data	15
φ_{MUR}	-12.6[k]	Regional data	15
Domestic Hot Water$_{SFDD}$ (GJ / Cap)	7.71[k]	Provincial data	12
Domestic Hot Water$_{SFDA}$ (GJ / Cap)	8.30[k]	Provincial data	12
Domestic Hot Water$_{MUR}$ (GJ / Cap)	9.89[k]	Provincial data	12
	Building Energy Use Intensity Properties		

Single Family Detached Properties	**Heat (GJ/m^2)[k]**	**Electricity (kWh/m^2)[l]**	**Avg Floor Area**		

			(m^2)[k]		
Before 1946	1.01	40.9	148.24	[k] Provincial data, [l] regional estimate from literature	12
1946–1960	0.74	40.9	126.69		12
1961–1977	0.60	39.5	143.24		12
1978–1983	0.51	39.5	169.53		12
1984–1995	0.44	37.7	189.56		12
1996–2000	0.37	37.7	187.77		12
2001–2005	0.36	37.7	195.66		12
2006–2012	0.29	37.7	195.66	[k] 2006 held constant	12
2012-2050	0.24	37.7	195.66	[k] 2006 -2012 held constant	12
Single Family Attached Properties [k]	**Heat (GJ/m^2)**	**Electricity (kWh/m^2)**	**Floor Area (m^2)**		
Before 1946	0.91	40.9	125.05	[k] Provincial data, [l] regional estimate from literature	12
1946–1960	0.67	40.9	126.68		12
1961–1977	0.54	39.5	114.36		12
1978–1983	0.46	39.5	122.31		12
1984–1995	0.39	37.7	119.55		12
1996–2000	0.33	37.7	133.39		12
2001–2005	0.32	37.7	147.29		12
2006–2012	0.29	37.7	147.29	[k] 2006 held constant	12
2012-2050	0.24	37.7	147.29	[k] 2006 -2012 held constant	12
Multi-Unit Residential Properties	**Heat (GJ/m^2)**[k]	**Electricity (kWh/m^2)**	**Floor Area (m^2)**		
Before 1946	0.7	40.9	84.1	[k] Provincial data, [l] regional estimate from literature	12
1946–1960	0.5	40.9	83.7		12
1961–1977	0.4	39.5	85.2		12
1978–1983	0.4	39.5	96.3		12
1984–1995	0.3	37.7	90.2		12
1996–2000	0.3	37.7	85.6		12
2001–2005	0.3	37.7	96.5		12
2006–2012	0.2	37.7	97.1	[k] 2006 held constant	12
2012-2050	0.2	37.7	97.1	[k] 2006 -2012 held constant	12
Single Family Home Detached Retrofit Improvements (OEE, 2010)					
	Natural Gas	**Electricity**			
before 1946	-26.63%	-10.26%		Regional data	12
1946 to 1960	-25.25%	-12.29%			12
1961 to 1970	-22.42%	-10.01%			12
1971 to 1980	-18.78%	-10.00%			12
1981-1990	-16.39%	-9.14%			12
1991-2000	-16.96%	-5.22%			12
2001 – 2010	-15.87%	-6.17%			12
Single Family Home Attached Retrofit Improvements (OEE, 2010)					
	Natural Gas	**Electricity**			
before 1946	-26.62%	-7.75%		Regional data	12
1946 to 1960	-25.48%	-8.88%			12
1961 to 1970	-22.77%	-6.52%			12
1971 to 1980	-20.04%	-9.83%			12
1981-1990	-17.81%	-12.15%			12
1991-2000	-16.06%	-9.78%			12

2001 – 2010	-15.83%	-2.34%			12
Multi Unit Residential Retrofit Improvements (OEE, 2010)					
before 1946	-24.32%	-37.15%		Regional data	12
1946 to 1960	-26.51%	-9.54%			12
1961 to 1970	-12.04%	-14.44%			12
1971 to 1980	-26.46%	-1.88%			12
1981-2010 (due to small sample size)	-22.33%	-15.75%			12
Commercial and Institutional Buildings – 2008 Intensity (OEE, 2010)					
Sector	**Electricity (MJ/m^2)**	**Natural Gas (MJ/m^2)**	**Fuel Oil (MJ/m^2)**		
Wholesale Trade	914.7	840.1	23.5	Provincial data	12
Retail Trade	932.8	854.5	23.9		12
Transportation and Warehousing	675.0	728.1	72.3		12
Information and Cultural Industries	894.4	681.3	131.1		12
Offices	752.2	691.8	61.3		12
Educational Services	894.4	770.0	63.5		12
Health Care and Social Assistance	1,352.2	1,145.4	147.3		12
Arts, Entertainment and Recreation	999.3	767.2	147.8		12
Accommodation and Food Services	1,242.2	1,235.0	73.8		12
Other Services	855.5	718.9	91.1		12
Commercial and Institutional Buildings – Energy Intensity of High-Performance Buildings [m]					
Sector	**Electricity (MJ/m^2)**		**Natural Gas (MJ/m^2)**		
Wholesale Trade	434.6		158.2	Regional data	12
Retail Trade	559.5		442.9		12
Transportation and Warehousing	251.5		128.7		12
Information and Cultural Industries	496.2		169.5		12
Offices	380.9		224.9		12
Educational Services	305.0		255.8		12
Health Care and Social Assistance	400.1		171.1		12
Arts, Entertainment and Recreation	485.3		217.6		12
Accommodation and Food Services	495.1		1102.8		12
Other Services	423.1		319.1		12
Commercial and Institutional Sector Properties					
Sector	**% of GDP Growth** [j]	**\$ GDP / m^2** [j,k]	**2008 Floor Space (m^2)** [j,k]		
Wholesale Trade	10.4%	\$1,993.04	9,486,293	[j] Regional data; [k] Provincial data scaled by regional activity	16
Retail Trade	6.9%	\$ 668.20	9,517,943		16
Transportation and Warehousing	5.2%	\$ 1,632.15	5,561,269		16
Information and Cultural Industries	6.9%	\$ 3,454.68	3,614,344		16

Offices	51.9%	$ 1,424.22	61,761,851		16
Educational Services	5.6%	$ 700.72	14,577,699		16
Health Care and Social Assistance	6.6%	$ 1,696.24	7,177,312		16
Arts, Entertainment and Recreation	1.2%	$ 909.59	2,422,883		16
Accommodation and Food Services	2.3%	$ 849.92	4,966,584		16
Other Services	3.1%	$ 2,202.57	2,450,530		16
Waste					
Waste Generated – SFD (t/cap)[n]		0.370		Regional data	17
Waste Generated – MUR (t/cap)[n]		0.220		Regional data	17
Treatment Parameters					
Fraction of Methane in LFG (F)[o]		0.5		Estimates from respective literature sources	18
LFG Oxidation Rate (Ox)[o]		0.1			18
LFG Recovered (R)[o]		0.75			18
GWP of Methane[p]		25			18
Incineration Oxidation Factor (OF)[p]		1			18
Material	**% of Waste Generated**	**2050 Waste Treatment Target w/ 2005 Percentages on Diversion (L/AD/I/MC/BC/R)[q]**			
Metals	2.55%	100% Recycled (58 / 0 / 7 / 0 / 0 / 34)		Authors' estimates based on current policy directions in municipalities in the Greater Toronto Area	19, 20, 21
Glass	4.99%	100% Recycled (22 / 0 / 3 / 0 / 0 / 74)			19, 20, 21
Food Waste	22.23%	96% Anaerobically Digested, 4% Backyard Compost (47 / 41[r] / 7 / 0 / 4 / 0)			19, 20, 21
Garden	11.37%	92% Incinerated, 8% Backyard Compost (0 / 0 / 0 / 91 / 8 / 0)			19, 20, 21
Paper	23.68%	100% Recycled (36 / 0 / 6 / 0 / 0 / 57			19, 20, 21
Textiles	4.34%	100% Incinerated (90 / 0 / 10 / 0 / 0 / 0)			19, 20, 21
Nappies	1.90%	100% Incinerated (73 / 4 / 22 / 0 / 0 / 0)			19, 20, 21
Rubber / Leather	0.14%	100% Incinerated (92 / 0 / 7 / 0 / 0 / 1)			19, 20, 21
Plastics	7.71%	100% Recycled (74 / 1 / 7 / 0 / 0 / 17)			19, 20, 21
Other inert waste	11.78%	100% Landfilled (80 / 0 / 6 / 0 / 0 / 1)			19, 20, 21
Sludge	8.00%	100% Anaerobically Digested (100 / 0 / 0 / 0 / 0 / 0)			19, 20, 21
Wood / Straw	1.29%	100% Incinerated (93 / 0 / 6 / 0 / 0 / 1)			19, 20, 21
Forestry					
Average Forest Age		60 years (softwood and hardwood)[s]		Regional data	23
Area of Forest Stand		65,400 ha		Regional data	23
% Hardwood[t]		66.67%		Regional data	23
% Softwood[t]		33.33%		Regional data	23
Area of Crown Cover		47,200 ha		Authors' estimates	24
Crown-based Growth Rate[o]		2.9 tC ha^{-1} yr^{-1}		Estimate from literature	24

[a] Ontario Ministry of Finance, 2009; [b] Greene, 2006; [c] Statistics Canada, 2011b; [d] Davis et al, 2010; [e] USEPA 2010a; [f] Shiau et al. 2009;
[g] Torchio and Santarelli, 2010 ; [h] Zackrisson et al. 2010; [i] Ontario Ministry of Transportation, 2010; [j] Statistics Canada, 2006; [k] Office of Energy Efficiency, 2010; [l] From Dong et al, 2005; [m] Approximated using USGBC (2011) case studies; [n] Stewardship Ontario, 2009; [o] IPCC, 2006;

[p] IPCC, 2007; [q] L = Landfilled, AD = Anaerobically Digested, I = Incinerated, MC= Municipally Composted, BC=Backyard Composted, R = Recycled; [r] Assumes all source-separated organic waste is AD'd; [s] Gillis and Power, 2001; [t] Ontario Ministry of Natural Resources, 2001

Electricity Generation

The Ontario Government has set an aggressive strategy to reduce the emissions intensity of its power generation, with plans to close all coal-fired electricity generating stations by 2014 (Ministry of the Environment, 2009). Grid GHG emissions intensity (gCO_2e / MJ) up until the final decommissioning of these plants is provided by the OPA (2010, personal communication). It is assumed that after 2015, emissions intensity is held constant (Figure 2). The losses due to transmission are held constant, but since the structure of the model allows them to be variable, this does not have to be the case. There is currently a limited strategy for distributed power generation within the Greater Toronto Area (some allocation for roof-top PV, but minimal when considering total grid capacity), with the future plans for the grid relying predominantly on centralized technologies such as nuclear, natural gas, solar/wind farms and hydro electric (OPA, 2008).

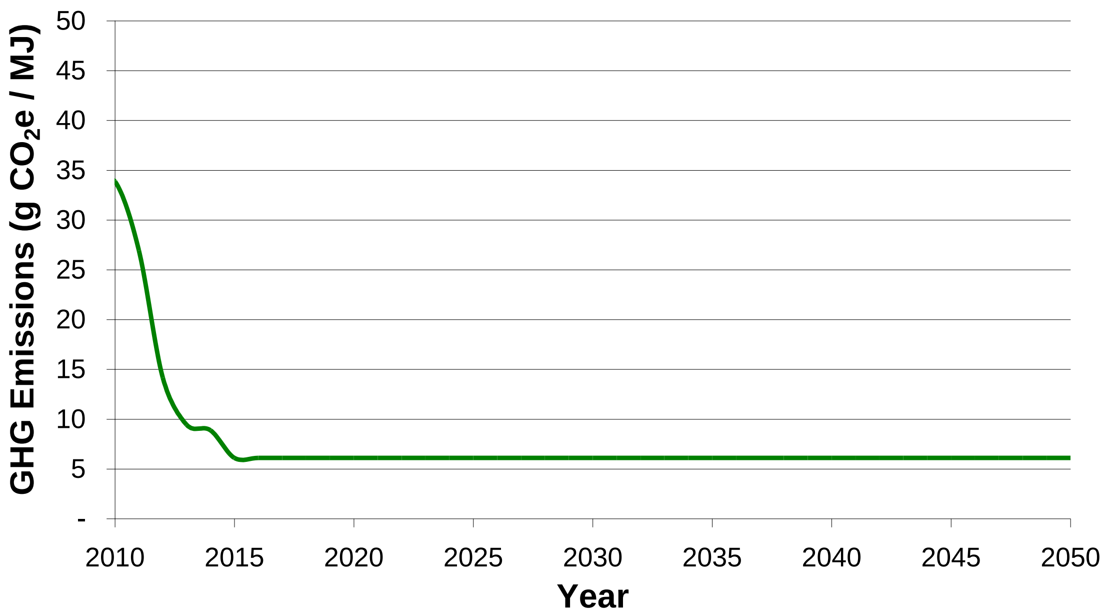

Figure 2: Unofficial OPA projections for grid emissions intensity to 2050

Transportation

The province of Ontario plans for 1 in 20 vehicles to be electric vehicles (EVs) by 2020 (Government of Ontario, 2009). Interpreting this, 5% of all vehicles on the road (as opposed to annual sales) will be electric-based (Battery Electric Vehicles (BEV) or Plug-in Hybrid Electric Vehicles (PHEV)). In order to accomplish this, the government currently provides rebates of up to $10,000 toward the purchase of an EV (depending on vehicle battery capacity). Applying the Greene model along with the parameters outlined in Table 2, the entire vehicle stock in the GTA in 2020 is estimated to be 2.97 million; this would require 150,000 electric vehicles to be operating on GTA roads at that time if "1 in 20" target is to be met. Emissions intensity of gasoline is held constant, given that there are no provincial/federal programs currently in place that would reduce the carbon intensity.

All alternate vehicles assessed here have an electric component (HEVs, PHEVs, & BEVs); hence, they are categorized into a single replacement technological category (i.e. all alternative replacing ICEs). This assumes that gains in battery technology (storage capacity gains, economies of scale, and progress ratios in general) benefit all electric vehicle types. It is assumed that HEVs are a transitional technology towards PHEVs and BEVs (Suppes, 2006).

The path of alternative technology vehicle adoption is examined within both the context of the diffusion trends observed in US sales data and from the goal stipulated by the Ontario government. Historical US vehicle sales data (2000-2010) provide the first part of a substitution curve for alternative vehicle diffusion (HEVs; USEPA, 2010a). Applying these alternative vehicle substitution data to fit a curve and using the Excel Solver tool to provide a rate of diffusion for that provides the 150,000 vehicle figure (yielding values of *b* of 0.4908 and 0.4926 for PHEVs and BEVs, respectively; see Equation 11), a technological replacement curve is developed. The change in percentage of battery-based vehicle sales is seen in Figure 3, with both the current diffusion rate (based on regression of current sales) and the diffusion rate required to achieve the "1 in 20 by 2020" goal. In both cases, the rapid adoption rate suggests all new vehicle sales by 2030 will be battery-based vehicles – an optimistic scenario for this technology.

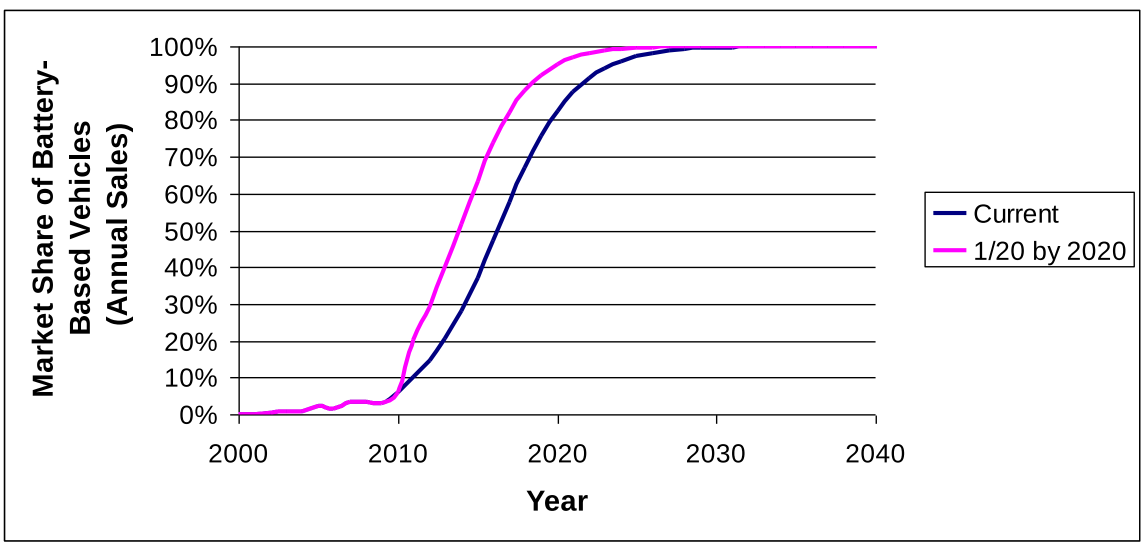

Figure 3: Projections of Market Diffusion of Alternative Vehicles Using Current and Government Rates of Adoption

A metric used to determine the relative speed of diffusion of a given technology is the profile of diffusion rate (or Δt), the time elapsed between 10% and 90% market penetration (Grubler, 1997). The current rates of diffusion, using historical US sales data and Ontario government targets, demonstrate Δt's of 11 and 8 years respectively.

Whether or not these seem to be realistic diffusion rates can be determined by examining the diffusion of previous automotive technologies. For passenger cars, port metering, variable valve timing and front-wheel drive, as examples, demonstrate Δt's of 10, 15 and 19 years, respectively (USEPA, 2010a). Given market subsidies for their adoption, it may be possible that diffusion rates for battery-based vehicles fall at the lower end of this range.

Buildings

With a fixed or growing population, building energy consumption reductions can only occur either through building retrofits / equipment upgrades or through demolition and rebuilding of existing structures. The PURGE model is able to model both of these approaches in the transition to a more efficient building stock.

There are currently three programs that would impact both of the approaches mentioned above. The first is the national Eco-Energy Retrofit program which provides financial incentives to residential and ICI sectors to retrofit existing structures to reduce energy use. The second is the 2012 update to the provincial building code, which will impact the energy efficiency of new construction in industrial, commercial and institutional (ICI) and residential sectors after 2011. The final program is the Tower Renewal Strategy, which aims to encourage the retrofitting of existing multi-unit residential (MUR) buildings (City of Toronto, 2010).

The Eco-Energy retrofit for homes program was a federal program (provided in conjunction with a similar scheme at the provincial level) that targeted specific retrofit strategies for subsidisation (e.g. high efficiency furnaces, air-source heat pumps). This program accepted applications from 2007-2009 and again in 2011, and required pre- and post-retrofit energy audits to verify improvements. Detailed data from these audits were collected by the Office of Energy Efficiency, allowing for the assessment of energy savings and energy-use intensity (EUI) per unit of area by era of construction. The adoption curve presented in Figure 4 summarizes the number of residences retrofitted nationally by the end of the first quarter of 2011, suggesting an exponential growth in the number of adopters. This is the basis for the use of a logistic curve for adoption of retrofits. Applying energy savings data for the GTA, an approximation has been made on energy savings by dwelling age, along with the rate of adoption. It is assumed that complete adoption of retrofits is accomplished by the building stock (a *K* value of 1, using Equation 11).

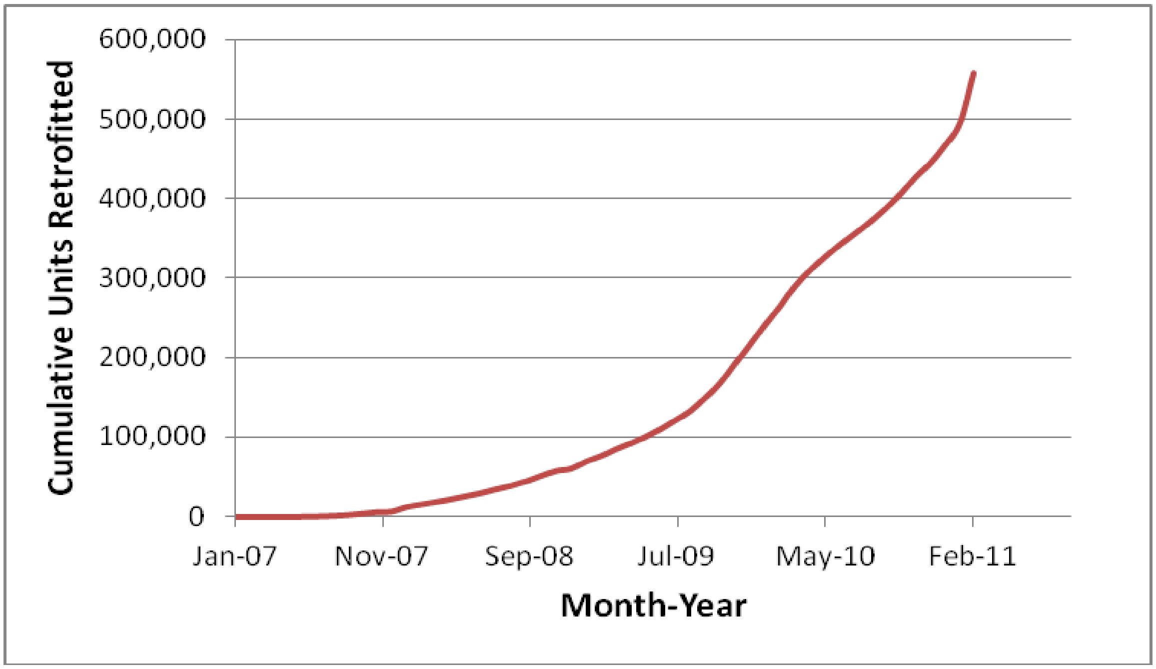

Figure 4: Number of Retrofit Exit Audits Registered Over Time (Source: Personal Communication, Office of Energy Efficiency, 2011)

The 2012 building code update states that the improvements will result in 35% energy savings relative to the existing code (Ministry of Municipal Affairs and Housing, 2010). For application to the PURGE model's BAU scenario, the 35% savings is applied to space heating energy requirements for all new construction occurring in 2012 and beyond.

The contribution of commercial and institutional sectors to GDP in the GTA is taken from provincial and regional data (Statistics Canada, 2006; 2011c). GDP and energy intensity of industries (per m^2) is tabulated using the data from OEE (2009). Sectors examined are seen in Table 2, as well as the contribution of each sector to GDP growth (assumed constant). Retrofits are assumed to follow a sigmoidal path, to the point where they achieve a 10% reduction in energy use by 2014 (Greening Greater Toronto, 2011). For the retrofit model for commercial and institutional buildings, the initial adoption parameter is 40% of that applied for residential buildings (since total floor area of is 40% that of residential buildings; OEE, 2009) and rate of adoption is selected so that it provides a complete retrofit by 2015. New commercial buildings are assumed to follow a sigmoidal path to reduction of energy use intensity as more efficient methods diffuse into new construction practices. This is suggested by the exponential increase seen in LEED-registered non-residential developments in the GTA (shown in Figure 5) and nationally in the US since 2004 (Yudelson, 2010). High-performance building attributes from LEED certified buildings with similar end uses are used as the ultimate energy intensities of these buildings, using data from LEED certified buildings (USGBC, 2011). Fuel oil in new buildings is assumed to be negligible, as its usage has declined in recent years due to rising prices (OEE, 2009; Stat Can, 2011a).

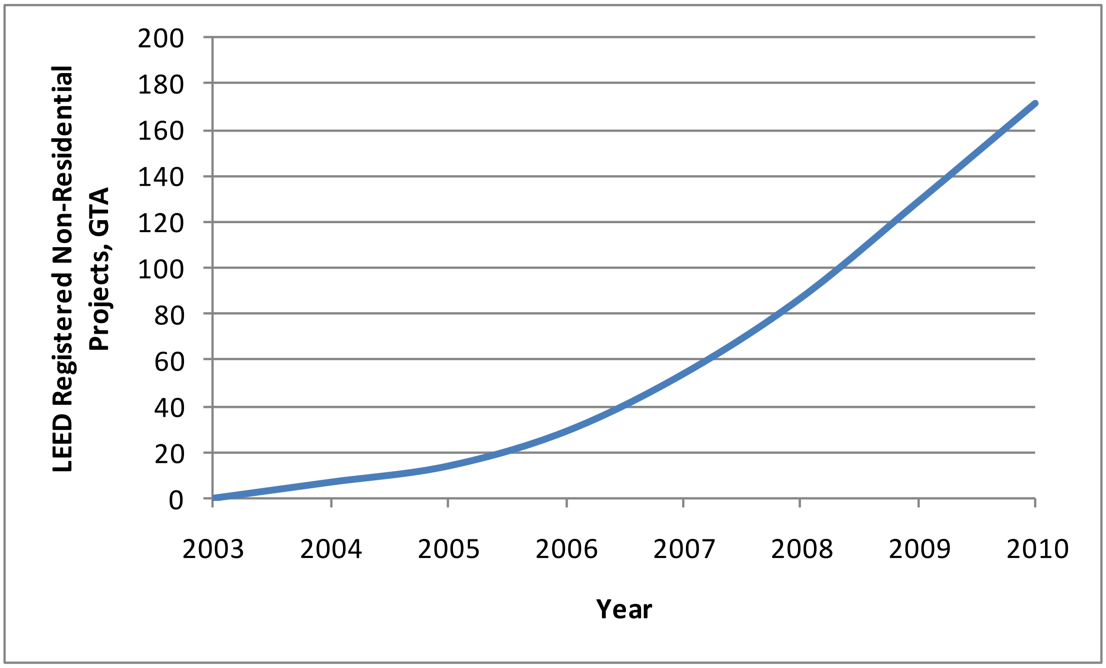

Figure 5: LEED-Registered Non-Residential New Construction Projects in the GTA, 2003-2010 (CaGBC, 2011)

Waste

All municipalities in the GTA have issued long-term waste management strategies for achieving greater diversion from landfills. Generally speaking, municipalities have targeted a 70% diversion rate by 2015. The BAU scenario projects beyond the time horizon suggested by these strategies; hence, the diversion rate is presumed to have exceeded the 70% target by 2050 and reaching 88% (and 100% of organics, which is an optimistic strategy). The diversion targets for each material are reached using a linear interpolation approach (see Table 2 for details). Assuming that the ultimate goal is to minimize landfill as a treatment option while reducing GHG emissions and increasing electricity generation, the diversion strategy summarized in Table 2 is applied to individual materials of interest. It should be noted that these strategies may not in fact be optimal for achieving life cycle GHG emission reductions; they are an estimate based on current trends.

Forestry

The potential expansion of forestry for direct (and indirect) carbon benefits can be categorized into three main groups; urban forestry growth, regional forestry maintenance, and regional afforestation. Urban forestry targets have been identified for a number of cities, while no change is assumed for regional forestry and afforestation. That is to say, it is assumed that no afforestation will take place in the region and existing forests will not be cleared, hence existing regional forests will continue to accumulate carbon in their biomass and within DOM.

The City of Toronto has set a target to increase its urban canopy from its current 17% to 34% (City of Toronto, 2007b). Additionally, the Town of Oakville, with its canopy currently at ~29%, aims to increase its canopy to 40% by 2040 (Town of Oakville, 2006). Since most municipalities in the GTA have yet to complete a UFORE study, an assumption of 17% canopy coverage is applied. Changes in annual carbon sequestration figures are projected to 2050 using the 17% figure and a GTA target of 35% urban canopy. An IPCC (2006) default value of 2.9 t C / ha is applied in this study for CRW (see Equation 24).

Results & Discussion

The City of Toronto states that its medium- and long-term climate goals are to reduce emissions by 30% and 80% by 2020 and 2050, respectively, applying a 1990 baseline (City of Toronto, 2007b). If one were to apply this same target to the GTA, scaling Toronto's per capita emissions to the GTA (using a 1990 inventory completed by Harvey (1993) and 1990 GTA population data) would produce 2020 and 2050 targets of 24.5 and 7 Mt CO_2e, respectively.

Applying the strategies described above using the PURGE model provides results that suggest that these targets are infeasible, primarily due to growth in GDP and population (Figure 6). Total emissions in 2050 are roughly 24 Mt CO_2e, applying a BAU approach that incorporates existing policy initiatives. It is important to note that this scenario does not include future policy or innovations that may result in further efficiency gains of the technology stock, but emphasizes their importance.

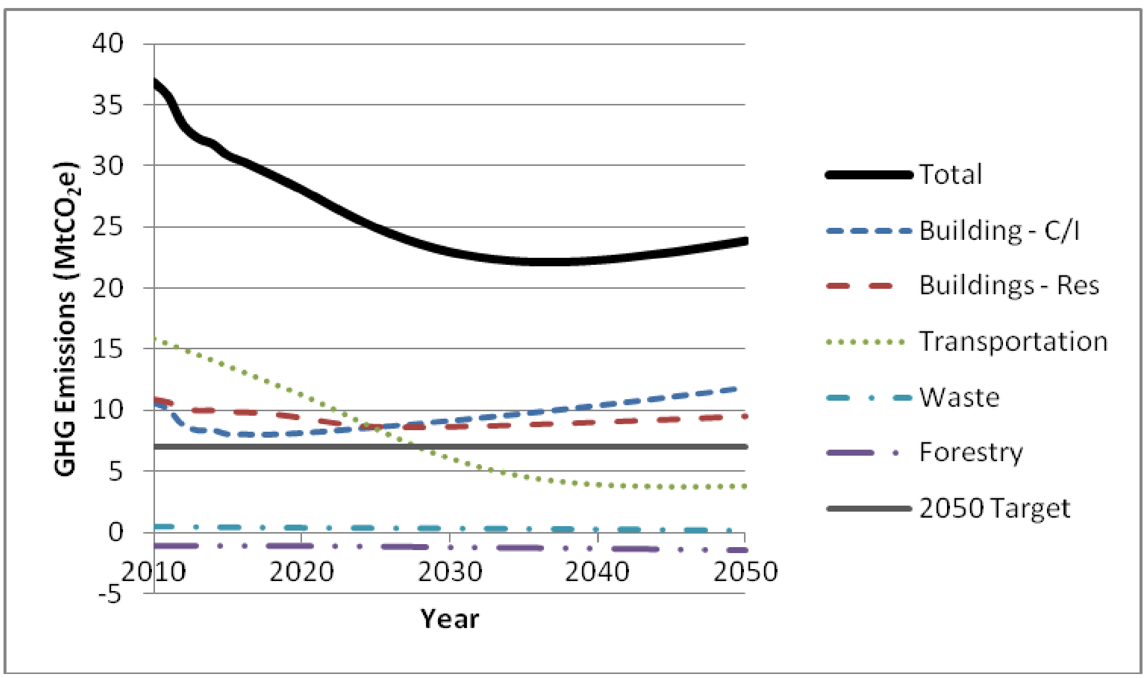

Figure 6: GHG Emissions from sectors quantified using the PURGE model.

Emissions from waste in 2050 (78 kt CO_2e) were reduced to a level that is roughly an 85% reduction from the 2008 estimate. Most of this is attributable to the declines in landfill gas emissions. Further reductions could be realized if petroleum-based plastics are not incinerated. It is of interest to note that 2050 emissions from waste are roughly 5% of the estimated 1.5 Mt of CO_2e stored in urban and regional forests in that year.

Growth in demand for residential and commercial/institutional buildings will be difficult to overcome, in addition to the slow replacement of existing buildings. The modeled scenario above uses a relatively rapid rate of stock demolition and replacement, using data on stock change from given eras suggested by the OEE (2009), roughly 0.4% of the single family unit stock annually. However, by examining building permit data, these estimates may be optimistic; within the City of Toronto, on average, 0.25% of its single family dwelling stock has been demolished per year between 2000-2010 (Personal Communication, City of Toronto, June 2011). The target for complete adoption of retrofits is also likely ambitious, as current retrofits under the program total 7% of the national single-family dwelling building stock; one of the most successful retrofit programs in Canadian history enabled improvements in roughly one third of eligible households (Ferguson, 1993). In addition, average energy savings from subsidized home retrofits were 24% and 5% savings for natural gas and electricity, respectively (dependent on the era of construction; personal communication, Natural Resources Canada, June 2011). For comparison, new housing will result in a 15% and 94% increase to the 2008 total of natural gas and electricity, respectively, for single family dwellings.

To achieve the building sector emissions reductions goals, deeper savings in retrofits and/or a greater rate of replacement are required. As well, future reductions in the building energy code beyond the current 35% target are necessary to prevent increases from this segment of the building stock, as soon as is feasible (revisions would likely be necessary at least every 5 years). Greater measures are required in addressing non-residential building energy consumption, given that current plans only call for a 10% reduction. Finally, retrofitting buildings to utilize non-fossil, low-carbon energy sources for low-grade heating requirements (such as biomass-based furnaces or ground source heat pumps) will be required to maintain low emissions, especially in the context of a growing commercial/institutional building stock and increasing population; this will only be realistic in a scenario that also includes significant demand reduction.

The greatest source of emission reductions was observed in passenger vehicle transportation, primarily due to the transition to battery-based vehicles that rely on a relatively low-carbon electricity grid. Using the diffusion parameters that match government projections in the PURGE model, GHG emissions from GTA private vehicles reach 4 Mt by 2050, a 75% reduction from a modeled 2005 baseline. This suggests that if the government is successful in reaching its goal of an electric-based vehicle stock through its subsidy programs (followed by improved market acceptance), dramatic emission reductions can be achieved; however, it should also be noted that the PURGE model predicts that 20% of new vehicles sold in 2011 will be based on alternative propulsion systems (HEV, BEV, or PHEV). This is a very aggressive target, when considering that 2010 HEV sales in the US were roughly 6% of all vehicles (USEPA, 2010a) and hence the transition to these types of vehicles will likely follow a much slower trajectory (as suggested by Bandivadekar et al, 2008). Additionally, HEVs have an advantage in their adoption since no new infrastructural support is required for their use; BEVs and PHEVs will require significant investment in charging-related infrastructure, which may slow their adoption relative to HEVs. Finally, the model presented here does not apply the rebound effect (unlike the Greene model presented above), which will likely further increase transportation energy demand (and related emissions) when compared to the estimates presented above. Considering these sources of error that will favorably skew emissions reductions, the current strategies for emission reductions may not be sufficient to achieve an 80% reduction (roughly 1.7 $MtCO_2e$ for transportation) from the 1990 baseline.

The scale of adoption of vehicles that rely predominantly on their electric drivetrain has been constrained to 70% (30% BEV, 40% PHEV), with the remaining 30% allotted to HEV; if an alternative system that provides the energy density of fossil fuels, as well as a relatively low purchase price, becomes widely available (i.e. compressed hydrogen, second generation biofuels, ammonia, advanced battery technology, etc.) this could resolve the issue of vehicle range that is assumed to prevent wider adoption.

Fundamentally, eliminating fossil fuels from urban energy systems and shifting towards electricity-based technologies to provide energy services in the building and transportation sectors are vital to attain the IPCC 2050 targets. Additionally, retrofits and building code improvements must be aggressive in their approach, or at least some measure of flexibility to low-carbon alternatives must be implemented in these strategies. Similar conclusions have been observed in other jurisdictions, including the California Council on Science and Technology (2011), which also focuses on decarbonizing industrial energy consumption, such as through the development of a low or zero carbon electricity grid and the application of carbon capture and storage technology. Industrial emissions are a component of urban emissions that have been neglected in PURGE model.

It should be highlighted that behavioral change has not been addressed in this paper, as it was stated earlier that technological change has often been described as the most socially and politically palatable means to mitigate GHG emissions. Even in the context of a developed nation with a relatively stable economy such as Canada and the inclusion of optimistic assumptions in the BAU scenario, current strategies for technological change will likely be insufficient to meet long-term GHG reduction targets. This underscores the need for supporting both behavioral change (e.g. reducing VKT, building thermal energy demands, etc.), as well as more aggressive technological improvements (e.g. deep retrofits, low-carbon propulsion systems in vehicles). The ultimate solution to the climate change mitigation will likely impose a balance of both of these approaches in aggressive doses.

Finally, it is important to note that this research has only examined direct emissions / sinks associated with the GTA. Significant emissions sources exist upstream (such as those embodied in materials and fuel products; Lenzen and Peters, 2009) that must also be addressed on the path to a low-carbon city.

Conclusion

The PURGE model is a tool for emissions scenario development and the results provided must be viewed within the context of the uncertainty of the BAU projection. Generally speaking, the assumption of continued population and economic growth greatly influences the upward GHG emissions trends in the absence of technological change. However, limits on the scale of energy reductions on retrofits that are currently undertaken in the buildings sector will prove to be a major obstacle towards the emissions levels prescribed by the IPCC. Deep retrofits and more stringent building energy code requirements for new construction are necessary, as well as an electricity grid dominated by renewable energy technologies to provide a low-emissions alternative to heating from fossil fuels.

In addition, greater reductions from private vehicle stock change will require infrastructural support (i.e. charging stations) and increased vehicle range. Manufacturing capacity of vehicles incorporating electric propulsion technologies must evolve rapidly to match current government projections; however, the feasibility of industry to do so (as well as the required increase in market demand) is in question.

Waste emissions can achieve the reductions on the scale necessary but only if there is greater diversion of organics and harvested wood products, the benefits of which would provide indirect emissions reductions elsewhere. Urban and regional forest biomass expansion could sequester carbon to offset emissions and should be encouraged, especially in urban areas where additional energy demand reduction benefits can be realised (such as building shading and the mitigation of urban heat island effect). Current policy initiatives are a reasonable starting place, but more aggressive policy must be planned for and adopted to meet the targets required for global equity in efforts to reduce GHG emissions. Additionally, behavioral change, whether instigated through price signals or government subsidies, will be a necessary component of deep emissions cuts.

Give that the rate of diffusion of alternative vehicles, the complete adoption of retrofits in the residential building sector and the anticipated diversion rate of waste from landfill all apply optimistic assumptions, it is clear that a significant challenge lies ahead to meet the 7 Mt emissions target for the GTA. While cities must attempt to meet this challenge, it appears to be prudent policy to consider climate change adaptation measures within the urban context as well.

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